# Investigation into crawling behaviour of a friction based reverse float-over operation

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MSc Thesis

TU Delft

# Investigation into crawling behaviour of a friction based reverse float-over operation

by

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*This thesis is confidential and cannot be made public until July 7, 2022.*



TU Delft

# Preface

In front of you lies a graduation report which investigates friction force calculations between a barge and a topside during a reverse float-over operation. This research is conducted at the of office Heerema Marine Contractors, and under guidance of the TU Delft.

A special thanks goes out to my supervisors at HMC. Job Bokhorst and Pandu Samudero, who have guided me through the process in a really enjoyable way. Apart from a lot of technical knowledge you showed me how projects are approached within big companies like HMC, and I could always approach you with the many questions I had. Thank you for this.

I would also like to thanks my supervisors at the TU Delft, Professor Metrikine and Jeroen Hoving. Professor Metrikine, thank you for giving your vision on my progress during the meetings we had. You always had a great helicopter view on my research, and I learned from you that a research should always be a representation of what happens in reality, and not the other way around. Physical processes are critical for theoretical analysis. Jeroen, thank you for the meetings we have had looking into the friction force calculations. I believe I can say without a doubt I have never met someone in my life with a bigger passion for friction force calculations than you.

The group of friends who have studied, or are currently working at HMC greatly increased the amount of joy I have had in this company during the past 10 months. From all these friends a special thank goes out to Christof, Luis, Jelle and Gijs-Jan. Apart from enjoying the social aspect within and outside the office, you showed me your visions on writing a thesis, and I would like to thank you for that. After all, ”het moet wel leuk blijven”.

I really enjoyed meeting people from other departments and the fleet and talk with them about their work and visions and experiences.

# Abstract


Heerema Marine Contractors (HMC) is a world leading marine contractor in the international offshore oil and gas industry. HMC specializes, among other activities, in the decommissioning of offshore located oil platforms. Current methods exist for safely removing topsides and substructures, yet research into new and cheaper ways is continuously done at HMC. Common practice now is to remove the topside with the use of a Semi-Submersible Crane Vessel (SSCV) and lift the topside onto a barge. With a new method, a reverse float-over operation, the SSCV would not be needed at all for this procedure.

This operation has not been performed before. The set-up for this research is a barge which will connect to the topside due to friction forces on the interface between these two bodies. The use of stabbing cones or clamps would increase the horizontal station keeping of the barge beneath the topside during this operation. As this would require a lot of work being done on the topside before this operation can take place they are not used in this research. Therefore it was chosen to have the barge stick to the topside due to friction. In computer simulations a model of the H-851, a HMC owned barge, is located beneath an earth fixed topside. The deballasting of the barge is simulated by applying an external lift force on the centre of gravity of the barge. External wave forces are acting on the barge. When the barge is being pushed against the topside, friction forces allow the barge to crawl beneath the topside due to a stick slip mechanism. This thesis looks into the crawling behaviour by making a new friction model.

A simplified model was created to improve the understanding of the friction forces between 2 bodies. A sensitivity study has been performed to analyse the crawling behaviour of the barge as a function of five parameters: Deballast velocity, vertical interface stiffness, horizontal interface stiffness, horizontal interface damping and coulomb friction coefficients. This is done by defining a base case and changing parameters to check the influence on the crawling behaviour.

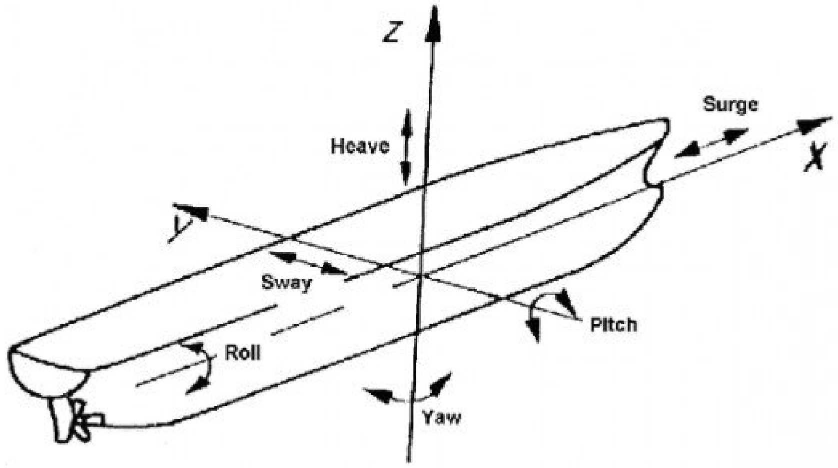
Crawling behaviour is observed during two phases: The initial contact phase, where the barge alternately makes contact with the topside, and the compressed interface phase, where the barge is in constant contact with the topside. As waves travel in positive x direction, the barge shows crawling behaviour in negative x direction in the initial contact phase. In the constant compressed phase the barge shows crawling both in negative and positive x direction. During the initial contact phase more friction is applied when the barge moves in positive x direction.

Optimisation runs have shown the influence of the 5 parameters on the crawling behaviour of the barge. Increasing the horizontal damping reduces the crawling distance of the barge. When the friction coefficients are increased the barge reaches a stick condition sooner. With higher coefficients there is also more crawling behaviour in negative direction. Increasing the deballast velocity reduces the crawling distance of the barge. Varying both the horizontal and vertical interface stiffness changes the dynamical behaviour of the barge, and thus also the crawling behaviour.

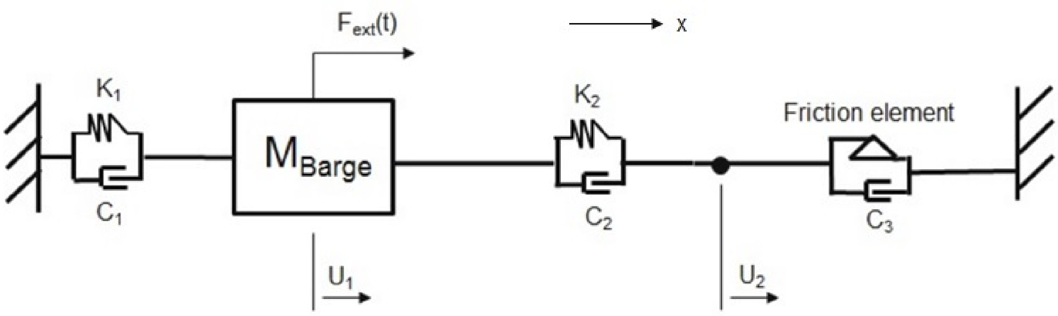
The case used in this research is a simplified case. Further research into the crawling behaviour, and different behaviour, is needed to model a reverse float-over operation.

# Sign Convention

The sign conventions in this report are shown below, and in accordance with common practice [6].




The sign convention in the matlab model is shown below.



# Contents

# 1 Introduction

## 1.1. HMC

Heerema Marine Contracters (HMC) has been active in the offshore engineering business for over 50 years. The activities were in the beginning mainly focused on the development and installation of oil platforms. HMC started operating in the harsh environments of the North-Sea. HMC was the first offshore company to use a semi-submersible crane vessel (SSCV) for offshore purposes. The current practice of HMC is heavy lifting, topside installation, subsea development and decommissioning and removal. The decommissioning of a platform can be split up in several different phases. The topside has to be prepared, the wells plugged and abandoned, the conductor has to be removed and finally the platform removal has to be mobilized [8]. The common practice is to lift the topside from the substructure with a SSCV, and than place it on a barge. The barge will then transport the topside to the yard. Heerema has earlier looked into new ways of the last step of these decommissioning phases. With a new method, called a 'reverse float-over operation', the barge itself will lift the topside from the substructure. This research was set out to model this new decommissioning method in a way representing reality in a best possible way.

## 1.2. Problem description

Decommissioning a topside with a reversed float-over operation can be split up in 4 different phases.

1. Moored barge beneath topside
2. Initial contact phase
3. Compressed interface phase
4. Stick and lifting phase

Since this operation has not been done before, a research into this topic can focus on many different aspects of the operation. For research purposes it is important to zoom in on a topic and make certain assumptions. During the initial contact phase the slamming loads on the big structures can be large, while there can also be coupling between the environmental loads and barge pitch motions. During the lifting phase it is important the topside does not slam into the substructure when the topside is being lifted. During this research the focus was on the third phase, the mating phase. In this phase the fenders are assumed to be always compressed, but the barge is not yet in a stick condition with the topside due to the friction of the interface between the barge and the topside. This stick slip behaviour, also referred to as 'crawling behaviour', can be crucial in the reversed float-over operation. The barge will be moored beneath the topside in a way the strong points on the interface align with the correct locations on the topside. When the barge changes position due to the stick slip behaviour in the mating phase this can lead to misalignment. This is something that can not be accepted, and therefore further research into this crawling behaviour is needed.

For this research the program aNySIM is used. aNySIM provides a time domain description of the motions of a system involving several floating bodies and dry bodies, in a total system with Nbody*6 degree of freedom [1]. aNySIM is used inside HMC for model simulations and calculations. This research is set out to answer the question: Will the crawling effects be significant for the operation, and which parameters are the biggest contributors to this crawling behaviour of the barge?

## 1.3. Objectives

A computer model will always make assumptions to mimic reality in a way which is acceptable to the engineer. The objective of this research is to look into the crawling behaviour of the barge in computer simulations during the mating phase in the reversed float-over operation. The physics behind the crawling behaviour must be understood, and the findings from simulations must be supported with the physics.

## 1.4. Approach

In order to reach the objectives the following approach will be taken:

1. Create an aNySIM model with a barge used by HMC
2. Create a base case for the mating phase of the operation
3. Create an interface between the barge and topside, and observe if crawling behaviour is observed

## 1.5. Structure report

The report will first look into the different phases of the research. Than will be looked into the model set-up for the research. Problems accounted with this model will be described and analysed. The known literature of stick-slip behaviour will than looked into, and later applied in an own model. A sensitivity study will be done on the new model for optimisation on the crawling distance of the barge during the mating phase.

# 2

# phase

## 2.1. starting the research

This research investigates a new possible decommissioning method for offshore located topsides. The reverse float-over operation can only be done on topsides where a barge can be located underneath. This is only possible if these platforms are installed with a float-over operation, otherwise the substructure will be prevent the barge to sail underneath the topside.

As mentioned in the chapter 1, 4 different phases can be distinguished during the reversed float-over operation. These phases are:

1. Moored barge beneath topside
2. Initial contact phase
3. Compressed interface phase
4. Stick and lifting phase

## 2.2. Phases during the operation

A short description of these phases follows below.

### 2.2.1. Moored barge beneath topside

In this phase a barge is moored beneath the topside that will be decommissioned. To ensure there is an air gap between the interface on the barge and the topside, most of the ballast tanks of the barge will be filled. In this phase the barge is subjected to wave loads, and is restrained by mooring lines. This phase is denoted as the free floating phase.

### 2.2.2. Initial contact phase

When the barge is aligned with the topside the draught can be reduced by pumping out water of the ballasting tanks. During the deballasting the air gap will decrease until there is initial contact between the interface on the barge and the bottom of the topside. When the first contact is made, the environmental loading will have an effect on the heave, roll and pitch motion of the barge. During the initial contact phase the interface between the barge and the topside will be partially compressed at certain moments in time, yet not all the time. It is possible in this phase the barge is totally disconnected from the topside.

### 2.2.3. Compressed interface phase

In this phase the interface on the barge will always be in contact with the topside. The interface will have a certain stiffness, and compression of the interface will result in normal forces applied to both bodies. When the interface is compressed, there will be friction forces between the two bodies. The friction calculated in the interface is dependant on the normal force given in the fender. It is possible in this phase for the barge to move underneath the topside due to the environmental loading.

### 2.2.4. Contact and Lifting phase

When the barge is deballasted by emptying the ballast tanks, the draught gradually decreases. When the interface gets compressed more and more, the mean normal load in the interface increases. When this increases, the threshold which has to be reached to go from a stick to slip transition also increases. At a certain point the environmental loads will not exceed this threshold and the barge will stop moving beneath the topside. This phase is denoted as the contact phase. After the contact phase the topside will have to be lifted off the substructure.

## 2.3. Problem per phase

There is no protocol for the reversed float-over operation, nor is it ever executed before. This means that in every phase many things can happen which hasn't been investigated properly before. Each problem can be analysed in its own best way, and some analyses will take more time than others. In the following section the biggest problems for each phase will be described, after which the choice of the problem selected for this thesis will be explained.

### 2.3.1. Problems: Moored barge beneath topside

The horizontal station keeping of a barge in the ocean with environmental waves is quite a well known topic. It is important to limit the movement of the barge before the deballasting of the tanks starts. There are wave-, wind- and current-loads which effect the movement of the barge. These loads, especially the wave loads, have first and higher order effects. The secondary order wave forces will result in a mean displacement which will have to be taken into account. With mooring lines, fenders on the side of the barge and docking lines between the barge and the substructure this movement can be restricted in a controlled manner.

### 2.3.2. Problems: Initial contact phase

During the initial contact phase the impact loads can be seen as the most crucial. The topside is constructed in such a way it can endure many loads during its lifetime. It is not built to withstand a barge slamming into it from the bottom during its decommissioning. The structural strength of the topside is different for each topside, and the loads it can withstand will have to be calculated very precisely with detailed software. Building such a model would take a large amount of time for someone who is not familiar with this topic, and the thesis would have therefore probably been limited to creating a structural model of a specific topside. Even though this is valuable for a company, this is not considered ideal for a master thesis graduation topic.

### 2.3.3. Problems: Compressed interface

The horizontal station keeping of the barge under the influence of environmental loads is mentioned in section 2.3.1. Where the behaviour of a moored barge can be calculated and predicted for different sea states very precisely, the behaviour with a compressed interface is less straight forward. The friction forces applied on the interface are crucial for determining the movement of the barge in this phase of the operation. In literature there is a difference made between static friction, when there is yet no movement between 2 bodies, and kinetic friction, when there is a movement between two bodies. The friction force is also dependant on the compression of the interface, as the friction of a body will be higher when the vertical load to the body is increased. These different aspects have to taken into account when making a model of the horizontal movement, and possible crawling behaviour, of the barge.

### 2.3.4. Problems: Contact and Lifting phase

In the contact phase the barge is under constant stick condition beneath the topside. This means that the environmental loads acting on the barge will never be strong enough to exceed certain friction threshold, and the barge will stay in the same position. When the ballast tanks keep losing water, more weight of the topside is put on the barge instead of the substructure. At a certain point the barge is lifting so much of the weight of the topside, the topside can be lifted off the substructure by the barge under the influence of waves. It is possible the topside slams into the substructure if it is not dealt with properly.

## 2.4. Phase selection

Looking to the problems in the 4 previously written sections, a choice had to be made for the topic of this master thesis. Combining academic difficulty with research valuable for HMC, the decision has been made to analyse the possible problems arising at the mating phase 2.3.3. Many factors such as; Deballasting velocity, friction coefficients, and stiffness- and damping coefficients can have an large effect on the horizontal positioning of the barge beneath a topside.

For float-over installations, such as the Wheatstone project in Australia or Arkutun Dagi at Sakhalin, HMC has used the barge H-851.

Figure 2.1: The H851 is used in the Arkutun Dagi float-over installation

Using an existing barge owned by HMC has two big benefits:

1. The reverse float-over operation will probably be done by this barge. Any calculations done using this barge can directly be applied on future decommissioning projects.

2. There is information available about this barge. Models in existing computer programs are already constructed, and there are done model tests which can be compared to computer models.

# 3
# Model Set-up

Within HMC the program aNySIM is used for hydrodynamic analysis. aNySIM is created by the Maritime Research Institute Netherlands (Marin). Marin is an institute well known in the offshore industry for their expertise in the field of offshore hydromechanics. aNySIM is the main hydrodynamic toolbox used within Marin, combining different tools which were developed for specialised areas[4]. aNySIM provides a time domain description of the motions of a system involving several floating bodies and dry bodies, in a total system with Nbody*6 degree of freedom. aNysIM is a software tools that uses rigid bodies, so there is no bending or deformation of beams or structures, or any energy dissipation through the materials.

It is important to note that the aNySIM software has advantages for research in comparison to an own made model. More realistic and complex analyses can be performed using this software tool. The downside of this software, which will be come back on later, is that it is a black box toolbox. A run performed with certain input parameters can be analysed by checking the output of the run. The calculations done in each time step are not recorded. When non-expected behaviour is observed, it can be hard to say what physical underlying process is responsible for that specific behaviour. In sections 3.2 and 3.3 this will be shown in more detail.


Figure 3.1: H851

## 3.1. aNySIM model set-up

For this researh the barge H851 is used in the modelling. Input parameters are needed to create an aNySIM model. The details of these parameters, and how to acquire them, will be listed below.

### 3.1.1. LIFTDYN

A HMC in-house program called LIFTDYN is used for frequency domain analysis. Starting with a model in LIFTDYN an aNySIM model can be created. Input for the H851 is gained from multiple sources.

1. Mass properties

2. Additional properties

3. Damping Hydrostatic properties

In image 3.1.2 the liftdyn interface can be seen.

### 3.1.2. Mass properties - Sinai

The H851 is a barge owned by HMC, and the details are listed below.


Figure 3.2: Information on the H851

The mass distribution can be found with the program called Sinai. The H851 consists of ballast tanks used to regulate the draught and stabilization of the barge. These tanks are located throughout the hull of the barge. To prevent sloshing in the tanks, which must be prevented, the tanks must be either $< 5\%$ or $> 95\%$ full. The tanks have to be filled manually in Sinai. In image 3.1.2 is shown how this is done. The graph in the lower right bottom of the image shows the static trim and roll of the barge. For a reverse float-over operation the deck surface has to be level, so a trim and roll of 0% is required. When the barge is at the required static condition, Sinai gives the 6x6 mass matrix and radii of gyration.

The Draught of the barge is chosen at $T = 12.4m$. A deep draught increases the stability. The deep draught also ensures a big enough air gap between the topside and the interface that will be located onto the barge.


3.1.2 Liftdyn interface


3.1.2 Sinai interface

### 3.1.3. Additional properties

[redacted]

**??** Mass properties for the LIFTDYN model

The additional properties ask for spring and damping terms for the barge. With the additional spring and damping terms the mooring can be added to the model. A natural surge period of the H851 of $T_{Nat} = 130s$ and a stiffness of $K_1 = 40(mT/m)$ are assumed to be a realistic value for the moored barge.

$$T_{Nat} = 130s = \frac{2\pi}{\sqrt{\frac{k}{m+a}}} \tag{3.1}$$

$$\zeta_{crit} = 20\% = \frac{c}{2\sqrt{k(m+a)}} \tag{3.2}$$

Using equations 3.1 and 3.2 the values given in **??** are calculated. For the stiffness in surge and sway direction the same value is used. The added mass term differs for these conditions, so the natural period will differ slightly. The stiffness is not adjusted in order to maintain the same deviation in both directions when the same force acts on the body in different directions.

### 3.1.4. Hydrostatic properties - HYD file - WAMIT

An important parameter for the model is the HYD file. The hydfile is a hydrodynamic database file resulting from the diffraction calculations on the hull of the submerged body. This file can be constructed using the software package called WAMIT. The interaction between waves and floating bodies is calculated with linear and second-order potential flow theory. The velocity potential and fluid pressure on the submerged surfaces of the bodies is are solved with the boundary integral equation method (BIEM) [5]. WAMIT works with the shape of the submerged body and sees it as a sum of small panels that interact with the incoming waves. The mass distribution is also important for the hydrostatic and dynamic behaviour.

## 3.2. Simulations in aNySIM

When the LIFTDYN model has the correct input parameters it can be turned into an aNySIM model. The aNySIM model can calculate the forces on and acceleration of the barge in time domain simulations. The current aNySIM model consists of a free floating barge with its corresponding stiffness and damping coefficients.


(a) H851 initial model


(b) H851 with an interface represented by 4 fenders

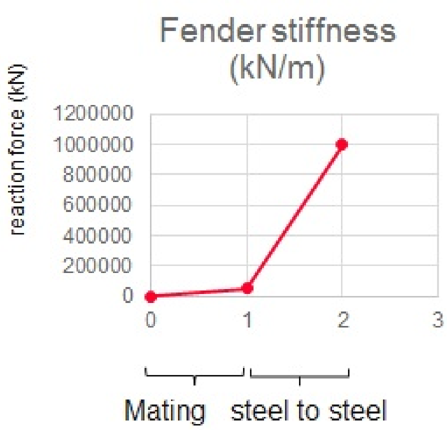
Figure 3.3: aNySIM barge

### 3.2.1. Interface

On top of the barge an interface will be located. This interface is modelled with the use of a module within aNySIM named "fender module". 4 fenders represent the interface in this stage. The fenders are located symmetrically $\pm 20m$ in x direction and $\pm$ in y direction of the CoG of the barge. This fender is shown in 3.4 as a spring on top of the barge. The fender stiffness is shown in graph 3.2.1. The first meter of compression shows the stiffness of the first meter of the interface. A steel to steel interaction is mimicked after 1m of compression to mimic by increasing the stiffness by a factor $\pm 30$. In reality there will be deformation when there is a large force in steel to steel contact. In a rigid body model this can not be modelled, therefore a relatively large stiffness is modelled. It is important to analyse the behaviour of the barge in all phases. The focus of this research is on the mating phase. If a wave excitation forces the barge into compressing the fenders into the steel to steel contact region the behaviour of the barge and the forces given must be realistic.

| Compression (m) | Force (kN) |
|---|---|
| 0 | 0 |
| 1 | 33.026 |
| 2 | 100.000 |

3.2.1 Fender Stiffness




3.2.1 Fender stiffness curve

When this fender is compressed this compression must be converted to a force in the normal direction. When a compression results into a normal force, a friction force within the horizontal plane is also calculated [3]. The friction within the fender is calculated as Coulomb friction. This is done by multiplying the normal force in the fender with a constant $\mu$. A friction coefficient is also introduced at low velocities to prevent numerical oscillations around 0. Section 4.2 will go into the physics of this mechanism in more detail.

$$\mu_{kinetic} = 0.2 \tag{3.3}$$

$$b_{friction} = 1e9(Ns/m) \tag{3.4}$$

### 3.2.2. External loading

The next step towards the mating phase simulation is applying external loading onto the system. Environmental loads as wind, wave and current loads can be exerted onto the barge. Wave loads described in will be used for environmental loading in these simulations.

**??** Wave conditions

For the reversed float-over operation the barge will slowly be compressed against a topside. For this stage of the research the topside can be considered earthbound, as the initial impact will not lift the topside from the substructure. There will be an air gap between the topside and the interface located on the barge. An air gap of 1m is assumed. Reducing the air gap by deballasting the barge will be simulated by applying an external force onto the Centre of Gravity (CoG) of the barge. The location of the CoG is given in **??** indicated from the local origin, located at the keel of the barge on the stern. The loss of mass during this process is neglected and the mass is kept constant.

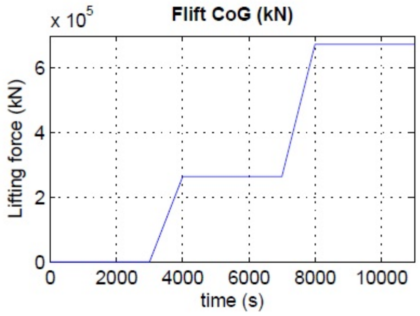

(a) schematic drawing 3d


(b) 1d schematic with the air gap


(c) 1d fender compression

Figure 3.4: Schematic overview of the aNySIm model

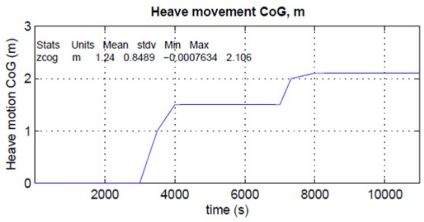
The fender will be lifted out of the water by applying an external force to the CoG of the barge. In this simulation was tried to observe the behaviour of the barge in the free-floating stage, the mating phase and the steel to steel contact phase. The forces are plotted in figure 3.5. After a period of $t = 3000s$ the CoG is lifted $\Delta z = +1.5m$, where the fender is compressed for $\Delta diameter = -0.5m$ between $t = 4000s$ and $t = 7000s$. At $t = 7000s$ the barge is lifted into the steel to steel contact area, where the fender is compressed $\Delta diameter = 1.05m$. The fender is compressed 0.05 m into the steel to steel contact region to make sure wave excitations are not big enough to barge is going back to the mating phase. The barge is kept at this position between $t = 8000s$ and $t = 11000s$ seconds.



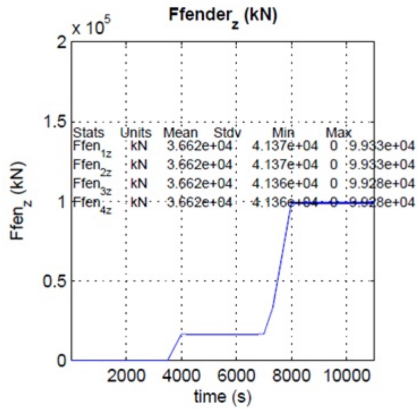

(a) Lifting force

| t(s) | Fx(kN) | Fy(kN) | Fz(kN) |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 3000 | 0 | 0 | 0 |
| 4000 | 0 | 0 | 264210 |
| 7000 | 0 | 0 | 264210 |
| 8000 | 0 | 0 | 673735.5 |
| 11000 | 0 | 0 | 673735.5 |

(b) lifting force details




(c) Heave movement




(d) normal force of 1 fender

Figure 3.5: Lifting force

Earth and Body fixed forces

In aNySIM forces can be earth fixed and body fixed. An earth fixed force in z direction acting on a body will keep working on the body in z direction. A body fixed force working on a body in z direction will move if the body is rolling or pitching. In early simulations a minor pitch occurred when the barge was deballasted. The combination of a relatively high force with a minor pitch angle resulted in surge behaviour due to a body fixed force. The unwanted surge behaviour was removed by making the force earth fixed.

### 3.2.3. Numerical Oscilations

As mentioned in the beginning of this chapter The calculations performed by aNySIM are not registered, and finding the origin of non expected behaviour can prove to be difficult. The differential equations solved by aNySIM are solved by a second order Runge-Kutta method in this case [9].

During simulations numerical oscillations were observed in the steel to steel contact phase. During a run waves with characteristics given in 3.2.3 hit the barge.

| | |
|---|---|
| Hs (m) | 1.5 |
| Tp (s) | 8.0 |
| Heading (deg) | 45 |

Wave conditions

| t (s) | Flift (kN) |
|---|---|
| 0 | 0 |
| 10000 | 0 |
| 11000 | 264210 |
| 21000 | 264210 |
| 22000 | 673735.5 |
| 32000 | 673735.5 |

Lift force

The motion of the 6 degrees of freedom is shown in 3.2.3.


The oscillations, shown in 3.2.3, were removed by reducing the time step of $dt = 0.1$ to $dt = 0.01s$. The reduction in time step is needed for accurate modelling. In the $dt = 0.1$ case the forces acting on the body were so high the estimated movement by the second order Runga-Kutta solver were no longer giving accurate result. A higher order solver, or smaller time step remove these osculations. in these runs the second order waves have been switched of.//

### 3.2.4. Crawling behaviour

The previous runs were done with waves hitting the barge under an angle of 45 degree, to observe possible crawling behaviour in both x and y direction. The force acting on the barge in y direction also induced a large yaw movement. The stiffness has later been increased to reduce this movement. This behaviour also led to the decision to make the incoming wave heading 0 degree. In that way there was no yaw moment induced, and the possible crawl behaviour could be isolated better.

In the new set-up waves hit the barge with a wave heading of 0 °. The barge is lifted into the initial contact phase, to see if any crawling behaviour is observed. In figure 3.6 the heave and surge movement of the CoG of the barge is observed within a model with and without friction modelled in the fender. In 3.6a it can be observed that the barge has a vertical displacement of 1.5m, there is no influence on the movement in x direction by the CoG. In the x direction the barge oscillates around 0. When there is friction modelled into the model, with a Coulomb coefficient and friction slope described in 3.2.1 and 3.2.1, different behaviour is observed. This is shown in 3.6b. The region within the red box shows surge movement in the x direction. After roughly $\pm$100s a new equilibrium is found +0.50m of the original equilibrium position. This behaviour was anticipated in the 2.3.2. Potential movement of the barge during the mating phase can have large consequences during the entire reverse float-over operation, and is therefore interesting to investigate. The red box shows a small window of time in which the external forces in x direction acting on the barge are high enough to push the barge forward, after which the barge sticks to the topside due to friction, until a next wave hits the barge. In 3.6b this is $\pm$ 100s, after which the threshold of the friction force is to high for the wave forces to reach. For the next step of the research a new run will be set out to force the barge into this crawling window for a longer duration of time, to analyse the behaviour in this region.


(a) barge movement without fender friction


(b) barge movement with fender friction

Figure 3.6: Barge movement without and with fender friction

## 3.3. Crawling behaviour analysis

A new loading case is determined to analyse the crawling behaviour. The environmental data is given in 3.3.

| | |
|---|---|
| Hs (m) | 1.5 |
| Tp (s) | 8.0 |
| Heading (deg) | 0 |

In this loading case the barge is lifted 1m by an external force between $t = 0s$ and $t = 2000s$. Between $t = 2000s$ and $t = 7000s$ the fender is compressed into the region where crawling behaviour is observed. The heave, surge and pitch motion of the barge in a free-floating and crawling case are plotted in 3.3.


Figure 3.7: Surge, Heave and Pitch motion of the CoG of the H851

The blue line in 3.3 shows the free-floating loading case, and the expected behaviour is observed. There is no lifting force applied and only wave forces act on the barge. A small oscillation is observed in x direction around $x = 0$, in the $z$ direction the influence of the wave forces are small. For the crawling case interesting behaviour is observed. When the barge is lifted in the crawling zone, $2000s < t < 7000s$, movements in the x direction are clearly observed. The amplitude of the surge motion increases. There is also negative crawling behaviour observed. The barge moves $\pm 0.70m$ in the direction the waves are coming from. This negative crawling behaviour originates from a mean negative friction force in the fender. This behaviour is unexpected.

### 3.3.1. mean negative surge

6 new simulations were done. All conditions are kept constant, the wave seed used only differs. The surge motion of these 6 runs are shown in fig 3.3.1.


3.3.1 crawling behaviour with 6 different wave seeds.

In **??** the mean data from the 6 runs with different wave seeds is shown. The mean wave force is almost 0 with a value of $0.840kN$. The mean force given in the fender on the other hand is $-31.545kN$. This mean negative force in x direction calculated in the fender has as a concequence that there is a mean negative surge. It can be concluded that crawling behaviour observed in 3.3 is not incidental. Something in the friction calculation within the fender module accounts for this mean negative fender force. In section 4.2 will be looked into the friction force calculation within the fender.

# 4 Literature Study

in 3.3.1 was concluded that further research into the friction force calculation within the fender was needed. In this chapter is looked at the way this is modelled, and if this is in agreement with known literature. For this research focusing on stick-slip behaviour the friction force plays a fundamental role. Acceptable assumptions in other models might not be acceptable for this research.

## 4.1. Friction literature

When a body is in contact with a surface there will be friction between them. If there is an external force applied to one of the bodies, a reaction force will counteract the external force at the interface between the two bodies, as shown in figure 4.1. The mass is called to be in stick condition in this phase. The force acting on the body is counteracted by the friction force, holding the mass in place.

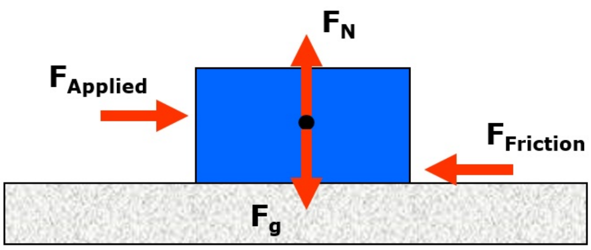



Figure 4.1: Friction force reacting when a force is applied on a body

In stick condition:

$$F_{Applied} = F_{Friction} \tag{4.1}$$

When the applied force reaches a threshold $F_{Crit}^{Static}$, the friction force will not be high enough to keep the mass in place. When condition 4.3 is met, there will be acceleration of the mass described in 4.4. When the body moves the friction force acting on the body is called $F_{Friction}^{Kinetic}$. There is a distinction between static and kinetic friction.

$$m\ddot{u} = F_{Applied} - F_{Friction} \tag{4.2}$$

if

$$F_{Applied} > F_{Friction} \tag{4.3}$$

than

$$m\ddot{u} \neq 0 \tag{4.4}$$

The $F_{Friction}^{Kinetic} < F_{Friction}^{Static}$. The kinetic friction force can fundamentally only be less or equal to the $F_{Friction}^{Static}$. The case where $F_{Friction}^{Kinetic} > F_{Friction}^{Static}$ does physically not make sense, since the $F_{Friction}^{Kinetic}$ will stop the motion before acceleration has begun. figure 4.1 shows 2 cases. In 4.3a the kinetic friction is equal to the threshold of the static friction, in figure 4.3b the kinetic friction is in this specific case half the static friction threshold. The ratio between $\mu_{Static}$ : $\mu_{Kinetic}$ depends on the materials at the interface. When the barge has stopped moving completely after travelling a certain distance it returns to the stick condition.

$$F_{crit}^{Static} = \mu_{Static} * F_{Normal} \tag{4.5}$$

$$F^{Kinetic} = \mu_{Kinetic} * F_{Normal} \tag{4.6}$$

$$\mu_{Static} = 0.2 \tag{4.7}$$

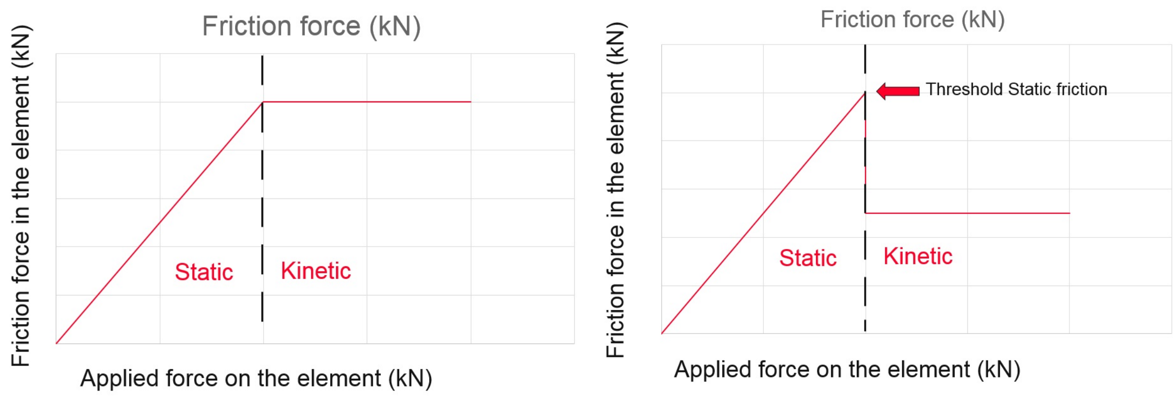
$$\mu_{Kinetic} = 0.1 \tag{4.8}$$

**Table 6.2** KINETIC AND STATIC FRICTION COEFFICIENTS[a]

| *Materials* | $\mu_k$ | $\mu_s$ |
|---|---|---|
| Steel on steel | 0.6 | 0.7 |
| Steel on lead | 0.9 | 0.9 |
| Steel on copper | 0.4 | 0.5 |
| Copper on cast iron | 0.3 | 1.1 |
| Copper on glass | 0.5 | 0.7 |
| Waxed ski on snow | | |
| at −10°C | 0.2 | 0.2 |
| at 0°C | 0.05 | 0.1 |
| Rubber on concrete | ~1 | ~1 |

[a] The friction coefficient depends on the condition of the surfaces. The values in this table are typical for unlubricated, dry surfaces, but should not be trusted blindly.

Figure 4.2: Static and kinetic friction coefficients for different materials




(a) Friction force

(b) Static and kinetic friction

Figure 4.3: Friction force in an element

## 4.2. aNySIM Fender module

[redacted]

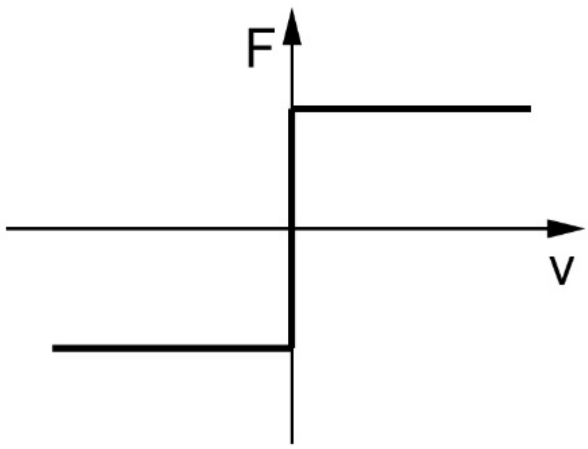



Figure 4.4: Coulomb friction as a function of velocity

[redacted]

[redacted]


Figure 4.5: friction slope: aNySIM's solution for zero velocities

For every time step both **??** and **??** are calculated, and the smallest of the 2 values is used in the model. The fender compression force $F_N$ and relative velocity $v_{rel}$ are calculated with the 2 constants $\mu_{Kinetic}$ and friction slope $b$. The value for $\mu_{Kinetic}$ can be found in the literature, $b$ has to be selected with care. If this value is too low, the friction will always be calculated with **??**, and the friction force used can be an underestimation of reality. When a high $b$ is taken, **??** will give the smallest value for $F_{Friction}$. In the next section is looked into the consequence of calculating the friction force in this manner if the barge is in stick condition.

Runs have been performed to check the behaviour of the barge with this numerical approximation of the friction force with the friction slope. A base case has been set out, shown in **??**, and multiple runs with different values for $b$ are shown.

[redacted]

[redacted]

The external force in this base case is a sinusoidal force with an amplitude of $4 * 10^5 N$. The $F_N$ and $\mu_{Kinetic}$ are chosen in such a way the $F_{Critical}^{Static}$ threshold is exceeded when $F_{Ext}(t)$ exceeds $2 * 10^5 N$. In the following figures runs are shown when $b$ is varied.

This 1d model is constructed in aNySIM. A matlab model has been made with the same input, the difference between the 2 runs being that matlab solves the equations analytically. The runs are plotted next to each other. The left figure is the aNySIM run, and the right figure is the matlab run. Below each run the taken value for $b$ will be given.


4.2 aNySIM run vs matlab run. $b = 10^4 (Ns/m)$


4.2 aNySIM run vs matlab run. $b = 10^6 (Ns/m)$


4.2 aNySIM run vs matlab run. $b = 10^8 (Ns/m)$


4.2 aNySIM run vs matlab run. $b = 10^{10} (Ns/m)$

A few conclusions can be drawn from these simulations:

1. The aNySIM and matlab model describe the same behaviour
2. When $b = 10^4 (Ns/m), 10^6 (Ns/m)$ the mass starts moving as soon as the force is exerted onto the mass.

3. at $b = 10^8 (Ns/m)$ the friction force is changes the shape of the position and velocity plot. The mass is not yet in stick condition with this value of $b$.

4. at $b = 10^{10} (Nm/s)$ the mass stays at the initial location, until the $F_{Ext}$ exceeds the $F^{Static}_{Critical}$ threshold.

5. at $b = 10^{10} (Ns/m)$ oscillations can be observed in the aNySIM run. When $F_{Ext}(t)$ starts acting on the mass the result is a small displacement of the mass. Due to the high $= 10^{10} (Ns/m)$ value, the smallest value for $F^{Friction}$ is the **??** condition. This force is large enough to counteract the external force. After the next time step the friction force has induced a motion in a negative direction, which is than counteracted by the friction force. This goes on, until the $F^{Static}_{Critical}$ threshold is exceeded.

6. in the $b = 10^{10} (Ns/m)$ matlab run there are no oscillations, since the velocity can be 0 this simulation.

## 4.3. Conclusion

The friction force calculations used in the aNySIM fender module are replicated exactly in a matlab model. After investigation the following conclusions can be drawn:

1. The use of a friction slope in numerical modelling causes a mass to oscillate around the location the mass would be in stick condition in an analytical simulation.
2. When the statical friction threshold is reached both in an analytical and numerical model the mass starts accelerating in the way the force is acting on.
3. The literature shows the kinetic friction force is lower than the statical friction threshold. In the numerical friction model there is no distinction between kinetic and static friction, there is only kinetic friction.
4. There is no stiffness or damping modelled in the horizontal plane in the fender module. In real life the upper layer of the interface will not be made out of metal to absorb slamming loads during initial contact. An interface with a top layer of softer materials will have a stiffness and damping in the horizontal direction. This would allow small displacement and velocities of the mass to occur when the top of the interface located on the mass is in stick condition with the topside.
5. The mean negative force in the fender module can not be explained by analysis of the friction force calculation. the aNySIM fender module is a black box, and the origin of the mean negative force is not due to something within the fender module

### 4.3.1. Next step

The last point in the conclusion describes the difficulty of using a black box software tool. A non-expected behaviour is observed, yet the origin of this behaviour could be due to many factors. In this research was chosen not to continue with the fender module, and go deeper into the friction force calculation within an interface. This will be done by making a 1 dimensional model in matlab. Creating a new model has advantages:

1. The engineer has full control over the entire simulation.
2. The fender module can be expanded. Horizontal stiffness and damping, which was not included into the aNysIM module, can be added into this model. A distinction between static and kinetic friction can be made.
3. With full control over all the parameters, a sensitivity study can be performed on the crawling distance of a mass under the influence of an external force.

# 5

# New Model

# 6 Optimization

The 1 dimensional model described in the previous chapter is modelled in matlab, yet analysing a reverse float-over operation is a > 1 dimensional situation. For that reason data obtained from an aNySIM run has been used in the 1D matlab model. Wave forces and fender compression are extracted from the aNySIM run. The focus of this research has been directed to friction modelling. The movement of the barge with the use of the original, and new friction model are different. This chapter will look into the optimization of the crawling distance, and analyse the influence of parameters used in the model.

## 6.1. Set-up Base Case

The analysis of parameters is done by varying the value of 1 of the parameters in different runs. To do this, a solid base case has to be used for analysis. 2 input parameters are obtained from a simulation in aNySIM.


Figure 6.1: Set-up used for the aNySIM run

### 6.1.1. aNySIM run

The set-up used is similar to the one described in 3.2.


(a) schematic drawing 3d

(b) 1d schematic with the air gap

(c) 1d fender compression

Figure 6.2: Schematic overview of the aNySIm model

In this 2 external loads are applied to the system.

1. $F_{Lift}(t)$ is acting on the CoG of the barge to simulate the deballasting of the barge
2. $F_{Ext}(t)$ are the wave loads acting on the body

The deballasting of the barge happens by emptying the ballast tanks. In the base case this is done with $20000mT/hour$. This corresponds to an $F_{Lift}(t = 1hour) = 196200kN$. The table below shows $F_{Lift}(t)$. $F_{Lift}(500s) = 119900kN$ as this is just before the barge exceeds the 1m air gap. In the simulations with a different $v_{Deb}$ the value for $F_{Lift}(4100s)$ is changed.


Figure 6.3: Lift force

The characteristics of the wave loads are given below.
The input described in the table above is used for the external waves applied to the system. A build up time is added, meaning that $Hs$ and $Tp$ reach the selected values at $t = 200s$.


Figure 6.4: Wave force acting on the CoG in x direction

The external loads cause the barge to move in 6 dof. Since the waves hit the barge from an angle of 0°, there are no sway, roll or yaw motions induced. The fender compression in $z$ direction and wave force in x direction on the CoG are measured. This data is used as input for the matlab simulation. Doing it in such a way could show interesting behaviour about the coupling between the wave force and fender compression. The friction coefficients in the aNySIM run have been set to 0, to have no influence on the behaviour of the barge.

## 6.2. Matlab model

The schematic drawing is given in figure **??**, and will also be plotted below.


Figure 6.5: Schematic set-up for a new 1 dimensional fender

Base case parameters for the matlab optimisation run
The mass depicted in the table above is the sum of the mass and added mass in x direction. The mooring stiffness $K_1$ has a value of $40(mT/m)$. The hydrostatic damping term $C_1$ is taken in such a way that the critical damping $\zeta_{crit} = 20\%$. The horizontal stiffness in the fender $K_2$ has a value of $5.6 * 10^8$, or $56.000(mT/m)$. The fender used in the simulation represents the interface between the barge and the topside, and the horizontal and vertical stiffness will be included in the $K_2$ and $K_3$ term. Deck Support Units (DSU's) used in previous research have a horizontal stiffness of 2800 mT when the DSU is compressed for $\Delta x = 0.30m$. This would convert to a value of $14.000(mT/m)$ when they are compressed for 1 meter[7]. The DSU's consist of stabbing cones and can therefore be expected to have a higher horizontal stiffness than an interface. A value had to be chosen for the base case, therefore this value has been used in this research. The horizontal fender damping term $C_2 = 3.3 * 10^7(Ns/m)$ to maintain a $\zeta_{crit} = 5\%$. When the value of $K_2$ is varied later during the optimisation runs the $C_2$ value will

change to keep the value of $\zeta_{crit} = 5\%$. $C_3$ is the damping term when the barge has contact with the topside and is in slip condition, and has a value of $10^6 (Ns/m)$. It is important to notice that the values of $K_2$,$C_2$ and $C_3$ are not dependant on the normal force on the interface. The values for $\mu_{static}$ and $\mu_{kinetic}$ are taken for steel to steel contact [2]. These values are used for the base case. In the next section the movement of the barge and the corresponding forces will be shown.

## 6.3. Base case

The position $u_1$ and the velocity $v_1$ of the mass and the position of the second point of interest $u_2$ and its velocity $v_2$ is plotted in 6.6. The corresponding force balance can be seen in 6.7.


Figure 6.6: Base case movement


Figure 6.7: Base case force balance

The phases described in 2.2 can be seen seen in these plots. The movement and forces in each phase for the base case will be given below.

- Moored barge beneath topside 6.3.1
- Initial contact phase 6.3.2
- Compressed phase 6.3.3

### 6.3.1. Moored barge beneath topside

In this phase the barge is moored beneath the topside. The barge is deballasted, the interface on the barge has not touched the topside yet. First and second order motions are clearly visible in 6.8 [10].


Figure 6.8: Base case: Moored barge beneath topside, movement


Figure 6.9: Base case: Moored barge beneath topside, forces

### 6.3.2. Initial contact phase

[redacted]


Figure 6.10: Base case: initial contact, movement


Figure 6.11: Base case: initial contact, forces


Figure 6.12: Base case: initial contact, movement


Figure 6.13: Base case: initial contact, forces

### 6.3.3. Compressed phase

During this phase the barge is in constant contact with the topside. The normal force keeps increasing as the barge is deballasted. As the normal force increases, $F_{Crit}^{static}$ increases, which can be seen in 6.16. The force acting on the friction element reaches the threshold less frequently in this phase as time passes. Image 6.14 shows the distance covered by the barge. The velocity of the barge is shown in the top right corner, and the bottom right corner shows the velocity of the top of the fender. When the barge is in stick condition, $v_2 = 0(m/s)$. In the 500 seconds of the compressed phase the barge has a crawling distance of $\Delta x = 0.30m$. after this period of time the barge has found its final position at $x = -1.20m$.


Figure 6.14: Base case: Compressed, movement


Figure 6.15: Base case: Compressed, forces

Figure 6.17 shows 50 seconds of the forces, and the barge goes from stick to slip 3 times in these 50 seconds. Small oscillations in the velocity of the barge can be seen, which happen due to the horizontal stiffness in the fender element.


Figure 6.16: Base case: Compressed , movement


Figure 6.17: Base case: Compressed, forces

The force acting on the friction element, $F_{fric}^{Applied}$ is shown in figure 6.17 by the cyan line. When the barge is in stick condition it can be observed this line follows the dark blue line, representing the external wave force $F_{External}(t)$. The fender has a horizontal stiffness term $K_2$

and damping $C_2$ which cause the oscillating behaviour of the applied friction force around the external wave force. When the $F_{fric}^{Applied}$ exceeds $F_{crit}^{static}$ the barge goes from stick to slip. The damping and stiffness term in the fender are important since they influence the oscillating behaviour of the applied friction force around the external wave force acting on the barge.

### 6.3.4. Conclusions base case

Conclusions can be drawn from the base case run:

- During the moored phase the barge has first and second order motions in the x direction, and a positive mean displacement due to the second order mean drift forces
- In the initial contact phase crawling motion in the negative x direction is visible. A coupling between the wave force in x direction and fender compression in z direction initiates crawling behaviour. The motion in positive x direction encounters more friction forces than the motion in negative x direction
- During the compressed phase a small positive crawling behaviour of $\Delta x = 0.30m$ is visible.
- Of all 3 stages the initial contact phase has the biggest influence on the crawling behaviour of the barge in the base case run
- The crawling behaviour during the compressed phase looks less unidirectional than in the initial contact phase

## 6.4. Optimization Parameters

5 parameters have been adjusted in optimisation runs to check the influence on the crawling behaviour of the barge.

1. Horizontal damping term while slipping $C_3$ (section:6.4.1)
2. Horizontal interface stiffness $K_2$ (section:6.4.2)
3. Static friction: Kinetic friction ratio $\mu_{static} : \mu_{kinetic}$ (section:6.4.3)
4. Deballast velocity $V_{Deb}$ (section:6.4.4)
5. Vertical interface stiffness $K_{vertical}$ (section:6.4.5)

For each parameter the influence on the crawling behaviour of the barge has been investigated. In the following sections they will be shown. For each parameters zoomed plots of interesting regions will be given. These regions can differ per parameter or parameter value.

### 6.4.1. Horizontal damping term while slipping $C_3$

4 values for $C_3$ have been used for analysis:

- $C_3 = 0(Ns/m)$
- $C_3 = 10^6(Ns/m)$
- $C_3 = 10^8(Ns/m)$
- $C_3 = 10^10(Ns/m)$

The influence of $C_3$ on the crawling behaviour of the barge is plotted in 6.18.


Figure 6.18: Horizontal damping term $C_3$

The crawling distance decreases when damping is applied. This can be seen when comparing the $C_3 = 0(Ns/m)$ and $C_3 = 10^6(Ns/m)$ runs. During the initial contact phase, between $t = 600s$ and $t = 1000s$ it can be observed that for high values for, $C_3 = 10^8(Ns/m)$ and $C_3 = 10^10(Ns/m)$, the barge moves in positive x direction. Too high values for $C_3$ disturb the force balance and results in non realistic crawling behaviour. When the damping term $C_3$ is taken too high, the model shows unrealistic crawling behaviour, due to high peaks in the force balance. Zoomed position and force plots will be shown below in figures **??**, **??**, **??** and **??**.

### 6.4.2. Horizontal fender stiffness $K_2$

- $K_2 = 5.6 * 10^6 (N/m)$
- $K_2 = 5.6 * 10^7 (N/m)$
- $K_2 = 5.6 * 10^8 (N/m)$


Figure 6.19: Horizontal stiffness term $K_2$

The above figure 6.19 shows the crawling behaviour for 3 values of $K_2$. The value of $K_2$ is important for the crawling behaviour of the barge.

During the initial contact phase large differences can be observed between the 3 runs with different values for $K_2$. The barge with the lowest value for $K_2 = 5.6 * 10^6 (N/m)$ shows little crawling behaviour. This can be explained by the fact that the friction forces are acting on top of the interface. With a low horizontal stiffness in the interface, the barge is only influenced a little by the friction forces applied on the interface. The largest crawling distance is found with $K_2 = 5.6 * 10^7 (N/m)$. Increasing the stiffness further $K_2 = 5.6 * 10^8 (N/m)$ reduces the crawling distance of the barge. An explanation for this behaviour can be found in the plots zooming in on a shorter time window figures **??**, **??**, **??** and **??**. The force and position plots for the $K_2 = 5.6 * 10^7 (N/m)$ and $K_2 = 5.6 * 10^8 (N/m)$ give an insight in difference in crawling distance. In all 3 of the runs the barge moves in negative x direction because more friction force is applied to the barge when moving in positive x direction. From these 3 runs the $K_2 = 5.6 * 10^7 (N/m)$ run experiences least amount of friction force is given when the barge moves in negative x direction. Therefore the crawling distance is largest in this run. Changing the horizontal stiffness changes the coupling which is observed between the vertical fender compression due to movements of the barge and the horizontal motion of the barge.

During the compressed interface phase the 2 highest values for the horizontal stiffness the barge shows crawling behaviour. For the $K_2 = 5.6 * 10^6 (N/m)$ the barge doest not crawl beneath the topside. For the other 2 runs, $K_2 = 5.6 * 10^7 (N/m)$ and $K_2 = 5.6 * 10^8 (N/m)$ the crawling behaviour observed is little.

When $t > 1500s$ the top of the interface is in stick condition for all 3 values of $K_2$. With $K_2 = 5.6 * 10^6 (N/m)$ the motion of the barge can be explained by the low stiffness. For the highest stiffness small horizontal motions can be observed. The $K_2 = 5.6 * 10^7 (N/m)$ shows interesting behaviour in this phase. When the topside of the barge is in stick condition with the topside, the barge reaches velocities of $v = \pm 0.20 m/s$. Figures **??** and **??** show the forces in this phase. In **??** the stiffness allows external wave forces to excite the motions of the barge. In **??** these excitations are not observed.

### 6.4.3. Static friction Kinetic friction ratio

- $\mu_{static} = 0.7$ $\mu_{kinetic} = 0.4$
- $\mu_{static} = 0.4$ $\mu_{kinetic} = 0.2$
- $\mu_{static} = 0.2$ $\mu_{kinetic} = 0.04$

The crawling distance for 3 runs with different static and kinetic friction coefficients are plotted in 6.20. It can be observed that the lower the values for $\mu$ are, the longer it will take before the barge is in stick condition. With a lower value for $\mu$ the amplitude of the oscillations in $F_{crit}^{static}$ will be lower as well. The coupling between the external for in x direction $F_{ext}(t)$ and normal force $F_N(t)$, which has been observed in 6.3.2 and 6.3.3 will therefore also be less.


Figure 6.20: Static friction: Kinetic friction ratio $\mu_{static} : \mu_{kinetic}$

### 6.4.4. Deballast velocity $V_{Deb}$

3 different deballasting velocities have been analysed.

- $V_{Deb} = 10.000(mT/hour)$
- $V_{Deb} = 20.000(mT/hour)$
- $V_{Deb} = 50.000(mT/hour)$

The crawling behaviour of these 3 runs is plotted below in 6.21. The deballasting velocity for the base case is $V_{Deb} = 20.000(mT/h)$. When the deballast speed is increased, the initial contact phase and compressed phase will be shorter. The barge will faster be in stick position. From the optimisation runs can be observed that in this model all 3 runs show crawling behaviour in the negative x direction. Increasing the static and kinetic friction coefficients reduces the 2 phases in which crawling behaviour is experienced, and therefore reduce crawling behaviour.


Figure 6.21: Deballast velocity $V_{Deb}$


Figure 6.22: Deballast velocity $V_{Deb}$

### 6.4.5. The vertical fender stiffness $K_{Vert}$

3 different values for the vertical fender stiffness $K_{Vert}$ have been analysed.

- $K_{Vert} = 10.000(mT/0.5m)$
- $K_{Vert} = 20.000(mT/0.5m)$
- $K_{Vert} = 40.000(mT/0.5m)$

An increase in the vertical fender stiffness of the fender reduces the heave motion of the barge. In the force plot **??**, **??** and **??** the difference in crawling distance can be seen. In these 3 plots the time window of $t = 50s$ is shown in which the barge crawls the most in negative x direction. When $K_{vert} = 20.000(mT/0.5m)$ this distance is the most, and the peaks of the $F_{Fric}^{Applied}$ align with the peaks of the $F_{Crit}^{static}$. In the bottom right corner of **??** the velocity of the top of the fender is plotted. Every time the barge starts moving in positive x direction, there fender gets compressed and the top of the fender sticks to the topside. The movement of the barge in the postive x direction is slowed, while the movement of the barge in negative x direction is not. This behaviour was also seen in the base case. The coupling between the fender compression and movement of the barge is dependant on the vertical fender stiffness $K_{Vert}$, and therefore influences the crawling behaviour of the barge.


Figure 6.23: Vertical fender stiffness $K_{Vertical}$

# 7 Conclusions and Recommendations

**Conclusions**
A model is build to investigate the crawling behaviour of a barge. The barge is being pressed against a topside while being subjected to wave forces. Multiple simulations are made, with varying parameters, in order to get a better understanding of their influence on the crawling behaviour of the barge.

Crawling behaviour was found in 2 phases. The initial contact phase, where the barge makes alternately contact with the topside, and the the compressed interface phase, where the barge makes constant contact with the topside. A wave travels in positive x direction and hits the barge. The initial contact phase has the biggest influence on crawling behaviour. during this phase the barge moves in negative x direction. It can be observed that the friction force is applied more often to the system when the barge is moving in positive x direction. This shows a coupling between the fender compression in z direction, and the motions of the barge in x direction. When the barge is in the compressed interface phase, the barge crawls both in positive and negative x direction. After these 2 phases the barge sticks onto the topside due to friction forces acting on the interface. An investigation on the influence of 5 parameters on the crawling behaviour is performed. The aim of this thesis is to improve the understanding of the crawling behaviour of a barge in a friction based reverse float-over operation. The main conclusions are listed below.

- [redacted]
- [redacted]
- [redacted]
- [redacted]

[redacted]

**Recommendations**

This model is constructed to improve the understanding of stick slip behaviour of a barge beneath a topside. A simplified model is constructed from which conclusions can be drawn. Improvements can be made to this model to make it more realistic. Recommendations for further research are given below:

- The terms $K_2$, $C_2$ and $C_3$ are independent of the normal force in the interface. Making these terms dependant on the normal force will improve the reliability of the model.
- Reduce the value $K_2$. This value was constructed by using data from a deck support unit, which is a stabbing cone, and can therefore be expected to have a significantly higher horizontal stiffness than an interface without stabbing cones.
- Further research can be done on the coupling between the horizontal and vertical motion of the barge.
- Wave parameters such as direction, period and height can be varied.
- Stick condition between the barge and topside happens purely due to friction. In further research other methods or combinations with other lock in mechanisms can be investigated.
- This model uses surge and heave motions of the barge. The model can be expanded to 6 dof's and used in other software models for friction force calculations.

# A

# State space notation

# B

# Optimisation run plots

# List of Figures

# Bibliography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