Interaction effects between a tanker and spread moored FPSO in tandem offloading during a squall

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Interaction effects between a tanker and spread moored FPSO in tandem offloading during a squall

by

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This thesis is confidential and cannot be made public.
Abstract

The offshore offloading of oil from spread moored FPSO’s can be performed in multiple ways. Tandem offloading is an offloading principle that is widely used and tandem offloading does not require additional components what is the case with offloading with the use of a remote buoy. However tandem offloading is vulnerable for safety hazards, one of these safety hazards are squalls. Squalls are rapidly changing wind events. Squalls begin suddenly with an increase in wind speed and a change in wind direction and have often a duration of around 30 minutes. Furthermore squalls are very difficult to forecast. In a squall event the offloading has to proceed because proper disconnection takes multiple hours. Therefore is it crucial to know what the responses of the tanker will be during tandem offloading in a squall and which of the different parameters will have an effect on the responses. Furthermore because the FPSO and the tanker are positioned in close proximity it is important to understand what the effect and the consequence will be of the interaction of wind and waves between the two vessels.

The literature describes several response based studies. In these studies the focus is on the effect of squalls to the response of the FPSO’s and the effect squalls have on different mooring systems of FPSO’s. In studies that were performed for tandem offloading is the interaction effect of wind called shielding or shallow effect often mentioned but because of it’s high complexity often neglected. Some studies focus on one position of the tanker but because of the transient effect of squalls this is not sufficient.

In this research is for the study of the ship motions of the spread moored FPSO and tanker in tandem offloading during a squall a numerical model developed in the software package aNySIM. The results provide a time domain description of the motions of multiple bodies for the different environment and loading conditions. Real time squall data is used as input of the model. The ship motions of the multi-body model in squalls are dependent on different parameters. The dependance on these parameters is studied with a sensitivity study for the following parameters: hawser length, tug pull, current speed and wave height. The results of the sensitivity study are use for the discussion of the multi-body responses.

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In the multi-body model in aNySIM is interaction of waves and wind not taken into account. Especially wind interaction can have a large effect on the ship motions during tandem offloading in squalls. The effect of wave interaction on the multi-body system is studied by performing multi-body diffraction with the software WAMIT. For the study of wind interaction a model will be developed in WINDOS. WINDOS works according to the building block model so the model can be build up from blocks from which the drag coefficients are determined with wind tunnel tests. The shielding is incorporated by using the reduced wind velocity from the wake to calculate the wind forces on the tanker. The wind forces will be used to calculate the wind coefficients with shielding. This is done for multiple positions behind the FPSO. The shielded coefficients will be used in time domain to get more insight in what really the effect from wind shielding is on the ship motions. Apart of the interaction does the tug strategy also influence the responses during offloading. The tug is used during offloading for the stationkeeping of the tanker and with the right tug strategy can the safety be improved. A dynamic tug models is developed by making a coupling between aNySIM and LUA.

The outcome of this research is that tandem offloading during a squall can lead to unsafe situations. Furthermore wind shielding has a large impact on the ship motions and should therefore be taken into account in the modeling of tandem offloading systems also the improved tug model will have a large effect on the ship motions.
Preface and Acknowledgments

The recent years there have been great achievements by mankind, we have travelled to the moon, sent spaceships to Mars, we were able to create organs based on DNA and we have the World Wide Web. Although we all learned to swim in the sea when we were little, we still do not understand all its secrets. One of these secrets are rapidly changing winds called squalls. What the effects of squalls are on ship motions is still not understood. Therefore I was pleased to conduct my research of my thesis in this challenging topic to obtain the Master of Science degree in Offshore engineering. My professor René Huijsmans had the confidence in this topic and in an early stage of my research he foresaw that shielding could have a large effect. Even though I sometimes needed some stir in the right direction, Professor René Huijsmans did not lose the confidence in me therefore I would like to thank him.

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I wish you an interesting read.

Leiden, December 2015

Olga
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Introduction

1.1. Background information

"How much longer will oil and gas be available in sufficient quantities to support the world energy demand", that was the question M. King Hubbert, a geologist from Shell asked in 1956 (Allmendinger (2007)). Current estimations for the world peak production will be between 2010 and 2040. Peak oil will occur because easily accessible oil reservoirs are exhausted. Therefore, the oil and gas industry is moving into more challenging areas like deep water, arctic and shale oil regions. Especially the deep water regions are a growth area for the oil and gas industry. Current deepwater areas are, for example the Gulf of Mexico, the Campos Basin offshore Brazil and offshore West Africa, see figure 1.1. This area is also called the Golden Triangle. In these deeper areas bottom founded structures such as jack-ups are not suitable, therefore floating structures are used. FPSOs are the prime choice for more remote areas because FPSOs have space for storage and processing units. Shell is also moving into deeper water and is expanding their number of floating systems. One of the deep water locations where Shell is active, is offshore Nigeria West Africa. A Shell asset in this region is the spread moored Bonga FPSO, which has been producing since 1996 from the Bonga Field, located 120 km offshore. Currently Shell is working on another project, Bonga South-West, which will also produce from the Bonga field.

Figure 1.1: Deepwater oil areas in the world.
The environmental conditions offshore Nigeria are benign with the dominant environmental condition being swell. However this region is also known for short wind events called squalls. During these events the wind speed increases rapidly and the wind direction changes. During the design, squalls play an important role and they can also have an influence on the offloading operability. The offloading from the Bonga FPSO is done with a Catenary Anchor Leg Moored (CALM) Buoy (see section 1.3.2) and a VLCC tanker. This arrangement, a common offloading principle means the tanker has a distance of approximate 2000 m from the FPSO. Collision of the FPSO and the tanker is very unlikely. However, instead of using a CALM buoy, tandem offloading is also being considered for economic reasons.

1.2. Problem description

The CALM buoy that is used for the offloading from the Bonga FPSO requires extensive maintenance due to part of the skirt is damaged, among other integrity issues. The Bonga FPSO is responsible for large production values, therefore stopping with the producing of the oil is not an option. Other offloading options were considered and tandem offloading was proposed as best option. Tandem offloading is often used in other geographical areas for offloading, like in the North Sea. Tandem offloading can be done with a dynamically positioned tanker which is done is the North Sea or with a tanker that is held in position with the use of tug boats. Which of these two tandem offloading principles is used is dependent on the environment, in the benign area offshore Nigeria a tanker with holdback tugs will have a preference over a dynamically positioned tanker.

The downside of tandem offloading is that tandem offloading is more vulnerable to squalls than offloading from a CALM buoy. The tug boat will hold the tanker into position if the tanker is pushed from its position due to the environment. Most of the time that is not a problem but because West Africa is squall prone area it can lead to potentially hazardous situations. Therefore it is important to first identify the risk that can occur during the tandem offloading process.

Potential consequences of tandem offloading during a squall:

- Collision of the FPSO and the tanker
- Hawser breakage
- Loading hose breakage
- Loss of cargo containment of FPSO or tanker
- Delay
- Failure of holdback tug towline
- Failure of communication

Some of these consequences will have more impact on people, assets, environment or reputation but other have a higher chance of occurrence. To make sure these events do not occur prevention barriers should be implemented and if these events do occur recovery barriers should be available. The presentation of the risks, barriers and consequences is done with a bow-tie analysis, see figure 1.2 below.

Figure 1.2: Bow-tie analysis for tandem offloading.
In the bow-tie analysis the top event is the loss of position of the tanker and on the left side of the top event the prevention barriers are found for the prevention of the top event. On the right side of the top event the recovery barriers are found to recover the tanker if loss of position has occurred.

Loss of position can lead to unsafe situations therefore is the understanding of the motions in a squall important. Furthermore will have many parameters influence on these responses and can have interaction of wind and waves a significant effect due to the close distance between the FPSO and tanker. Therefore is the goal of this research: understanding the responses of, and interaction between, a tanker and FPSO in a tandem offloading configuration during a squall.

1.3. LITERATURE REVIEW

The literature review will consist of four different parts, the first part will be about squalls, the second part will be about tandem offloading and offloading operability. In the last two parts the theory of ship motions and interaction of wind, wave and current will be discussed.

1.3.1. SQUALLS

Squalls are rapidly changing wind events. During a squall the wind speed increases rapidly and the wind direction changes. Squalls begin suddenly and therefore are difficult to predict. Apart from the change in wind speed and direction squalls are also known for their extreme weather as for example intense rainfall and thunderstorms. Squalls can be potential safety hazards for floating structures especially during offloading.

SQUALL FORMATION

Squalls form because of the downdraft of air within the cumulonimbus cloud. However a clear understanding of cumulonimbus clouds and their formulation is important. The name cumulonimbus clouds come from the combination of the latin words cumulus and nimbus meaning heap and rain cloud. Cumulonimbus cloud is a dense vertical cloud that looks like small tufts of cotton, as can be seen in figure 1.3 A cumulonimbus clouds are formed close to the earth surface and form due to condensation.

(a) Picture of cumulonimbus cloud  
(b) Schematic representation of cumulonimbus cloud

Figure 1.3: Cumulonimbus clouds

The rate a cumulonimbus clouds forms depends on the temperature difference between the air within the cumulonimbus cloud and the air in the environment. If the temperature between the cloud and the environment becomes larger, the buoyancy of the cumulonimbus cloud also increases. This is due to difference in air density between the air in the cloud and outside of the cloud. There is a upward motions of air within the cloud, in mature cumulonimbus clouds the vertical velocity of air can have a value as high as 40 m/s. For the estimation of the buoyancy the temperature in the cloud and outside the cloud should be known. The air temperature in the cloud can be found with the temperature, humidity and pressure of the air that enters the cloud. The outside air temperature can be measured.
at the location and will decrease with the height. Cumulonimbus clouds show that they have positive buoyancy throughout their vertical extent however close to the cloud base there is a layer of negative buoyancy, this means that the air in the cloud is colder than the environment. This layer is called the layer of convective inhibition (CIN). The CIN layer acts to inhibit the initial growth of the cloud and intermits cumulonimbus storms to develop even in regions were there is instability. A trigger is needed to overcome this CIN layer. Above the ocean this trigger is often fluctuations in temperature or wind which are dependent on recent antecedent cumulonimbus storms.

When the air lifts through the CIN layer the cumulonimbus cloud further develops in a period of around 30 minutes. During this development the particle sizes become larger, as a result the condensation rate decreases. This situation produced precipitation and the particles begin to fall down, resulting in a downdraft in the system. When the downdraft reaches the ground it spreads out horizontally.

The effect of the falling particles to air:

- **Downward force**
  The weight of the particles fallings downwards imposes a downward force to the air

- **Buoyancy reduction**
  Part of the particles that falls moves out of the cloud and mix with the unsaturated air outside the cloud. The precipitated particles evaporate, the air becomes colder than the environment and therefore the buoyancy is reduced.

During this downdraft the air descends rapidly, the winds associated with this downdraft is a squall. Winds are an important aspect in the development of storms because there should be a difference in wind with height, wind shear, to have downdraft and updraft simultaneously. As can be seen in figure 1.3(b) the cumulonimbus clouds are a bit tilted, without this tilting due to wind shear the precipitation falls into the updraft and the storm would not further develop. Due to the wind shear the downdraft falls through dry mid-level air without being disturbed by the updraft process. The intensity of the downdraft so also squall is influenced by the mid-level air. If the mid-level air is dry the evaporation happens faster and more efficient so this maximizes the evaporative cooling of falling precipitation.

**Squall structure**

A description will be given of the structure of a most common types of a squall. The squall structure consists of elements which can be experienced at a fixed location as for example a FPSO during the passage of a squall. The different elements will be explained using figure 1.4.

![Figure 1.4: Schematic squall structure](image-url)
1. Gust front
   The gust front separates the cold air associated with the squall from the environment. The gust front is the leading edge and the sea close to the gust front is more rough than the surrounding sea. The speed of the gust front is equal to the local wind speed. Due to friction drag between the cold air and the warmer air from the environment, a gust front has a nose. This nose is unstable and therefore the region is more turbulent.

2. Head region
   This is region behind the gust front. The air in this region is very turbulent, more turbulent than in the other parts. The turbulence is dominated by the Kelvin-Helmholtz instability (Cushman-Roisin 2014). This is the phenomenon where two layers have different velocities and because of this, shear is present. Waves grow in time and lead to overturning in the vicinity of the interface. In the head region the wind relative to the environment produces the high shear. The wind speeds within the head region can exceed the windspeed in the gust front because of turbulence.

3. Following flow
   This is the region behind the head region. This region is less turbulent because the turbulence in this region is due to friction instead of due to shear.

4. Jet like flow
   A jet like flow will occur if the downward momentum is high enough. In these jets the wind speed can be very high and there is vertical shear of the wind close to the ground.

All the different elements are described above and now the total vertical and horizontal structure will be evaluated. The vertical structure of the wind profiles in squalls is considered to be constant in the lower 100m (Sommeria and Testud 1984). This was also found in other studies, the wind profile is relatively uniform. However because of the turbulence in the gust front and head region the wind profile can not be described by the frequently used equations. In these regions the turbulent eddies are dominant.

To develop the horizontal structure of a storm the gust front is important. The gust front extends the life time of a cumulonimbus storm because the storm cells are regenerated at the gust front. An isolated storm is a storm where the interaction of the air and the gust front fails to generate new storm cells or where new storm cells are generated but only last for a few hours. Apart from the isolated storm there are also mesoscale convective systems (MCS), these systems are clusters of cumulonimbus storms that contain multiple squall line segments. A squall line is a quasi-two dimensional structure. Even though squall lines are two-dimensional systems, they consists of smaller isolated storm cells which are all embedded into the line and therefore the is a variability of squall winds along the squall line. The difference between an isolated storm and a squall line is that with squall lines the gust front and the downdraft are very close and is almost always accompanied with heavy rain, this is not the case for isolated storms.

**West-African squalls**

The West-African region squall lines are a characteristics phenomenon, with a long line length of 1000 km. But before going into detail on the squalls in this region it is important to understand why squall lines occur in this region that in general is considered to be a benign environment.

West-Africa is located close to the equator, the region is dominated by the West African Monsoon but also influenced by the Inter Tropical Convergence Zone (ITCZ). In this zone the north east trade winds from the northern hemisphere which move in a southwest direction and the southwest trade winds from the southern hemispheres which move to northwest come together. This circulation zone is called the Hadley cell as can be seen in figure 1.5 (a) below. A characteristic of ITCZ is that there is a narrow band of clouds with thunderstorms present. Furthermore the ITCZ migrates north or south of the equator because it follows the zone of the warmest sea surface temperatures. This causes a change in climate in the different seasons. At the equator the ITCZ is a straight line however when the ITCZ migrates this changes because of the existence of Coriolis. The Coriolis effect is the phenomenon that causes fluids to curve as they travel above the Earth’s surface. This phenomena occurs because the Earth has
a spherical shape and turns from west to east, the middle of the earth turns much faster than at the poles. The high pressure sides of a storm want to move to the low pressure centre, in the northern hemisphere the voids of air want to move to the right because of Coriolis and therefore a storm in the northern hemisphere will travel counter clock-wise but in the southern hemisphere the voids of air are moved to the left and therefore a storm travels clock-wise. In figure 1.5 (b) this difference is shown.

![Figure 1.5: Inter Tropical Convergence Zone (a) Hadley cell (b) Coriolis effect](image)

What happens with storms also happens with the ITCZ when it moves to the north or south of the equator. The ITCZ migrates to north or south till it reaches a balance between the the Coriolis effect and the pressure gradient from the ITCZ. The ITCZ is present in the period from January-June and active weather conditions and thunderstorms can be expected during this period.

In this study real time squall data will be used in the form of measured data from the Bonga FPSO location. The description of the measurement system, the data and the statistics of the squall will be described in chapter 3.

1.3.2. **Offloading**

An FPSO is not only designed to receive oil and/or gas from the subsea wells, separate the oil and/or gas and perform water and gas management but also stores the oil and other products in the storage tanks within the hull structure. There is only space in the storage tanks for a certain quantity, after a while the oil and other products have to be exported to an off take tanker. The capacity in the storage tanks together with the production influences the offloading rate. For the export of oil and gas to shore, also a pipeline can be used.

The offloading scenario has a large impact on the design and operation of an FPSO. The areas that are mainly influenced (Matsuura et al. (2005)):

- The economic performance of projects during the field development is largely influenced by the production. From the moment the product is produced at the platform it is critical that the product is transported to the customer. If this is not possible due to downtime of the offloading facility or weather the overall economic performance can be affected.
- The CAPEX and OPEX of a whole project are influenced by the offloading system. The CAPEX of a CALM buoy is much higher than with tandem offloading, however the OPEX of tandem offloading is considered to be higher due to the use of tug boats.
- The Health, Security, Safety and Environment are also strongly influenced by the offloading system. Large structures are operating in close proximity with a potential for collision what can lead to an oil spill, loss of life or other significant incidents.
The Bonga FPSO has a storage capacity of 2 million barrels with a production of around 200,000 barrels per day. This means that almost every week the oil has to be exported to an off-take tanker. The different offloading configurations for the tanker are connected to the bow or stern of the FPSO, connected to a remote offloading buoy and side-by-side of the FPSO.

**Side-by-side offloading**

The shuttle tanker is moored abreast of the vessel. Hoses are connected between the two vessels to transfer the cargo. These operations normally take place in a moderate wave climate. The two vessels are at a close proximity therefore the mooring system (lines and fenders) and the relative motions of the two vessels are critical. Side-by-side offloading is not an offloading type that is very common for spread-moored FPSOs because the tanker has to navigate between the bow and stern anchor patterns. Side-by-side offloading is not a suitable method for offshore West-Africa.

**Remote offloading buoy**

The buoy is located at a distance around 1800 meters from the vessel. The buoys are used as moored stations close to the FPSO. The offloading tanker is moored to the buoy with a synthetic rope called the hawser. The tanker can weather-vane while being connected to the buoy. The buoy is a Single Point Mooring (SPM) system and the mooring can have different types of configurations like Catenary Anchor Leg Mooring (CALM) or Single Anchor Leg Mooring (SALM). The product is transferred from the FPSO to the buoy with hoses. A tug can be used in severe weather for the maintaining of the hawser tension. The Calm buoy offloading system is shown in figure 1.6 below.

![Figure 1.6: CALM buoy offloading system](image)

The advantage of using a remote buoy is that there is a minimal risk for collision and the high uptime over the lifetime of the field however the CAPEX is high and the removal of the buoy from site requires major effort because the hoses under the buoy and the mooring chains also have to be dismantled.

**Tandem offloading**

The tanker approaches the FPSO from the aft or forward side. During this procedure the environment is the critical factor. The tanker is moored to the FPSO with a hawser and the product is transferred from the FPSO to the tanker’s manifold by a floating hose. For the station keeping of the tanker one or more tugs are used or tankers with dynamic positioning are used. Even though the FPSO and tanker are around 80 meters apart, tandem offloading is a well-established offloading configuration. In West-Africa tandem offloading is used for the offloading of the product from the spread-moored FPSOs but the experience from the different oil companies is limited. Such critical are the use of tugs for station-keeping; in some cases three tugs are estimated to be necessary. Tandem offloading can be vulnerable to a squall event because squalls can push the tanker from its position. What this exact location in which the tanker has to remain during offloading will be explained on page 9. See figure 1.7 on the next page for the tandem configuration.

An offloading operation consists of four phases (Matsuura et al. (2005)): 
1. **Approach**

This phase starts from the moment that the Mooring Master boards the tanker at a distance of around 4800 meters from the FPSO and ends with a distance of 250 meters between the bow of the tanker and the FPSO. The FPSO heading is fixed so the approach strategy has to be adapted to the local prevailing wind and current at the time. It is important that during the approach the environmental conditions are monitored. After a certain approach strategy is chosen, the tanker approaches the FPSO in a given heading. The assistant tug is connected to the tanker with a distance of 1600-3200 meters from the FPSO. The speed of the tanker is controlled by the tanker’s rudders and the tug. The tanker’s rudders are used so they can be used at all time and given the possibility to control the heading during the stopping period. It is important that the approach goes very slow, some tankers have a steady state speed that is considered too high so the tanker’s engines are stopped several times during the approach. The tanker is stopped with its bow 250 meters off the FPSO.

2. **Hawser connection**

The speed of the tanker at the beginning of this phase is around 0.25 m/s. At the end of this phase the mooring hawser should be connected to the tanker. The personnel on the tanker lowers one or two messenger lines through the forward fairleads which are used for the connection of the hawser mooring. Another way to transfer the FPSO hawser messenger to the tanker bow is compressed air line throwing. The workboat connects the messenger line to the hawser pick up line. If the lines are connected, the tanker manoeuvres to the final mooring position. The messenger is winched on board followed by the pickup rope till the chafing chain passes though the tanker bow fairlead and is secured in the bow chain stopper. From the moment the chafe chain is secured the tanker should be able to settle back slowly on the hawser. After the mooring hawser is connected the floating cargo hose is connected to the loading manifold of the tanker.

3. **Off-take**

This phase starts from the moment the mooring hawser is connected till the cargo hose is disconnected. The offloading of 1 million barrels takes around 24 hours. The aim during this phase is to keep the tanker within the safe operation envelope, the heading, position, hawser angle relative to the FPSO and the hawser load are important. The changing environmental loads want to set the orientation of the tanker therefore one or more tugs have to actively counteract these forces. There is a significant distance between the FPSO and the tug, around 650 meters, therefore reaction to situations is difficult and the communication between the crew of the FPSO and tug is important.

The limits of tanker heading and hawser angle are defined in guidelines. The general consensus is that the relative heading of tanker may differ 30 degrees and should not exceed 45 degrees, for the hawser similar limits are applied.

The engine of the tanker is not used during the off-take phase, however the engine should be ready for immediate use in the case of an emergency disconnect. Emergency disconnection takes around
15 till 30 minutes: shut down of the pumps, hose disconnection and release of the hawser.

4. Departure

This phase starts after the disconnection of the loading hose but with the hawser and the tug still in place. The disconnection of the hawser cannot take place if the hawser is still under tension. Sufficient slack in the hawser is provided by the FPSO. The tug stops pulling and the engines of the tanker need to give a kick ahead. The disconnection of the hawser takes around five to ten minutes and the also the tug needs around the same time to pull the tanker astern from the FPSO. The disabled tanker drifts down the FPSO with the tug stand by for assistance in case of failure.

Also pipelines can be used for the transportation of oil or gas. For deep water or remote field the use of a pipeline is an expensive solution. Furthermore the use of a pipeline does not provide flexibility for growth or expansion even if the pipeline is over-designed in terms of diameter. The shuttle tanker is one of the key components of the offloading system. The tankers are available in different sizes from 50 000 DWT to 500 000 DWT. The VLCC tanker used for the offloading of the Bonga FPSO has a DWT of 300 000. This is approximately 2000 000 barrels storage capacity. The size is measured in deadweight (DWT) and is the maximum cargo weight. The volumetric density of crude oil is around 0.14 DTW (tonne/barrel). Apart from the capacity, the engine of the tanker is very important for the approach, off-take and departure. The modern tankers have engines with ultra-long stroke for low speeds. The engine is very efficient and has high thermal efficiencies by low RPM.

**Offloading operability**

During tandem offloading the tanker has to stay in the offloading zone. The offloading zone is the zone where the tanker can safely perform offloading without severe risks for potential hazards like the collision with the FPSO. If the tanker is moving out of this zone the tug will respond so the tanker is pulled back into the offloading zone. In figure 1.8 below a theoretical example of offloading zones, is given.

![Figure 1.8: Offloading operability zones](image)

Figure 1.8: Offloading operability zones
For every location the offloading zones can be a bit different. However figure 1.8 gives a good representation of these zones. In the shown case two different zones are considered:

- The first zone is that the bow of the tanker has to stay within the green area with a preference of a distance of 70 m from the FPSO, if the bow of the tanker moves out of this green area it reaches the orange area were there is an increased risk and therefore the pumping of the oil will be stopped, if the bow moves out of this area it reaches the red zone where an emergency disconnection has to take place to prevent hazardous consequences.
- The second zone is limited with the angle of the bow relative to the back of the FPSO. The advisory angle is 25 degrees. The pumps are stopped if the 35 degrees is exceeded and is the angle larger than 40 degrees there will be a disconnection.

As mentioned in the section discussing tandem offloading, the tandem offloading process can be vulnerable to squalls because it can happen that the tugs are not able to hold the tanker in the offloading zone and therefore the tanker will lose position. Loss of position in this research is the movement out of the offloading zone. The offloading zone for the Bonga FPSO is only defined with a angle limit of the tanker of 60 degrees (Clarke and McBride (2014)). However for the mitigation of the loss of position of the tanker given in this research a more general definition of the offloading zones be used, based on the offloading zones of figure 1.8.

1.3.3. SHIP MOTIONS

Floating structures are subjected to the environment. The environment will transfer energy to the floating structure and as response the floating structure will move. In this section the ship motion theory will be explained applied to both single floating structure and multiple floating structures which is critical during tandem offloading.

**Single floating structure**

A floating structure can be described as a rigid body. The dynamics of a rigid body are governed by a combination of the external forces and the inertia of the body, this is according to Newton’s second law.

\[ F = m \cdot a_c \]  

Where \( F \) is the force that acts on the body, \( m \) is the mass of the body and \( a_c \) is the acceleration. A floating structure in water can be described as a single mass spring damper system. The external forces that act on the body are the wave exciting forces \( F_w \) that are produced by waves interacting with the restrained body and the hydro mechanical forces \( F_h \) on the body that are induced by the harmonic oscillations such as damping force, restoring spring force and added mass (Journee and Massie (2001)). By implementing these forces that acts on the body to equation 1.1 the equation becomes:

\[ F_h = -a \ddot{z} - b \dot{z} - cz \]  

\[ F_w = F_z \]  

\[ (m + a) \ddot{z} + b \dot{z} + cz = F_z \]

Where \( m \) is the mass of the body, \( a \) the added mass of the body, \( b \) the damping coefficient, \( c \) the spring coefficient and \( F_z \) the wave force in z-direction. The general linear equations of motions for a six degrees of freedom in the frequency domain are:

\[ \sum_{j=1}^{6} (M_{i,j} + a_{k,j}(\omega_c)) \ddot{x}_j(\omega_c, t) + b_{k,j}(\omega_c) \dot{x}_j(\omega_c, t) + c_{i,j} x_j(\omega_c) = F_{wa,i} \cos((\omega_c t) + \epsilon_i(\omega_c)) \]  

for \( i = 1, 2 \ldots 6 \)
1.3. Literature review

**Multiple floating structures**

In the case of tandem offloading there are two structures present: the FPSO and the tanker. Equation 1.6 needs to be extended. The dynamic response of coupled floating structure can be described by a damped mass spring system and has 12 degrees of freedom (Tromans (2009)). In matrix form the equation of motion for $N$ degree of freedom:

$$[A]\ddot{x} + [B]\dot{x} + [C]x = F(t)$$  \hspace{1cm} (1.7)

where $A$ is the combined mass and added mass matrix, $B$ the damping matrix, $\ddot{x}$, $\dot{x}$ and $x$ are the acceleration, velocity and the displacement vectors respectively and $F(t)$ is the total dynamic force vectors acting on the floating structures.

In this research the focus is on the horizontal motions called surge, sway and yaw. The amplitude of these motions is affected by the damping. The damping matrix $B$ of equation 1.7 consists of different damping components: radiation damping, wind damping, viscous damping, wave damping and mooring line damping. For the surge, sway and yaw motions in the low-frequency range it is viscous damping that is more important than for example radiation damping. Viscous damping is due to the friction between the hull and the water particles. Viscous damping is difficult to determine numerically therefore it is often determined during the scale model tests.

1.3.4. Interaction

During tandem offloading both the structures are subjected to the environment. Therefore interaction between the structures can occur, one of these types of interaction is shielding. Shielding is the effect that the environmental forces on one body is influenced by the presence of another body. In the tandem offloading configuration the tanker can be shielded by the FPSO and this could decrease the environmental forces but sometimes this can lead to an increase. Shielding effects are often neglected because of the high complexity, however if it is incorporated in models it is often done by means of scale model tests. Some findings of the influence of shielding will be discussed below.

**Current shielding**

The effect of the current shielding on a tanker during offloading operations of a FPSO in spread moored configuration has been studied by (Illuminati et al. (2009)). In this research a model was developed and the model was validated with small-scale experiments. During the oil transfer under a constant current speed of 1 m/s it was found that the shielding effect will be around 5.3 per cent compared with the unshielding case. If the current speed is increased to 2 m/s, current shielding becomes more important. However the current in West-Africa is not a fast current, in 50 per cent of the cases the current is smaller than 0.3 m/s (van der Borch (2013)). The shielding effect on current is assumed to be very small and therefore it will be neglected. Furthermore in this research the current was coming from the bow of the FPSO and therefore the tanker is positioned in the wake of the FPSO, for the Bonga FPSO this is not the case so the shielding effect will even be less.

**Wave shielding**

The general opinion is that wave shielding can be well predicted with two-body diffraction analysis (Buchner and Bunnik (2002)). Feikema et al. (1992) used scale model tests and found that the mean wave drift forces reduce for head-waves but the reduction reduces in magnitude once the direction is bow-quartering. For the study of the hydrodynamic interaction between multiple floating bodies, Pinkster (1995) uses a computational model for the study of wave interaction. He finds that especially the mean surge wave drift forces on the tanker are lowered. Hong et al. (2002) find as well that the surge wave drift force was significantly reduced by carrying out model tests and Chen et al. (2005) also report a decrease of the second order surge drift force. Pinkster (1995) mentioned that if you want a proper simulation of the motions of the tanker it appear necessary to take the hydrodynamic interaction into account. However for tandem moored FPSO-tanker system Hong et al. (2002) found that interaction effects on the linear responses are negligible, which means that the first order forces are almost not
Wave shielding is normally implemented in numerical models for side-by-side offloading. However for tandem offloading this is not common practice. In the numerical model that will be developed of the multi-body system wave shielding is not part of the software package so therefore additional input models have to be developed to implement the wave shielding in the model. Because the importance of wave shielding for the development of these numerical models for tandem offloading is not well understood, a two body diffraction analysis will be executed. By doing two body diffraction analysis the question can be answered if wave shielding plays also an important role for tandem offloading. Furthermore is the wave shielding is significant, it could be implemented in the multibody time domain model.

**Wind shielding**

Wind forces on the offloading tanker that is moored behind the FPSO are influenced by shielding effects. These effects are caused by the distorted wind flow field, in the wake of the FPSO. The influence of wind shielding on the surge, sway and yaw motions is studied in different studies. Feikema et al. (1992) found using scale model tests that for the longitudinal wind force, also called surge force, there is almost no influence on the force when the export tanker and the FPSO are in line. However in a sideways position, with the same heading, the disturbed wind field leads to an increase in the force. This increase is due to the fact that the disturbed wind field behind the FPSO becomes more turbulent and locally increased wind speed will be present. The increase in the wind force on the export tanker increases even more in sideways position if the tanker makes an angle of 165 or 150 deg. Buchner and Bunnik (2002) found a decrease in the longitudinal force but they used different vessel positions.

For the transverse wind force, also called sway wind force Buchner and Bunnik (2002) and Feikema et al. (1992) found the same result. If a major part of the export tanker is shielded the wind force will reduce but in a sideways positions the disturbed wind field leads to an increase. For the wind moments Feikema et al. (1992) considered an export tanker with a heading of 150 and 165 degrees. A reduction is found if the export tanker is in the lee of the FPSO. Apart from the influence wind shielding has on the wind moments, the connection between the tanker and the FPSO, the hawser will also influence the wind moment. Feikema et al. (1992) found that this influence will even be more significant that the wind shielding effect on the wind moments.

From the previous it can be concluded the wind shielding is something that could have a significant influence on the wind forces acting on the tanker. For the development of a valid numerical model wind shielding should be considered. But at the moment there are no methods available to compute the wind and current forces of the tanker in or aside of the wake of the FPSO. In numerical models the wind coefficients are used to calculate the wind forces by multiplying these with the dynamic pressure \( \frac{1}{2} \rho v^2 \) where \( \rho \) is the density of air and \( v \) is the wind velocity and the area. The wind coefficients are determined during wind tunnel tests and are only applicable for only one relative position of the vessels. During offloading the preference for position of the tanker is in line with the FPSO. Wind shielding for this position can be included however if the vessel change its alignment, the results are less reliable because the wind coefficients change. For getting the most accurate results, the wind coefficients should be updated during the simulation.

The Dutch Aerospace Laboratory carried out research to study wind shielding and to develop a model to predict the shielding effects. In this research a model was developed to calculate the wind forces and moments of the tanker if the wake field behind the FPSO is known. This model was validated with wind tunnel tests. The downside of this model is that the wake model first has to be determined, this can be done is different ways but are all time consuming and expensive. Therefore an alternative approach was considered to study wind shielding. The approach is based on the book the Boundary Theory of Schlichting. Schlichting studies turbulent flows, one of these free turbulent flows are wakes. With the description of the wake behind a body, the increase or decrease of the wind velocity behind a body
can be calculated. Knowing the shielded wind velocity the shielded wind force can be calculated. By dividing the unshielded wind velocity with the shielded wind velocity a shielding rate can be determined.

1.4. **Thesis solution strategy**

In the literature review the most important elements of this research were introduced and evaluated. In the previous research models for ship motions during tandem offloading have been developed but no research was identified on the effect of squalls or interaction on these ship motions during tandem offloading. Furthermore the impact of squalls and the interaction on the safety during tandem offloading were never identified. In this section the solution strategy of this research will be discussed.

For the study of ship motions of a multi-body system, the FPSO and the tanker, a numerical model will be developed. The results of this model will give insight in the responses of both vessels. This model will be developed with the use of the software package aNySIM. aNySIM provides a time domain description of the motions of multiple bodies for different environmental loadings. Within the software there is the possibility to use real time squall date as input of the model. For the validation of the aNySIM model, the scale model tests will be used. These model tests were performed during the design of the Bonga FPSO but do not include the response of the tanker. However the model tests were used to obtain critical information for the input of the numerical model as well as for validation of the Bonga FPSO model.

The response of the multi-body model with the FPSO and the tanker is dependent on the input values of the model. Different simulations will be performed in the sensitivity study. In the sensitivity study the impact of, for example different current speeds on the responses will be studied. This is done because it can be assumed that the system is more sensitive to particular parameters. The results of the sensitivity study will be used for the effect squalls have on the responses and for the mitigation strategies if loss of position occurs.

The wave and wind interaction is not part of the multi-body model. This interaction will be studied separately and, if the influence is significant, a coupling could be made to incorporate this effect in the multi-body model.

- **Wave interaction**
  The wave interaction will be studied with a two-body diffraction analysis in WAMIT. The results of WAMIT will include the effect that interaction has on the wave responses of the FPSO and the tanker. A comparison can be made between these responses and the wave responses without interaction.

- **Wind interaction**
  For the study of wind interaction a model will be developed in WINDOS. In WINDOS the Bonga FPSO can be built up from smaller blocks. The shielding is incorporated by using the reduced wind velocity from the wake to calculate the wind forces on the tanker. The wind forces will be used to calculate the wind coefficients including shielding. Using this approach the significance of wind interaction is studied for different positions of the FPSO and the tanker.

Apart from interaction with the ship motions, squalls can also affect the ship motions during tandem offloading because of their transient behaviour and this could lead to unsafe situations. A tug boat is used for the stationkeeping of the tanker to prevent loss of position. The tug boat in the multi-body model is an important element because the right response of this tug boat could improve the safety. However the way the tug boat is modelled in the multi-body model is too simplistic as the response of the tug boat is modelled static, a dynamic behaviour is more realistic and gives more flexibility in the mitigation. Improvement of the tug model will be carried out by making a coupling of the multi-body system using a Lua script.

To conclude the strategy will yield to a complete solution. It is expected that from this clear conclusions and recommendations can be drawn. A significant academic step can be taken in the knowledge about
wind interaction and the modelling of tug boat response.

1.5. Objectives

The goal of this research is to develop a multi-body model that can be used to simulate the vessel responses during tandem offloading within a squall. To gain insight in the effect of wind and wave interaction during tandem offloading and improve the tug model to get a more realistic representation of the tug and its response during a squall. To reach this goal the following objectives are defined.

The objectives for the multi-body model and the sensitivity study:

- Develop a multibody model in aNySIM
- Validate the multi-body model with the Bonga scale model tests
- Identify the parameters that could influence the responses of the multi-body model
- Study the influence by variation of the parameters of the developed multi-body model

For the study of the interaction and the tug model the objectives are:

- Create and validate a WAMIT model for the loaded and ballast conditions and obtain hydrodynamic database
- Create and validate a WINDOS model for the loaded and ballast condition and obtain the shielded wind coefficients

The objectives for the improvement of the tug model are:

- Develop a tug strategy for tandem offloading
- Develop a coupling between aNySIM and LUA

After all the above objectives were met, the following final objectives were defined:

- Analysis and interpretation of the data
- Implement the outcome of the interaction study into the multi-body model
- Brainstorming about the conclusion and recommendations
- Deliver a final report for the graduation committee

1.6. Coordinate system

The coordinate system that will be used in this report is the ship fixed coordinate system. The ship fixed coordinate system is for both the FPSO and the tanker positioned in the centre of gravity (CoG) of the ship. The ship fixed coordinate system is placed within the earth fixed coordinate system. In simulations of the used software at t=0 the ship fixed coordinate system is placed within the earth fixed coordinate system. The main reason of the use of the earth fixed coordinate system is the placement of the tanker relative to the FPSO.

The ship fixed coordinate system has its origin at the CoG, positive in the x-direction from stern to bow, positive in y-direction from starboard to Portside and in rotation around the z-axis it is positive from bow to Portside. The representation of the ship fixed coordinate system is shown in figure 1.9. The earth fixed coordinate system has its origin at the waterline and uses the same conventions at the ship fixed coordinate system.

Every ship has the same basic motions, three translations of the CoG in the directions of x-, y-, and z-axes and three rotations about these axes. In total six degrees of freedom. This is visualised in the table 1.1 containing the most relevant notations.
1.7. Thesis structure

The structure of this thesis is according to the defined objectives. Chapter 1 is the introduction to this research with the context, solution strategy, goal and the objectives.

Chapter 2 is about the development of the aNySIM model and the results of the tandem offloading system are described. Chapter 3 describes the identification and variation of the parameters in the sensitivity study. Chapter 4 and chapter 5 respectively describe the interaction of wind and waves. The development of the models and the results of the models are discussed. Chapter 6 contains the mitigation of the loss of position with the outcome of the sensitivity study and the description of the tug model.

Finally in chapter 7 the conclusions of the research are discussed and the recommendations for further research.
Responses of tandem offloading systems to squalls

For the study of motions related to a tandem offloading system a numerical model will be developed. The modelling will be done with the time domain program aNySIM. In this chapter the development and all the different elements of this model are evaluated. The model is validated with the model test performed for the Bonga FPSO. Also the results of the motions of the ballast and full load tanker under the effect of only the squall, the comparison of offloading in normal wind conditions and squall wind conditions, the effect that the addition of current and waves have to the models and the hawser tension in a squall are discussed.

2.1. aNySIM

aNySIM is a time domain simulation program. In aNySIM the ship motion theory described in equation 1.6 or the linear frequency domain approach can not be used to describe the responses of a floating structure with mooring under arbitrary environment in time domain. This is because the hydrodynamic coefficients are frequency dependent as well as that the restoring forces of the mooring system are non-linear. To solve this problem the impulse response theory is used to describe the fluid reactive forces. According to the impulse response theory, when the response \( R(t - \tau) \) of a system to an unit impulse at time \( t = \tau \) known than is the response to an arbitrary impulse \( \delta \) the following:

\[
x(t) = \delta R(t - \tau) = F(\tau) \triangle \tau R(t - \tau)
\]  

From linearity the overall response of the system to a force \( F(t) \) can be found by superposition:

\[
x(t) = \lim_{\triangle \tau \rightarrow 0} \sum_{\tau} F(\tau) R(t - \tau) \triangle \tau
\]  

Because \( \triangle \tau \) is gets smaller the limit can also be written as the limit of a sum, this expression is known as the Duhamel integral. Cummins (1962) used the impulse response theory for the formulation of the equation of motion for a floating structure. The reaction forces due to the water velocity potential may be derived by the impulse response theory, taken the velocity of the vessel as system input:

\[
\sum_{j=1}^{6} (M_{kj} + m_{kj}\ddot{x}_j) + \int_{-\infty}^{t} R_{kj}(t - \tau)\dot{x}_j(\tau)d\tau + C_{kj}x_j = F_k(t)
\]  

Where \( M \) is the inertia matrix, \( m \) the added inertia matrix, \( R \) the matrix of retardation functions, \( C \) the matrix of hydrostatic restoring forces, \( x \) is the motion in the j-th mode and \( F \) the time dependent external force such as first order wave forces, second order wave forces, wind forces, mooring line forces etc. The retardation functions and the coefficients of added inertia can be derived from frequency dependent damping values and the added mass at one frequency. Once the system of coupled differential
equations is obtained, the arbitrary time varying loads (non-linear mooring forces, current forces etc.) may be incorporated as external forces. So with this approach all the hydrodynamic reaction forces and other external loads are calculated separately.

The equation of motion is solved according to the following procedure. At a time $t$ the equation of motion have to be solved for $t + \Delta t$ but first the velocities for smaller fractions are predicted. With numerical integration the new position and heading are calculated. The forces on the vessel at these new coordinates and time can be determined. The forces are inserted into equation 2.3 to calculate the acceleration. By integration of these accelerations the velocities can be compared with the estimated velocities. If these are within an acceptable margin the computation continues, else the procedure has to be repeated with smaller fractions.

2.1.1. ENVIRONMENTAL AND STRUCTURE SPECIFIC INPUT

To be able to perform calculations in aNySIM particular environmental and vessel specific input data is required. Below figure 2.1 highlights the input needed for the development of an aNySIM model. The model developed in this research required further input data; for example the mooring. The specific input for this research will be discussed in more depth in section 2.2.

Some of the input data require preparation like the hydrodynamic coefficients, these can be calculated with diffraction analysis. The wind and current coefficients to be used are determined in a model test basin or with the use of a separate program. aNySIM also has the option for wind to be given a time trace instead of the use of constant value or wind spectrum.

2.1.2. OUTPUT AND POST PROCESSING

The output of aNySIM is given in time traces for the duration of the simulation with a specific interval. During the model development the desired output of the model has to be added as output lines. In this research the following output signals are identified in the input file:

- The motions of the FPSO and tanker relative to their CoG
- The surge, sway and yaw motions of the tanker in the earth fixed axis system
- The tension force in the hawser
- The force in the fairleads of the mooring system
- The wind forces on the FPSO and tanker
- The current forces on the FPSO and tanker
- The wave forces on the FPSO and tanker
aNySIM does not have a post processing function, so therefore in order to study the results, a Matlab script is written to load the time traces into Matlab. After the data is loaded into Matlab the surge, sway and yaw motions can be plotted as well as other parameters.

2.2. Simulation set up

The aNySIM model is built up of different environment and various other components. In this section these different elements are described in more detail. In figure 2.2 below the overall set up of the model is shown. On the left part of the image the location of the FPSO and tanker in offshore Nigeria.

Figure 2.2: The location of the FPSO and the tanker offshore Nigeria and the elements of the model

2.2.1. FPSO

The model of the FPSO in aNySIM consists of the main particulars of the Bonga FPSO. With these particulars the hydrostatics are solved. Two separate models will be developed for the ballast and fully laden case of the FPSO. The fully loaded case has a draft of 23.9 m and the ballast case has a draft of 10.14 m. The hydrodynamic properties of the FPSO are added as an hyd-file. This hyd-file contains the fluid reaction forces in terms of added mass and damping coefficients. These hydrodynamic properties are determined numerically with diffraction software, for more details see chapter 5. Damping caused by radiation is included but viscous damping has to be added separately. The viscous damping coefficients found in the model test (Cozijn (2001)) are used.

<table>
<thead>
<tr>
<th>Mode of motion</th>
<th>Loaded FPSO</th>
<th>Ballast FPSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>377 [kNs/m]</td>
<td>336 [kNs/m]</td>
</tr>
<tr>
<td>Sway</td>
<td>1191 [kNs/m]</td>
<td>656 [kNs/m]</td>
</tr>
<tr>
<td>Yaw</td>
<td>$1.0 \cdot 10^7$ [kNs/m]</td>
<td>$5.1 \cdot 10^6$ [kNs/m]</td>
</tr>
</tbody>
</table>

Table 2.1: Linear damping coefficients Bonga FPSO from model test

To verify the FPSO model a still water test is performed because apart form the FPSO no other components or environment are included in the model at this stage. The FPSO should be in an equilibrium position and the heave motions should be equal to zero. As can be seen in figure 2.3, on the next page, this is the case for both the ballast and fully loaded case, where the heave is almost zero. (Respectively $3 \cdot 10^{-3}$ for the ballast and $1.8 \cdot 10^{-3}$ for the full load case.) The reason that the heave response is not exactly equal to zero is because the Centre of Gravity of the FPSO is not exactly at the location as defined in the model. However this difference is that small that the heave can be considered to be zero.
2. Responses of tandem offloading systems to squalls

(a) Ballast case
(b) Full load case

Figure 2.3: aNySIM still water test for the FPSO

(a) aNySIM results
(b) Bonga model test results

Figure 2.4: Comparison of the roll decay test of the full load case in aNySIM and Bonga model test

For the free floating FPSO also a roll decay test is performed, to find out if the natural period found in the aNySIM simulations is equal to the natural periods found in the model tests. The natural period of a motion $T$ is the period of one oscillation. In the model test report the roll decay test is carried out by giving the FPSO an initial angle and then releasing the FPSO.

This approach is also used for the roll decay test in aNySIM. The FPSO is at initial angle of 6 degrees at $t=0$ and then released. The comparison of the roll decay tests results performed in the model test and aNySIM simulation are shown in figure 2.4 above. There is a good agreement found between the natural period, in the model test the natural period for roll $T_\phi$ in the fully loaded case was 17.60 s and the natural period for roll $T_\phi$ found the aNySIM simulation was 17.53 s. A $T_\phi$ of 16.85 s for ballast in the model test and $T_\phi$ 16.90 s in the aNySIM simulation were found. However the damping found in the aNySIM roll decay test was around 5 per cent higher than the damping of the model test. Because the roll in this research does not play a very important role no further adjustments will be made.

2.2.2. Mooring

The Bonga FPSO is spread moored, with 12 lines divided in 4 bundles of 3 lines. All the lines have the composition of chain - steel wire - chain. The mooring is asymmetric because the risers and oil offloading lines attached to one end of the vessel result in asymmetry of the external forces. Of the four bundles, two bundles are identical and the other two are both different. In total there are 3 different types of lines. The mooring will be modelled in aNySIM in a quasi-static manner that is based on the catenary formulation. The approach does account for the axial stiffness of the mooring lines but not
2.2. Simulation set up

account for the inertia, bending stiffness, drag forces and sea bed friction. The location of the fairlead and the anchor are fixed, the initial state of the shape of the mooring line can be calculated with the anchor radius and line azimuth angle as input, aNySIM calculates the pretension and the pretension angle. Also other ways can be used to calculate the initial stage but in the model tests only the anchor radius and the line azimuth angles were determined in equilibrium position. The equilibrium position is when the mooring has found its equilibrium and the zero position is at t=0 when the mooring lines are attached. In the model test was in the zero position the pretension and the pretension angle determined. The BOORs (Bonga Oil Offloading Risers) were also part of the model used in the model test. The BOOR was modelled as an extra external force. In aNySIM the BOORs are not part of the model and therefore the zero position of the model test will not be equal to the zero position in aNySIM. As a result the pretension and pretension angle will also be different so hence these are not used as input for the model.

Equilibrium position

Firstly the equilibrium position, in this research called zero values, has to be determined. In table 2.2 the zero values found in aNySIM for the two loading cases are showed, these values are the location of the Centre of Gravity of the FPSO with mooring.

<table>
<thead>
<tr>
<th>Mode of motion</th>
<th>Loaded FPSO</th>
<th>Ballast FPSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>14.67 [m]</td>
<td>13.65 [m]</td>
</tr>
<tr>
<td>Sway</td>
<td>-9.30 [m]</td>
<td>-8.70 [m]</td>
</tr>
<tr>
<td>Yaw</td>
<td>0.14 [deg]</td>
<td>0.15 [deg]</td>
</tr>
</tbody>
</table>

Table 2.2: Zero values of the ballast and full loaded FPSO with mooring

To be able to compare these values with the zero values of the model test, the BOORs have to be added to the aNySIM model. This is done by adding two external forces in X- and Y direction to the existing model. The comparison of the zero values of the model test and the aNySIM model with the riser is shown in table 2.3 below. As can be seen, the surge position especially is the same for model test and aNySIM. Also the sway position gives a satisfying result. The yaw shows a larger difference, this is because in the model test the BOOR will also lead to an additional moment in Z-direction. In the aNySIM model with the BOOR this additional moment is not included.

<table>
<thead>
<tr>
<th>Mode of motion</th>
<th>Bonga Model test</th>
<th>aNySIM simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>-3.53 [m]</td>
<td>-3.53 [m]</td>
</tr>
<tr>
<td>Sway</td>
<td>3.06 [m]</td>
<td>3.23 [m]</td>
</tr>
<tr>
<td>Yaw</td>
<td>-0.46 [deg]</td>
<td>-0.20 [deg]</td>
</tr>
</tbody>
</table>

Table 2.3: Comparison of zero values model test and aNySIM FPSO and mooring

The tension in the different mooring lines should also be different because of the asymmetric mooring system. This is also the case with the tensions of the mooring lines in the aNySIM simulation. The two identical bundles both have the same tension in the anchor chain, with the tension highest in the shortest mooring line and lowest in the longest line. This is also what was found in the model test results.

Decay tests

Model validation test will be performed with decay tests. The decay test that will be performed are roll, surge, sway and yaw. These last three decay test were performed because these motions are the main interest in this research. The natural period of a motion $T_0$ is the period of one oscillation. The damping of the aNySIM simulation will be compared with the model test with the use of the logarithmic
decrement $\delta$. The logarithmic decrement is described in formula 2.4 below, in which $N$ is the number of oscillations, $\phi_i$ is the motion amplitude of the $i$-th oscillation.

$$\delta = \frac{\ln \phi_i - \ln \phi_{i+N}}{N}$$  \hspace{1cm} (2.4)

The roll decay test is performed in the same manner as in section 2.2.1, by giving the FPSO with moorings a roll angle of 4 degrees before releasing the system. In the model test the natural period $T_\phi$ was 17.3 seconds. In the aNySIM model the natural period $T_\phi$ was 17.4 seconds, this is a difference of less than 1 per cent. The logarithmic decrement found $\delta$ in the model test was -0.114. In the aNySIM model the roll logarithmic decrement was $\delta$ -0.131. The surge and sway decay test was in the model test different performed than in the aNySIM model, in the model test the model was released after a initial displacement of 40 meters, in aNySIM a force is built up and then released. The surge natural period $T_\phi$ found in the model test was 770 seconds in aNySIM 786 seconds. The surge logarithmic decrement $\delta$ in the model test was -0.36 and in the aNySIM model -0.33. For sway the natural period in the model test was $T_\phi$ 620 seconds and in aNySIM 591 seconds, the sway logarithmic decrement $\delta$ in the model test was -0.52 and in the aNySIM model -0.47. The yaw decay test is in the same way performed as the roll decay test. The natural period $T_\phi$ of yaw in the model test was 300 seconds in the aNySIM decay test 269.6 seconds. The yaw logarithmic decrement was $\delta$ -0.36 and in aNySIM -0.28. The surge, sway and yaw decay tests performed in aNySIM are shown in figure 2.5. It will be almost impossible to get

![Figure 2.5: aNySIM decay tests for surge, sway and yaw](image)

exactly the same natural periods and damping when a comparisons are made between the model tests and aNySIM. However from the results there is a reasonable match of the natural period and damping found in the model test and aNySIM. In aNySIM the viscous damping has to added because this is not accounted for in the program. In the hydrodynamic file the roll damping $b_{44}$ is accounted for, this is approximately 4 per cent of the critical roll damping. Furthermore because of the asymmetric mooring system all the motions are coupled, this is not accounted for in aNySIM.

2.2.3. TANKER WITH HAWSER

After the model was calibrated for the FPSO, the tanker was added. For the set up of the tanker section of the model the same approach is used as for the FPSO. The main particulars of a VLCC tanker are added for the full load and ballast case with respective drafts of 21.20 m and 8.70 m. The hydrodynamic properties of the tanker are added as an hyd-file and the wind- and current coefficients for the calculation of the wind and current loads are added. The tanker is placed 80 m behind the back of the FPSO. The FPSO and the tanker are connected with a line called the hawser. The hawser is
modelled as a spring and is connected at the back of the FPSO and to the front of the tanker. In figure 2.6 the load elongation curve is plotted of the Nylon hawser.

![Figure 2.6: Hawser Load elongation curve](image)

### 2.2.4. Tug boat

The tanker is able to move besides of the hawser the tanker is not moored. For the stationkeeping of the tanker a tug boat is used. In the model the tug boat is modelled as an external force attached at the back of the tanker. This is done because by adding the the tug boat as another body requires all the input values of the tug boat as third body to be implemented. The external force is in the negative surge direction and is constant over time. In the zero environment case the tanker will still move because the tanker is attached from the beginning when the FPSO has to find its equilibrium and therefore the tanker will get an offset. In the zero environment the tug will have a bollard pull of 10 tonnes to keep the tanker from moving. In benign environmental condition a tug with a bollard pull of 40 tonnes should be enough to hold the tanker in position during offloading.

### 2.2.5. Environment

In this research all the local environment is considered to be a good representation of the environment offshore Nigeria. In design studies often 100 year or sometimes 1000 year extreme environmental events are used. However because this research does not focus on design but focus more on an operability perspective, values are used that attempts to describe a set of data by identifying the central position within the set of data (Dekking et al. (2005)). For central tendency the mean, median and mode are often used. In different situations some of these measures are more appropriate. The three different measures of central tendency will be described here:

1. **Mean**
   
   The mean value is the average of all the values. The mean is obtained by the summation of all the values and divide by the sample size. The mean value is not the value that is expected during sampling, only for infinite sample size. The average approached the expected value when the sample size increases.

2. **Mode**
   
   The mode is the value that appears most of all the values. If the data consists of large or small values, the mode is not an accurate way to represent the data.

3. **Median**
   
   The median is the middle values , when arranging values from small to large. The median is also called the $P_{50}$ value. The mean is the best estimate. The estimated median value is the value that is exceeded in 50 per cent of the cases.
From these different measures the median is chosen because the median is not affected by extreme values, furthermore the mean can sometimes be misleading in a symmetric or skew distribution, with the median this is not the case. In the base case the median or $P_{50}$ value will be used for the environment and other values. In the sensitivity study of chapter 3 also the $P_{10}$ and $P_{90}$ will be reviewed.

**Waves**

In aNySIM the wave forces on the vessel are updated during the simulation when the position of the vessel changes. In aNySIM long-crested waves are considered. The wave elevation is defined with a wave spectrum and can be written as a superposition of linear wave components. Offshore Nigeria there are the waves generated by the wind called wind sea and the swell waves generated at a distant location. The wind sea is small to medium with heights up to 2.5 m. The wind sea is represented with a JONSWAP spectrum based on the Pierson-Moskowitz spectrum. With JONSWAP spectrum the assumption is that a wave spectrum can never be fully developed, as non-linear wave-wave interactions continue to shape the spectrum (Hasselmann et al. (1973)). For the JONSWAP spectrum a peak enhancement factor $\gamma$ has to be defined, which determines the peakedness of the spectrum. Peak enhancement factors $\gamma$ vary between 1 to 5, in this study the value of 3.3 is used. The low frequency swell peaks resemble a Gaussian (normal) distribution (van der Borch (2013)). For the Gaussian spectrum a parameter defining the width of the symmetric swell spectrum $\sigma$ has to be defined. For all sea states the width of the swell spectrum $\sigma$ has a value between 0.005 and 0.08, however for more extreme swell events, which is the case offshore Nigeria, a spectral bandwidth $\sigma$ of 0.02 is used.

For the swell and the wind-sea the significant wave height $H_s$, peak period $T_p$, and the wave direction has to be defined. These are defined according to the operational conditions for waves, the used data is coming from the West Africa Normal’s and Extremes (WANE-2) hindcast database and covers a continuous period of 15 years between 1992-2006. In the pivot table 2.7 the data of the significant wave height $H_s$ and peak period $T_p$ is shown. With this data the median is calculated of the significant wave height $H_s$ and peak period $T_p$. With the rose plot, see figure (2.8) the swell and wind-sea direction is calculated. In table 2.4 below the input data is summarised calculated with the rose plots and pivot tables.

In the aNySIM model also the wave seed has to be defined. The wave seed is a random nonnegative number representing a random wave train which are a number of component waves from which the amplitudes and periods are selected by aNySIM.

![Figure 2.7: Mean wave direction data of swell and wind-sea (WANE-2)](image)
2.2. Simulation set up

(a) Swell  
(b) Wind-sea

Figure 2.8: Rose plots with swell and wind-sea direction (WANE-2)

<table>
<thead>
<tr>
<th>Input data</th>
<th>Wind-sea</th>
<th>Swell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave $H_s$</td>
<td>0.51 [m]</td>
<td>1.41 [m]</td>
</tr>
<tr>
<td>Wave $T_p$</td>
<td>3.70 [m]</td>
<td>12.19 [m]</td>
</tr>
<tr>
<td>Direction</td>
<td>202 [deg]</td>
<td>192 [deg]</td>
</tr>
</tbody>
</table>

Table 2.4: Median values of the significant wave height, peak period and direction

**CURRENT**

The current forces are calculated according the OCIMF definition, this means that the area used is the length of the vessel multiplied with the draft:

$$F_{\text{current}} = \frac{1}{2} \cdot \rho \cdot C_D \cdot U^2 \cdot A_c$$

$$M_{\text{current}} = \frac{1}{2} \cdot \rho \cdot C_D \cdot U^2 \cdot A_c \cdot L$$

(2.5)  
(2.6)

Where $F$ is the current force, $M$ current moment, $\rho$ the water density, $U$ the current speed, $C_D$ the current force coefficient that are supplied in a separate file, $L$ the length of the vessel and $A_c$ the current area. In the input file the different current layers are defined with the upper and lower bound and the current direction. aNySIM calculates the current force for every layer and the forces are summed. The data used is coming from the SATOCEAN hindcast data, this is based a combination of satellite data and numerical modeling. With these data the median is calculated and a current profile is defined, see figure 2.10. The current direction is assumed to be constant over the different layers and is determined with the roseplot of figure 2.9.
2. Responses of tandem offloading systems to squalls

**Wind**

The wind forces are calculated with the following formula:

\[
F_{\text{wind}} = \frac{1}{2} \cdot \rho \cdot C_D \cdot U^2 \cdot A_c \quad (2.7)
\]

\[
M_{\text{wind}} = \frac{1}{2} \cdot \rho \cdot C_D \cdot U^2 \cdot A_c \cdot L \quad (2.8)
\]

Where \( F \) is the wind force, \( M \) wind moment, \( \rho \) the air density, \( U \) the wind speed, \( C_D \) the wind force coefficient, \( L \) the length of the vessel and \( A_c \) the wind area. The wind area \( A_c \) is dependent on the mode of motion the side wind area of the front wind area. For the wind a time trace will be used containing real time wind data. In the time trace the wind speed and wind direction is defined. Beside from the squall events, the wind speed offshore Nigeria is benign with mean values between 3 to 8 m/s. The first hour of the time trace contains the monsoon wind, after this hour the squall event starts.

The used data is recorded at the top of the a drilling rig, used for drilling in the Bonga field. The recording started 26 November 1996 and lasted till 20 July 1998. The sensor had a sample interval of 1
2.3. Results

Results

The data from the squall events are selected according to the engineering definition of a squall as defined by the World Meteorological Organisation (Atkinson and Caine (2015)). The wind must increase by at least 8 m/s and must attain a top speed of at least 11 m/s, lasting at least one minute. After the event selection time series of three second scalar mean wind speed and associated mean direction were derived for each squall. In total 22 squalls were identified. In figure 2.11 an example is shown of one of the squall records, where the steep increase in wind speed and change in wind direction clearly is showed. In appendix A all the time traces of the 18 used squalls are plotted. Squall number 20 and 21 were not used because a large part of the time trace had undefined values, squall number 9 and 10 were of a different length than the other time traces.

Different characteristics of squalls may influence the response of the vessel, some of these characteristics are the peak wind speed, the rise time of the wind speed, rate of change of the wind direction, decay half time and the magnitude of the wind speed increase (Minnebo et al. (2012)). In table 2.5 the distribution of the peak wind speed of the squall events is shown, squall 11 has the highest peak wind speed with a value of 24.4 m/s. Classifying squalls becomes very difficult because of all these different characteristics like the build up to peak wind speed happens in different ways for different squalls. Furthermore because of all these different characteristics is every squall different and therefore the response of the vessel will also be different.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of squalls</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.5: Peak wind speed distribution of the squall data

Build up environment

The environment is build up in the model, this is done to make sure that the equilibrium position of the FPSO is not affected by the environment. The FPSO with the tanker finds its equilibrium position in around 7200 seconds, this period is quite long because of the large natural period of the FPSO with mooring. In table 2.6 the build up of the environment is shown; current is constant from the beginning of the simulation because the current speed is very low in this region also constant during the whole simulation. After the linear build up and applying of a constant environment the time trace of the wind will start after 10800 seconds, this is because after 10800 seconds the system with its environment founds its equilibrium. The time trace has a length of 10800 seconds and therefore the total simulation time is 21600 seconds. The build up of environment is done for every simulation.

<table>
<thead>
<tr>
<th>Time</th>
<th>0-3600 s</th>
<th>3600-7200 s</th>
<th>7200-10800 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>Linear build up</td>
<td>Linear build up</td>
<td>Constant</td>
</tr>
<tr>
<td>Waves</td>
<td>Linear build up</td>
<td>Linear build up</td>
<td>Constant</td>
</tr>
<tr>
<td>Current</td>
<td>Constant</td>
<td>Constant</td>
<td>Constant</td>
</tr>
</tbody>
</table>

Table 2.6: Build up of environment

2.3. Results

In this part of the chapter all the results found with the time domain simulation of multi-body system in aNySIM will be discussed. The results will be discussed for the ballast and loaded cases separately. Also the effect of only the wind loads in the multi-body system are also reviewed.
Firstly the comparison will be made between the surge, sway and yaw motions of the VLCC tanker during squall 1 in ballast and full load conditions without other environmental inputs, see figure 2.12. The first part of the time trace is the hour before the squall, the tanker motions are not very large as can be seen for both the ballast and full load conditions. The tug controls especially the surge motion because the tug gives a astern pull in surge direction therefore it is the sway motions in the first hour that are a bit larger than the surge motions.

The squall starts after the first hour for both cases, the motions become very large. For the ballast case the deflection is the largest because the wind area is larger. For the lateral wind area this is a difference of a factor 1.38 and for the frontal this difference even 1.97. Furthermore the mass of the ballast load case is lower, the mass of the ballast load case is a factor 2.55 lower compared with the full load case. Apart from the larger motion of the ballast case when hit by the squall, the motions are also more chaotic, this becomes more clear in figure 2.13. In this figure the trace of the VLCC path is plotted for both cases, after the hit the response for the ballast case is larger but becomes back close to its original position. However for the full load case the response is smaller but does not come back to its original position, the response of the full load case even looks like the movement of a pendulum with its rotation point at the back of the FPSO. This motion is called fishtailing and according to Lee and Choi (2002) the most important parameter is the ratio between wind and current and not the hawser length what is often assumed. The study of the effect of the relative motion of the tandem offloading system shown that the relative motion brings damping effects. However this damping enlarges the unstable region, which is the galloping phenomenon. It is used by Lee and Choi (2002) that this is caused by the phase difference between sway and yaw motions.

Figure 2.12: Motions of the ballast and full load VLCC tanker during squall 1 with 40 tonnes pull
2.3. Results

In the previous results the only environment effect considered is the wind. This is done to get a better insight in to what the effect of only the wind has on the tanker during offloading. However offshore Nigeria current and waves are also prevent. In figure 2.14 the results are shown of the effect of different environment on the motions during a squall for both loading cases. For both the loading cases the same trends are found, the squall has also with all the environment a large effect on the responses during offloading. However the effect of the current is considerable, during the hit of the squall the surge, sway and yaw motions are damped and after the squall passed the systems becomes stable much faster especially for the full loaded tanker. The effect of the current loads on the full load tanker are more considerable because the current forces are dependent on the surface, which is larger for the full load case. It is assumed that the water clearance beneath the keel does not play a role because of the deep water. The current is coming from a direction between beam and astern current therefore the current is responsible for a load in an opposite direction as the direction where the squall is coming from, see figure 2.2 for the environmental setup. The effect of the waves on the responses is much smaller. The difference between offloading in normal monsoon wind conditions and a squall will now be evaluated.

Figure 2.14: Motions during squall 1 with different environment

This is done because in these simulations a tug boat with a bollard pull of 40 tonnes is used, it is assumed that for tandem offloading in normal conditions this should be sufficient. In figure 2.15 the comparison is made between normal wind and a squall event. On the left the start position of the tanker and FPSO is shown for every situation, on the right the response to normal wind and a squall. In normal wind conditions the tanker is not completely stable but loss of position is not occurring.
Figure 2.15: Comparison between offloading in normal wind and squall
Beyond the significant influence of squalls on the responses of the tanker also dynamic effects what will occur as a results of the tension in the hawser. Sometimes the loads in the hawser can become so high that the hawser breaks. Below in figure 2.16 the tension in the hawser during the squall is shown. The tension before the squall is around 400 kN; this is due to the bollard pull of 40 tonnes of the tug boat. During the squall the tension increases rapidly up to a value of 1217 kN. In this case the hawser will not break because the maximum allowed hawser load is around 3914 kN. During this squall the maximum hawser load is 31.1 per cent of the maximum allowed hawser load. This peak in the hawser tension is because the FPSO and the tanker both respond differently to the squall, this behaviour is amplified because both vessels have different loading conditions (Zhong et al. (2005)).

![Figure 2.16: Tension in the hawser during squall](image)

### 2.4. Chapter summary

From the results the key knowledge obtained is that during tandem offloading in squalls severe loss of position occurs. This is the case for both the ballast and full load case of the VLCC tanker. If a comparison is made between the two loading cases the ballast loading condition is governing because due to the lower mass and larger wind area the motions become larger, the full loaded tanker shows fishtailing motions if only the wind is considered. When the comparison is made between tandem offloading in normal conditions and squall conditions the conclusion that can be made is with a 40 tonnes astern bollard pull of a tug boat in normal conditions tandem offloading is possible however during a squall this is not the case. Furthermore the tension in the hawser increase rapidly during a squall and hawser breakage could occur in severe squalls. In this chapter was first only the effect of the squall wind studied, these results were compared with the effect current and waves have on the responses. The current dampens the responses considerable, the full loaded tanker shows due to the adding of current a large decrease in fishtailing motions. The waves does not seem to have much effect. However in order to study the effect of the environment and other parameters on the results of the time domain model in more detail a sensitivity is performed, this sensitivity study will be discussed in the next chapter.
3 Sensitivity study

In chapter 2 the responses were studied of the tanker during a squall. This was done for the ballast and fully loaded condition with a hawser length of 80 meters, a tug bollard pull of 40 tonnes and the current and waves $P_{30}$ values. However the responses of this multi-body system are dependent on different parameters, therefore a sensitivity study is performed. The sensitivity study will be performed for the ballast loaded tanker because this case is assumed to be critical. The goal of the study is to analyse the dependence of different parameters on the ship motions during a squall, this will be done with a trend analysis for the different parameters.

3.1. Identification of parameters

Here the sensitivities to be studied will be discussed. In this sensitivity study only the full FPSO and ballast loading condition of the tanker will be considered because in chapter 2 it is found that during squalls this loading condition is limiting the offloading. Furthermore the time required for one simulation is around 20 minutes, this makes the sensitivity study time consuming so studying both the loading cases would take a lot of additional time.

3.1.1. Hawser length

In figure 2.16 the influence of the squall on the hawser tension is shown. Significant dynamic effects occur, these effects are due to inherent instabilities in the horizontal motions of the tanker, which are related to the length of the hawser (Journee and Massie (2001)). For the stability of the system the hawser length plays an important role (Lee and Choi (2005)) however the stability also affects the risk level for tandem offloading. By increasing of the hawser length the separation distance also increases; this increases the area where the tanker can be during the offloading process and there is more time to react. Furthermore tanker captains who participated in a questionnaire survey wanted to have a longer separation distance in the range of 100-150 m while the current separation distance is often below the 100 m (Chen and Moan (2005)). However the increase of separation distance also adds complexity to the marine operations and will mean the tanker will be able to pick up a higher speed what could result in higher impact energy in case of collision. On the contrary The extra time available with a longer hawser length may lead to an increase of safety due the tug having more time to react. In the sensitivity study hawser lengths of 80 m, 120 m and 160 m will be used.

3.1.2. Tug pull

In section 2.3 it is discussed that tandem offloading in normal conditions is done with a pull of 40 tonnes however during squalls this is not sufficient. In a study performed by J.Wichers about the investigation of tandem offloading systems. Two tugs were used both with a bollard pull of 75 tonnes to provide additional pull to ensure sufficient clearance between the tanker and the FPSO and to prevent yaw
instability of the system (Wichers and Van Dijk (2000)). The tug boat is an important element for the station keeping and by increasing of the bollard pull the tanker can potentially be kept in the offloading zone. In the sensitivity study tug bollard pull of 80, 100 and 200 tonnes will be used.

3.1.3. Current and waves

For the current and waves the $P_{50}$ values were used and in section 2.3 it is shown that the current dampens the motions during a squall and that the effect of the waves is not significant however is this behaviour the same for faster current speeds and higher wave height. Therefore in the sensitivity study the $P_{10}$ and $P_{90}$ values will be used for the current speed and significant wave height for the wind sea and swell. For the wind sea and the swell the same $P$ value will be used. The direction is considered as a separate parameters because the uncertainties in the direction of current and waves is small (van der Borch (2013)). Especially the swell is always coming from the same direction because the swell is generated by depressions in the South Atlantic and Southern Ocean.

3.2. Sensitivity cases

With all the above mentioned parameters a run schema is developed. In table 3.1 the different cases for hawser length, tug pull, waves and current are summarised, apart of these cases also the 18 squalls. By taken all the possible combinations into account the amount of aNySIM simulations is 1422. To be able to do all these simulation a batch file is used.

<table>
<thead>
<tr>
<th>Hawser length [m]</th>
<th>Tug pull [tonnes]</th>
<th>Wind sea and swell</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>40</td>
<td>$P_{10}$</td>
<td>$P_{10}$</td>
</tr>
<tr>
<td>120</td>
<td>100</td>
<td>$P_{50}$</td>
<td>$P_{50}$</td>
</tr>
<tr>
<td>160</td>
<td>200</td>
<td>$P_{90}$</td>
<td>$P_{90}$</td>
</tr>
</tbody>
</table>

Table 3.1: All the sensitivity cases for the full load FPSO with ballast tanker

3.3. Results

In this part of the chapter all the results will be discussed obtained with the sensitivity study in aNySIM. All the results were processed with a Matlab script. In figure 3.1 the results are plotted of the absolute maximum values of surge, sway and yaw of the FPSO and the VLCC tanker during the 18 squalls.

Figure 3.1: Max. values surge, sway and yaw of 1422 simulations
3.3. Results

3.3.1. Hawser Failure

The values for the VLCC tanker can be very large especially the absolute maximum for surge. It reaches values of around 10000 m. This is not seemed realistic and can be explained using figure 3.2 below. The dotted line in the figure is the hawser breaking load of 3914 kN, as can be seen that for squall number 2, 3, 5, 11, 12, 13, 15, 18 and 22 this value is exceeded. During a simulation when this value is exceeded the hawser breaks but the simulation does not stop and therefore these maximum values of figure 3.1 are so large. This is also something that could happen in reality therefore hawsers with larger breaking loads have to be used. The simulations where the hawsers tension exceeds the breaking load will not be used in the other results of this sensitivity study.

![Figure 3.2: Max. hawser tension of all the 1422 simulations](image)

From the 1422 simulations performed, in 172 occasions the hawser breaks, this is 12.1 per cent of the cases. As mentioned above, the hawser does not break for all the squalls but for 50 per cent of the 18 squalls that were used. For these 9 squalls an analysis is performed to examine which of the parameters described in section 3.1 result in failure of the hawser. In table 3.3.1 the failure cases are subdivided over the different parameters. The results from table 3.3.1 indicate that the peak wind speed has an influence on the hawser failure. Squalls 11 with the highest peak wind speed 24.4 m/s of all the used squalls is responsible for 20.9 per cent of the failure cases. Squalls 12 and 15 with respectively lower peak wind speeds have as expected a lower amount of hawser failure cases; these two squalls are responsible for 4 per cent of all the hawser failure.

Furthermore the results of the hawser failure cases for current and waves show that the influence of the faster current and higher significant wave height does not influence the chance of hawser failure. For current speed there is a difference of only 0.6 per cent in the amount of hawser failure. The results for waves show also small difference of 1.2 per cent for the $P_{10}$ and the $P_{50}$ value and 1.7 per cent difference for the $P_{50}$ and the $P_{90}$ case. However the results for the hawser length indicate that the hawser failure is dependent of the hawser length. Hawser length of 80 m leads to hawser failure in 38 cases, this is 22.1 per cent but for a hawser length of 160 m it leads to failure for 83 times, 48.3 per cent. The reason for more hawser failure cases with a longer hawser is due to the fact that the tanker will pick up a higher speed and that a longer hawser indicate more instabilities in the system. However is can still be the case that with a longer hawser there is more time to react what could lead to increase in safety during offloading but there is an increased chance of hawser failure for longer hawsers.

Furthermore the results of the different tug bollard pulls indicate that also the tug pull influence the chance of hawser failure. With a pull of 40 tonnes the hawser fails in 72.7 per cent of the times, with 100 tonnes
in 27.3 per cent and with 200 tonnes the hawser does not break at all. The reason for this is because with a higher bollard pull of 200 tonnes the hawser is already under a large tension, as can be seen in figure 2.16, the hawser breaks not because the constant load reaches the breaking load but because the peak loads in the hawser become large. With a higher hawser tensions these peak loads will be smaller and therefore the hawser will break less often than in the case with lower tug bollard pulls.

<table>
<thead>
<tr>
<th>Squall nr.</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>15</th>
<th>18</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak wind speed [m/s]</td>
<td>22.7</td>
<td>18.3</td>
<td>19.3</td>
<td>24.4</td>
<td>15.6</td>
<td>21.0</td>
<td>13.9</td>
<td>20.0</td>
<td>20.5</td>
</tr>
<tr>
<td>Amount fails [-]</td>
<td>27</td>
<td>6</td>
<td>14</td>
<td>36</td>
<td>4</td>
<td>26</td>
<td>3</td>
<td>24</td>
<td>32</td>
</tr>
<tr>
<td>Percentage fail [%]</td>
<td>15.7</td>
<td>3.5</td>
<td>8.1</td>
<td>20.9</td>
<td>2.3</td>
<td>15.1</td>
<td>1.7</td>
<td>14.0</td>
<td>18.6</td>
</tr>
</tbody>
</table>

| Current $P_{10}$ [m/s] | 12 | 0 | 5 | 12 | 0 | 9 | 3 | 7 | 9 | 57 |
| Current $P_{50}$ [m/s] | 7 | 3 | 4 | 12 | 2 | 9 | 0 | 9 | 12 | 58 |
| Current $P_{90}$ [m/s] | 8 | 3 | 5 | 12 | 2 | 8 | 0 | 8 | 11 | 57 |
| Waves $P_{10}$ [m] | 9 | 2 | 4 | 12 | 1 | 9 | 1 | 9 | 10 | 57 |
| Waves $P_{50}$ [m] | 10 | 2 | 5 | 12 | 2 | 8 | 2 | 7 | 11 | 59 |
| Waves $P_{90}$ [m] | 8 | 2 | 5 | 12 | 1 | 9 | 0 | 8 | 11 | 56 |
| Length 80 [m] | 5 | 0 | 0 | 8 | 0 | 8 | 0 | 6 | 11 | 38 |
| Length 120 [m] | 10 | 0 | 0 | 10 | 0 | 9 | 1 | 9 | 12 | 51 |
| Length 160 [m] | 12 | 6 | 14 | 18 | 4 | 9 | 2 | 9 | 9 | 83 |
| Tug pull 40 [t] | 5 | 6 | 5 | 26 | 4 | 26 | 3 | 24 | 26 | 125 |
| Tug pull 100 [t] | 22 | 0 | 9 | 10 | 0 | 0 | 0 | 0 | 6 | 47 |
| Tug pull 200 [t] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 3.2: Hawser failure cases divided over the different parameters

The hawser failure cases are not within the range of expected values and therefore these values are not further used, the results shown below are of the 1250 simulations without hawser failure. In figure 3.3 the absolute maximum surge, sway and yaw values without the failure cases are plotted for the FPSO and the tanker. The influence of the hawser failure for the motions of the FPSO are small because the FPSO is moored to the sea bed with its own mooring system, but the motions for the tanker show a large different because maximum surge motions are in the range of 0 - 600 m instead of 0 - 10000 m.

Figure 3.3: Max. values surge, sway and yaw without hawser breakage
3.3.2. Trend analysis

In figure 3.4 the results are shown of the trend analysis for the different parameters. In every figure the median \( \mu \) and the median plus or minus the standard deviation \( \sigma \) are also plotted. In table 3.3.2 the median \( \mu \) and standard deviation \( \sigma \) are displayed. The meaning of the median is explained in section 2.2.2 and is the mid value of the data set. The standard deviation gives an idea how close the entire data set is to the average value. A small standard deviation is tightly grouped and a larger standard deviation means that the data is spread out over a wide range of values.

Below the results will be evaluated for the different parameters:

1. Current speed
   The results for current show for sway and yaw that increase in current speed lead to a decrease in the response. For surge this is not the case for \( P_{50} \) value. A faster current speed will lead to higher current forces on the tanker and therefore the motions will be damped. In general the effect of current is considered to be not very large, for surge and yaw the difference is 8 per cent between \( P_{10} \) and \( P_{90} \) and for sway 13 per cent. The standard deviation is large so the data is spread.

2. Wave height
   The results for waves show that with higher significant wave height the responses become larger for surge but the effect for sway and yaw is almost negligible. In figure 3.4 the plot for waves is
almost a horizontal line. The standard deviation is large for surge, sway and yaw so the data is spread. For surge and yaw are most of the values in the lower past of the plot so the median is relative small, for sway the median is more close to the mean.

3. Hawser length
The results for increase in hawser length show that a longer hawser results in larger surge and sway motion this difference for a length of 80 m or 160 m is respectively 18 per cent for surge and 25 per cent for sway. Larger responses due to a longer hawser does not mean that there is a larger chance of collision because the distance to the FPSO is also larger. However if the same offloading zones are used with the same surge and sway offloading limitation shall the offloading being stopped faster. For this parameter the standard deviation is for a hawser length of 120 m in the same range as for current and waves however for the 80 m hawser the standard deviation is smaller and larger for 180 m hawser length.

4. Tug pull
The results for the tug pull show a large decrease in motion for surge, sway and yaw. The use of tugs with higher bollard pull is very effective for the stationkeeping. With a bollard pull of 40 tonnes the surge motions are the largest of all the different parameters. The decrease is the biggest for surge with a difference of 68 per cent between 40 tonnes and 200 tonnes, this is due to the fact that the tug is pulling in astern direction and therefore compensated especially surge motions.

<table>
<thead>
<tr>
<th>Motion</th>
<th>Surge[m]</th>
<th>Sway[m]</th>
<th>Yaw[deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current speed</td>
<td>0.11</td>
<td>0.29</td>
<td>0.58</td>
</tr>
<tr>
<td>µ</td>
<td>145.50</td>
<td>147.97</td>
<td>134.14</td>
</tr>
<tr>
<td>σ</td>
<td>123.99</td>
<td>130.68</td>
<td>126.33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Motion</th>
<th>Surge[m]</th>
<th>Sway[m]</th>
<th>Yaw[deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave height</td>
<td>0.15</td>
<td>0.51</td>
<td>0.85</td>
</tr>
<tr>
<td>µ</td>
<td>139.34</td>
<td>143.95</td>
<td>144.20</td>
</tr>
<tr>
<td>σ</td>
<td>124.12</td>
<td>128.53</td>
<td>129.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Motion</th>
<th>Surge[m]</th>
<th>Sway[m]</th>
<th>Yaw[deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawser length</td>
<td>80</td>
<td>120</td>
<td>160</td>
</tr>
<tr>
<td>µ</td>
<td>129.22</td>
<td>145.12</td>
<td>153.09</td>
</tr>
<tr>
<td>σ</td>
<td>108.59</td>
<td>128.55</td>
<td>141.56</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Motion</th>
<th>Surge[m]</th>
<th>Sway[m]</th>
<th>Yaw[deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tug pull</td>
<td>40</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>µ</td>
<td>246.90</td>
<td>249.95</td>
<td>79.56</td>
</tr>
<tr>
<td>σ</td>
<td>166.91</td>
<td>107.88</td>
<td>10.14</td>
</tr>
</tbody>
</table>

Table 3.3: Median μ and standard deviation σ for the different parameters
3.4. **Chapter summary**

The trend analysis that was performed with the results of the sensitivity study showed that increase of current loads has a dampened effect for sway and yaw and for surge only for the faster currents. The effect of waves on the responses is found to be not significant. But the increase of the hawser length shows an increase in the responses of surge and sway but a small decrease in the yaw motion. The different tug pulls have a large effect on surge, sway and yaw.

Of all the 1422 performed simulations in the sensitivity study was the maximum allowed hawser breaking load in 12.1 per cent exceeded. Of all these simulations was the hawser with the longest length that had the largest effect on the exceedance of this load. It was found that the responses of the time domain model will give a good representation considering of the above evaluated parameters only the tug pull will have a significant effect on the responses of the tanker. Furthermore, it is the use of a longer hawser in tandem offloading operation not favorable, not only was there a small increase of the responses but also the chance of hawser failure increases.

The effect of the different parameters on the tanker responses were studied in detail but the interaction of wind and waves was not part of the time domain model. Because it is assumed that this can have a significant effect is the wind interaction studied with the use of the building block approach based on Schlichting boundary layer theory for two dimensional flows. In the next chapter will the wind interaction study be discussed.
Wind interaction

In this chapter the effect of wind interaction on the wind loads and motions of the tanker are discussed. The chapter will consist of the following elements: the theory behind the building block approach, the effects the different elements of the building-block model have on the wind loads, the development of the single body model of the FPSO and tanker and the multi-body interaction study by first study the effect of interaction on the wind loads and than the implementing of the calculated shielded wind coefficients in time domain.

There are different types of wind interference like buffeting, channeling, interaction and shielding. In this research the focus is on wind shielding because during tandem offloading the tanker is shielded by the FPSO.

During tandem offloading the FPSO and tanker are in close proximity. Shielding can influence the tanker’s relative heading during offloading. According to studies performed by Feikema et al. (1992) and Fucatu et al. (2001) the shielding effect can be significant, but wind shielding is very complex. In order to have a reliable numerical model for tandem offloading, wind shielding should be taken into account.

4.1. Methods to obtain wind loads on offshore structures

The wind coefficients are needed to calculate the wind forces. For tankers these coefficients are often taken from OCIMF standards (OCI (1994)). The advantage of using these coefficients is that they are easily applicable but the accuracy of these is limited and lift effects on decks and interaction effects are neglected. There are other options available that take wind interactions into account: wind tunnel tests and Computational Fluid Dynamics (CFD). During wind tunnel tests only a limited amount of configurations can be tested but the wind loads on the tanker vary with relative wind direction, relative distance between the FPSO and tanker and the orientation of the tanker relative to the FPSO therefore wind tunnel test are time consuming and costly.

Another option to take wind interference into account is CFD. CFD programs like ReFRESCO and CFX solve multiphase unsteady incompressible flows using the RANS (Reynolds-averages Navier-Stokes) equations, complemented with turbulence models and volume-fraction transport questions for each phase. The equations are discretised using a finite-volume method with cell-centred variables in physical space. The implementation is face-based, which permits grids with elements with an arbitrary number of faces or locally refined grids with hanging nodes (MARIN, 2010). CFD is a cost-effective alternative for wind-tunnel tests with reasonable accuracy. The downside of CFD is that CFD is effective to “model the model” so after performing of wind tunnel tests, the same dimensions for the vessels, orientation and wind speed as used in the wind tunnel are used as input for the CFD model.
because validation of the CFD model is required. The validation of a CFD model is often done with the wind tunnel tests. Apart from the fact that CFD is also very time consuming, CFD gives a reasonable answer for the wind coefficients of a single vessel but for tandem offloading no good agreement is found between CFD results and wind tunnel tests (Koop et al. (2010)). In figure 4.1 an visualisation is shown of results obtained with a CFD analysis.

Figure 4.1: CFD results from ReFRESCO, velocity distribution in the wake of the FPSO for 150 degrees wind heading

The software used for the development of the time domain model, aNySIM, has a module included taken from the Shuttle program and is based on model tests in the wind tunnel of Nederlands Lucht- en Ruimtevaartcentrum (NLR). In the wind tunnel tests the wind wake field of a tanker was measured for different headings with respect to the wind direction at a distance behind the FPSO. The module scales and extrapolates the measured wakes to any other distance behind the upstream vessel. For the use of this module a wake model has to be implemented. Actual flow data is required for the development of a wake model, therefore the use of this module was not preferred. Furthermore the module extrapolates the wake field from the original wake field, but different alignments are not considered.

Another approach for obtaining wind loads on vessels is the building block approach. In the building block approach a structures is built up by standard components with known force characteristics. The interaction between these components is accounted for in the wind loads. The building block approach is developed by Marin and NLR.

4.2. BUILDING BLOCK APPROACH

The building block approach is the most promising discussed approach and gives insight in the influence of different topsides of the vessel, distance between the vessels, wind speeds and alignments therefore this approach will be used for the study of wind interaction even though this approach is a quasi-static method for the consideration of wind interaction.

The program WINDOS uses the building block approach to calculate wind forces and coefficients. The multi-body model of the FPSO with the oil tanker is built of different blocks in Windos. The objective of the study is to find if the wind forces on the tanker are influenced by the presence of the FPSO. If this is the case the amount of shielding is studied. However for this purpose first the validation of the program WINDOS should be studied.
4.3. Theory of Windos

Windos is used in house in Shell for the study of wind interaction between the different elements of the topside of one vessel but is never used before for the study of a multi-body model. For the analysis of the multi-body wind interaction model the following approach is used:

1. Development of the Windos model for the Bonga FPSO for the full load and ballast case
2. Comparison of the wind coefficients and wind forces obtained with Windos and the wind coefficients and forces found during the wind tunnel tests. The comparison is made to validate the Windos model that will later be used for the multi-body analysis. An important aspect is how in Windos the wind coefficients are calculated. See below for the calculation of the wind coefficients in Windos:

\[ C_{\text{windos}} = \frac{F_{\text{tot,Windos}}}{\frac{1}{2} \cdot \rho \cdot u^2 \cdot A} \]  
\[ F_{\text{tot,Windos}} = F_{\text{Block1}} + F_{\text{Block2}} + F_{\text{Block3}} + \ldots + F_{\text{Blockn}} \]

Where \( C_{\text{windos}} \) is the wind coefficient calculated in Windos, \( F_{\text{tot,Windos}} \) is the wind force calculated in Windos, \( \rho \) is the air density, \( u^2 \) the wind speed used in Windos. Because the wind coefficients are calculated with the use of the total wind force \( F_{\text{tot,Windos}} \) it is important that the other variables are the same in both Windos and the wind tunnel tests. The area \( A \) that is used in Windos for the calculation of the wind coefficients is the transverse area \( A_T \) or longitudinal area \( A_L \) however in the wind tunnel test as area is \( B^2 \) used, \( B \) is there the breadth. Therefore shall the same area be used for the comparison of Windos and the wind tunnel test.

3. Development of model of the VLCC tanker and add the model of the FPSO and the tanker together in multi-body model in Windos for the ballast and full load case
4. In order to get a understanding of the working of Windos and the influence different components in the model different cases will be studied. The effect of different freeboards, topsides and distance of blocks will be evaluated.
5. Perform the simulations with the developed multi-body model. In table 4.1 the simulations that will be performed are defined. These values for X and Y are used because so the influence of shielding for the different location can be studied.

<table>
<thead>
<tr>
<th>Shift of axis</th>
<th>Unit</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>[m]</td>
<td>20 40 60 80 100 120 140 - -</td>
</tr>
<tr>
<td>Y</td>
<td>[m]</td>
<td>20 40 60 80 100 120 140 - -</td>
</tr>
<tr>
<td>X,Y</td>
<td>[m]</td>
<td>55,105 55,157 55,188 105,128 105,192 105,230 65,197 85,213 95,222</td>
</tr>
</tbody>
</table>

Table 4.1: Simulations for the study of shielding in Windos.

6. Use the shielded coefficients of the cases shown in table 4.1 in the time domain model in aNySIM
7. Develop a tool to predict the wind shielding

4.3. Theory of Windos

In this section will the theory of Windos be evaluated according to the Windos Manuel (Van Walre). For the calculation of the forces on the different components not only the force coefficients are important but also the local wind velocity characteristics. The local wind climate is influenced by the interaction of the wind climate with the sea and the component induced velocities. The interaction of the wind climate over the sea will be discussed first.

4.3.1. Wind Climate

The wind velocity profile above homogeneous land in stationary conditions has been well predicted with the Monin-Obukhov similarity theory (MOST) and surface layer scaling (Pena et al., 2007). The wind
velocity profile above land is governed by the two aspects that the velocity is zero at ground level and that turbulence is the highest close to the ground level.

The wind velocity profile describes the momentum loss between the different layers caused by mixing depended of turbulence and velocity gradient with height.

An important variable is the roughness length \( z_0 \). The roughness length is equivalent to the height at which the wind speed is theoretically becomes zero. The logarithmic wind velocity profile above land is defined in terms of roughness length:

\[
\frac{V(z)}{V_r} = \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_r}{z_0}\right)} \quad (4.3)
\]

\( V(z) \) represents the local wind speed at a height \( z \) and \( V_r \) is measured at height \( z_r \).

For wind velocity profile above the sea the roughness length depends on the wind speed at 10 meters above sea level \( V_{10} \) because the surface moves with the wind and the roughness presented by the surface waves varies with wind speed and the roughness length is much smaller than it is above land.

\[
z_0 = 7.31 \cdot 10^{-7} \cdot V_{10}^2 + 8.68 \cdot 10^{-8} \cdot V_{10}^3 \quad (4.4)
\]

Furthermore the logarithmic wind velocity profile can also be used close to the sea surface but to cover the whole range of height when considering ships the power law wind profile will be manipulated that in the logarithmic wind profile range the profile is also applicable. This is done by choosing an upper height of interest \( z_2 \) and lower height of interest \( z_1 \), a curve can be chosen at the average velocity height \( \sqrt{z_1 \cdot z_2} \) that will remain very close to the range of interest. The power law velocity profile is given by:

\[
\frac{V(z)}{V_r} = \left(\frac{z}{z_r}\right)^p \quad (4.5)
\]

\[
p = \frac{1}{\ln\left(\frac{\sqrt{z_1 \cdot z_2}}{z_0}\right)} \quad (4.6)
\]

For the calculation of drag an effective wind speed is used:

\[
V^2 = \frac{1}{z_2 - z_1} \int_{z_1}^{z_2} V^2 \, dz \quad (4.7)
\]

4.3.2. Turbulence

As mentioned above is the turbulence at sea level the highest. Turbulence is a continuous, stochastic and three-dimensional process. In turbulence large vortices transfer energy to smaller vortices till viscous dissipation occurs at the smallest vortices. In this case turbulence will be described by two parameters the turbulence intensity \( T_i \) and turbulence scale \( T_l \). The turbulence intensity \( T_i \) is given by:

\[
T_i = \frac{\sqrt{u^2}}{V_r} \quad (4.8)
\]

Where \( u^2 \) is the mean square value of the velocity fluctuations \( u \). Turbulence has a big influence on the drag and therefore also on the wind force. A range of values of the turbulence intensity and turbulence are given in table 4.2.
### 4.3. Theory of Windos

#### 4.3.3. Local wind characteristics

The local velocities of the flow are in relation to the undisturbed velocity determined by different effects like velocity gradients in the boundary layer, separation regions and component interaction. A flow that flows over a body builds up a boundary layer $\delta(x)$ due to viscous effects. At the edge of the body there is a constant velocity distribution perpendicular to the body, if the distance from the edge becomes larger, the layer of particles slowed down by the friction and the layer becomes thicker.

For ships and offshore platforms the height of the boundary layer is around several meters and for a main deck with infinite width that is also smooth and thin the boundary layer characteristic can be determined accurately but in reality this is not the case because the boundary layer is not as well conditioned. This is due to several reasons:

1. **Flow separation**

   The flow will separate from the leading edge corners because of the thickness of the main deck. A separation bubble will form. The separated flow is divided from the part outside of boundary layer by a thin region with high shear and vorticity. This region is called the free shear layer and this layer is similar to the boundary layer but is not attached to the surface of the body. Separation of the fluid appears where the pressure increases due to the formation of vortices. In the separation point the velocity gradient becomes zero therefore the shear stress also becomes zero:

   \[
   \tau_w = \mu \left( \frac{\partial u}{\partial y} \right)_w = 0 \quad \text{(separation)} \quad (4.9)
   \]

   In the figure 4.3(a) a symmetric flow passes a blunt body, the FPSO and the tanker can also be considered as a blunt body. From D to E the flow accelerated and will experience a pressure drop, in the part from E to F the flow decelerate and the pressure increased. In the beginning when the boundary layer is very thin an almost inviscid flow first forms, in the outer layer of the flow pressure is transferred into kinetic energy from D to E and from E to F kinetic energy

<table>
<thead>
<tr>
<th>Height above ground</th>
<th>$T_i$ (10m)</th>
<th>$T_i$ (30m)</th>
<th>$T_i$ (100m)</th>
<th>$T_i$ (300m)</th>
<th>$p$ for mean hourly wind vel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open sea: large stretches of open water</td>
<td>0.11</td>
<td>0.10</td>
<td>0.08</td>
<td>0.05</td>
<td>95</td>
</tr>
<tr>
<td>Open country with few, low, obstacles</td>
<td>0.18</td>
<td>0.16</td>
<td>0.11</td>
<td>0.07</td>
<td>75</td>
</tr>
<tr>
<td>Low density built-up areas; small towns; suburbs; open woodland</td>
<td>0.25</td>
<td>0.19</td>
<td>0.14</td>
<td>0.08</td>
<td>60</td>
</tr>
<tr>
<td>Town and city centers with high density building; broken country</td>
<td>0.25</td>
<td>0.24</td>
<td>0.16</td>
<td>0.09</td>
<td>55</td>
</tr>
</tbody>
</table>

Table 4.2: Typical wind and turbulence characteristics for some general environment (Windos manual).
is transferred into pressure. In the thin frictional layer the friction forces are so strong that a particle loses so much of its kinetic energy that it cannot get over the “pressure mountain” from E to F and comes to a standstill. The particle is pushed into backwards motion by the pressure distribution of the outer flow. The final state of the flow will be as shown in figure 3(b). In the region with vortices a negative pressure is present. This negative pressure results in large form drag of the body. The size and shape of this region is related to the geometry of the bodies.

![Image](image-url)

(a) Separation of boundary layer and vortex formation
(b) Turbulent flow

Figure 4.3: Process from a very thin boundary layer to vortices

2. Deck width
The deck width relative to the length is short therefore at the edges of the deck the boundary layer will be disturbed. This will mostly happen for oblique flows.

3. Topside
Apart from the influences of the deck there is also the influence of the topsides. The topsides will influence the boundary layer and will affect other elements by their wake.

4. Lift force
Furthermore additional velocity components should be added if the deck produces a lift force.

A mathematical description of all the above mentioned is not existing because of its high complexity. Therefore a global description of the velocity field is used. The model is based on model tests and potential theory. The axis system used for this mathematical description is given in figure 4.4 below.

![Image](image-url)

Figure 4.4: Axis system for potential flow formulations.

The values of $V_x$ and $V_y$ in the figure above can be calculated as follows:

\[
V_x = V \cos \alpha \left( \frac{1}{\pi} \left[ \arctan \left( \frac{d - y}{x} \right) + \arctan \left( \frac{d + y}{x} \right) \right] + 1 \right) \quad (4.10)
\]
\[
V_y = V \left( \frac{\cos \alpha}{2\pi} \ln \left( \frac{(d + y)^2 + x^2}{(d - y)^2 + x^2} + \sin \alpha \right) \right) \quad (4.11)
\]

In which $\alpha$ represents the angle between the undisturbed flow $V$ and the body length axis. The coefficient $d$ is half the body thickness and $x$ and $y$ are local coordinates. The description of $V_x$ and $V_y$ give a good agreement outside of the separation zone and over the centerline of the deck. The described model is
for a two-dimensional potential flow therefore the flow behind the separation bubble and the effect at
the side of the deck are not accounted for. These effects are incorporated with correction on \(V_x\) and \(V_y\)
found in the wind tunnel tests. This approach leads to a description of the flow field around and above
main decks. Main decks in perpendicular flows give better results than the flows in oblique flows, here
are the uncertainties larger.

4.3.4. **Components**

The components used to describe the different structures have known force coefficients. These coef-
ficients are obtained from experiments. In total there are 6 different types of components available:
cylinder, rectangular prism, flat plate, ship hull, lattice structure and various. The type 'various' is
used for the applications beams and cables. Hereby a description of the most important components:

1. Hull of a ship

   The hull of a ship can be described as a low aspect ratio wing. The aspect ratio is the freeboard of
   the ship divided by the length. The shape of the bow, stern and aspect ratio have a large effect on
   the magnitude of the force coefficients. Wind loads on the hull are determined with wind tunnel
test. The loads on the hull cannot contain the loads of the superstructures so it is possible to
determine wind loads on a combination of components in an arbitrary position. In Windos some
typical hulls are available in ballast and full load situation. The force coefficients are taken from
the wind tunnel results that were reliable and gave information that was needed to eliminate the
wind loads due to the superstructure.

2. Rectangular prism

   Most of the blocks of the superstructure of an FPSO are rectangular prisms. ESDU data sheet
   71016 gives a description of the forces, pressures and moment coefficients for the use of the
   estimation of the forces, pressures and moments on rectangular blocks are presented (710 (1978)).
   ESDU data sheet 80003 proves information of the mean forces and moments on surface-mounted
   rectangular prisms in turbulent shear flow (800 (1986)). With these two data sheets a description
   of the force coefficients can be made. In these data sheet the drag coefficients as a function of
   the dimensions of the prisms and the incident angles of the wind force is given. The side force
can have the same magnitude of the drag force at incidence. The side force can add to the total
   overturning moment. The boundary layer separates at the sharp corners so no Reynolds number
   effects occur. Furthermore the drag and side fore on the prisms are determined by the pressure
   forces and not by the skin friction so the surface roughness is not taken into account.

   No correction is taken into account for turbulence even though the turbulence characteristics of
   the free flow influence the forces on the prisms because the available correction factors show scatter
   for prisms with low aspect ratios.

   Prisms attached to the surface experience higher drag because the low pressure region behind the
   prisms near the surface cannot be reached by the free flow with the higher pressure. Lift forces
   can also be experienced due to the accelerated flow and reduced pressure over the top face. The
   center of pressure position is assumed to be the center of geometry of the prism.

3. Flat plate

   A flat plate is considered to have the same force characteristics as a rectangular prism with a
   negligible thickness. According to ESDU 70015 (700 (1972)) for flat plates normal to the flow the
   normal force coefficient is:

   \[
   C_n = 1.1 + 0.02 \left( \frac{DY}{DX} + \frac{DX}{DY} \right) \quad (4.12)
   \]

   This coefficient will be increased if the stream is turbulent. The normal force is dependent on the
   incident angle \(\alpha\) and the aspect ratio \(\frac{Dy}{Dx}\). The tangential force and the Reynolds number effects
can be neglected. With the coefficient calculated in equation 4.12 the lift and drag coefficients
can be calculated. The centre of pressure position is dependent on the aspect ratio \(\frac{Dy}{Dx}\) and the
4. Wind interaction

A helideck is a type of flat plate that is placed in the horizontal plane. Flat plates under a small incident angle (till 25 degrees) are lifting surfaces. If the helideck is places outside of the main deck it can experience an up flow angle up to 25 degrees and the dynamic pressure is twice the free stream value. Therefore helidecks experience large lift forces and can contribute significantly to the overturning moment.

4. Lattice structure

A lattice structure is considered as a framework. The forces on the framework are calculated with the bulk method. In the bulk method the forces are obtained from empirical formulations for the force coefficient for just a single framework related to the shape of the framework and the solidity. The solidity is the ratio of the area of a single element to the total area. The interaction of the different elements of the structure is also included. The bulk method is obtained from ESDU data sheets 81027 and 81028. In the data sheet three different chord members are considered: triangular, square and rectangular. The structural members can be flat faced or circular. The solidity ratio is corrected for the gusset plates. The force coefficients are calculated with the following relation:

\[ C_{D, S} = C_{D, S0} f_\delta f_\beta f_s \]  
(4.15)

In which \( C_{D, S0} \) is the drag or side force coefficient and is dependent on the chord arrangement and member type, \( f_\delta \) is the correction factor for the solidity ratio, \( f_\beta \) is correction factor for wind inclinations and \( f_s \) is the correction factor for the shielding effects.

4.3.5. Interaction: Shielding

Components that are subjected to flow of a fluid can be influenced by other components, this may lead to interaction effects. Some examples of this interaction is the exposure of downstream components to reduced velocity and turbulence due to the wake of upstream components. The reduction of the forces on a downstream component is called shielding. The Schlichting boundary layer theory (Schlichting (1979)) is used to describe the velocity in the wake \( V(Y) \) of components see equation 4.16. The components are considered to be bluff bodies. However this theory cannot be used for too short distances because in this case the upstream body is affected too much by the presence of the downstream body.

\[ \frac{V(Y)}{V} = 1 - 0.98 \left[ \frac{X}{C_D d_W} \right]^{P_1} \left[ 1 - \left( \frac{2Y}{b} \right)^{1.5} \right]^2 \]  
(4.16)

\[ b = 1.14[C_D d_W X]^{P_1} \]  
(4.17)

Where \( b \) is de wake width, \( C_D \) is de drag coefficient of the upstream component, \( d_W \) is the upstream component width, \( X \) and \( Y \) are local coordinates, \( V \) is the undisturbed velocity. The values of \( P_1 \) and \( P_2 \) are dependent on the flow type, for three-dimensional flows the value of \( P_1 \) is 0.33 and \( P_2 \) is -0.67.

The influence of the shielding on the downstream element is included into the dynamic pressure by multiplying the dynamic pressure with a reduction factor \( f \). The velocity in the wake \( V(Y) \) is still dependent on the location, to consider the total pressure reduction on the downstream body, the shielded velocity is integrated over the shielded area with a width \( b_s \) and a height \( h_s \).

\[ V_s = \frac{1}{b_s} \int_{-h_s}^{h_s} V(Y) dY \]  
(4.18)
4.4. Influence of components

With the velocity \( V_s \) the dynamic pressure reduction factor \( f \) can be calculated:

\[
f = \frac{V_s^2 b_s + V^2 (A_p - h_s b_s)}{V^2 A_p} \tag{4.19}
\]

Where \( V_s \) is the mean velocity in the shielded area, \( V \) is mean undisturbed velocity and \( A_p \) is the projected area of the downstream area. For the interaction of components that are close to each other use is made of wind tunnel experiments because in literature no data was found. All the above mentioned is for the interaction of two components, but often this is not the case. More components are affected. The interaction for groups of bodies is difficult to quantify. The reduction factor for components at a distance are close to 1 while the factors for components nearby are close to zero. This would mean that on an average the reduction factor would be around 0.5 but this is not correct. Therefore the following approach is used. For a component that is shielded by other components, the lowest reduction factor \( f_s \) is used, if this component is as well affected by other components in a side-by-side manner the largest reduction factor \( f_i \) is multiplied with the lowest factor \( f_s \), this results in the total dynamic pressure correction \( f_i \):

\[
f_i = f_{s, \text{min}} f_{i, \text{max}} \tag{4.20}
\]

4.4. Influence of components

For the use of WINDOS it is important to know what the effect of different components on the wind force and wind coefficients. In this section the influence of different components will be studied in order to get a better understanding of the developed models.

4.4.1. Freeboard

![Figure 4.5: Velocity distribution in the wake](image)

![Figure 4.6: Effect of different freeboards on the wind forces and moment](image)
In figure 4.6 the influence of different freeboards of ship hulls are shown on the wind forces calculated with WINDOS. If the freeboard increases the wind areas becomes larger, this will lead to an increase of the force in x, y direction and the moment around the z axis. The force in x-direction has a maximum at 0 and 180 degrees because the wind area is the largest here, the minima are at 90 and 270 degrees because in this direction no force is excited into x-direction. Where the force in x-direction has its maxima, has the force in y-direction its minima. The shape of the figure for the yaw moment is very much dependent on the superstructure of the vessel, here the minima are 0 and 180 degrees and maxima at 90 and 270 degrees.

4.4.2. Different topsides

Apart of the influence of different freeboards on the wind loads, it is also interesting to study the effect of adding additional component because in the single but also multi-body in WINDOS multiple components will be used with different positioned relative to each other. In figure 4.7 the results of these effects are shown. Six different layouts are used to study this effect, on the bottom rights the different layouts are shown. Layout number 1 is responsible for the lowest force in x-direction because the added block has a small surface at the side were the block is subjected to a flow in x-direction. Layouts number 2, 3 and 4 have almost all the same force in x-direction for 0 and 180 degrees however the x-force for layout is a bit higher because by adding an additional block in layout 4 the wind forces increase, this effect is amplified for layout number 5 and 6. In the results for the force in x-direction some of the wind forces have a minimum at 180 degrees in the range from 135 to 225 degrees (4,5) but other have a maximum here (1,2,3,6). The affected wind areas decreases for layouts 1,2,3 and 6 when the wind direction goes from 180 to 190 for example however with for layout 4 and 5 this is the other way around because the block that is behind the other block at 180 degrees is also responsible for an additional wind force at 135 and 225 degrees. The difference between layout 4,5 and 6 becomes clear in the results for 45 to 135 degrees. Layout 5 and 6 have the same values in this region because in this region there is no blockage or interaction of the two blocks and therefore the wind forces have the same values. The two blocks of layout 4 are so closely positioned that there is interaction between the two blocks and therefore the wind force is lower.

![Figure 4.7: Effect of different topsides on the wind forces and moment](image-url)
Layout 2 is responsible for the lowest force in y-direction. Layout 4, 5, and 6 have the same value in 0 and 180 degrees but layout is different outside of these values, however 5 and 6 do have over the whole range the same force in y-direction. Layout 4 is responsible for a lower force in y-direction compared with 5 and 6 because one of the two blocks is shielding the other one.

The moment around the z-axis is the smallest for layout 6, this is because the moment is taken around the z-axis in the middle of the vessel, the two blocks are located at the two ends of the vessel, the moments abolish each other. Layouts number 1, 3, and 5 have their moments close to each other. The block that is located in the middle of the vessel of layout 5 does not apply a moment and is therefore almost the same as layout 3. Layout 4 is responsible for the largest moment because both of the blocks apply a moment in the same direction and therefore the overall moment is largest.

### 4.4.3 Shielding due to loading condition and distance

In this study the effect of the draft and topsides are of interest but also the shielding effect. Therefore the shielding effect due to the presence of the FPSO in front of the tanker will be studied. Only the forces on the tanker will be evaluated for the two drafts: loaded and ballast with different distances between the FPSO and tanker. In figure 4.8 the effect of loading condition with distance is shown. For heading of 0 degrees will the tanker be in the lee of the FPSO and therefore will the tanker be shielded by the FPSO, for a heading of 180 degrees the FPSO will be shielded by the tanker but this is out of the research scope. The results for the force in x-direction clearly show the shielding effect, the larger the distance between the FPSO and tanker the higher the absolute force. In table 4.3 the reduction is shown as percentage between the absolute values at 180 and 0 degrees. For all the different distances there is a reduction of the wind loads in x-direction present and especially for the full load tanker. If the distance is 10 meters and the tanker is full load the wind loads in x-direction even become zero for 0 degrees.

![Figure 4.8: Effect of different loading condition and distance on the wind forces and moment of tanker](image)

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>BL 10 m</th>
<th>BL 80 m</th>
<th>BL 250 m</th>
<th>FL 10 m</th>
<th>FL 80 m</th>
<th>FL 250 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage</td>
<td>35.62%</td>
<td>32.88%</td>
<td>23.29%</td>
<td>-</td>
<td>89.29%</td>
<td>64.29%</td>
</tr>
</tbody>
</table>

Table 4.3: Percentage shielding between 180 and 0 degrees for absolute values of the tanker

So for different distances and draft shown especially a decrease for the range from 270 till 90 degrees most of all for the surge force with 0 degree heading, shielding effect is the largest here. In the region from 90 to 270 degrees there is no shielding of the tanker by the FPSO for the surge and sway force.
4.5. Single body model

The influence of different components and the interaction of components in groups on the total wind force is studied in the previous section 4.4. In this section the development of the models for the Bonga FPSO and VLCC tanker will be discussed. These models are developed with the different components available in Windos. Furthermore a comparison will be made between the results of Windos and the results of the wind tunnel test performed during the design of the Bonga FPSO. For the Bonga FPSO and the VLCC tanker two models will be developed: ballast and full load case. VLCC tanker model is developed with the vessel drawings and for the Bonga FPSO model the drawings from the wind tunnel model are used. This is done to reproduce the conditions of the wind tunnel test.

4.5.1. Bonga FPSO

The model consists of 63 components, the risers, porches and caissons are not included into the model. Hereby a description of the most important components:

- The hull of the FPSO is modeled as one of the standards hulls in Windos. In Windos there is one standard full loaded hull and for the ballast case there are two hulls that can be chosen. There are two ballast hulls available because the aspect ratio in the longitudinal plane has a significant effect on the side force and the yaw moment.

\[
\frac{2A_L}{D_X^2} \tag{4.21}
\]

Where \( A_L \) is the lateral hull area. The result of equation 4.21 should be close to one of the values of table 4.4. According to this table ballast hull of type 1 is used for the model.

<table>
<thead>
<tr>
<th>Ballast hull type</th>
<th>( 2A_L/D_X^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.052</td>
</tr>
<tr>
<td>2</td>
<td>0.129</td>
</tr>
</tbody>
</table>

Table 4.4: Values for two ballast hulls

- The deckhouse is modelled with 3 rectangular prisms.
- The flare is modeled as a triangular lattice structure.
- The model has 3 cranes, the cranes consist of a pedestal that is modelled as a circular element and the boom is modelled as a lattice structure.
- The modules like process, power and water flood modules are modelled as rectangular prisms. These modules are lifted from the hull therefore the flow can also flow underneath the components.
- The helideck is modelled as a flat plate and rests on a support which is modelled as a prism with a solidity ratio of 0.5.

In figure 4.9 below a visualisation is shown of longitudinal and side view of the Bonga FPSO model and of the ballast and full load model. In the figure the different blocks are clearly shown. In Windos only the part above the waterline is considered but the model is developed in a sense that the draft and freeboard can be adjusted so models for other loading conditions are easily be obtained.
4.5. Single body model

(a) Longitudinal and side view of the FPSO model

(b) The ballast model of the Bonga FPSO

(c) The full load model of the Bonga FPSO

Figure 4.9: Windos model of the Bonga FPSO

4.5.2. VLCC Tanker

The superstructure of a VLCC tanker does not contain a lot of components. The VLCC tanker model consists of 9 components. The smaller elements of the VLCC superstructure as hose candling cranes and other deck machinery are not included into the model, because it is assumed that the contribution of these elements to the total force can be neglected. The main elements are the deckhouse with the accommodation area and the pipe for the exhaust gases coming from the engine room. All the components are surface mounted and have a solidity ratio of 1. In figure 4.10 a visualisation is shown of the VLCC tanker model.

(a) The full load model of the VLCC tanker

(b) The ballast model for the VLCC tanker

Figure 4.10: Windos model of the VLCC tanker
4.5.3. **Wind Tunnel Test**

During the design of the Bonga FPSO wind tunnel test were carried out with a 1:200 scale model of the FPSO in a 2.6m wide Boundary Layer wind tunnel (Larsen and Jensen (2001)). The static wind loads on the FPSO are obtained with a strain-gauge force balance. The strain-gauge measure a force by stretching of an electrical element. The stretching changes the resistance of the gage which changes the measured current according to Ohm’s law. A six components balance is used so the lift, drag, pitch, side force, roll and yaw can be determined and the model can be rotated. The model was situated at the centre of a turntable.

In figure 4.11 a picture is shown of the front part of the model. As wind profile a natural ocean wind profile is used so similarity could be obtained between the ocean wind and the win-tunnel flow though the test section. Furthermore initial Reynolds tests were performed to ensure that the Reynolds numbers applied during the wind tunnel tests will be high enough so severe scale effects are avoided. A tunnel speed of 9.6 m/s free stream is applied this corresponds in a Reynolds number of calculated for the $L_{pp}$. The longitudinal force and lateral force component and the heeling moment are calculated as follows:

$$
C_{Fx} = \frac{F_x}{\frac{1}{2} \rho V^2 B^2} \quad C_{Fy} = \frac{F_y}{\frac{1}{2} \rho V^2 B^2} \quad C_{Mz} = \frac{M_z}{\frac{1}{2} \rho V^2 B^3}
$$

Where $B$ represents the reference length, in this case 58 m the breadth of the vessel, $V$ represents the longitudinal mean wind speed, $\rho$ the density of atmospheric air with a value 1.21 $\text{kg/m}^3$ at 20 degrees Celcius.

4.5.4. **Comparison Windos vs Wind Tunnel Test**

A comparison will be made between the results of the wind tunnel test for the Bonga FPSO and the Windos model of the Bonga FPSO. This is done for the verification of the Bonga FPSO model. The results are shown in figure 4.12.

The comparison of the results from Windos and the wind tunnel show good agreement, especially for surge and sway. However the yaw coefficients are in Windos significantly under-predicted. The shape of the hull’s bow and stern have a large effect on the yaw coefficients. In Windos were the flow effects around the hull’s bow and stern was not reproduced.

The surge coefficients for Windos shows a small peak at 180 degrees while this peak is not observed for the surge coefficients of the wind tunnel test. During the study of the influence of different components was this also observed in the results of section 4.4.2. In figure 4.7 of this section was for 4 of the results for surge an peak observed at 180 degrees and for the other 2 this was not the case. Here the difference between the results that showed a peak and the ones that did not shown a peak is already observed from 135 degree some results showed here a decreasing others an increasing line. This difference was explained by the difference in affected wind area. The cases where a peak was observed did the wind area increased from 135 degrees to 180 degrees while for the other cases this area decreased. The decrease or increase of affected wind area is influenced by the different elements of the topsides. It is used that this is also the explanation for the difference of the surge coefficient of the Windos and wind
4.6. Multi-body model

In section 4.5 the results of the models of the FPSO and the tanker are discussed and the FPSO model is verified with the DMI wind tunnel tests. In this section the study of wind interaction will be performed for the multi-body model. For this study, the two models of the Bonga FPSO and the VLCC tanker will be added together. The focus is the shielding of the tanker by the FPSO. The results of the time domain model in aNySIM shown that during squalls the tanker has large motions, due to shielding these motions can be actually smaller and therefore will the effect on the tanker can be very significant. Furthermore the results of section 4.4 have shown that the position of the two vessels have a large influence on the shielding. Therefore different position will be studied of the tanker relative to the FPSO: different positions in x-, y- and a combination of x- and y- positions. The different positions in x-direction will show the different between the FPSO and the tanker on the x-axis, the y-coordinate is here zero. The different positions in y-direction will show the difference from the y-coordinate zero, but will have an x-coordinate of 80 meters. The x-coordinate of 80 meters is here used because this is the preferred distance of the tanker behind the FPSO. For the combination of x- and y-positions will the x-position always be the distance relative to the FPSO and the y-positions always relative to the y-coordinate of zero.

![Figure 4.12: Comparison of the Windos and wind tunnel test results](image-url)

Figure 4.12: Comparison of the Windos and wind tunnel test results
4.6.1. Description of the model

The model consists of 72 different elements, 63 are for the model of the FPSO and 9 for the tanker. The simulation will be performed with a wind speed of 10 m/s at a height of 10 meters. Two different input models will be used one for every loading condition: ballast and full load. Furthermore the wind speed coming from 360 degrees is considered. Even though the wind interaction can be expected for the surge for in the region from 270 till 90 degrees, the whole 360 will be considered so see if interesting effects occur outside of this region. For every 10 degrees the wind forces will be calculated so in total wind forces for 36 directions.

4.6.2. Runs

Three different position of the tanker will be studied:

1. x-direction
   The tanker will have in an ideal situation a distance of around 80 meters between the stern of the FPSO and the bow of the tanker. However due to the environment the tanker can move more closely to the FPSO or can be pulled astern by the tug boats or environment. Seven different x-positions will be studied: 20, 40, 60, 80, 100, 120 and 140 meters. These distances are between the bow and stern so not the position of the Centre of gravity.

2. y-direction
   The tanker will also be placed in different positions by moving the tanker in y-direction. For the y-direction the same seven positions will be studied: 20, 40, 60, 80, 100, 120 and 140 meters. Because of symmetry only positive y-position will be studied.

3. x- and y-direction
   The tanker will most of the time move in x- and y-direction at the same time. Therefore the combination of these motions are studied. In section 1.3.2 the offloading operability was evaluated, during offloading the tanker has to stay for example in the area shown in figure 1.8. The offloading area is equal on both sides of the x-axis therefore only one side will be used for the study of the influence of translations in x- and y-direction of the tanker. The area is enclosed by a boundary with a minimum x value of 55 m and maximum of 105 m and under an angle of 40 degrees. This boundary will be used for the wind interaction study.

4.6.3. Results

The results of Windos are the wind loads for the FPSO and tanker, within Windos it was not possible to define the separate bodies so the 9 elements of the tanker are added to that of the FPSO. In order to study the wind loads on the tanker all the loads on the elements of the tanker are added up so the total wind force in the different direction could be plotted. Below the results for the different positions of the tanker are shown and evaluated.

Different positions in x-direction

In figure 4.13 the results are shown for different distances in x-direction for both the full loaded and ballast loaded tanker. In the lower past of the figure are the difference x-positions showed that were used for obtaining the results. The results show that the effect of shielding on the forces is the largest for the full loaded tanker because the FPSO is ballast load so high in the water and the tanker low. Furthermore is the wind shielding for both sides of the tanker the same, this can be explained by the FPSO and the tanker being in line so the wake will be the same on both sides of the tanker. The results for the yaw moment show a larger effect of the different x-positions, here the moment increases when the distance between the tanker and the FPSO increases, what means that the shielding effect decreases with larger distances between FPSO and tanker because the wake is less disturbed.
Figure 4.13: Different distances in x-direction
**Different positions in y- direction**

In figure 4.14 the results were showed of the different distances in y-direction for both the full loaded and ballast loaded tanker. Here are also the different y-positions used for the simulations, showed in the lower part of the figure. The results for y-direction show also the largest influence of shielding for the full loaded tanker. Furthermore are the results for not symmetric for both sides of 180 degrees, what was the case for the x-positions. This is because only for one side on the y-axis positions were examined and the flow over the tanker for different y-positions will be asymmetric.
### Different positions in x- and y-direction

In figure 4.15 the results were showed of the combination of different distances in x- and y-direction for both the full loaded and ballast loaded tanker. In the bottom of the figure the positions were showed for which the results were obtained. In the results the same asymmetric effect is observed as with the different y-positions and that the full loaded case shows the largest shielding effect.

Even though the results showed some shielding effect of the wind forces, the effect of shielding does not look very significant. Apart of the asymmetric wake for the y-positions and the combination of the x- and y-positions is there also not a very large difference observed between all the different positions. However the results will be used as input in the time domain model to see if the shielding effect is more significant in time domain.
4.7. **Application of wind shielding in the time domain**

In section 4.6 the effect of shielding because of the presence of the FPSO to the tanker wind loads is studied for different positions in X, Y and XY direction. A reduction is observed of the wind loads when the tanker is positioned closer to the FPSO in other words when the tanker is positioned in the wake of the FPSO. However a reduction in wind forces and moment on the tanker does not predict the responses on the tanker in time domain. Therefore with the wind forces and moment found in section 4.6 the wind coefficients will be calculated. These coefficients are the shielded coefficients for only one particular position of the tanker, by using these coefficients as input for the time domain simulation the effect can be studied of the effect of shielding in time domain.

The wind coefficients that will be used in the time domain simulation in aNySIM are calculated according to the following formula:

\[
C_{Fx} = \frac{F_x}{\frac{1}{2} \rho V^2 A_T} \quad C_{Fy} = \frac{F_y}{\frac{1}{2} \rho V^2 A_L} \quad C_{Mz} = \frac{M_z}{\frac{1}{2} \rho V^2 A_L L_{pp}}
\]  

(4.23)

Where \( \rho \) and \( V \) are respectively the used air density and wind speed in Windos. \( A_L \) and \( A_T \) are the longitudinal and transverse wind area of the tanker. After the coefficients are obtained, some changes need to be made for the coefficients for the different Y and XY positions. In figure 4.16 it is shown that for different Y positions simulations are performed like for example a shift to an Y position of 20 meters, so therefore shielding is expected when the wind is coming from the region between 270 and 0 degrees but not between 0 and 90 degrees. Because of symmetry the coefficients for Y an XY are changed so the shielding is included for a position of for example a shift of 20 meters (red star in figure 4.16 but also minus 20 meters (white star in figure 4.16).

Figure 4.16: Positions of changed coefficients

Figure 4.17: Changed squall 5

The squall data available from the Bonga FPSO that was used in this study did not contain squalls coming from the region where shielding of the tanker by the FPSO is very much expected. In order to study the shielding effect in the time domain, squall data is used this shielding effect is expected. Therefore the wind direction of squall number 5 is shifted with 50 degrees but the wind speed is not changed. In figure 4.17 the data of squall 5 is shown after the shift of minus 50 degrees.

The time domain simulations are performed for both ballast and full loaded tanker. For the results of the time domain simulations of the different positions in X, Y and combination of X and Y a comparison will be made between the result where the tanker is considered without shielding. Of this last mentioned case where no shielding is considered are the results evaluated in chapter 2. By making this comparison the impact of shielding in time domain can be discussed but also the effect shielding has on the different
positions in X,Y and a combination of X and Y direction on the ship motions.

In figure 4.18 the results are shown of the fully loaded tanker, this is the case were most of shielding is expected because the FPSO is ballast loaded and therefore has a large freeboard. In the figure the surge, sway and yaw are showed. The results for surge show that during the squall that starts around 3600 seconds, a reduction of the surge response is observed for the different positions because of shielding and the case considered without shielding shown larger motions. The shielding effect for the different positions in Y direction is for the cases when the tanker is shifted 20 and 60 meters. This can be explained by the fact that the boundary layer that is effected by the presence of the FPSO will be much larger in X direction than Y direction so if the tanker is shifted 140 meters in Y direction the shielding effect will be much less and therefore will be closed to the no shielding case. For the surge responses for the different cases in X direction show that all the shielded case are actually quite close to each other what means that the effect of shielding with a difference of 20 meters or 140 meters is not very large. In the largest peak is the shielding effect for the position of 60 meters in X behind the FPSO is 10.1 per cent and for the shift of 60 meters in Y direction this is effect 8.4 per cent. This effect is considerable but not very large. If the case with different shifts in X and Y is considered there is also the reduction observed by the shielding effect during the squall. Comparing the case X 55 m and Y 104.55 m and X 55 m and Y 188.13 m the effect is observed what is also the case with only Y shifts, if the tanker is position further aside of the FPSO the shielding effect becomes smaller but the trend of the two lines are equal. Of all the case for shift in X and Y is the case where X has a value of 105 m and Y 230 m most similar to the case without shielding, but the peaks are shifted. This could be explained by the fact that the tanker will move in yaw direction and therefore other wind coefficients will be used for the calculation of the wind forces.

The results for sway show the largest shielding effect from the three considered motions. This effect of shielding for sway motions is the largest for the different Y positions, for a shift in Y direction of 140 meters the reduction is 43.3 per cent and for 60 meter shift even 89.2 per cent. However also for X positions there is a considerable effect for a tanker that is positioned 140 meters behind the FPSO the reduction is 11.7 per cent and for 60 meters 25.9 per cent. Furthermore for the positions in X,Y and X and Y is the trend of the sway motions all the same, for the surge motions this was not the case, especially for the combination of X and Y positions. The shielding effect for the yaw motions is also observed during the squall. The effect is the largest for the different positions in Y direction. The results for the shifts in respectively X positions and Y positions, show the same trends in the combination of X and Y. Only for the surge motions some other effects are observed but this is due to the fact that in the combination of X and Y, the largest value in Y direction is 230 meters and in the shift in Y direction the largest value is 140 meters, the effects for these two cases are different and this is also observed in the results. In figure 4.19 the results are shown of the ballast loaded tanker. The shielding effect on the ballast loaded tanker is to be less than for the full load tanker, this is due to the fact that the FPSO is higher in the water but because in the time domain simulations that were performed in chapter 2 the results show that during squalls the ballast loaded tanker is the worst case so therefore is it very interesting to see what shielding does with the motions. For surge the shielding effect is observed during the squall but this effect is also as with the full load case not very large, for the different distances between the tanker and the FPSO in X direction is this effect around 10.1 per cent in the largest peak during the squall and for the shifts in Y direction 7.9 per cent. The results for surge for the combination of X and Y show that the three cases where the tanker is positioned X 55 m and Y 188.13, X 85 m and Y 213.3 and X 105 m and Y 230 m in X direction and Y direction behind the FPSO the response is very different, but the two other cases show a more similar trend that the no shielding case.

The shielding effect is also for the ballast loaded tanker the largest for the sway motion. For Y positions, for a shift in Y direction of 60 meters is the reduction 55.0 per cent and for a distance of 60 meters between tanker and FPSO the reduction is 41.8 per cent. This is much larger than the 25.8 per cent reduction found for the sway motions for the distance of 60 meters between the FPSO and tanker. The results for sway for the combination of X and Y show the same trend as for surge, here also the cases where the tanker has a distance in Y of 213 and 230 shifted show a different results than the other cases. The result for yaw also show a reduction in the responses for the different cases, this reduction
Figure 4.18: Results of shielding in time domain for the full load tanker

is the largest for the different Y positions. For the combination of X and Y the same trend is observed as for surge and sway.

When the comparison is made between the full load and ballast loaded tanker it is interesting to note that for the results of the ballast loaded tanker for different cases for different X and Y positions are almost the same so the no shielding case shows very different results and that for the ballast loaded tanker the combination of X and Y show for X 85 m and Y 213.3 m and X 105 and Y 230 m a complete different results than the other cases of the combination of X and Y. Furthermore for all the cases a shielding effect is observed this shielding effect show for the surge motions for ballast and full load the smallest effect and for sway the largest. In other to evaluate the shielding effect in relation with the hawser tension two cases of the results of figure 4.18(c) and 4.19(c) are used. The two cases are X 55 m and Y 104.55 m and X 105 m and Y 230 m. These two cases are used because the tanker will always move in X and Y direction instead of only in one of these two directions, furthermore the cases with a combination of X and Y direction are all at the boundary of the offloading zone defined in figure 1.8. The two cases are respectively the cases where the most shielding (X 55 m and Y 104.55 m) is expected.
because the tanker is the closest position close behind the FPSO and the least shielding (X 105 m and Y 230 m) is expected because the tanker is shifted 230 meters in Y direction what could mean that the tanker is placed outside of the wake of the FPSO.

In figure 4.20 the offset is shown of the different cases. For three of the four cases the shielding effect lead to a decrease in offset: both the shielding cases for the full load tanker but for the ballast loaded tanker only X 55 m and Y 104.55 m. In table 4.5 is the percentage shown of the decrease or increase of the maximum offset of the tanker during tandem offloading in a squall. The percentages are the difference between the respective case and the unshielded case. The increase of the motions for the case X 105 m and Y 230 m was also observed in figure 4.19 (c), even though shielding is considered is the the response for especially sway and yaw larger than the unshielded case. If the wind coefficients of the case X 55 m and Y 104.55 m and X 105 m and Y 230 m are compared it shows that there can be large differences of 400 per cent between the two cases. For some headings the tanker can move out of the wake and gets the full blow or even in the shielding zone an increase can occur because of large vortices, the acceleration of the flow increase what lead to an higher pressure and so wind force. The
Figure 4.20: The effect of shielding on the offset during a squall

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Position</th>
<th>Maximum offset</th>
<th>Shielding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full load</td>
<td>X 55 m Y 104.5 m</td>
<td>120.86 m</td>
<td>-26.02%</td>
</tr>
<tr>
<td>Full load</td>
<td>X 105 m Y 230 m</td>
<td>145.03 m</td>
<td>-11.23%</td>
</tr>
<tr>
<td>Ballast load</td>
<td>X 55 m Y 104.5 m</td>
<td>113.16 m</td>
<td>-34.04%</td>
</tr>
<tr>
<td>Ballast load</td>
<td>X 105 m Y 230 m</td>
<td>194.82 m</td>
<td>+13.55%</td>
</tr>
</tbody>
</table>

Table 4.5: Percentage of shielding of the maximum offset of the tanker

The results show that shielding not always lead to an decrease in motions but sometimes even in an increase. But is this effect also observed in the hawser tension. In figure 4.21 is the effect of shielding on the hawser tensions showed during a squall as percentage of the maximum allowed hawser load. During the squall large peaks loads are observed for both the loading conditions but for the ballast loaded tanker are the hawser loads the largest for the unshielded case, the loads are even 70 per cent of the maximum hawser load, for the full load tanker is the maximum 45 per cent. However for the two cases in ballast and full load a decrease in hawser load is observed due to shielding. In table 4.6 below the hawser loads are showed as percentage relative to the unshielded case. The case with the largest...
First a comparison was made between the wind coefficients found with the use of wind tunnel tests and the building block approach. A good agreement was found for surge and sway but the yaw coefficients were underestimated with the building block approach.

For the study of wind shielding of the tanker were first the forces on the tanker that were shielded by the FPSO were obtained by placing the tanker in different positions relative of the preferred position of the tanker direct behind the FPSO with a separation distance of 80 meters. The different positions were positions with a change in only X or Y or X and Y direction. The rotation of the tanker was not taken into account. The obtained wind forces for the different positions showed shielding effect especially for the full loaded tanker. But in general was not a large shielding effect observed for the different cases. However when from the wind forces the wind coefficients were calculated and implemented in the time domain model, large effect were observed between the responses of the different shielding cases but especially between the responses of the unshielded and shielded tanker. The surge and yaw showed shielding effect but the sway response of the full load tanker gave the largest effect, for a shift of 60 meter and 140 meter Y direction was a reduction of the responses by shielding 89.2 per cent and respectively 43.3 per cent, relative to the unshielded tanker. For the ballast tanker was

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Position</th>
<th>Maximum load</th>
<th>Shielding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full load</td>
<td>X 55 m Y 104.5 m</td>
<td>1139.7 kN</td>
<td>-35.58%</td>
</tr>
<tr>
<td>Full load</td>
<td>X 105 m Y 230 m</td>
<td>954.2 kN</td>
<td>-46.07%</td>
</tr>
<tr>
<td>Ballast load</td>
<td>X 55 m Y 104.5 m</td>
<td>1040.3 kN</td>
<td>-62.28%</td>
</tr>
<tr>
<td>Ballast load</td>
<td>X 105 m Y 230 m</td>
<td>1774.3 kN</td>
<td>-35.67%</td>
</tr>
</tbody>
</table>

Table 4.6: Shielding of maximum hawser loads relative to the unshielded case

decrease in offset due to shielding: X 55 and Y 104.55 with a ballast loaded tanker is also the case with the largest decrease in hawser load but the other cases show another trend. The hawser load is not only dependent on the response of the tanker but also that of the FPSO so therefore leads an decrease in offset not always to an decrease in hawser load. Furthermore leads shielding often to an decrease of the wind loads of the tanker what will directly affect the hawser tension so is there in the results for the ballast loaded tanker with the case X105 m and Y230 m a peak in the hawser tension observed after the squall but the response of the tanker is not directly affected by the decrease or increase in wind loads.

4.8. Chapter summary

Figure 4.21: The effect of shielding on the hawser tension during a squall
the sway response reduced by 55 per cent for 60 meter shift and 41.8 per cent for 140 meter shift in Y direction. Furthermore was not for all cases an decrease in the responses found by shielding. Shielding can also lead to an increase of the responses because the tanker can move out of the shielding zone where the wind coefficients are much larger. With large wind speeds of squalls, become the wind loads suddenly very large and this could lead to an increase in the response. The effect of shielding on the hawser tension was also studied, here is a decrease observed for all the different cases up to 60 per cent. Furthermore it is assumed that the hawser loads will be more easily effected by the reducing of the wind loads due to shielding than the responses of the tanker.

For a the modelling of a tandem offloading system in squalls should wind interaction being included in the time domain model, because the effects are found to be significant. If wind shielding is included a better decision can be made if tandem offloading in squalls is feasible, however not all the squalls are responsible for shielding of the tanker because it is very dependent on the wind direction in a squall. The effect and consequences of wind interaction was studied but wave interaction can also have an effect on the responses in time domain because in the current model the hydrodynamical coupling of the tanker and FPSO is neglected. The effect of wave interaction is studied in the next chapter.
5

Hydrodynamic interaction

In this chapter the wave interaction study that is performed will be discussed. The FPSO and the tanker are mechanically coupled during tandem offloading due to the hawser that is connected between the two vessels, but there is also some hydrodynamic coupling between the FPSO and the tanker due to wave shielding and wave interaction. According to Pinkster (1995) the hydrodynamic interaction should be taken into account for a proper simulation of the motions of the tanker. The hydrodynamic interaction is influenced by different parameters such as the distance between the amount of bodies, the body draft and the amount of bodies.

Other performed studies focused on side-by-side offloading where the two vessels are at very close proximity (distance of 4 m) and the vessels are in a parallel orientation. Because of the close proximity one of the vessels is shielded by the other vessel and the parallel orientation makes that the vessels are exposed to diffracted and radiated wave fields.

During tandem offloading the distance between the two vessels is larger than with side-by-side offloading and the tanker is positioned in the lee of the FPSO. Therefore, the wave interaction due to diffracted and radiated wave field is considered lower. But the question arises if this interaction can be neglected as Hong et al. (2002) states.

In order to evaluate the interaction between the FPSO and the tanker a two-body diffraction analysis will be performed with the software package WAMIT. In section 5.1 the Potential theory behind the software WAMIT is discussed, followed by a comparison of the RAO’s of single body ballast and full load case of the FPSO obtained with WAMIT and a diffraction analysis performed by Marin in section 5.2, the multi-body analysis is evaluated for difference separation distances in section 5.3.

5.1. THEORETICAL BACKGROUND WAMIT

The software package WAMIT performs a diffraction analysis to calculate the hydrodynamic properties of a vessel: added mass coefficients, damping coefficients and first- and second-order forces on the body. These properties are given as a function of incoming wave direction, frequencies, response mode and, in the multi-body analysis, the relative position of the bodies. The diffraction analysis is based on the linear and second order potential theory.
WAMIT uses a Cartesian coordinate system (x,y,z) as shown in Figure 5.1. The axis system is right handed system of axes and with z-axis vertically upward. The origin of the body lies on the free body, only the interaction between structure and fluid is taken into account up to the still waterline. The wave heading is considered as coming from, when $\beta$ is zero the waves are coming from zero degrees. The three-dimensional methods to evaluate the hydrodynamic loads and motions of floating structures in waves are based on linear three-dimensional potential theory.

According to linear potential theory the total potential of a floating body is a superposition of the potentials of the incoming wave $\Phi_w$, the potential due to diffraction of the undisturbed incoming wave $\Phi_d$ and the radiation potentials of the six body motions $\Phi_r$.

5.1.1. Assumptions potential theory

Potential theory is based on assumptions Holthuijsen (2007):

- The fluid behaves an ideal fluid
  Because the fluid is considered to be ideal, the following is assumed:
  - The fluid is incompressible
    The stresses are so small that the compression of water can be ignored.
  - The fluid is continuous
    The fluid water is normally quite continuous but can contain discontinuities in the form of air bubbles. When waves break the potential theory does not apply.
  - The fluid is free of surface tension
    The fluid should be subjected to only one external force: gravitation.
5.1. Theoretical background WAMIT

- The fluid is frictionless
  Friction is neglected because this is a local effect and generates turbulence. This local effect will not be transported into the main water body.

- The fluid has a constant density in space and time
  The horizontal distance over which the density normally varies in the ocean is in the range of dozens of kilometers; this is much larger than the scales used in potential theory.

- The fluid has no viscosity
  Because the fluid has no viscosity and a constant density the normal stress $\sigma$ and shear stress $\tau$ in the momentum equation can be simplified as:

\[
\sigma_{xx} = -p + 2\mu \frac{\partial u}{\partial x} = -p \tag{5.1}
\]

\[
\tau_{xy} = \mu \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) = 0 \tag{5.2}
\]

- The amplitude of the waves is small relative to the wave length and water depth. The water surface slope is small, this means that the wave steepness ($\zeta/\lambda$) is small and that terms in the equations of the waves with a magnitude in the order of the steepness squared can be ignored. According to potential theory the harmonic displacements, velocities and accelerations of the water particles and the harmonic pressures will have a linear relation with the wave surface elevation Journee and Massie (2001).

- The motion of the water particles are irrotational because of absence of shear. The water particles do not rotate around their own axis, this is assumed because vorticity can only be generated by turbulence, as mentioned above this is neglected because this does not penetrate into the main water body.

These assumptions make the linear potential theory valid in which the total potential can be decomposed into a number of separate potentials: $\Phi_w$, $\Phi_d$ and $\Phi_r$. Total potential:

\[
\Phi(x, y, z, t) = \Phi_w(x, y, z, t) + \Phi_d(x, y, z, t) + \Phi_r(x, y, z, t) \tag{5.3}
\]

$\Phi_w$ is the undisturbed incident wave potential, $\Phi_d$ is the wave diffraction potential and $\Phi_r$ is the wave radiation potential. These potentials can be solved by applying the boundary conditions.

5.1.2. Boundary conditions

The velocity potential for waves has to fulfill four requirements. Therefore, two additional requirements have to be added to apply the velocity potential for floating bodies:

1. Continuity Condition and Laplace Equation
   The velocity of the water particles in three translational directions follow from the definition of the velocity potential:

\[
u = \frac{\partial \Phi}{\partial x}, \quad v = \frac{\partial \Phi}{\partial y}, \quad w = \frac{\partial \Phi}{\partial z} \tag{5.4}
\]

Because the fluid is homogeneous and incompressible the Continuity equations becomes:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{5.5}
\]

By substituting the velocity of the water particles in the above stated Continuity Equation it results in the Laplace Equation.

\[
\nabla^2 \Phi = \frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} \tag{5.6}
\]
2. Sea bed Boundary Condition

The vertical velocity of the water particles at the sea bed is zero. Meaning no water can leak through the sea bed.

$$\frac{\partial \Phi}{\partial z} = 0 \quad \text{for: } z = -h$$  \hspace{1cm} (5.7)

3. Free surface Dynamic Boundary Condition

At the free surface of the fluid $z = \zeta$ the pressure $p$ is equal to the atmospheric pressure. The pressure can be written in terms of the velocity potential $\Phi$ using Bernoulli:

$$\frac{\partial \Phi}{\partial t} + \frac{1}{2} (u^2 + v^2 + w^2) + \frac{p}{\rho} + gz = C^*$$  \hspace{1cm} (5.8)

Assuming two dimensions and small steepness the Bernoulli equation at the surface becomes:

$$\frac{\partial \Phi}{\partial t} + \frac{p_0}{\rho} + g\zeta = C^* \quad \text{for: } z = \zeta$$  \hspace{1cm} (5.9)

The constant part of the equation $\frac{p_0}{\rho} - C^*$ can be included into $\frac{\partial \Phi}{\partial t}$ because this part will not influence the velocities from the potential $\Phi$. The equation becomes:

$$\frac{\partial \Phi}{\partial t} + g\zeta = 0 \quad \text{for: } z = \zeta$$  \hspace{1cm} (5.10)

A Taylor series expansion is used to find the potential at the free surface.

$$\{\Phi(x, z, t)\}_{z=\zeta} = \{\Phi(x, z, t)\}_{z=0} + \zeta \cdot \left\{ \frac{\partial \Phi(x, z, t)}{\partial z} \right\}_{z=0} + \zeta^2 \cdot \left\{ \frac{\partial \Phi^2(x, z, t)}{\partial z^2} \right\}_{z=0} + ...$$  \hspace{1cm} (5.11)

Assuming small wave steepness and small resulting motions the potential can be written as:

$$\left\{ \frac{\partial \Phi(x, z, t)}{\partial t} \right\}_{z=\zeta} = \left\{ \frac{\partial \Phi(x, z, t)}{\partial t} \right\}_{z=0} + \mathcal{O}(\epsilon^2)$$  \hspace{1cm} (5.12)

Linearisation of the boundary condition yields the free surface dynamic boundary condition for $z=0$:

$$\frac{\partial \Phi}{\partial t} + g\zeta = 0$$  \hspace{1cm} (5.13)

Or as a function of the wave profile

$$\zeta = -\frac{1}{g} \frac{\partial \Phi}{\partial t}$$  \hspace{1cm} (5.14)

The above stated boundary conditions are general and apply for all possible wave conditions. However, in linear potential theory regular waves are studied, waves with a small steepness and sinusoidal. The linear potential $\Phi$ can therefore be written in a space-dependent and time-dependent part because the linear potential $\Phi$ is a function of the earth-fixed coordinates and of time.

$$\Phi(x, y, z, t) = \phi_w(x, y, z) e^{-i\omega t}$$  \hspace{1cm} (5.15)

Furthermore, the radiation potential which is the oscillation of the body in still water can be decomposed in six degrees of freedom.
5.2. SINGLE BODY

Firstly diffraction analysis will be performed separately for the FPSO and the tanker. In order to make a comparison between the results of the multi-body and the single body case. The panel model of the tanker cannot be provided by Marin because this is not in the contract with Shell. The panel model of the Bonga FPSO was available and this panel model is used as input for the VLCC tanker by scaling. Aside from the panel model there are three other input file needed for WAMIT. In the potential file are the water depth, amount of wave periods and direction defined. For all the simulations all 360 degrees are considered and 39 periods. In the configuration file is the location of the software defined. The force file contains the water density, location of the Centre of Gravity and the mass, damping and stiffness matrix. The z-coordinate for the centre of gravity is different because only the area up to the still waterline is considered, the z-coordinate is calculated as follows:

\[ z_G = KG - T \]  (5.16)

Where \( KG \) is the vertical position of the centre of gravity and \( T \) the draft. The mass matrix is calculated as follows:

\[
M = \begin{bmatrix}
m & 0 & 0 & 0 & m \cdot z_g & -m \cdot y_g \\
0 & m & 0 & -m \cdot z_g & 0 & m \cdot x_g \\
0 & 0 & m & 0 & -m \cdot x_g & 0 \\
0 & -m \cdot z_g & m \cdot y_g & m \cdot (k_{roll}^2 + y_g^2 + z_g^2) & -m \cdot x_g \cdot y_g & -m \cdot x_g \cdot z_g \\
m \cdot z_g & 0 & -m \cdot x_g & -m \cdot x_g \cdot y_g & m \cdot (k_{pitch}^2 + y_g^2 + z_g^2) & -m \cdot y_g \cdot z_g \\
-m \cdot y_g & m \cdot x_g & 0 & -m \cdot z_g \cdot z_g & -m \cdot y_g \cdot z_g & m \cdot (k_{yaw}^2 + y_g^2 + z_g^2)
\end{bmatrix}
\]  (5.17)

Where \( m \) is the body mass, \( x_g, y_g \) and \( z_g \) are the coordinates of the Centre of gravity and \( k_{roll}, k_{pitch} \) and \( k_{yaw} \) are the radii of gyration referred to the Centre of gravity. The additional roll damping is a percentage of the critical damping, the critical damping and the additional roll damping is calculated as follows:

\[
C_{cr} = 2 \cdot \sqrt{(\rho \cdot g \cdot V \cdot GM_T) \cdot (I_{rollCOG} + A_{44})}
\]  (5.18)

\[
C = \frac{\zeta_p}{100} \cdot C_{cr}
\]  (5.19)

\[
GM_T = KMT - KG
\]  (5.20)

\[
I_{rollCOG} = m \cdot k_{roll}^2
\]  (5.21)

\[
A_{44} = I_{rollCOG} \cdot 0.278494243
\]  (5.22)

Where \( \rho \) is the density of water, \( g \) the gravity acceleration, \( V \) the displacement volume, \( GM_T \) metacentric height, \( I_{rollCOG} \) the baricentric moment of inertia for roll, \( \zeta_p \) is percentage of critical damping here assumed to be approximately 4 per cent and \( KMT \) height of metacenter above keel.

5.2.1. BONGA FPSO

![Figure 5.3: FPSO panel models](image)

(a) Full load  (b) Ballast load

The panel models used for the ballast input model contains 3052 panel of which 2542 body panels and 510 free surface panels. The loaded input model has 2970 panels of which 2626 body panels and 344 free surface panels. In figure 5.3 the panel models of the FPSO are shown.
In order to verify the FPSO model that will be used for the multi-body diffraction model, a comparison will be made between a diffraction analysis performed in this research with WAMIT and the diffraction analysis performed by Marin for the Bonga FPSO by comparing the response amplitude operators (RAO’s), which are the response of a vessel for a particular degree of freedom to a 1 meter wave for a certain frequency. This will be done for both loading conditions. In figure 5.4 the results are shown of the comparison made for the full load FPSO and in figure 5.5 the comparison for the ballast loading condition. The results are shown for a wave direction of zero and 90 degrees. With a wave direction of 0 zero degrees a good agreement is found between the two simulations, the sway, roll and yaw RAO’s are zero. The RAO for surge becomes zero with high frequencies because the high frequency waves are not able to get the vessel into motion. Furthermore, the heave RAO becomes 1 for the limit to zero because with long waves the elevation of the ship is the same as of the vessel.

Figure 5.4: Comparison RAO’s full load diffraction analysis Marin - WAMIT simulation
For a wave direction of 90 degrees also a good agreement is found between the two simulations. The surge, pitch and yaw RAO are very small for 90 degree waves. In 90 degree waves the FPSO will move in sway direction and will have coupled heave and roll motion. In the result for the sway RAO there is a small difference between the WAMIT and Marin result. The sway RAO found with WAMIT has a peak between 0 and 1 rad/s, this is more clear for the ballast case. The peak is due to the fact that the Centre of Gravity of the FPSO is not equal to the point of rotation therefore there is a peak for that frequency. This peak can also be seen for the roll and yaw motion because they are coupled. The peak in the sway RAO is not there in the Marin result because probably the Centre of Gravity is adjusted after the first simulation so the rotation point becomes equal to the Centre of gravity.

![RAO comparison](image)

Figure 5.5: Comparison RAO’s ballast load diffraction analysis Marin - WAMIT simulation
Furthermore the natural roll period $T_\phi$ in the diffraction analysis in WAMIT for the full load FPSO is 17.99 s and in the model tests 17.60 s. This is a difference of 2.2 per cent. For the ballast loaded FPSO the natural period for roll $T_\phi$ found with WAMIT is 16.99 s and in the model test 16.85 s, a difference of only 0.8 per cent.

5.2.2. VLCC tanker

In section 5.2 is was mentioned that the VLCC panel model was developed by scaling the $x$, $y$ and $z$-coordinates of the FPSO panel model for both the loading cases with the following factors:

$$
\begin{align*}
    x - \text{coordinate} &= \frac{L_{ppVLCC}}{L_{ppFPSO}} \\
    y - \text{coordinate} &= \frac{B_{VLCC}}{B_{FPSO}} \\
    z - \text{coordinate} &= \frac{D_{VLCC}}{D_{FPSO}}
\end{align*}
$$

(5.23)

Where $L_{ppVLCC}$ the length between perpendiculars is, $B$ the breadth and $D$ the depth of the vessels.

In figure 5.6 the results are shown of the diffraction analysis performed for the VLCC tanker for waves coming from 0 and 90 degrees.

For 0 degrees the RAO’s for sway, roll and yaw are also zero. The surge RAO also goes to zero for large frequencies and the heave RAO goes to one when taken the limit to zero. The narrow trough and peak in the surge motion seem to be connected to the pitch motion, which has resonance at the same frequency. For 90 degrees the surge, pitch and yaw motions are small. However the RAO’s for the VLCC tanker are larger than for the FPSO. The peak observed for the sway RAO for the FPSO is also observed for in the sway RAO for the tanker but for the tanker no influence is seen on the yaw RAO.

5.3. Multibody

The multi-body model was developed with the FPSO and the tanker input data described in section 5.2.1 and 5.2.2. The force file contains the combined mass and damping matrixes and the position of the CoGy of both the vessels. Apart from a file containing the panel models, an extra file is added where the placement of the two vessel is described within the coordinate system. Three cases are considered: the FPSO and the tanker positioned at close distance of 10 meter from each other, the FPSO and the tanker position far from each other with a distance of 5000 m and the FPSO and the tanker 80 m positioned behind each other, 80 m is the distance between the two vessel. When the FPSO and the tanker are positioned 5000 m from each other, there can be assumed that the interaction effects...
are negligible and when two vessels are positioned only 10 meters apart that the interaction would be more significant. These two cases are used to make a comparison between these two cases and the case where the distance 80 m is between the two vessels in order to study the wave interaction effects during tandem offloading. Furthermore two wave directions are considered, when the waves are coming from 0 and 90 degrees. In figure 5.7 the results are shown of the RAO’s of the FPSO and tanker for 0 degrees. Only the surge, heave and pitch RAO’s are shown because the RAO’s for the other values are 0.

Figure 5.7: RAO’s for the FPSO and tanker with wave heading of zero degrees
The results for the FPSO indicate that in the ballast load condition the FPSO is influenced by wave interaction for the close and 80m distance case even though the FPSO is not directly shielded by the tanker because the FPSO is position before the tanker. The wave interaction is coming from the diffracted waves and radiated waves of the tanker and is found to be around 0.3 rad/s. For surge and heave motion, this response is for both close case and 80 m case found, for pitch was this effect only for the close case. This interaction is not found in the full load case of the FPSO. This is due to the fact that the mass of the full load case is larger therefore the response to the diffracted waves of the tanker is smaller. However, around the natural frequency there is a small difference found between the different distances between tanker and FPSO, a small increase in the RAO and the natural period for the 80 m and close case are a bit shifted relative to the single body FPSO.

The surge, heave and pitch motions of the tanker are in general reduced by the presence of the FPSO because the wave energy is reduced. However for the ballast loaded tanker is this difference in surge very small what assumes that the shielding effect on the surge RAO is small and that the difference in the surge response for the full tanker is due to the diffracted and radiated waves between the FPSO and tanker. Furthermore the interaction effects are all observed with a frequency larger than 0.4 rad/s. Low frequency waves have a long period therefore wave length. The total wave induced energy density consists of the kinetic wave energy and the potential wave energy. Both depend of the the amplitude of the waves squared. Because of the low energy in the lower frequency waves is the difference in the response of the different cases not significant.

The RAO’s of the FPSO with waves coming from 90 degrees are shown in figure 5.9 and on the next page for the tanker in figure 5.8. The sway, heave and roll motions are dominant for waves with a direction of 90 degrees. However, the surge, sway and yaw responses are of the most interest for this research all six degrees are considered. The RAO for sway and roll for the FPSO and tanker are for all the cases the same, this is also what is expected when waves are coming from 90 degrees. In the results for the FPSO there are some small difference shown for the FPSO and tanker position close from each other but for 80 m difference the RAO’s are similar to those for a single FPSO. For the tanker small differences are shown of the heave, pitch and yaw RAO’s but because these RAO’s are very small and the difference is especially observed at the close case these effects are considered not very significant.

Figure 5.8: RAO’s FPSO for waves coming from 90 degrees
5.4. Chapter summary

The wave interaction was researched with multi-body diffraction for 3 different positions of the tanker relative to the FPSO: 10, 80 and 5000 meters. The RAO’s of the FPSO and the tanker with the hydrodynamic interaction was compared with the RAO’s of the single FPSO or tanker. The results showed for a wave direction of 0 degrees, some small interactions in the heave RAO of the ballast loaded FPSO, this interaction is due to the diffracted and radiated waves between the tanker and FPSO. The RAO’s for the tanker showed for 10 and 80 m a reduction because of a reduction of wave energy by the presence of the FPSO. For waves coming form 90 degrees the only interaction was found for the tanker with a separation distance of 10 meters. The found interaction effect will have a small influence on the first order motions during a squall in time domain. However the spread mooring of the FPSO will suppress the ship motions. The results of the tanker show that there will be a small overestimation of the first order wave responses in time domain but this effect is not very significant so therefore will the hydrodynamic coupling not be included in the time domain model.
The effect of wind and wave interaction are studied in chapters 4 and 5. But another parameters that could have influence on the response according to the sensitivity study results, was that the tug has the most effect on the responses during a squall. Therefore is in the next chapter the current tug model evaluated and a new tug model was developed by making a coupling of the aNySIM time domain model and the commercial code LUA.
Mitigation plan

In the sensitivity study performed in chapter 3 it was found that of all the different parameters the tugboat has the largest effect on the motions in a squall. However the current tug model is static because the magnitude and direction do not change of time, therefore the development of a new tug modelled is discussed and the effect of this new model on the responses. First the different ways are evaluated to increase positional stability.

The preference is to prevent loss of position instead of trying recovery if the loss of position already occurred. However if loss of position does occurs there are several options like try to bring the tanker back to its position or disconnection of the tanker from the FPSO. Some of the tanker have emergency shutdown (ESD) systems, for oil tankers this is not a requirement of the IMO code, however some of the oil tankers have this option. During ESD1 all manifolds and tank filling values are held in the shut position and the cargo and spray pumps are held in off position. The cargo compressors may be operated as normal but will stop if the ESD is initiated. ESD2 will results int he same actions as ESD1 plus the initiation of a dry break of the hoses from the ship(tan (2009)).

For the prevention of loss of position there are several ways :

- **Forecasting system**
  An accurate forecasting system can increase the prediction time for squalls, with an increase in the prediction time the captain can decide not to start the offloading or if the offloading already stared to prepare for the squall event. The pumping of the oil can be put to hold or if the direction where the squall is coming from is known the tanker can be position in a way that the squall will not hit the tanker beam on.

- **Dynamic positioning**
  The tankers in the North sea have all dynamic positioning, this is due to the inclement weather. Dynamic positioning works with wind-feed forward. The system counteracts the wind-induced forces as soon as they are detected. In the time between detecting of wind and the movements of the vessel, the DP systems reacts (Holvik (1998)). Therefore is would be a good solution for response of vessels to squalls however these systems are expensive and in the benign environment of West-Africa not used.

- **Increase the hawser length**
  In chapter 3 the influence of the increase of the hawser length is studied. The results show that the increase in hawser length lead to an increase in the ship motions, however with the right tug strategy an increase of hawser length still lead to an increase of offloading zones and during loss of position there is more time to respond.

- **Use of thrusters of the tanker**
  According to Jan Teertstra (Shell-STASCO) the Marine head offshore Nigeria are the thrusters...
of the tankers often used during offloading in squalls. The engine of the tanker has a power of 30,000 hp, this is in the same range as the power of the tug boats used in this region. By using the engines of the tanker in for example in astern dead-slow, an additional pull of 20-30 tonnes will be available. But according to the guidelines the engines should be switched of during offloading because of fire hazards.

- Tug strategy
In chapter 3 the effect of different bollard pulls were studied, the results show that the increase of bollard pull lead to a decrease of the responses, especially the surge response. With a bollard pull of 200 tonnes not only does the median $\mu$ decreases but also the standard deviation $\sigma$. Even though the sway response decreases with higher bollard pulls, it could still lead to collision. Therefore apart of an increase in bollard pull also a change in the tug strategy should be considered for a proper prevention of loss of position.

Of the above mentioned ways for the prevention of loss of position are the use of the thrusters of the tanker and the tug strategy the most feasible prevention options. In the time domain program aNySIM what is used for the simulation of the ship motions is the tug modelled as a external force see section 2.2.4. The external force does not change over time and is constant independent of the movement of the tanker, this way of modelling is very different than the response of the tug boat during offloading operations therefore a coupling will be made between aNySIM and the commercial code Lua to make a dynamic tug.

6.1. Coupling of aNySIM and Lua

In the aNySIM input file a plug in of the Lua is present. Here the reference is made to the Lua file. Every time step the position of the tanker is checked, if the tanker moves out of the defined zone the tug pull increases and the thrusters of the tanker add some additional pull. In figure 6.3 the script is shown of the tug model developed in Lua. Tug starts working from the beginning of the simulation. Every time step the position of the tanker of it’s Centre of Gravity is read by the Lua script called in the script the refpos, also the yaw motion of the tanker is read by Lua. The response of the tug will be relative to the bow of the tanker so the refpos and yaw of the tanker have to be compensated so the values are used at the bow and not in the Centre of Gravity. In figure 6.3 two functions are present, the first functions is used to make vectors of the strings that come out of aNySIM. The second function consist of two parts.

![Figure 6.1: The set up of the surge compensation of the tug in Lua](image)

The first part is only compensation the surge motion of the tanker, this can be seen as one of the tugs because often with multiple tugs is one responsible for the stirring of the tanker and the other for keeping the hawser line under tension or as the thrust of the tankers thrusters. For the compensation of only the surge responses six different area are defined for which the tug pull is defined. The built up of the tug pull has a linear built up to decrease the dynamics effects if the load would increase from one time step to another time step by 20 tonnes. The tanker has a preferred position, this is 80 meters
behind the FPSO. The preferred location of the tanker is in the first zone, here the tug has a bollard pull of 40 tonnes. If the tanker moves closer to the FPSO or further away of the FPSO, the tanker will go to the second zone with a tug pull of 60 tonnes and moves the tanker out of this zone the tug pull will be 80 tonnes. If the tanker also moves out if this zone the tug pull will be decreases to 0.1 tonnes because the tanker will move out of the safe zone and offloading is not feasible. In figure 6.1 the set up of the compensation of the surge motions is described, also the linear build up and the zones with the different tug pulls.

The second part of the second function uses not only the surge value of the Centre of Gravity of the tanker but also the sway position of the Centre of Gravity of the tanker and the yaw motion of the tanker. With the surge and sway values a circle is defined, the tug pull increases if the tanker comes closer to the side of the circle. The yaw responses are compensated separately, this is done for positive and negative yaw angles.

In figure 6.2 the effect is shown of the tug used in the aNySIM model and the tug model developed with Lua. Even thought it is a first set up of the new tug model there is already a large improvement observed. In the tug used in aNySIM there was a collision with his squall but with the use of the new tug model this does not happen.

![Figure 6.2: the results for surge, sway and yaw for the aNySIM tug and improved tug model](image-url)
Figure 6.3: Script for the tug in Lua
6.2. Chapter summary

The used tug model in time domain had a static response during the squall, the magnitude and direction of the tug were constant over time so only the surge responses were reduced. Therefore a dynamic tug model was developed by making a coupling between the time domain model and a tug algorithm. The implementation of this model showed large improvements of the responses and the new tug model is also more similar to the tug response in real tandem offloading operations.
Conclusions and recommendations

At the beginning of this research the following goal was defined:

“Understanding the response of, and interaction between, a tanker and FPSO in a tandem offloading configuration during a squall”.

To achieve this goal a ship motion time domain model was developed in aNySIM. For the wind interaction Windos was used, which uses the building block approach to obtain the shielded wind coefficients that were later used in aNySIM. To analyse wave interaction a diffraction analysis was performed. This chapter will be a reflection upon this goal by providing the conclusion in section 7.1 and recommendation in section 7.2.

7.1. CONCLUSIONS

First a time domain model was developed in which only wind as environmental factor was taken into account. The results showed large tanker motions after a squall hits the system. This was found for both the ballast and fully loaded tanker. The deflection is the largest for the sway motion because the surge motions are suppressed by the tug. When a closer look is taken by comparing the results of the ballast- and fully loaded tanker different responses were observed. The ballast loaded tanker shows very chaotic responses during a squall compared to the fully loaded tanker, this is due to the lower mass, larger wind area and lower viscous damping than. During the squall the fully loaded tanker showed a fishtailing response. In case of fishtailing the ratio between the current and wind loads is the most important parameter. The relative motions have damping effects that enlarges the unstable region, which is called galloping.

Without the presence of squalls it is assumed that tandem offloading can be performed in normal wind conditions, by using a tug with a bollard pull of 40 tonnes. In this research this was investigated and it was found that in normal conditions tandem offloading can be performed with a 40 tonnes tug; however, in a squall this pull is not sufficient. Also the dynamic effects in the hawser during a squall were studied; in squall a peak is observed in the hawser loads. These large peak loads are due to the large amplitudes in horizontal motions during a squall and because of a difference in response of the FPSO and the tanker.

Initially only the effects of squalls were studied with the time domain model. The results were later compared to the effect that current and waves have on the responses. The current dampens the responses considerably; the fully loaded tanker shows a large decrease in fishtailing motions due to the adding of current. The waves do not seem to have much effect. However, in order to study the effect of the environment and other parameters on the results in more detail a sensitivity study is performed. This is done by varying several parameters: hawser length, tug pull, current speed and wave height. The sensitivity study will only be performed for the ballast loaded tanker because this is assumed to be

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Conclusions and recommendations

The critical case. The trend analysis that was performed with the results of the sensitivity study showed that an increase of current loads has a dampening effect for sway and yaw. This dampening effect for surge was only visible for faster currents. The effect of current on the responses depends mostly on the direction of the squall relative to the current. The effect of waves on the responses is found to be insignificant. However, the increase of the hawser length shows an increase in the responses of surge and sway but a small decrease in the yaw motion. The different tug pulls have a large effect on surge, sway and yaw. The surge responses show the largest decrease due to an increase in tug pull, because the surge responses are corrected by the tug.

Of the 1422 performed simulations in the sensitivity study, the safe breaking load of the hawser was exceeded in 12.1 percent (127/1422) of the cases. Hawser length had the most effect on maximal hawser load exceedance; a longer hawser was more likely to exceed its safe breaking load. By increasing the hawser length the tanker will have larger amplitudes in the horizontal motions, thus the instabilities in the hawser will increase. Considering all the evaluated parameters above, only the tug pull will have a significant effect on the responses of the tanker. Furthermore, the use of a longer hawser in tandem offloading operation is not favourable. Not only was there a small increase of the responses, but also the chance of hawser failure increased.

The effect of the different parameters on the tanker responses were studied in detail, but the interaction of wind and waves was not part of the time domain model. However, it was assumed that this could have a significant effect. Therefore the wind interaction was studied with the use of the building block approach based on Schlichting boundary layer theory for two dimensional flows. First a comparison was made between the wind coefficients found with the use of wind tunnel tests and the building block approach. A good agreement was found for surge and sway but the yaw coefficients were underestimated using the building block approach. It is assumed that the underestimation occurs due to different hull shapes. For the surge coefficients at 180 degrees there was an increase observed in the computer model, while there was a decrease observed in the coefficients of the wind tunnel test. This was also observed when the effect of different topsides were studied. This is expected to be because there is a small difference in wind area. Therefore it is assumed that between the model of the building block approach and the model used in the wind tunnel test there is also a small difference in wind area. Furthermore, it is very complex to determine the exact solidity ratio of the elements in the wind tunnel tests. This will have an effect on the building block approach model.

First the forces on the tanker that were shielded by the FPSO were obtained by placing the tanker in different positions relative to the preferred position of the tanker, directly behind the FPSO with a separation distance of 80 meters. The different positions were positions with a change in only X or Y, or X and Y direction. The rotation of the tanker is not taken into account. The obtained wind forces for the different positions showed shielding effect especially for the fully loaded tanker. Generally there was not a large shielding effect observed for the different cases. However, when the wind coefficients were calculated from the wind forces, and included in the aNySIM time domain model, larger effects were observed between the responses from the shielded and unshielded tanker. The surge and yaw showed shielding effect but the sway response of the fully loaded tanker gave the largest effect. A 60 and 140 meter shift in y-direction gave a reduction of the responses by 89.2 and 43.4 percent respectively, compared to the unshielded tanker. For the ballast tanker the sway response was reduced by 55 percent for a 60 meter shift and 41.8 per cent for a 140 meter shift in Y direction. However, not every shielded case showed a decrease in the responses compared for the unshielded case. Shielding can also lead to an increase of the responses because the tanker can move out of the shielding zone where the wind coefficients are much larger. With large wind speeds of squalls, the wind loads become suddenly very large and this could lead to an increase in the response. The effect of shielding on the hawser tension was also studied, here a decrease is observed for all the different cases of up to 60 per cent. Furthermore, it is assumed that the hawser loads will be more easily affected by the reduction of the wind loads due to shielding than the responses of the tanker itself.
For modelling a tandem offloading system in squalls wind interaction should be included in the time domain model. This is because the effects are significant. If wind shielding is included a better decision can be made if tandem offloading in squalls is feasible or not; however not all the squalls are responsible for shielding of the tanker because it is very dependent on the wind direction of the squall.

The wave interaction was researched with a multi-body diffraction analysis for three different positions of the tanker relative to the FPSO: 10, 80 and 5000 meters. The RAO’s of the FPSO and the tanker with the hydrodynamic interaction was compared with the RAO’s of the single FPSO or tanker. The results showed some small interactions in the heave RAO of the ballast loaded FPSO for a wave direction of 0 degrees. This interaction is due to the diffracted and radiated waves between the tanker and FPSO. The RAO’s for the tanker showed a reduction for 10 and 80 m distances because of a reduction of wave energy by the presence of the FPSO. For waves coming from 90 degrees the only interaction was found for the tanker with a separation distance of 10 meters. The found interaction effect will have a small influence on the first order motions during a squall in time domain. However the spread mooring of the FPSO will suppress the ship motions. The results of the tanker indicate that there will be a small overestimation of the first order wave responses in time domain, but this effect is not expected to be very significant. Therefore the hydrodynamic coupling will not be included in the time domain model.

According to the sensitivity study results the tug has the most effect on the response during a squall. The used tug model in time domain was based on a static response during the squall; the magnitude and direction of the tug is constant so only the surge responses were reduced. Therefore a dynamic tug model was developed by making a coupling between the time domain model and a tug algorithm. The implementation of this model showed large improvements of the responses and the new tug model is also more similar to the tug response in real tandem offloading operations.

7.2. **Recommendations**

At the beginning of this research very little was known about the effect of wind- and wave interaction on tandem offloading in squalls. Now it is known what happens with the tandem offloading system in a squall, which parameters have the largest influences, what the effect- and consequences is of wind and wave interaction, and the first step is made towards an improved, more robust, model of the tug. This section will describe the recommendations for future work that could further increase the knowledge of tandem offloading in squalls, and the effect and consequences of wind- and wave interaction.

First the main recommendations will be discussed; these are the recommendations that would increase the knowledge related to tandem offloading in a squall and the interaction effects. After the main recommendation additional recommendations outside of the research scope will be discussed.

**Main recommendations:**

- *Investigate the change of wave climate during a squall*
  In the time domain model in aNySIM the swell and wind-sea were modelled separately. The significant wave height and peak period of the waves are kept constant during the simulation. The wave climate offshore Nigeria is benign, however during a squall the waves increases and this could have an effect on the responses of the tanker. Therefore it would be very interesting to let the wave climate change during the squall, what also happens in reality.

- *Investigate the changes in current direction*
  In the sensitivity study the current speed was investigated, but the current direction was kept constant. The current direction offshore Nigeria changes a couple times a year, in this case the current is going to the same direction as where the squall wind often are going to. In the sensitivity study it was found that current load dampens the responses however with a change in current direction this can be different.
Perform sensitivity study for a fully loaded tanker
The sensitivity study was performed for a ballast loaded tanker because the amplitudes of the horizontal motions were the largest and the motions also very much chaotic. However, because it was found that the responses of the two loading conditions were very different, it would also be interesting to investigate which of the parameters have the largest effect for the fully loaded tanker.

Investigate the effect of change in hawser stiffness
In the sensitivity study different hawser lengths were used, but the hawser stiffness was not investigated. Because the increase of hawser stiffness could suppress the dynamic effect of the hawser it would be very interesting to also investigate this effect.

Investigate the effect of different sets of wind coefficients for one tanker during a squall
In the time domain study performed for wind coefficients with and without shielding, one set of wind coefficients were used. However the tanker has a length of more than 300 meters so at the bow of the tanker or at the stern of the tanker the wake is different which leads to a change in the shielding effect. Therefore it would be very interesting so see what the effect is when different sets of wind coefficients were used for the investigation of wind shielding in a squall.

Investigate the options of the updating of wind coefficients during time domain simulations
The wind shielding is in the research studied by using wind coefficients for different locations behind the FPSO. However, these coefficients are actually only valid for that specific location. Therefore the accuracy of the model could be improved by investigation a strategy to automatically update the different wind coefficients in the time domain model.

Investigate the shielding effect while the placement of the tanker under an angle
The different position chosen for the study of wind shielding were a translation in X, Y or a combination of the two. However, the rotation of the tanker was not investigated. This means the tanker was always positioned in the same direction. Because the results showed that the tanker will also have large yaw motions it would be interesting to investigate the wind shielding for a tanker that is also rotated.

Investigate the wind shielding for a larger range of distances
The wind shielding was investigated for distances in X and y-directions separate, from 20 to 140 meters between the tanker and FPSO. Also a combination of X and Y has been investigated. The combination of X and Y shows larger positions for the Y coordinate: 230 meter. However for these positions there is still a large difference between the unshielded and shielded responses. Therefore it would be very interesting to investigate larger distances from the FPSO to see when the wake behind the FPSO is equal to the wind profile in front of the FPSO.

Perform a time domain simulation with a hydrodynamic file for both the FPSO and tanker
The results found in the investigation for wave interaction were not implemented into the time domain model. However, it would be interesting to perform a time domain simulation with these hydrodynamically coupled coefficients in order to see what the effect is in time domain.

Investigate wave interaction for second order
The wave interaction study performed was only done for first order motions: the effect on the RAO's. Not a large effect was found but this does not mean this is also the case for second order. Therefore it is recommended that wave interaction is also investigated for the second order motions.

Improvement of the tug algorithm
In this research the first step was made in the development of a tug model that can respond to the position of the tanker. The use of this dynamic tug model is realistic, and more linked to how a tug boat is used in operations. However the tug model in LUA was a first set up and can be improved by letting the tug respond to surge, sway and yaw motions.

Additional recommendations:

Investigate the combination of time domain simulations and navigation simulation studies
In the industry the feasibility of the use of tandem offloading in squalls investigated with the use
of navigation simulation studies. However in these simulators often only one squall record is used, and the simulators are actually meant for the training of captains. Time domain programs as aNySIM are developed for ship motions but the human factor in processes as tandem offloading is very difficult to implement. If a combination of a time domain model with navigation simulations can be developed, then a correct model of the ship motions and the human factor in the tug response can be combined.

- **DP tanker simulations**
  In the North Sea Dynamic Positioned tankers are used for the offloading. But because of the benign environment VLCC tankers are used in West-Africa. The use a DP tanker would be very expensive and not even feasible. However, it would be very interesting to investigate if the DP system can compensate for the response of the tanker during a squall. This may be possible due to the wind-feed forward system, with which it can compensate for the motions of the tanker in the squall.

- **Perform Windos simulations for changes in design**
  For the design of floating system wind tunnel tests are performed in the beginning of the design. However, in time the design changes and also the topside of the vessel changes. It can happen that the wind tunnel test has to be performed again, which is very expensive. This problem can be solved by making use of the building block model in Windos for a first approach of the wind loads in the beginning of the design so changes can be easily updated, and its effects analysed.
Bibliography


Van Walre, F. Wind loads on offshore structures user’s manuel to Windos. Marin.


Figure A.1: Wind velocity- and direction for squall 1
Figure A.2: Wind velocity- and direction for squall 2

Figure A.3: Wind velocity- and direction for squall 3
Figure A.4: Wind velocity- and direction for squall 4

Figure A.5: Wind velocity- and direction for squall 5
Figure A.6: Wind velocity- and direction for squall 6

Figure A.7: Wind velocity- and direction for squall 7
Figure A.8: Wind velocity- and direction for squall 8

Figure A.9: Wind velocity- and direction for squall 11
Figure A.10: Wind velocity- and direction for squall 12

Figure A.11: Wind velocity- and direction for squall 13
Figure A.12: Wind velocity- and direction for squall 14

Figure A.13: Wind velocity- and direction for squall 15
Figure A.14: Wind velocity- and direction for squall 16

Figure A.15: Wind velocity- and direction for squall 17
Figure A.16: Wind velocity- and direction for squall 18

Figure A.17: Wind velocity- and direction for squall 19
Figure A.18: Wind velocity- and direction for squall 22