
# A BARGE INTEGRATED TOPSIDES JACKING SYSTEM

A barge integrated topside jacking system

By

K.A. Haring

in partial fulfilment of the requirements for the degree of

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Student number: 4867955

Thesis committee:

| | | |
|---|---|---|
| Dr. Ir. J.O. Colomes Gene, | Chair | TU Delft |
| Ir. J.S. Hoving | Chair | TU Delft |
| Ing P. Geene, | Supervisor | Heerema Marine Contractors |
| Ir. F.C. Lange, | Supervisor | TU Delft |

**PREFACE**

This thesis is submitted in partial fulfilment of the requirements for the master's degree in Hydraulic Engineering at Delft University of Technology. I was given the opportunity by Heerema to research a novel float-over method for installing offshore substations in the near future.

The concept provided by Heerema was in its very early stages, which granted me significant freedom in design and analysis. As a civil engineer eager to expand my knowledge, I focused more on the marine engineering aspects of the concept.

I would like to express my gratitude to my company supervisor, Paul Geene, for guiding me throughout the thesis-writing process and pushing me to do my best. His critical and technical expertise helped me view things from different perspectives and critically analyse my results. I would also like to acknowledge my university supervisors, Frank Lange, Oriol Colomes and Jeroen Hoving for their supervision and critical view on my work.

I am grateful to my colleagues in the decommissioning department of Heerema for their support, motivation, and encouragement during challenging times. Especially my colleagues from the Dunlin project team, if it weren't for them, I might never have started my Master's program; their support prevented me from making one of the biggest mistakes of my life.
This thesis has significantly increased my knowledge of the offshore industry and challenged me to improve my weaknesses.

Finally, and most importantly, I want to thank my family and friends for their unwavering support throughout my entire academic career.

K.A. Haring

Zegveld, July 2024

**ABSTRACT**
This thesis is a about a novel float-over concept for the installation of offshore substations in the Dutch North Sea. This new technology is a topside jacking system integrated into the H-851 float-over barge which should be able to jack the topside to a higher elevation before a float-over installation.

First, a high-level concept design of the novel float-over technology is presented. Thereafter, the stability for the jacking stage is investigated via hand calculations. Analytical models are developed to model the jacking system during select stages of the float-over and jacking of the topside. These models are used to verify the assumed design loads on the jacking system and other components required to install the offshore substation. As of now, the design loads are based on guideline for a different type of float over making the design loads a guestimate.

The float-over barge H-851 proved to be very stable without ballasting during the jacking of the topside. Initial ballast errors did not affect the barges stability significantly, the effect was only a 30% increase in heeling angle for the worst case. The effect for wind loading was more profound as the heeling angle increased with 100%. Due to the large initial stability of the barge, the heeling angle after jacking is still of no concern. For the investigated cases, however, care should be taken to ballasting the barge before jacking as initial errors become larger after jacking.

It was found that the driving systems for the jackings system can be designed in the global horizontal direction using less than 5% of the topside weight, given the sea states in this thesis. A lower stiffness jacking system resulted in lower horizontal loads on the driving system. The jacking system showed a difference in local horizontal loads over the jacks from stern to bow as great as 150%. This is due to the position of the topside with respect to the centre of the barge and in combination with the roll, pitch and heave behaviour of the barge and topside.

The mating analysis had multiple findings. It was found that the impact loads on the LMU's were significantly lower by using the jacking system compared to the DSF for North Sea waves. However, the effect of the horizontal load (compression force) was less significant which resulted in lower or equal loads on the LMU's. The horizontal loads at the interface between topside and barge were larger for a jacking system compared to a DSF.

Increasing the stiffness of the jacking system resulted in an increase of loads on the jacks and LMU's. This was found due to the lower eigen period in the dominant motion for stiffer jacks. An interesting finding is a torsion moment with its centre at the interface between barge and topsides. This point was found to be dependent on the stiffness of the interface.

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**NOMENCLATURE**

| | |
|---|---|
| ASTS | After steel to steel |
| BSTS | Before steel to steel |
| CoG | Centre of Gravity |
| DSU | Deck support Unit |
| DSF | Deck support frame |
| HMC | Heerema Marine Contractors |
| HTV | Heavy Transport Vessel |
| LMU | Leg Mating Unit |
| LSF | Loadout support Frame (equal to DSF) |
| mT | Metric tonne |

# 1.0 INTRODUCTION

The offshore wind industry is rapidly developing towards higher capacity wind turbines and thus generating more electricity, in order to transport the electricity towards the shore, substations are used. The trend towards larger substations is exemplified by the introduction of new high-capacity offshore platforms. These platforms are designed to convert the electricity generated by wind parks from AC to DC. To support this trend, installation contractors are employing vessels and barges for the installation of the jackets and topsides of these heavy substations. Heerema plans to use the SSCV Sleipnir and their largest float-over barge, the H-851, for these installations.

## 1.1 Design objective

Heerema initiated a study towards an alternative float-over technology for the installation of the offshore substations in the North Sea. The current method for the installation of heavy substations involves a stern load-out, followed by jacking the topside with land-based equipment on the float-over barge. Thereafter, the topside is lowered onto a deck support frame(DSF) whereafter the deck support frame is skidded to the bow.

The proposed alternative is as follows: By using existing technologies found in jack-up vessels and land-based jacking equipment, a jacking system would be built into the H-851 float-over barge. By using proven technology, the system can be relatively simple and reliable. The concept can be seen as a jack-up vessel upside down but then with more legs/columns. The jacks will have to fit between the frames of the H-851 to avoid large modifications to the H-851. The jacks are thus limited in diameter. The system will be removable from the barge when it is not needed. The design is intended to give more flexibility, less dependency on external contractors, thus saving money and creating a value adding asset.

The barge integrated topside jacking system will eliminate jacking before transport. Using the new concept, the topside can be skidded directly to the bow and when a favourable weather window is available, sail out to the float-over location with the topside at a low elevation. At site, the jacking systems raises the topside to the desired height and the float-over is performed. Furthermore, the jacking system in the H-851 will create a possibility to investigate a direct bow loadout onto the H-851, because it does not need the deck space on the stern which is currently reserved to be used for jacking purposes.

**Motivation**

Jacking of the 32.000mT topside on the barge by an external contractor and the construction cost of the DSF are expensive operations. Additionally, the DSF has to be skidded under the elevated topside. This brings additional costs and is time consuming. After the topside is placed on top of the DSF the equipment must be demobilised. The topside and DSF have to be skidded back in place and the connection between the DSF, topside and barge has to be made(seafastening).  If one could replace the jacking operation, skidding and construction of the DSF a substantial reduction in cost and time could be made. Because the framework consists of a minimum of five topside which are not identical, the DSF has to be changed for every installation. Furthermore, the money spent on the DSF, skidding, and jacking operations are sunken costs.

## 1.2 Problem statement

An integrated jacking system in a barge has not existed before and no research on the matter could be found which could be directly applicable to this specific case. The jacking system is intended to be built using proven technology, therefore the system itself does not need to be investigated. However the combination of all the proven technology is not done before and thus its behaviour is unknown and has to be investigated in this thesis. The risk of using the wrong design loads is present as they are from a different float-over technology. The jacking system with many legs without bracing is relatively flexible compared to the DSF and a float-over using this technology has not been implemented or investigated yet. This means that the loads of the entire system are unknown during the mating operation. Furthermore, the lower stiffness of the jacks compared to the DSF is an unknown.

## 1.3 Research questions and sub questions

The thesis started with a design objective to investigate an alternative float-over method. It is essential to know what makes this method different and if an alternative method would be useful. Based on this thoughts, the following main research question has been defined:

*How does the jacking system influence the float-over operation ?*

Alongside the main research question, the following sub-questions have been defined to delve deeper into the topic:

- What happens during the jacking stage to the barge's stability?
- Can the design loads of the jacking system be determined through a simple model?
- How does the horizontal stiffness of the jacking system influence the loads during the mating operation?
- What is the difference between the float-over with a DSF and with the jacking system?

## 1.4 Methodology

The research questions have been derived by the following methodology:
A literature study towards float-over installations and its components is performed. Thereafter jacking systems from the offshore and onshore industry are investigated.

Based on the results from this literature study, three concepts have been developed on a high-level basis. These concepts form the basis of the jacking system design which is the main topic of the thesis. The concepts include the driving and locking mechanism of the jacks, the rough dimensions and strength of the jacks are determined and most importantly the stiffness of the jacks is calculated. This design raised additional questions which followed into the research questions defined in the section above.

The stability of the barge is investigated by hand calculations which provided insight. The concern being if stability was an issue due to the jacking system or if it is was of no concern. A sidestep of this phase is looking into whether ballasting during the jacking operation is required. Furthermore, the wind loading is a topic that is addressed. An interesting unknown is how close the natural roll period of the barge is to the peak period of the wave spectrum.

To get an understanding on how the horizontal stiffness of the jacks influences the loads on the jacks. A simple model has been created for a frequency domain solution and a simple time domain solution. The calculation and visualization of these models is done in Python. The input values of the model have been determined or calculated parallel to the setup of the model.

A model for the jacking stage is created in the frequency domain solver Liftdyn to investigate the response of the barge topside before the float-over. This should give an insight into the motions of the system depending on the stiffness of the jacking system and topside weight. This model is expanded to estimate the impact loads on the LMU during the first stage of float-over. Thereafter, it is changed to get the loads on the LMU and jacking system during the final stage of the float-over.

The model for the first stage of the float-over (before steel to steel) has been recreated into a time domain model to accurately generate the loads on the LMU and the interface between the topside and barge. Here it should become clear whether the loads on the LMU are within the design criteria and whether the horizontal loading on the jacking system is in line with the initial design criteria.

## 2.0 FLOAT-OVER INSTALLATION

This thesis will focus on a topside installation with the H-851 float-over barge of Heerema.
The float-over installation method has been around for a long time (Seij, 2007). However, this time it will be done differently. The substation will arrive in the Netherlands on a HTV (Heavy Transport Vessel), first must be loaded out onto the H-851 float-over barge and finally be jacked-up and is placed on a DSF. Heerema has the idea to eliminate the land-based jacking system and the DSF, by replacing them with a jacking system which is integrated into the H-851 barge.

The jacking system integrated into the H-851 will be used for the float-over installation, therefore it is key to have a clear view of the float-over operation and its components. Float-overs have been performed for more than 30 years and the number of float-overs per year is increasing as the demand for heavier topside increases (Seij, 2007).

In this section the typical float-over steps and components that are important for the operation are discussed and explained. Next to that, the relevant studies that have been done are analysed. Furthermore, proven float-over technologies are described and the conceptual float-over installation techniques that are described in the literature are investigated.

### 2.1 Float-over stages

A float-over installation can be divided into multiple stages. This section will describe the float-over stages applicable for the topside float-over without the use of the integrated jacking system in the H-851.

- Transport to the Netherlands

As the topside is likely to be manufactured in Asia it has to be transported from the yard in Asia, to the Netherlands. It will be transported on a heavy transport vessel to the port of Rotterdam.

- Floating to floating or loadout

The Heavy Transport Vessel (HTV) will not install the topside as it is planned to be installed by the H-851, therefore the topside must be skidded from the HTV onto to stern of the H-851. On the H-851, it will be skidded to the bow of the H-851, which is the narrowed section of the barge. Before the topside is ready to sail out on the H-851, it must be elevated and placed on a DSF.

The jacking operations starts when the topside is loaded onto the H-851. It needs to be jacked about fifteen meters to create the required installation height. This jacking will be done by a land-based jacking system on the stern of the H-851. After the topside has been raised, the Deck Support Frame (DSF) which is a very stiff steel structure, located on the bow of the H-851 will be skidded to the stern of the H-851 under the raised topside. Next, the topside will be lowered onto the DSF. Finally, the DSF must be skidded back to the stern of the H-851 and sea fastened.

- Transport to the float-over location

The float-over location is close to the port of Rotterdam and thus the H-851 will perform the ballast operations inshore and wait in the port until the weather window is suitable for the critical float-over installation.

- Preparations and jacking

Once the barge is on location, it will be connected to the pre-laid anchors and the sea fastening connecting the topside to the barge will be cut.

If the jacking system is used, an additional step will be added to the process and therefore increases the offshore time. Then, after the sea fasting has been cut, the topside will be jacked to the desired height using the integrated jacking system.

- Docking in the float-over slot

The docking phase starts by slowly moving the barge towards the slot in the jacket by using the winches on the barge.

- Mating (float-over installation)

The mating stage is the phase where the topside is lowered onto the jacket. The lowering of the topside will be done by increasing the draft of the barge by rapid ballasting. The driving system of the jacking system will not be used for lowering of the topside meaning that procedure of mating is the same as if an DSF is used. The mating phase is generally split into two phases of load transfer. These phases are before steel-to-steel and after steel-to-steel. The before steel-to-steel (BSTS) load transfer has no definite boundaries of percentage in load transfer as literature manages different definitions. However 0 till 49% of load transfer is used in this thesis. The mating starts with first contact between the topside's legs and the LMU in the jacket legs. After first contact the weight of the topside is gradually transferred onto the jacket. Next, is the after steel-to-steel phase with a load transfer of 50 till 100%. Mating is the most critical part of the entire float-over operation, as it can damage the topside supports or the jacket legs.

- Undocking

After the topside is installed, the barge moves out and the mooring lines are being disconnected.

## 2.2 Float-over components

There are many components that influence the cost, operability, and the design conditions of a float-over installation. These components are described in more detail in the following section as they are from the boundaries of the model.

### 2.2.1 Leg mating unit (LMU)

The LMU (Leg Mating Unit) plays a crucial role in float-over operations during the docking/mating phase using conventional methods like HIDECK and UNIDECK. The LMU is located at the top of the jacket leg. It is specifically designed to capture the stabbing cone of the topside leg, as the gap between topside and the jacket reduces. Controlling the position of the float-over vessel and the watch circle of each stabbing cone is vital to prevent disconnection. The LMU not only aids in reducing impact loads and providing flexibility during load transfer but also ensures steel-to-steel contact between topside and jacket legs upon completion. The design involves a sturdy steel housing, piston stroke calculations, and elastomeric components for energy absorption, making it a technically demanding component in installation projects. Typically, LMU designs are made by engineers of the LMU manufacturer rather than installation contractors due to their complexity.

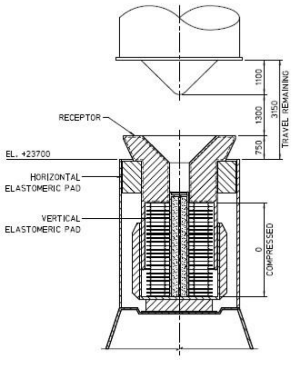


**Figure 2-1 LMU sketch**

The key roles of the LMU are:

- Reduce vertical and lateral impact loads between the topside mating columns and jacket legs at the initial stages of the load transfer in the mating process
- Provide horizontal and vertical flexibility in the connection between jacket legs and the topside during the load transfer at mating stage.
- Ensure the steel-to-steel contact between the topside column flange and the jacket leg at the completion of mating operation.

### 2.2.2 Deck Support Unit (DSU)

The deck support unit is the connection between the topside and the deck support frame (DSF). The DSU is characterized by having a remarkably high vertical stiffness, because it must support the topside weight. It is designed to have no or little horizontal resistance during load transfer. The design of the DSU is not fixed and varies between manufacturers. It is designed to let the topside slide into position during load transfer.

Many papers have been written about the impact loads on the LMU and DSU. (Young Myung Choi, 2014) found that for the stiffer LMU, the impact load is much higher than for a softer LMU and its oscillatory period after the impact is much shorter after first contact.

The maximum horizontal impact load on the LMU occurs during the 0% load transfer according to (Min He, 2011). The maximum vertical load on the LMU will occur during the 100% load transfer. For the DSU its the other way around, having the highest vertical load during 0% load transfer.

### 2.2.3 Deck Support Frame (DSF)

The DSF is a large steel frame with many braces supporting the topside. It is the connection between the barge and the topside. The DSF is only required when a high gap float-over is needed like with a HIDECK float-over which is the most typical type of float over.

### 2.2.4 Fender system

The jacket slot is slightly wider than the width of the barge to create some tolerances. A manner to fill the created gap is to use fenders along the barge and jacket. They are used to mitigate the movement of the barge in surge and sway.

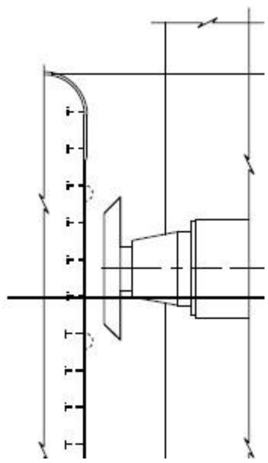

**Figure 2-2 Sketch of a fender**

Surge and sway fenders serve the purpose of absorbing impact loads on the jacket and maintaining the barge's position. Sway fenders are tapered to aid the barge's entry into the jacket slot, as depicted in figure 2-2. Depending on the gap between the barge and jacket legs, either rigid fenders (for narrow gaps) or soft fenders (for wider gaps) can be employed. Designing the fender system requires careful consideration of deformation and energy absorption capabilities. The stiffness of the fender system is generally described by the manufacturer.

### 2.2.5 Docking lines

The float-over barge does not have propulsion of its own in contrary to a HTV (heavy transport vessel) and thus need to be moved into position by a tug or by docking lines connected to pre-laid anchors. The barge is equipped with winches that can move the barge into the jacket slot. A HTV does not always need docking lines as it can use its own engines to keep the vessel in position. (HEAVYLIFT NEWS, 2024)

### 2.2.6 Ballast systems

The H-851 is equipped with 35 ballast tanks which can be filled or emptied with ballast water depending on the situation. These tanks can be simply filled by opening the values and let gravity do its job or by mechanically pumping water into the tanks. The ballast system is used to increase or decrease the draft of the barge to get the desired airgap before mating. Furthermore, over the length of the barge, the ballast system is used to trim the barge. To increase the ballast rate, the rate at which the ballast tanks fill, additional ballast pumps can be placed on deck to pump water into the ballast thanks.

## 2.3 Float-over technologies

Over the past decades many float-over techniques and variations have been used or discussed. This section will give an overview of the existing techniques and the proposed concepts. After each technique is discussed, an overview will be given of their advantages and disadvantages.

The following existing and conceptual float-over techniques are discussed in the next sections.
Existing techniques:

- HIDECK
- UNIDECK
- Smart leg
- Catamaran
- Twin HTV / Barge installation
- Strand jack float-over
- Twin HTV/barge

Concepts:

- Twin marine
- DSIV
- FOHAG
- Forklift

### 2.3.1 Existing techniques

**HIDECK with DSF**

The HIDECK installation method is the oldest method (Seij, 2007) and considered the most conventional. It uses a deck support frame (DSF), sometimes called a loadout support frame (LSF), to create enough clearance between the barge deck and the jacket. A DSF is a very large truss frame which is very stiff and for a 37000mT topside the weight of the DSF is about 8400mT (Heerema archive ). The mating is done by ballasting the barge down to decrease the gap between the jacket LMU and the topside supports until the load of the topside is transferred from the barge to the jacket by ballasting the barge.

**UNIDECK**

The UNIDECK technology is developed and patented by TECHNIP. It uses a single barge to perform the float-over installation. The topside is placed on top of 4 to 8 units illustrated in the figure below. During the mating stage the jacks in the units are lowered to reduce the mating time2, because the gap between the jacket and topside is reduced due to ballasting and lowering of these jacks. Like the HIDECK technique, LMU's are required to reduce the impact loads on the jacket legs. The UNIDECK technique is developed for the West-African swell waves and proven to be effective with many successful topside installations. The reported sea states were Hs=1.5 m with a peak period of 10 seconds or Hs=1.2 m with peak period of 14 seconds for head waves.

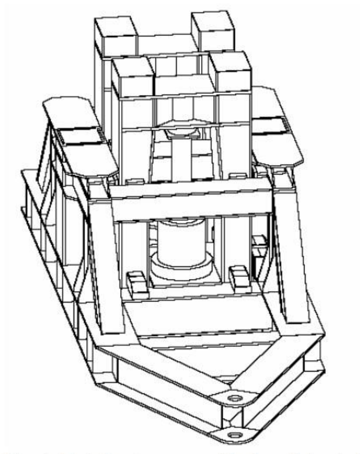

**Figure 2-3 UNIDECK**

*Horizontal loads on the jacks*

The hydraulic jacks are designed to withstand a horizontal load of 10% of the topside weight, however during model tests of (Xiaodong Bai, 2020). It was found that the maximum local horizontal load was about 18% of the topside weight. It was concluded that the suggested load given by DNV was too low for this float-over. As the horizontal loads are dependent on multiple factors which makes it difficult to set-up a design load covering all scenarios of sea states, topside weight, barge dimensions and horizontal stiffness of the interface between barge and topside. This means that attention should be paid to the horizontal design load. To make a concept design of a hydraulic jack, it should be investigated whether the 20% of the topside weight could be used as a horizontal design load. Attention should be paid on how the horizontal design load is defined. The horizontal design load can be defined in the topside CoG (global design load) or at the jacks (local design load).

**Smart-leg**

The smart-leg float-over technology does not require LMUs for mating. It uses the hydraulic rams in the legs and fenders to make smooth contact. Because of the many cylinders, it is a more complicated float-over technique compared to the HIDECK and UNIDECK techniques. It was designed and patented by the French company ETPM in 1993. The technique was intended to be used in relatively harsh weather conditions and long swell waves like there are in West-Africa. The most familiar installation was the EPKE platform installation in Africa.

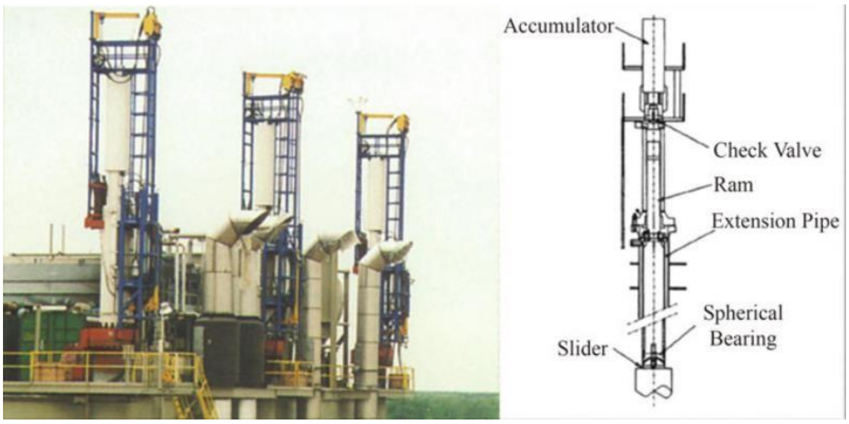


**Figure 2-4 Smart-leg**

**Catamaran (Allseas)**
Utilizing its Dynamic Positioning (DP) system, the vessel aligns itself around the preinstalled jacket. The motion elimination system comes into play, countering the ship's slow longitudinal and faster transverse movements. The vessel is then optimized by ballasting it to the ideal draft for the topside to gently touch down on the jacket. Using hydraulic systems, the topside are smoothly lowered within seconds.

Upon touchdown, the horizontal and vertical motion compensation systems transition to passive mode, allowing the platform structure to guide the topside lift beams' movements. For very lightweight topside, the active system maintains control to minimize forces on the structure.

Gradual ballasting of the vessel follows, transferring the entire topside weight to the jacket. This ballasting phase, which may last about two hours depending on topside weight, continues until the clamps reach a "neutral" elevation. At this point, the clamps can be safely opened, and the beams withdrawn.

Before the clamps are released, the vessel's drives in longitudinal, transverse, and vertical directions compensate for all forces on the clamps. This compensation ensures that when the clamps are opened, they experience minimal remaining force, primarily in the transverse direction. This controlled force guarantees the stationary position of the clamps during opening.

Once the beams are retracted, the vessel is free to withdraw from the site.

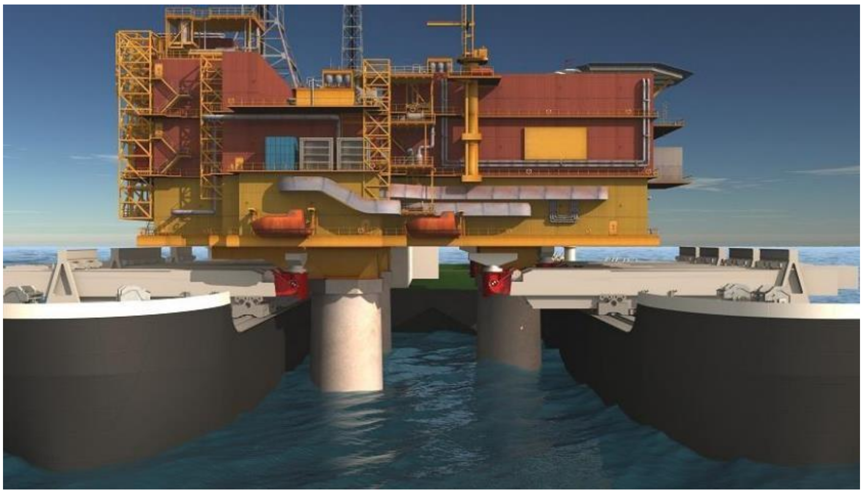

**Figure 2-5 Pioneering spirit**

**Twin HTV / Barge installation**
A twin HTV or twin barge float-over uses a tandem of floating vessels to perform the float-over operation. It can be used with a HIDECK or UNIDECK technology. The twin barge float-over needs a transport barge or a HTV to perform the loading of the barges. The platform below was transported on the White Marlin from South Korea to Stord, Norway. In Norway, the topside is transferred from the HTV onto the sister barges. Where the float-over was performed. It should be noted that this required strict coordination between the dynamic positioning of the two vessels and that the float-over was preformed inshore.


**Figure 2-6 Twin barge float-over (Ace winches, 2023)**

Another type of twin barge float-over is the installation of Ninian central. This float-over was preformed inshore but with the addition of lift towers built onto the barge to raise the topside to the required height as can be seen below.

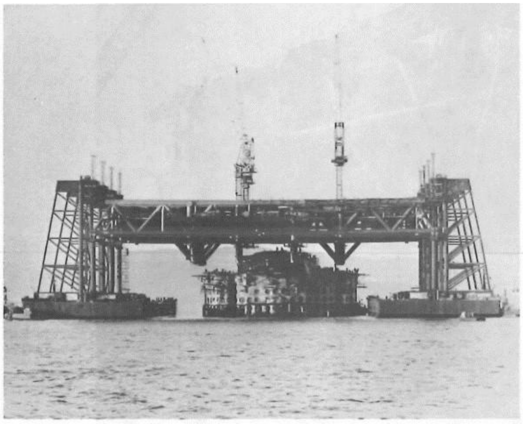

**Figure 2-7 Twin barge float-over (Wortman, 1978)**

**Strand jack float-over**
Another float-over technique that transports the topside on a low height and preforms a low deck float-over. The float-over is performed by lifting the topside of the barge after the topside is docked in the jacked slot. When the topside is raised from the barge until its final elevation the created gap is filled with infill legs. These legs are first welded to the jacked legs where after the topside is lowered onto the legs. This method and the failure that occurred during the installation of the LF7-2 topside is described by (M. Wang, 2018)

The advantage of a low deck float-over with strand jacks to raise the platform to the required airgap, is that less stability is required during transport therefore a narrower and shorter barge can be used. Furthermore, the topside does not require to be lifted onshore on a DSF, saving the production costs of a DSF. It comes with the cost of a longer installation time offshore because offshore welding is required as the connection between the legs and jacket need to be welded.

### 2.3.2 Concepts

As the float-over market is evolving, it drives companies to develop or investigate new float-over technologies that make competitive alternatives compared to the traditional methods. The section below will describe the alternative float-over concepts described in literature.

**TWIN Marine**

The twin marine lift system employs two vessels equipped with lifting arms, allowing them to simultaneously raise the topside. Buoyancy tanks are utilized to generate the necessary lifting force, as depicted in Figure 2-8. The lift operation involves de-ballasting the inner tanks and ballasting the outer tanks (not shown in the figure), creating a lever effect that elevates the topside. This system boasts a lifting capacity of 34,000 metric tons which would be it slightly lower than the largest float-over done by the H-851 float-over barge of Heerema. The installation limits of this method are unknown, because there have not been more publications ever since and thus is the technology still a concept.

**Figure 2-8 Twin marine concept**

**Technip DSIV**

The new float-over technique described by (Jean-Marc Cholley, 2009)is a method for installing production decks onto fixed or floating substructures in deep water. It involves using a specially designed multipurpose vessel, which is a linked catamaran-shaped vessel that can go around the substructure. The deck is then lowered and stabbed onto the substructure using motorized "legs" for weight transfer. This technique is aimed to allow for rapid load transfer even in severe sea states and is aimed to achieve high air gap installations up to 20m. It was believed by the designers that it offers a cost-effective alternative to traditional heavy lift vessel methods and reduces the need for extensive offshore hook-up (Jean-Marc Cholley, 2009).The technique is also intended to topside removals and transoceanic transports, increasing the range of construction yards available. The rated capacity is 20,000 mT with four lift towers, the concept capacity can be uprated to 25,000 mT with six lift towers. The conceptual operational limits can be found in the table below. It is in line with Technips HIDECK technology without the need of a DSF and a jacking system.

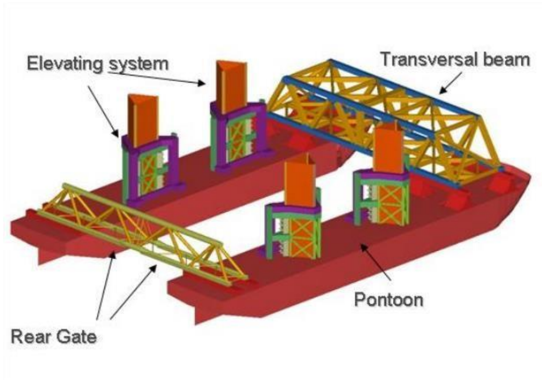


**Figure 2-9 DSIV**

| **20 000T** topside | Tp < 8 s | Tp < 10 s | Tp < 13 s | Tp < 15 s |
|---|---|---|---|---|
| Surge motions (m) | 0.11 | 0.19 | 0.43 | 0.56 |
| Surge accelerations ($m/s^2$) | 0.14 | 0.14 | 0.14 | 0.14 |
| Heave motions (m) | **0.50** | **0.70** | **0.85** | **0.89** |
| Heave accelerations ($m/s^2$) | 0.30 | 0.32 | 0.32 | 0.32 |
| **➔ Allowable Hs (m)** | **1.60 m** | **1.14 m** | **0.94 m** | **0.90 m** |

**Figure 2-10 Proposed operational limits DSIV**

**Float over high air gap (FOHAG)**
The FOHAG concept system is a modular system that can be installed on barges and HTV's. It incorporates a proven rack and pinion components from the established TPG 500 jack-up production platform, deployed in the North Sea and Caspian Sea. The FOHAG system is designed for installing a 20,000 metric tonne deck with a 20-meter air gap.

The system is built up with the following specific elements:
- Transverse beams: These adaptable beams rest on the transport vessel and can adjust to various vessel widths, their quantity dependent on deck weight.
- Jacking systems: Motorized columns with rack plates guiding the installation, positioned at both ends of each transverse beam.
- Motorized columns: Box-shaped, these columns feature a conventional rack plate flange.
- Interface components: Shock pads on the columns absorb impact loads, ensuring stability during the installation phase.
- Hydraulic equipment: Each jacking system is complemented by hydraulic machinery, facilitating precise control.

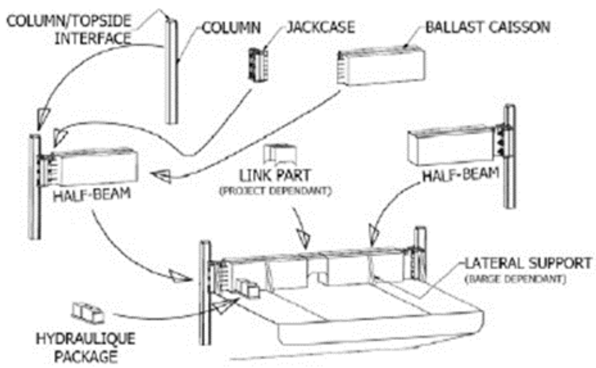


**Figure 2-11 FOHAG main structural parts (Cahay, 2007)**

The installation limits vary between a Hs of 1.75m for waves with a period between 4.5s and 7.5s and a Hs of 1.5m for 7.5s till 10.5s. This is illustrated in Figure 2-12

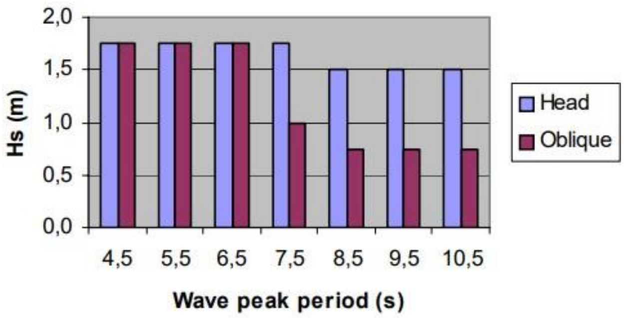


**Figure 2-12 Proposed operational limits FOHAG (Cahay, 2007)**

**Forklift (HMC)**
The forklift concept was developed and investigated by HMC, however is has been abandoned for several years. The concept was as follows: the tilting beams of the H-851 were extended so the topside could be placed on top of the beams and be used for a float-over. Between the modified tilting beams DSU's or jacks of the UNIDECK could be placed to enable installations by higher sea states. The Forklift concept had exciting potential in the topside installation of spars using a vertical coupling system between the H-851 and the spar.

### 2.3.3 Comparison of float-over technologies

After many installation methods have been discussed an overview of techniques will be given after which the relation will be made to the Heerema jacking system.

**Table 2-1 Float-over methods compared**

| Technique | Air gap | LMU (required) | Stability requirement (Transport) | Installation limits | Reference |
|---|---|---|---|---|---|
| Existing | | | | | |
| HIDECK | Large | YES | HIGH | Hs 0.5m and Hs 1.5m | (Heerema archive ) |
| UNIDECK | Small or large | YES | HIGH OR LOW | Hs 1.5m Tp 10s<br>Hs 1.2m Tp 14s | (Yu, 2018) |
| Smart leg | Small | NO | LOW | Hs 1.5 m to 2m | (Gengshen Liu, 2018) |
| Catamaran (Pioneering Spirt) | High | YES | HIGH | Hs 1.5m till 2m (known) | (Allseas, 2023) |
| Twin HTV/BARGE | Small or large | YES | INSHORE ONLY | N.A. | (Boskalis, 2023) |
| Concepts | | | | | |
| Twin marine | Small | | LOW | Unknown | (Gengshen Liu, 2018) |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| DSIV | HIGH | YES | LOW | Hs0.90 till Hs1.6m | (Jean-Marc Cholley, 2009) |
| FOHAG | HIGH | YES | LOW | Hs 1.5m till Hs 1.75 | (Cahay, 2007) |
| Forklift | Medium | YES | LOW | Hs 0.5 till Hs1.5 | (Heerema archive ) |

The North Sea substation installation study requires a high airgap offshore installation. Furthermore, the jacket is designed for a single barge with a width of 42m and the jacket design is fixed. This means that the following methods are not an option, because the jacket or topside is not designed for such installation method. They are summarized below, and an explanation is provided why they are not suitable for the substation installation.

Smart leg: This requires welding cylinders on the topside
Twin barge/ HTV: The float-over is offshore, which is not possible with a twin barge
Twin marine: No information on the concept status
DSIV: The concept is too small to fit around the jacket
FOHAG The jacking system makes the barge wider, because it will be installed to the side shell. This results in the requirement for a smaller barge than the H-851
Forklift The concept is designed for a topside installation of a floating spar and not for a jacket.

This means that the HIDECK and UNIDECK are the only conventional options next to the Heerema jacking system concept. With the jacking system the topside can be transported on a lower elevation above the barge deck in contrary to the HI- and UNIDECK. The advantage of a low deck transport is less sea fastening by the same sea state and a lower stability requirement, because of the smaller height of the topside. As Heerema's intent is to use the HIDECK for the topside installation, only this technique will be compared to the proposed jacking system.

## 2.4 Float-over modelling

All the float-overs that have been modelled use the same approach of combining the barge and DSF into one body and the topside as a separate body. Furthermore, the float-over is split in two or more different models, as the system changes throughout the operation.

The models are generally solved in the time domain, because of the nonlinearities of the for example LMUs and the impact modelling. However (Zhu, 2021) used a different approach by starting in the frequency domain and later made the step towards the time domain.

## 2.5 Motion compensation techniques

A motion compensated float-over system, based on the Appelman platforms, which are well known for its capabilities of compensation movements in the 6 degrees of freedom, has been investigated for a 12000mT topside installation. A study in 2007 showed that an Appelman system and passive hydraulic jacks proved to be technical and financially feasible. However the weight of the studied topside is far lower than the 32000mT topside considered in this thesis (F.W.B. Gerner, 2007). During a later study, a simplified model was built to simulate the motion compensated topside float-over installation. It showed that during load transfer the amplitude of the vertical LMU load halved and the time of slamming reduced by nearly a factor of 6 (Zhou, 2023). The reason that this technique is not in use is because of its complexity. And 12000mT is not a heavy float-over in comparison to the aimed 32000mT substation which makes reducing the vertical loads not financially interesting.

## 2.6 Knowledge gap in literature

Traditionally float-overs have been performed with the HIDECK or UNIDECK techniques in combination with LMUs and DSUs. The DSUs were located on top of the DSF, which is very stiff, in the order of 100,000 mT/m. The difference between the stiffness of the DSF and the jacking system is significant. For the LMUs it is known that, the stiffer the system, the higher the impact load. It can thus be expected that a less stiff system, A jacking system instead of a DSF, will result in lower impact loads on the DSU and or LMU. For this study towards a substation installation it could be interesting to investigate what the effect of the lower horizontal stiffness of the jacking system is on the LMU loads and the interface loads (loads on the jacking system).

## 2.7 Discussion

The literature study towards float-overs focuses on the techniques and components affected by this process. It can be concluded that the jacking system is a combination of HIDECK and UNIDECK float-over techniques, as it involves a high elevation float-over based on ballasting with a soft interface connection between the topsides and barge. This raises uncertainty about whether the design conditions(Section 2.2.2) of either technology can be applied to the jacking system and how other float-over components will be affected by this new concept. Additionally, the sea states in which HIDECK and UNIDECK float-overs are performed are not comparable to the intended sea states for the new concept. The new concept is designed for head waves with a significant wave height (Hs) of 2.4 meters and a peak period (Tp) of 8 seconds, whereas HIDECK data only includes information for an Hs of 1.5 meters given the same direction and wave period (Table 2-1). Therefore, even if the design values from previous float-overs are used, they would not be meaningful, as design loads are heavily dependent on sea states. This means that the horizontal design loads have to be investigated.

## 3.0 JACKING SYSTEMS

The concept of the topside jacking system integrated into the H-851 is inspired by the jacking systems of a jack-up vessel and land-based jacking systems. The jacking system of the barge is supposed to be simple by using existing and proven technology to keep costs down and reliability up while having the advantage of the matured technology. Over the last decades many different jack-up variants have been constructed, all with its advantages and disadvantages. Another type of jacking systems can be found onshore. Jacking operations on land have been performed for many years and various on land jacking systems have been developed by heavy lift companies and its manufacturers.

The following section will describe multiple jack-up systems for vessels and onshore jacking systems followed by a summary and conclusion.

### 3.1 Driving systems offshore

The driving systems of the offshore industry will be described and compared in this section.

#### 3.1.1 Rack and Pinion

The most widely used jacking system is the rack and pinion type, known for its simplicity compared to other systems. It operates with pinions mounted on racks attached to the legs. These pinions are driven by gearboxes and either an electric or hydraulic motor. To reduce costs, the pinions have slightly fewer teeth than the ideal number, resulting in a smaller diameter. Despite this reduction, the teeth must be strengthened due to fluctuating transmission, variations in load sharing and backlash between racks and pinions.

Rack and pinion jacks exists as single rack and double rack models. A single rack runs parallel to the leg centre, applying both vertical and significant horizontal forces on the chords. In contrast, a double rack features two opposing racks on one chord, eliminating horizontal force and loading the leg with purely vertical loads. This design ensures efficient and precise vertical lifting, while minimizing unnecessary lateral stress on the structure

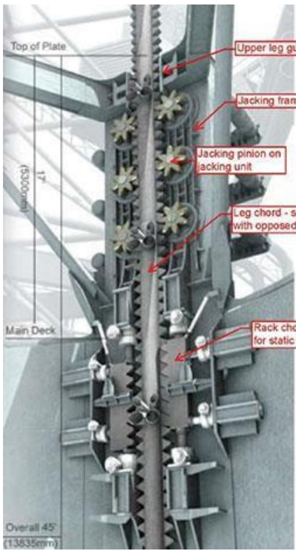


**Figure 3-1 Rack and Pinion system (ABB, 2023)**

### 3.1.2 Jacking cylinders

The jacking cylinder type typically comprises two separate ring structures, each linked to a leg and interconnected by jacking cylinders. The platform or leg movement occur through a repetitive process: first, releasing one ring and extending the cylinders before securing the ring again. Then, releasing the other ring, retracting the cylinders, and fixing this ring back in place. Although the movement is discontinuous, this method generates robust and forceful motion when repeated. The jacking assembly is generally hidden away in the jack house. The jacking cylinders are hydraulically driven. The climbing ring has multiple variants, it can be based on a pin which locks the ring through the leg see the system in as can be seen Figure 3-2 or the leg has rings on which the climbing ring can rest as can be seen in Figure 3-3

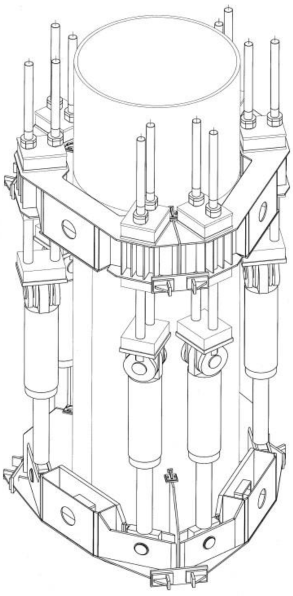

**Figure 3-2 Jacking system for one leg (Bærheim, Manschot, Olsen, & Eide, 1999)**


**Figure 3-3 Ripped jack**

### 3.1.3 Winches

A recent advancement involves utilizing winches to elevate a platform. The Jumping Jack barge built by Mammoet and Van Oord uses a complex winch assembly to elevate the barge. The structure features four boxed legs, each managed by three winches: two for lifting the Jack-up and one for generating counter-tension to raise the legs. These winches are centrally positioned on the platform, and guided by sheaves. The wires are directed to the head or foot of the leg. At opposite sides of the head and foot, there are sheave blocks, each housing eight guide sheaves. The upper sheave blocks at the head have larger diameters to prevent wire contact. The hull contains corresponding sheave blocks with seven guide sheaves each. The wires from the platform lift winches traverse the head of the leg, looping back fifteen times on one side before being guided to the other side. Similarly, the wires of the third winch follow a similar path, (Daily shipping, 2002) but lead to the foot of the leg.

**Figure 3-4 Winched jack (Daily shipping, 2002)**

Pulling the lifting winches results in the platform's upward movement or the legs' descent. Meanwhile, the counter-tension winch maintains tension in the wires to prevent slackness and can lower the platform back into the water. During transit, the legs are secured using sixteen hydraulic cylinders per leg. Four cylinders arranged vertically press the leg corners against the leg guide, creating enough friction to hold the legs securely in place. The 4-legged jumping jack has a deck loading capacity of 4000mT during jacking.

### 3.1.4 Strand jacks lifting

The jacks move along a cable composed of high-tensile strands, locking, and releasing grips (collets) using hydraulic systems. A hydraulic ram moves a locking plate allowing strand passage. Mini jacks engage the collets, mechanically gripping the strands for the next jacking stroke. Separate lifting and lowering jacks is necessary to maintain compression and control the descent rate, with pressure control switches regulating the hydraulic pressure to prevent rapid oil discharge (D.P. Tuturea – Conoco Inc, G.Jackson – Arup Energy, 2002).

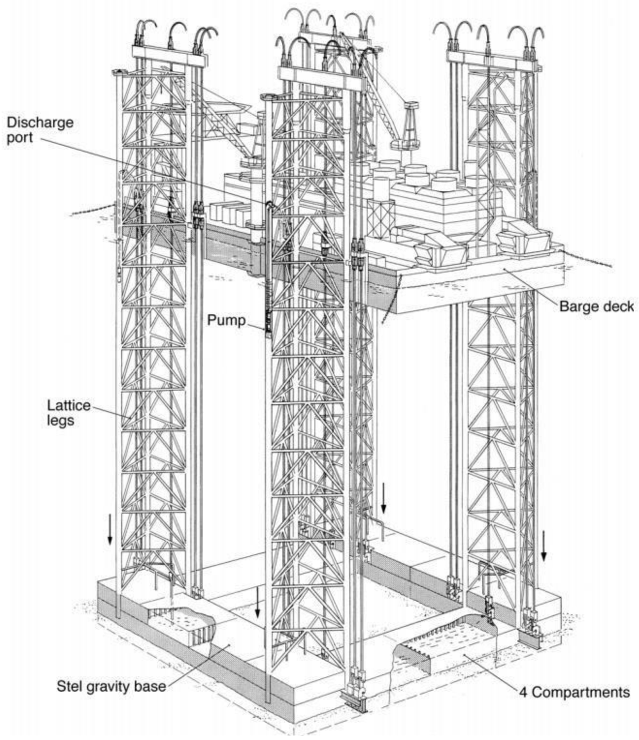


**Figure 3-5 Hang Tuah platform (D.P. Tuturea – Conoco Inc, G.Jackson – Arup Energy, 2002)**

The strand jack lifting is not a favoured technique offshore, since a costly failure has occurred during the installation of the LF7-2 DPP Topside.

## 3.2 Leg type

The jack-up vessels are built with several types of legs and different vessel shapes. The leg types are as follows: Truss frames, tubulars, box, square beams. The advantages and disadvantages are summarized below.

The advantages of a truss frame is that they have a high capacity and effective use of steel, because of the principle of a truss frame. A disadvantage is the complexity in the design and fabrication.

The advantage of round tubulars is the simplicity of the construction. However, the diameter size is limited to the rolling machine.

The advantages of square or rectangular sections depend on the combination of width the jacking system and the dimensions of the legs. As the rectangular sections are welded, the size can thus be bigger than rolled sections, however this increases the production cost. The rectangular sections in combination with the winches have the advantage of having a strong direction of loading and thus reducing the cost of steel.

## 3.3 Overview of Jack-ups

The table below will give an overview of the possible jack and leg combinations. Here the fixations and shock absorption are not explained. The reference vessels help to visualise the jack-up systems investigated in this chapter. The capacity has a broad range from 5mT per leg up till 10000mT per leg. There are many different combinations to end up with the same capacity jack-up, however cost, dimensions and complexity differ.

**Table 3-1 Overview jacking systems**

| Jack-type | Drive system | Leg-type | Fixation | Shock absorption | Capacity | Reference vessel |
|---|---|---|---|---|---|---|
| Rack and Pinion | Electric | Truss | Brake | Rubber pads | Very High | Innovation (DEME) |
| Jacking cylinders | Hydraulic | Cylindrical tubes | Cylinders | Jacking cylinders | Low to high | Volle Au Vent (Jan de Null) |
| Winches | Electric<br>Hydraulic<br>Pneumatic | Square tubes | Pins<br>Crossbar | Hydraulic<br>Nitrogen<br>Specific | Low to Medium | Jumping jack |

## 3.4 Jacking systems on land

The biggest difference between jacking systems offshore and onshore is the jacking height, the modularity and low stability requirements, due to the absence of (barge/vessel) motions. The subsections below will describe the onshore jacking systems.

### 3.4.1 Strand jacks

A strand jack is a hydraulic lifting device used to raise heavy structures, such as bridges and buildings, with precision and control. It operates by gripping a bundle of high-strength steel strands with hydraulic jaws. As the strands are pulled through the jaws, they are tightly gripped, preventing them from slipping back. Hydraulic pressure is then applied, causing the jaws to clamp onto the strands while lifting the load. By alternating the gripping and releasing of the strands in a synchronized manner, the strand jack incrementally lifts the structure. This method provides safe, controlled and synchronized lifting, making it ideal for various construction and engineering applications.

### 3.4.2 Hydraulic jacks

A hydraulic jack works by applying a small force to a small piston, generating pressure in the hydraulic fluid. This pressure is transmitted to a larger piston, amplifying the force to lift heavy loads. By utilizing fluid pressure, hydraulic jacks provide a mechanical advantage, allowing effortless lifting of heavy objects with minimal input force.

Mammoet Push-up
The jacking system designed by Mammoet can be used for jacking and skidding of large and heavy objects. It uses two skid tracks for skidding accompanied by a push pull unit on each skid track. For the jacking operations four hydraulic cylinders are used to jack the topside up. The jack column is a modular design and is therefore made of multiple cans that need to be added to the column after each jacking stroke. The push-up assembly has a capacity of 2400mT (Mammmoet, 2023).

(Zhao, 2012) investigated the technical specifications, credibility and security during the continuous lifting systems which would be the 4000mT version of the Mammoet push-up. Their conclusion was that a jacking height of 10m with 4000mT per jack column is technically feasible.

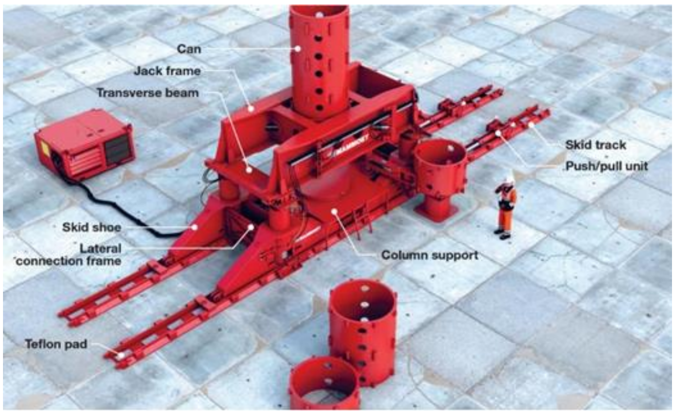


**Figure 3-6 Mammoet jacking system (Mammmoet, 2023)**

Mammoet Mega Jack / Sarens CS5000

These jacking systems are the heaviest available and have a similar design. These are self-climbing towers and are jacked-up by four hydraulic cylinders per tower. After each stroke, another cradle is inserted into the tower increasing its height. The Sarens CS5000 has a capacity of 5000mT and the Mammoet mega jack 5200 has a capacity of 5200mT (Sarens, 2023).


**Figure 3-7 Sarens CS5000 (Sarens, 2023)**

## 3.5 Discussion

The jacking system concept is based on the principle of an inverted jack-up vessel, replacing land-based jacking systems. The literature study focused on jack-up vessel legs and driving systems as well as land-based jacking systems because one is replacing the other. It can be concluded that land-based equipment primarily focuses on vertical capacity, as no useful information was found for horizontal loading. Furthermore, land-based equipment is modular, intended to be moved around the world, meaning it is not suitable for offshore jacking and mating.

In Chapter 2, it became clear that horizontal loading during float-over is as significant a design factor as vertical loading. This means that land-based jacking equipment should not be used for a float-over. While the driving systems and legs of jack-up vessels do not provide information about their horizontal design loads, they are used to elevate vessels weighing over 32,000 metric tons. Jacking of vessels occurs when they are subjected to wind and wave loading. This suggests that the driving systems and legs of offshore vessels could be a viable option for the concept design, given their use case. This means that a concept can be created using the a combination of jack-up vessel driving systems and legs.

## 4.0 CONCEPT DESIGN

In order to answer the research question on how the barge integrated jacking system influences the float-over operation, a concept design has been made. The proposed concept of Heerema was a jacking system that could be integrated into the existing float-over barge H-851. Other requirements where that the barge's frames and bottom should not have to be modified. The jacking system should be made of proven technology to keep it simple and most importantly it should be able to install the 32000mT substation.

After Chapter 3, it became clear that the driving systems and legs of jack-up vessels could form the basis of a jacking system. In Chapter 2, it was concluded that the float-over using a jacking system combines HIDECK and UNIDECK float-over technology. This created uncertainty about the design loads. Additionally, there is a significant difference in horizontal stiffness between a conventional float-over and the concept,  its effect is also unknown. To investigate the stiffness, a design needs to be created, but to make a design, a design load is required. To address this problem, a concept design is made based on existing design loads found in the literature.

### 4.1 Design conditions

The following design choices have been made based on the literature study and requirements from the company:

- The horizontal or lateral loads
- The driving system of the jacks
- The shape of the jacks
- The locking mechanism
- The amount of jacks
- The jacking height
- No modifications to the barge

#### 4.1.1 Environmental conditions

The location and the month in which the float-over installation is executed determines the environmental design conditions. As the jacking system is focused and aimed to be used for an installation of the Dutch coast. The design conditions of the North Sea will be used and not the West African swell waves. African swell waves are considered as a difficult scenario for a float-over installations (Seij, 2007). Furthermore, the installation is planned to be executed in the summer, so the winter months and its weather and waves conditions are not considered.

The choice of return period of the environmental conditions, for which the system is designed is a critical decision in offshore engineering, typically set at either 100 or 10 years. This decision determines whether design is based on restricted or unrestricted weather conditions. In the study by (Morten Bærheim, 1999) incorrect design decisions were highlighted. They opted for restricted weather conditions during installation and transportation, but used a higher sea state for installation compared to transportation, resulting in multiple months of weather-related delays. A key lesson learned is that the topside should be jacked up under the same or higher sea states as during installation. This underscores the importance of aligning the environmental design conditions between the jacking stage and float-over processes with a jacking system.

#### 4.1.2 Topside weight and CoG

The vertical loads on the jacking system are primarily caused by the weight of the topside. In case of a centric CoG and considering a rigid topside, the weight of the topside is evenly distributed over the jacks. However, the topside will have a CoG envelop, this means that it is almost certain that the topside weight will not be evenly distributed over the jacks. Furthermore, the support conditions are statically indeterminate, this will result in different support reactions over the system and thus a higher maximal vertical load in the jack. Overall, this means a higher demanded jacking capacity for the jacking system as it is unknown which side of the system will be loaded more heavily than the other side. A hand calculation of the vertical load distribution over the jacks can be found in attachment one.

#### 4.1.3 Contingency

The failure of the strand jack lifting operation of the LF7-2 DPP topside showed the importance of contingency measures. The designers did not include any contingency measures to address the failure of outer leg lowering system (Wang, 2018). It was concluded that the float-over should be able to continue its operation without complete failure. This was not the case during the LF7-2 installation, because they could not return the topside to shore, nor could they install the topside. Furthermore, they advised a full contingency plan should be prepared in case of a local failure in the system.

#### 4.1.4 Horizontal design load

The horizontal load that the jack must be able to resist is a considerable influence factor. Because of the moment that is caused which be decoupled over the jack's diameter. This differs for the jacking stage and the mating stage as during the jacking stage the decoupled moment has to be taken by the driving system and during mating the decoupled moment will be taken by the locking mechanism.

The horizontal loads during mating are 10% of the topside weight according to the (DNV.GL Noble Denton, 2015). However model tests of (Bai, 2020) showed that the global horizontal load was about 18% of the topside weight. (Bai, 2020) recommended a horizontal design load of 20% of the topside weight. However, these horizontal loads were found by a stiff support frame and with a rapid load transfer float-over. As discussed earlier the horizontal loads are dependent on multiple factors, so care should be taken in choosing a design load. The horizontal loads are heavily dependent on sea states, topside weight, barge size and thus have to be investigated when a concept is developed.

For the jacking stage the wind will cause a horizontal force on the jacks itself and on the topside.

#### 4.1.5 Driving systems

The literature showed four driving systems that could be used for the jacking system. The strand jack system has proven to be difficult in use (Wang, 2018) and with a major installation failure, it will not be used to create a concept. This leaves three driving mechanisms: Rack and pinion, winches, and hydraulic jacks.

Rack and pinion are a proven technology on jack-up vessels, but require additional welding on the tubulars along its entire length. This drastically increases welding costs since the initial concept uses 52 jacks. Winches are proven to work on jack-up vessel, however do not give much stability when used as a jacking system. The stability of the jack must come from the tension in the wires or by friction in the guiding house. The stiffness of the wires is low compared to the other driving systems. Hydraulic jacks are used in jack-up and land-based jacking systems and are a reliable system. The hydraulic jacks must be used in combination with the locking mechanism and thus making the hydraulic jacking system the most efficient.

#### 4.1.6 The shape of the jacks

In the design process of the jacks, several crucial aspects demand careful consideration. Primarily, the strength of the jack must be assured, ensuring it provides the necessary support and stability. Material availability plays a significant role, influencing both feasibility and structural integrity. The chosen materials and construction methods should be durable enough to withstand environmental conditions and potential wear over time. The jacking system is loaded horizontally, and this requires the jack to be strong enough in horizontal direction to deal with a large bending moment.

Truss frames have a high stiffness and can elevate a heavy weight as shown by (Vatsvag, 2009) . In this paper discussed a 3-legged jack up which had a deadweight of 30000mT. However the cord-to-cord distance of the truss frame was about 4m which is too big to fit between the frames of the H851. Because the H-851 has a typical webframe spacing of 2500mm. Furthermore, the construction of a truss frame is labour intensive, since all the joints must be welded and the members must be cut to size.

Tubulars also have a high stiffness, but their strength comes from their diameter. The production of tubulars is relatively cheap, since they do not require extensive welding. The tubulars are a finished product after they leave the steel production facility. There are round and square tubulars that can be used where the round is the most material effective and has the highest torsional stiffness. The round tubulars will be used, because of the effectiveness of material and their strength properties.

### 4.1.7 The locking mechanism

Different options of locking mechanisms are possible as described in chapter 3. The following systems are considered: A pin through the jacks, a friction-based clamp, or a lock on a tooth rack. The locking mechanisms are related to the driving system. Since the application of a jacking system for a float-over is new not all decisions are based on pure calculations, but also on a failsafe system. The pin through the jacks and lock on the tooth are safe systems as they can lock themselves without needing to have a system locking on. The friction clamp is more sensitive to problems as it requires a system to apply a force to generate the friction. The friction of the system can accidently be lowered due to for instance an oil spill resulting in a (large) reduction of friction and thus capacity of the jacking system.

### 4.1.8 The number of jacks

The number of jacks is determined by taking the topside footprint and using that as the boundary of the jacking system in the barge. The locations of the jacks on the barge deck are limited to fit between the frames adjacent to the skid beams. The load per jack is dependent on the number of legs. The load in the jacks is calculated by the bolt theory, as can be seen in attachment one. After iterating with the number of rows and jacks per row, it was determined to use four rows of thirteen jacks. More legs mean a smaller diameter leg and thus a lower required capacity for the driving system. The starting point is that the jacking system covers the same area of the barge as a DSF would have, so in this stage the frames and bulkheads of the barge are not checked. The space between the jacks should be large enough to fit braces and seafastening for the topside during transport.

### 4.1.9 Jacking height

The length of the jacks is limited to the height of the barge and the above deck distance to the topside. It should be noted that the DSU or likewise system must fit between the jacks and the topside. The H-851 has an inside height of 14.8 meters and the topside needs to reach a height of 17.6 meters for this study. For the concept calculation the length of the jack will be 17.6 meters.

## 4.2 Concept 1: Cable, winch and pulley

The first concept is a steel tubular with a winch system as driving mechanism. This is a proven design for lowering and raising of spud piles. As can be seen in chapter 3. The winches require a capacity of 300mT each if a single cable is used. The four winches must be used simultaneously and do not have redundancy in this case this results in a total capacity of 1200mT. The capacity of the winch can be lowered by adding pulleys and using mechanical advantage. The winches lift the jacks via a padeye welded to the side of the jack. The locking mechanism is only used during the float over and not during the jacking phases. The jacking speed can be varied as the winches are hydraulically driven.

The principle of the system is very simple however it requires the entire deck around the jacks. Furthermore, the cable to lift the jack will elongate due to the loading of the jack. As the cables are not equal, length differences could occur during lifting. Using four winches per jack results in a total of 208 winches on the barge deck filling the space between the jacks. The deck of the barge will be completely filled when the generators and hydraulic pumps are added.

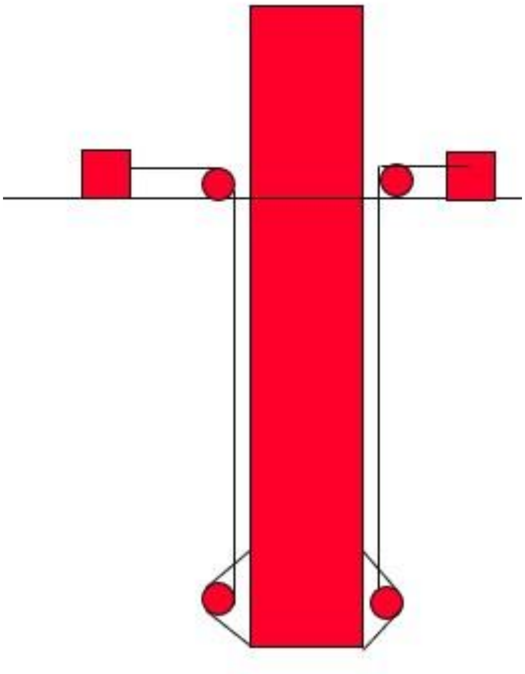

**Figure 4-1 Concept 1 Cable, Winch and Pulley**

## 4.3 Concept 2: Hydraulic jacks

The second concept is a steel tubular with a hydraulic driving system. Based on the patent shown in section 3. It uses 8 hydraulic cylinders to elevate the jacks in cooperation with a hydraulic lock. The jack is supported on four corners around the jack, two on each side on the webframe. The capacity of the driving system is 2450mT meaning that is has twice the required capacity calculated in attachment one. As the jack can be used with only two sides working, the jack has redundancy.

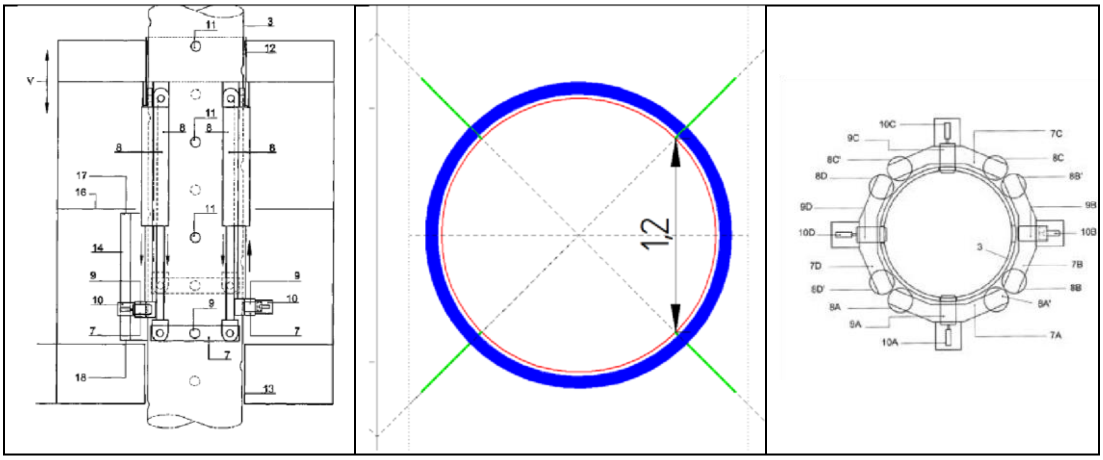

**Figure 4-2 Concept 2 Hydraulic jacks**

The concept is very compact as the driving and locking system is located around the jack itself. Here the space between the jacks can be left empty and the generators and hydraulic pumps can be located at the stern to have sufficient access to the topside.

## 4.4 Concept 3: Rack and pinion

The third concept is a tubular with a rack and pinion system. It will use four motors per side of the jacks, in total twelve per jack. This means that the driving system has a capacity of 2400mT that is twice the needed capacity and thus ensuring redundancy. The locking mechanism can be placed on the motors and the tooth rack resulting in a redundant lock.

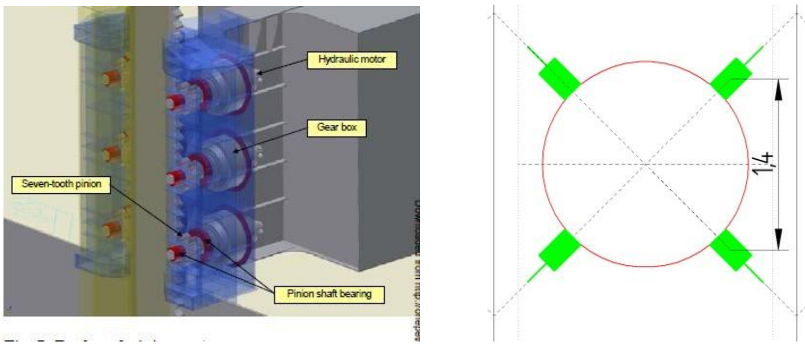


**Figure 4-3 Concept 3 Rack and pinion**

The driving system and locking system is located around the jack and thus safes deck space. However, the housing around the jack will extend about twenty five percent of the space between the jacks.

## 4.5 Final concept

| | Concept one Cable, winch, and pulley | Concept two Hydraulic jacks | Concept three Rack and pinion |
|---|---|---|---|
| Contingency | NO | YES | YES |
| Variable lifting speed | YES | YES | YES |
| Complexity of the driving system | Low | High | Medium |
| Capacity of driving system | Low | High | Very high |
| Deck space required | High | Low | High |
| Motion compensation potential | Little | High | NO |

**Figure 4-4 Comparison of the concepts**

Contingency is important as previously a failure strand jack float-over showed the drastic outcome if it is not present. The total capacity of the driving system should be sufficient for the base case float-over. However, having a high capacity can be favourable in the future as topsides are increasing in weight over time. Having enough fee deck space is essential as the topsides has to be seafastend for transport to the site.

Finaly the choice has been made for concept 2, a round tubular jack able to elevate the topside to 17.6m above the barge deck. It has a diameter of 1700mm and a wall thickness of 50mm. The driving system is driven by hydraulic cylinders. There are four clamps around the jack connected to two cylinders, the clamp has one lock that goes through the jack. The first concept was left out because the capacity was very low compared to the other two concepts. The decision to go for the hydraulic cylinder concept is because the driving system is very compact in comparison to the rack and pinion concept. As the aim is to design a system lower than the skid beams on the barge and little deck space between the jacks is used. The most compact concept wins if other factors are equal. An added advantage is the possibility to incorporate motion compensation, which will however not be investigated in this thesis.

The general properties are summarized below.

**Table 4-1 Overview of jacking system parameters**

| | | |
|---|---|---|
| Jack | | |
| Height | 17.6 | m |
| Diameter | 1700 | mm |
| Wall thickness | 50 | mm |
| Horizontal stiffness | 10,202 | kN/m |
| Vertical stiffness | 3,092,505 | kN/m |
| Horizontal design load Jacks (total) | 20% of topside weight | |
| Horizontal design load driving system (total) | 5% of topside weight | |
| Driving system per jack | Hydraulic | |
| Number of hydraulic cylinders | 8 | |
| Number of locks | 4 | |
| Number of supports | 4 | |

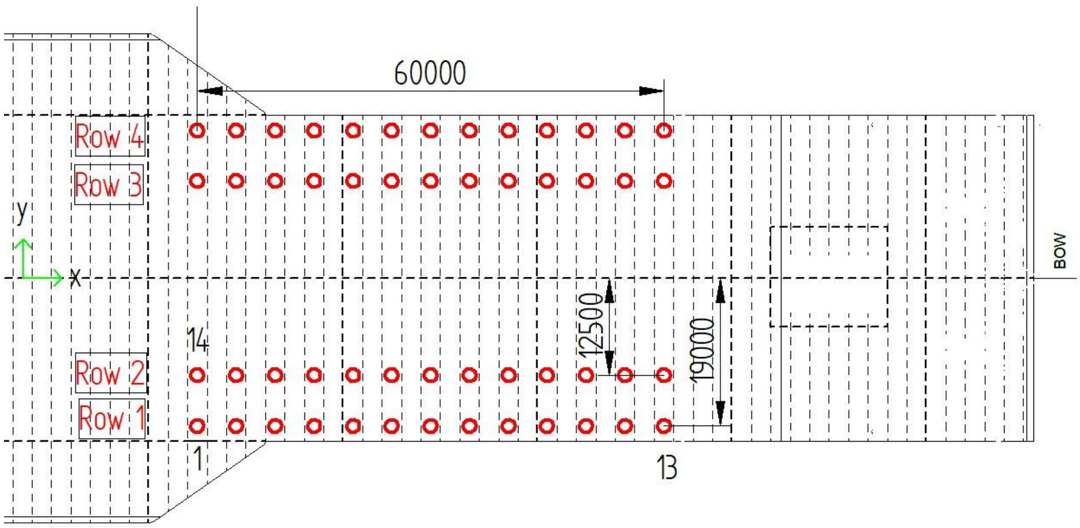


**Figure 4-5 Location of the jacks on the H-851**

The location of the jacks follow from the position of the topside on the barge which is as close to the middle as possible.

## 4.6 Identifying concerns with the concept

The entire float-over is split into various stages with each possibly their own requirements, however these requirements are now based on the conventional float-over technologies HIDECK and UNIDECK described in Chapter 2.3. With a conventional float-over the topside is already at float-over height, whereas a float-over using the barge integrated topside jacking system transports the topside at a lower elevation and the topside will be jacked at sea. The stages of the entire operation can be divided into the transport, the jacking, docking, mating, and undocking stages. The transport stage is not different for the float-over with a barge integrated jacking system compared to the conventional float-over. For this stage, the requirements are well defined and can easily be checked using for instance internal software as the transport phase is a standard. The jacking stage is new and does not have any relevant guidance from the regulatory organisations. The docking, float-over and undocking stage have some guidance, but still limited and requires an analysis.

**Stability**
It is aimed that the barge is ballasted to float-over draft, before the topside is jacked. It should be investigated, if the stability of the barge meet the stability requirements during the jacking phase to verify if the topside can be jacked without ballasting during jacking. The following cases are identified as a stability concern and must be checked.

- The stability could become a problem when the topside is jacked up into the air. This is because the centre of gravity moves up along the Z-axis meaning that the GM decreases. The GM is a measure of stability meaning that the barge has initial stability for a positive GM.
- The overturning arm due to wind loading increases because the topside has a big wind area which will be raised into the air. A sudden drop of wind means a reduction in overturning moment which leads to a heeling angle to the other side.
- An initial degree of heeling could result in a stability problem. Because the eccentricity moves along the fault error. This means that the error will become bigger, as the height increases of the topside.
- The natural periods of the barge topside change during the jacking phase which could have a positive or negative effect on the jacking system loads.

These identified stability concerns are investigated in the next chapter.

**Jacking system instead of a DSF**
When comparing the UNIDECK installation method, the capacity of the driving system is now based on a different float-over technology. The considered loads and the accompanying operational limits may not be applicable to the jacking system. To deliver a concept, these design loads for the driving system must be investigated for North Sea related sea states. Next, to the design loads for driving system, the horizontal loads on the jacks itself must be investigated to check if the jacking system can be used for the float-over or if the concept and or design sea states need to be revised. A jacking system on a barge has not been described in literature, which raises the question on how the jacking system can be modelled.

The jacking system is not the only component in the float over installation. The LMU's also have a limited capacity and thus the effect of the jacking system on the LMU loads must be investigated as well. The difference between the jacking system and the DSF being the difference in horizontal and rotational stiffness.

## 4.7 Discussion

Now that a concept design has been made, the validity of the considered design loads can be checked. Furthermore, the stiffness of the jacking system can now be calculated. The main research question is: How does the jacking system influence the float-over operation? The difference in horizontal stiffness, identified in Chapter 2, can now be investigated since the stiffness is known. Considering the environmental conditions, it was concluded that aligning the jacking and mating phases is essential. This means that the same sea states should be used for both stages. As the concept assumes no intermediate ballasting, the stability will be checked as explained in the next chapter.

## 5.0 STABILITY

A float-over using a barge integrated topside jacking system has not been performed or investigated yet. The barges and topside undergo various stages during the float-over. Starting with the topside on the barge deck followed by the topside at float-over height and finally, the mating of the float-over. It is unknown what the requirements during these stages are, as this float-over technology is new. The stability of the barge changes due to jacking of the topside and ballasting. Following the concerns of Chapter 4, the stability, heeling angle and the natural roll periods of the barge will be investigated in this chapter.

### 5.1 Stability requirements

The following organizations define regulations for stability during transport: IMO, GL Noble Denton, and DNV. The stability will be checked for intact stability, this means that the stability of a vessel in its undamaged condition, typically when it is upright and floating freely in calm water. Intact Stability criteria are checked as per rules based on types of vessels.

The IMO requirements of intact stability and thus used by the DNV are the following.

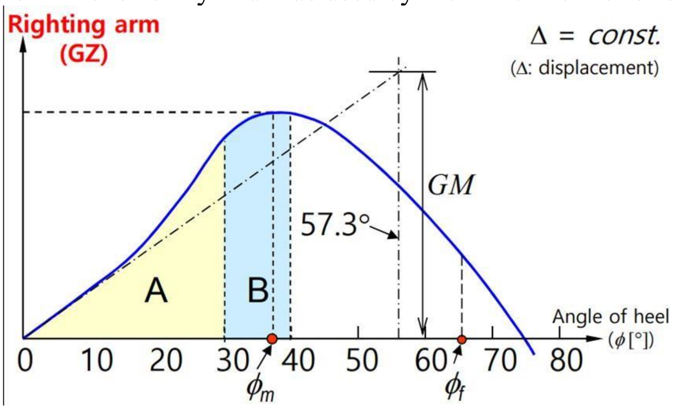


**Figure 5-1 Typical GZ curve example**

(a) Area A ≥ 0.055 (mrad)
(b) Area A + B ≥ 0.09 (mrad)
(c) Area B ≥ 0.030 (mrad)
(d) GZ ≥ 0.20 (m) at an angle of heel equal to or greater than 30□.
(e) Gzmax should occur at an angle of heel equal to or greater than 25□. (f) The initial metacentric height Gmo should not be less than 0.15 (m).

**Stability during installation**

During the float-over Noble Denton gives the following requirements:

Barge stability shall be shown to be adequate throughout the installation operation. Particular attention should be paid to:

Stability checks should be conducted for the full range of probable GM values, module weight and centre of gravity predicted during installation, this must include the effects of deballasting the barge and jacking the module where applicable.

Any installation with a small metacentric height, where an offset centre of gravity (structure) may induce a heel or trim during the ballasting / weight transfer i.e., when any transverse / longitudinal moment ceases to be restrained by the host structure.

Cases where a change of wind velocity or wave direction may cause a significant change of heel and trim during the installation.

During float-over installation it may be necessary to maximize float-over clearance by minimizing the barge draught within stability limitations. For this case only intact stability need be considered with a positive GM not less than the Flag State's minimum requirements.

During positioning of the barge an acceptable criterion for a flat top barge are:
$GM \geq 1.0m$
$f_{min} = 0.3m + 0.5H_s$ = Minimum freeboard

Using Hs = 2.4 results in a required freeboard of 1.5m

**Stability during jacking**
For the float-over, the deck is filled with float-over equipment such as ballast pumps, winches, positioning equipment and the integrated jacking system. To make sure that the barge stability stays within a workability limit, the following requirement is put in place. The barge deck should stay above the water. The sketch below shows that 9 degrees is the limit for the heeling angle before immersion. Additionally, should be checked if the guidance regarding a minimum freeboard is reached according to the DNV. In Figure 5-3 can be seen that the required freeboard of 1.5m results in a maximum heeling angle of 6 degrees which is still large but smaller than the angle of immersion.

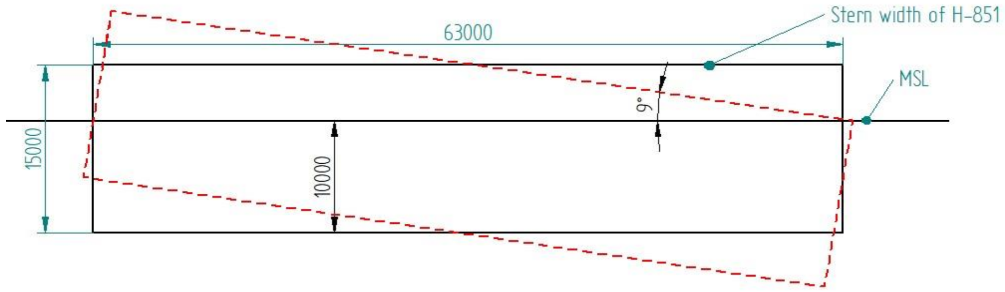


**Figure 5-2 Heeling of H-851 until deck submersion**

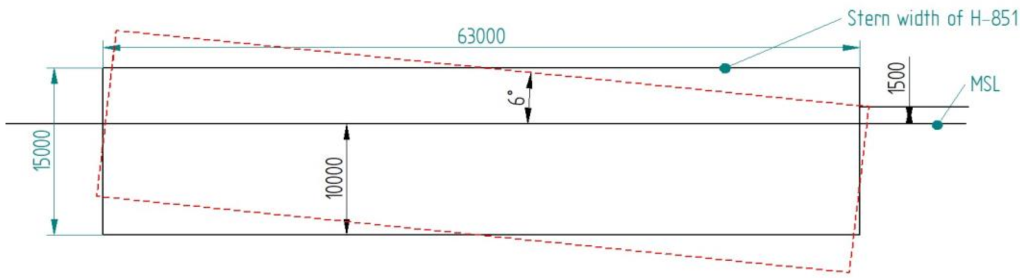


**Figure 5-3 Max heeling with required freeboard**

After listing the requirements for transportation, float-over and jacking we can conclude that the transportation phase is not interesting to investigate because a conventional float-over, transports the topside at a high elevation, while now the topside is transported on the skidbeams. The jacking stage is the interesting one because after each jack stroke, the characteristics of the system change. The float-over is only considered possible when the jacking stage meets the set criteria by the DNV.

## 5.2 Boundary conditions

To investigate the identified concerns, the barge shape and properties have been estimated. The barge is simplified to two squares without curves. This should be acceptable for a study and will be reflected on in the chapter's conclusion.

For the hand calculation the following properties are used, which are taken form the stability booklet of the H-851.

**Table 5-1 H-851 properties**

| Barge | H-851 | Unit |
|---|---|---|
| Light weight mass barge | 38273 | mT |
| Length | 260 | m |
| Beam | 42 at bow, 63 at stern | m |
| Depth | 15 | m |
| VcoG | 8.76 | m |
| Wetted area | 14154 | $m^2$ |
| It | $3.86 * 10^6$ | $m^4$ |

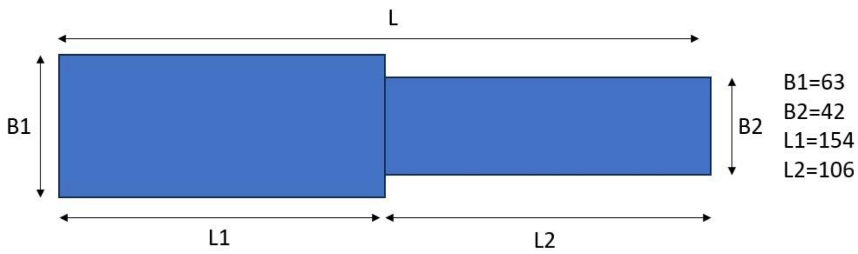


**Figure 5-4 Simplified shape of H-851**

The following properties of the topside are used.

**Table 5-2 Topside properties**

| Topside | | Unit |
|---|---|---|
| Mass | 30000 | mT |
| VcoG [z] | 17 with respect to underside topside | m |
| Length [x] | 122 | m |
| Beam [y] | 70 | m |
| Height [z] | 55 | m |
| Wind area [x, z] | 6710 | $m^2$ |
| Wind area [y, z] | 3850 | $m^2$ |

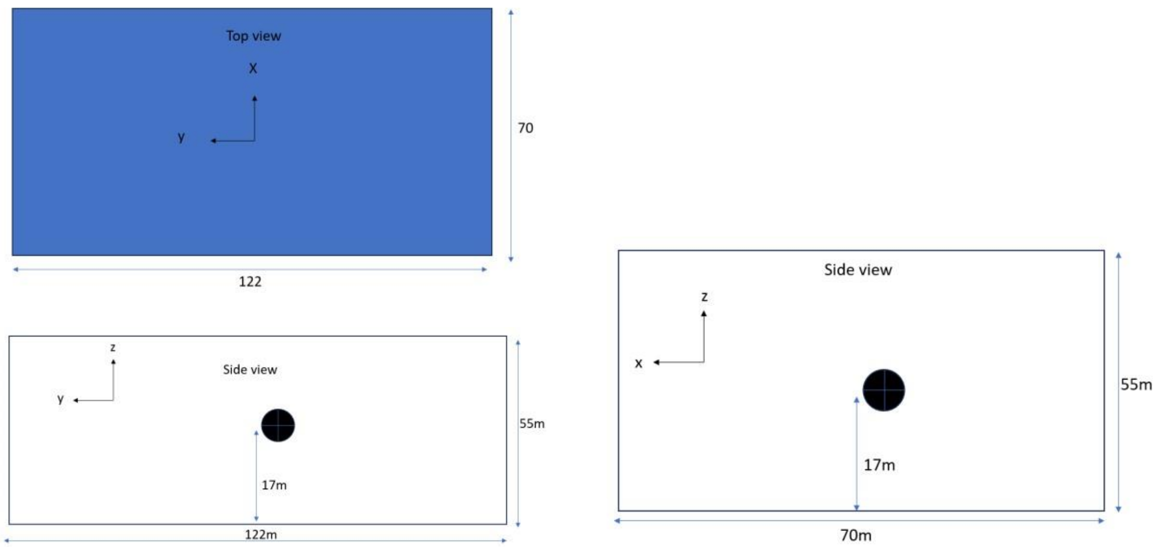


**Figure 5-5 Topside Centre of Gravity (CoG)**

For the jacking system the following assumptions have been made

**Table 5-3 Jack properties**

| Jacking system | | Unit |
|---|---|---|
| Mass jacks (Estimate) | 52*35 = 1820 | mT |
| VcoG | 7.5 with respect to deck | m |

## 5.3 Change in GM

In ship stability analysis, the metacentric height (GM) is crucial, especially during light heeling. When the ship heels slightly, the vertical buoyancy line crosses the vessel's centreline, marking a point called the metacentre (M). GM is the vertical distance between the centre of gravity (G) and the metacentre (M). This distance is a measure of the ship's initial stability during light heeling.

A higher GM means better initial stability, making it tougher for the ship to heel easily. A vessel with a large GM has a shorter roll period. So, GM is a key factor indicating how stable a ship is and how resistant it is to heel when it starts to heel. Furthermore, ship with a large roll period moves slower and thus has a lower maximal acceleration.

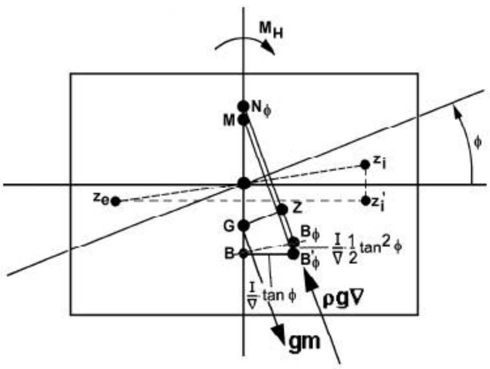


**Figure 5-6 Hydrostatics (Massie, 2001)**

KG Keel to vertical Centre of Gravity (vCoG)
KB Keel to Centre of Buoyancy
BM Distance between Centre of Buoyancy and metacentre
GM Distance between Centre of Gravity and metacentric height

$$KB = \frac{T}{2}$$

$$BM = \frac{I_T}{\nabla} = \frac{I_T}{A\_Barge * T}$$
$$GM = KB + BM - KG$$

First the GM is calculated for a perfectly ballasted barge with the topside resting on top of the skid beam of the barge as can be seen left, in de figure below.

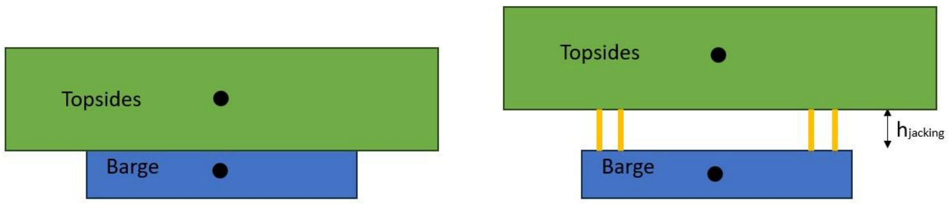


**Figure 5-7 Topside jacking stage start-end**

The GM reduction due to vertical displacement $h_{jacking}$ of mass $m_{topside}$ causes a change in the centre of gravity. This can be found with the 'law of shifting mass'. With $M_{total,}$ the total mass of the barge and the topside.

$$GG_1 = (m_{topsides} * h_{jacking})/M_{total}$$

$$G_1M = GM - GG_1$$

For five different topside weights the GM reduction is plotted against the jacking height.
The change in GM is investigated for a topside weight of 25,000 mT till 45,000 mT with steps of 5,000 mT.

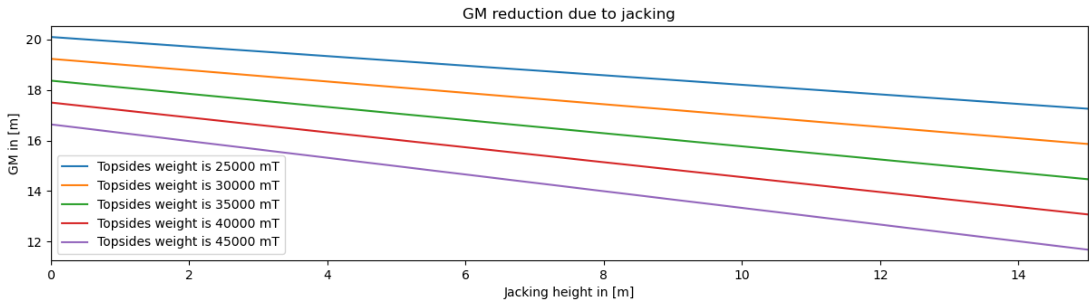


**Figure 5-8 GM Reduction due to jacking**

## 5.4 Additional heeling angle due to initial ballast error

The rotation of the barge around the x-axis is called the angle of heel. The ideal situation would be an angle of heel of zero degrees. However, it could be that due to a small ballast error the barge is ballasted with an initial angle of heel.

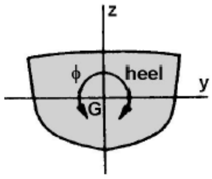


**Figure 5-9 sign convention of heel**

For an initial heeling angle, the barge experiences a rotation of the topside CoG with respect to its initial position. This causes a heeling moment that needs to be balanced by a stability moment.

The heeling moment can be calculated by the following equation.

$$M_{heel} = m_{topsides} * g * d_{shift} * \cos(\theta)$$

Where:

| | | |
|---|---|---|
| $m_{topsides}$ | = The mass of the topside | [mT] |
| g | = The gravitational acceleration | [m/s$^2$] |
| $d_{shift}$ | = CoG of set due to initial heeling | [m] |
| $\theta$ | = Heeling angle | [deg] |

The stabilizing moment is calculated by the following equation.

$$M_s = \rho * g * \nabla * GM * \sin(\theta) = \rho * g * A_{barge} * T * GM * \sin(\theta)$$

Where:

| | | |
|---|---|---|
| $\rho$ | = The density of the sea water 1.025 | [mT/m^3] |
| $\nabla$ | = Displacement of the barge | [mT] |
| GM | = Calculated GM per jacking height and topside weight | [m] |

Solving the equation $M_{heel} = M_s$ for theta

$$\tan(\theta) = \frac{m_{topsides} * g * d_{shift}}{\rho * g * \nabla * GM}$$

The change in the heel angle is investigated for a topside weight of 25,000mT till 45,000mT with steps of 5,000mT considering an initial heeling angle of 0.1 degrees.

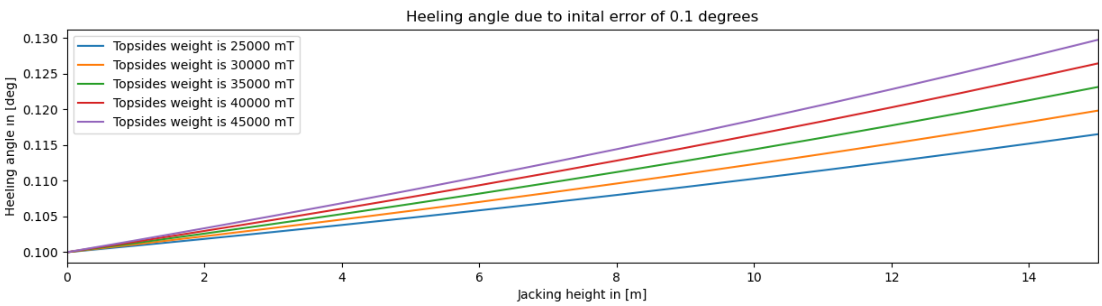


**Figure 5-10 Heeling due to initial ballast error**

The figure above shows that the heeling angle will increase with 0.015 degrees for the smallest and 0.03 degrees for the largest topside when the initial heeling angle is 0.1 degrees.

## 5.5 Heeling angle due to wind

The wind will cause a overturning moment on the barge. This moment increases during the jacking phase due to an increase in overturning arm. The change in heeling angle is investigated for a topside weight of 25,000mT till 45,000mT with steps of 5,000mT considering the wind speed and properties defined below.

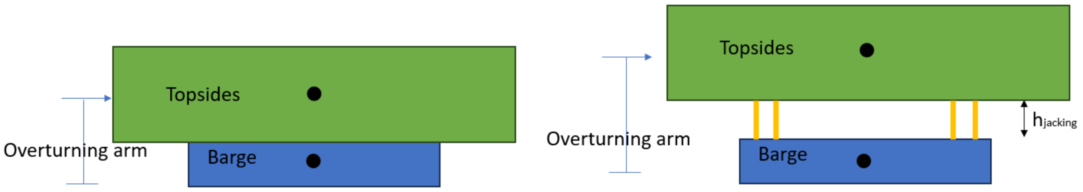


**Figure 5-11 Situation sketch of wind loading on topside**

The Heeling moment due to the wind load is calculated according to the following equation.

$$M_{hwind} = F_w * h_w$$

Where:

$F_w$ = The wind force in kN according DNV – RP – C205 section 5

$h_w$ =The overturning arm

$$q = \frac{1}{2} * \rho_a * U_{T,z}^2$$

q = The basic wind pressure or suction [Pa]
$\rho_a$ = The mass density of air, to be taken as 1.226 kg/m$^3$ for dry air at 15°C
$U_{T,z}$ = The wind velocity averaged over a time interval *T* at a height *z* meter above the mean water level or onshore ground [m/s] (10m/s) based on previous projects.
$C_p$ = Pressure coefficient
S = projected area of the member normal to the direction of the wind [m2]

The wind force is finally calculated with the following formula.

$\boldsymbol{F_w} = \mathrm{Cp} * \mathrm{q} * \mathrm{S}$

The stabilizing moment is calculated by the following equation.

$$M_s = \rho * g * \nabla * GM * \sin(\theta) = \rho * g * A_{barge} * T * GM * \sin(\theta)$$

Solving the equation $M_{hwind} = M_s$ for theta

$$\tan(\theta) = \frac{F_w * h_w}{\rho * g * \nabla * GM}$$

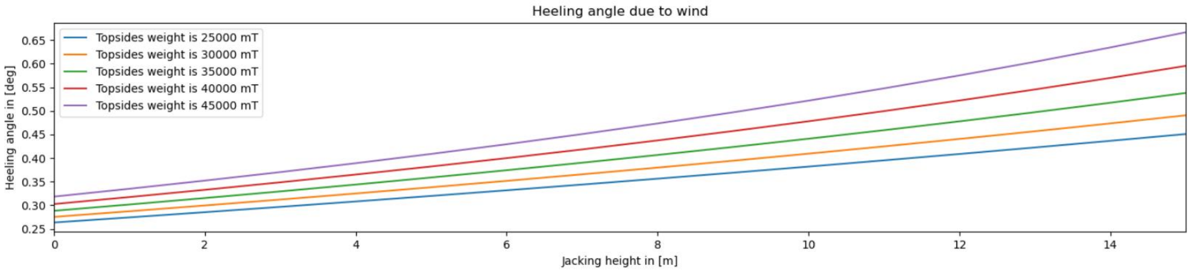


**Figure 5-12 Heeling due to wind**

The figure above shows that the heeling angle due to wind loading will almost double after the topside is jacked to height.

## 5.6 Change in roll period

The roll period is an important indication for the response of the barge. If the natural period of the barge is close to the peak period of the incoming waves, a heavier response is expected. The topside will be jacked in the air, therefore will the GM change and thus the roll period. This chapter will investigate the changes for a topside weight of 25,000 mT till 45,000 mT with steps of 5,000 mT .

The estimation formula given by the DNV section 4.2.1

$$T = \frac{2C * B}{\sqrt{GM}}$$

This formula is not used as it resulted in an unrealistic roll period. This is likely because the constant C (given by DNV) and the width of the barge, B, do not take the abnormal shape of the barge into account. The barge is T shaped, thus deviates form a rectangular shape.

The expected natural period is calculated according to:

$$T_n = 2 \cdot \pi \sqrt{\frac{Ixx + A_{44}(\omega_n)}{Kxx}}$$

With

| | | |
|---|---|---|
| $T_n$ | Natural roll period | [s] |
| $I_{xx}$ | Inertia about the longitudinal axes through the CoG | |
| $A_{44}(\omega_n)$ | Added inertia about the longitudinal axes through the CoG at the natural frequency (found iteratively from WAMIT results about CoG. | [m²mT] |
| $K_{xx} = \Delta * \text{GM}$ | Roll stiffness | [mT/m] |
| $Abarge$ | Wetted area of the barge | [m²] |
| $T$ | Draft of the barge | [m] |
| $\rho$ | Density of the sea water 1.025 | [mT/m³] |
| $\Delta = Abarge * T * \rho$ | Displacement | [mT] |
| $W$ | Width of the barge | [m] |
| $H$ | Height of the barge | [m] |
| $r_x = \sqrt{\frac{1}{12} * \theta_{roll} * (W^2 + H^2)}$ | Radius of Gyration | [m] |
| $\theta_{roll} = 1.5$ | Mass Distribution factor (EG-507) | [-] |
| $I_{x1} = r_{x1}^2 * m_1$ | Mass moment of inertia Barge | [m²mT] |

| | | |
|---|---|---|
| $I_{x2} = r_{x2}^2 * m_2$ | Mass moment of inertia Topside | [$m^2$mT] |
| $I_{xx} = I_{x1} + I_{x2}$ | Total Mass moment of inertia | [$m^2$mT] |

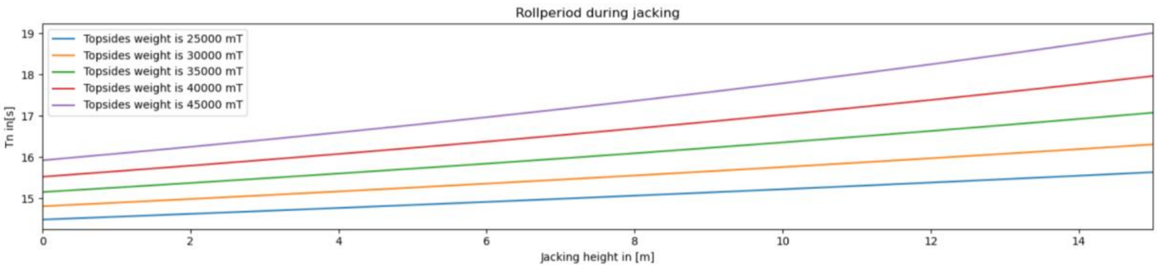


**Figure 5-13 Change in roll period due to jacking**

The plot above shows that the roll period will increase when the topside is jacked to height. This means that the roll movement of the barge will be slower and thus lower accelerations. Furthermore, the roll period will move further away from the wave peak period that is expected during the float-over. This means that the barge response will be more favourable when the topside is at height. However, this is not the case if there are long swell waves. The natural peak period of swell waves is longer, which could lead to the barges roll period nearing the peak period of the swell waves. However, in this region of the North Sea, 17 second swell waves are rare, because of its sheltered location behind the UK and the shallow water depth.

## 5.7 Change in GZ

The GZ curve, shown in section 5.1 is only interesting in the region where the curve is almost linear. In this region the small angle approximation can be used. This is from 0 degrees to 10 degrees which lays with the area of interest. Because the deck will be submerged after heeling 9 degrees and at angles larger than 6 degree the minimum free board is not reached. This means that the lever arm GZ can be calculated by GM * sin(theta), according to (Massie, 2001). Section 5.3 showed the trend of the GM reduction, which showed that the GM remained positive and thus the GZ will remain positive as well.

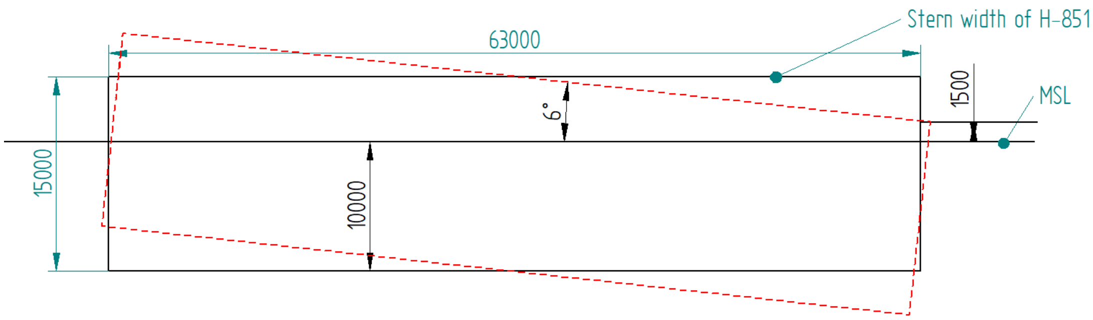


**Figure 5-14 Maximum heeling of H-851**

## 5.8 Conclusions

After investigating the concerns which were identified in section 4.7 we can draw the following conclusions. The GM requirement of +0.15 m of the transportation requirement is also valid after jacking without ballasting. The requirement will be met in the investigated cases by a significant margin. The governing case is a 45,000 mT topside with a GM of 11m after the topside has been jacked up to height. The stricter GM criteria of +1.0 m during positioning is also valid after jacking meaning that no intermediate ballast operations have to take place between arrival at sea and docking.

An initial heeling angle will result in a larger heeling angle after the topside has been jacked up to height. In the worst investigated case of a 45,000 mT topside, starting with a heeling angle of 0.1 degrees resulting in a heeling angle of 0.13 degrees. This means that due to rotation the topside CoG will shift 0.03m in the horizontal plane with respect to its original position. An initial heeling angle of 0.1 degrees will not result in the maximum heeling angle of 6 degrees after jacking. The heeling angle showed an increase of 30% after jacking. This means that attention should be made to the ballast plan to make sure that no intermediate or pre-mating ballasting is required in order to keep the heeling angle small.

The wind will generate a heeling angle which increases after jacking the topside. For the heaviest topside investigated, the heeling angle increases with about 0.3 degrees. This will result in a horizontal offset of 0.08 m over a height of fifteen meters. A windspeed of 10m/s will not result in the maximum heeling angle of 6 degrees after jacking. However, the ballast plan can be adjusted to a pre heel to compensate for the result of heeling angle due to wind.

The horizontal misalignment which is caused by the additional heeling due to a ballast error or wind loading is of no concern as 80mm much smaller than the diameter of the LMU which is 2000mm.

The roll period of the barge increases when the topside will be jacked up to height. This means that the motions of the barge will be more favourable after the barge is jacked up. This is independent of the weight of the investigated topside.

The GZ lever arm increases after barge heels more, but the GZ reduces after the topside is jacked into the air.

It can be concluded that the topside can be jacked up for the investigated cases without ballasting as the identified concerns in chapter 4 are of no concern. It is advised to pay attention to the ballast plan as jacking increases initial ballast errors by 30% and heeling due to wind doubles.

## 5.9 Discussion

The stability is not a concern due to the large initial static stability of the H-851 float-over barge. This means that no intermediate ballasting is needed. The H-851 also has a large initial roll period, which will increase after jacking. This means that the maximum acceleration experienced by the topsides, will be less after the topside is jacked to the float-over height. Under the conditions that the float-over is in the North Sea.

# 6.0 1D SIMPLIFIED FLOAT-OVER MODELS

The difference in horizontal stiffness identified in Chapter 2 is initially investigated using a 2-body 1D model. This approach helps understand the initial behaviour changes in the system and how other components, such as the LMU loads, are affected by changes in interface stiffness. Additionally, the behaviour over time is investigated to predict the behaviour of the larger 3D model.

Following the concerns of Section 4.6 regarding the horizontal design loads on the jacking system, the horizontal stiffness, and the LMU loads, a simple model is built in the frequency domain. The decision to use a frequency domain analysis is due to its simplicity. The results are instant and easy to check by hand. Its simplicity allows for many variations of variables, which can be useful in investigating the sensitivity of the horizontal stiffness. First, the after-steel-to-steel phase of the mating operation will be investigated because, at this stage, no impact loads are present as the barge topside and LMU are all in contact. This means that the effect of stiffness differences between the jacking system and DSF on the interface loads and LMU loads can be investigated via a simple frequency domain calculation. The model provides the eigenfrequencies, which can explain the loads in the system. Since the model is in the frequency domain, the effect of different wave spectra on the loads can also be investigated.

The second stage of the float-over is described as the post-steel-to-steel contact phase. This means that about 50% of the load has been transferred from the barge to the jacket. To gain insight into the effect of the horizontal stiffness of the jacking system in comparison to the horizontal stiffness of a float-over using a DSF, a simplified model has been created in 1D, in the surge or sway direction. This model should also provide insight into the load that goes through the jacking system at the interface between the topside and the barge. Currently, the design loads on the jacking system are based on a different type of float-over and according to the guidelines for float-overs (DNV.GL Noble Denton, 2015).

Input values for the stiffnesses and masses will be taken from previous projects within Heerema and the concept design of the jacking system of chapter 4. First, the simplification for the model will be explained. Thereafter, the methodology for calculating the mass and spring properties is shown. Then the displacement of the masses and the spring forces will be investigated. Finaly, a simple impact model will be investigated to gain inside in the time behaviour of the movement of the masses.

## 6.1 Model setup and methodology

Model setup

The barge and topside are modelled as two mass-spring systems. Here, mass one is the barge mass + added mass of the water  and mass two the topside mass. The system differs by using a DSF or the jacking system.

The figure below shows simplified model of the masses barge and topside and the springs Interface and LMU. The springs are built-up from multiple spring which will be explained in section 6.2.

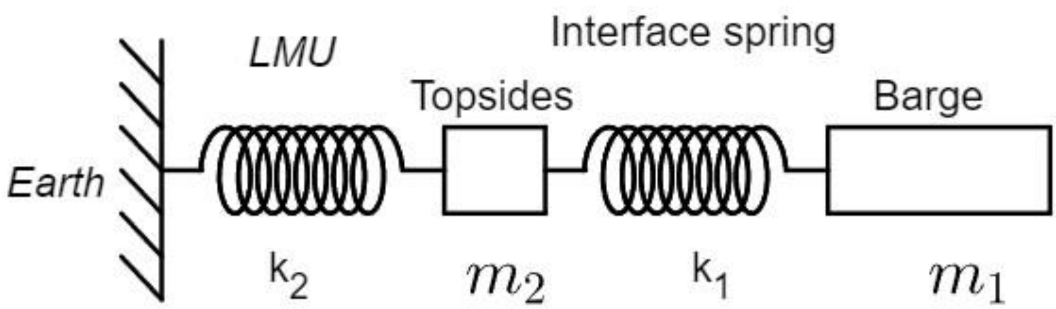


**Figure 6-1 Simple model of the barge and topside after steel-tot-steel**

As the model is in 1D, surge or sway direction, the mass and stiffness for the system per direction has been calculated. The decision for a 1D system is to keep the model as simple as possible and to create understanding in the behaviour of the barge topside system before moving on to a multidimension system. The model will used the properties of three completed projects with a DSF namely Kasawari, Wheatstone, Arkutun-Dagi and conceptual data from this North Sea study. Thereafter, the conceptual jacking system investigated in chapter 4 is used.

The methodology for calculating the spring properties of the jacking system is as follows. The jacking system is also a spring and thus the spring stiffness of an individual jack and the equivalent spring stiffness can be calculated.

The stiffness of the jacking system in the after steel-to-steel phase can be considered as a fixed free beam. The well known for get me not from the mechanics can be used

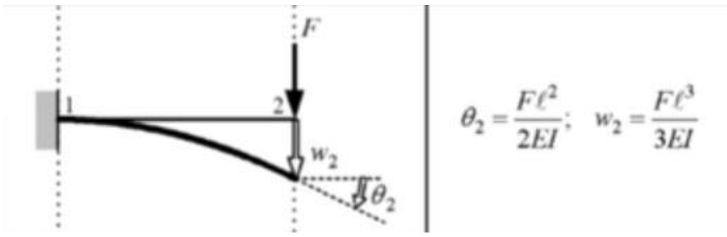


**Figure 6-2 For get me not of cantilever beam**

Using the relation of $F = k * w$ and the forget me not $w = \frac{F*l^3}{3EI}$ and rewrite them into the following form: $k = \frac{F}{w} = \frac{3EI}{l^3}$

The methodology for calculating the equivalent linear spring stiffness is based on the following equations.

For springs in series, we use the following formula:

$$\frac{1}{k_{eq}} = \frac{1}{k_1} + \frac{1}{k_2}$$

For springs in parallel we use the following formula:

$$k_{eq} = k_1 + k_2$$

The focus of the simple frequency domain calculation lays with the after steel-to-steel contact phase as no impact loads are expected. Typically, the barge and topside are connected to each other via eight parallel springs and the topside is connected to the earth (jacket via 8 LMU springs in parallel). Since the model is 1D these eight springs per connection must be added together to obtain one interface spring and 1 LMU spring. The springs act in the horizontal plane. The X-axis is the longitudinal direction, stern to bow and the Y-axis, is the transverse direction. As we calculate a 1D system, we must calculate spring stiffness in the investigated direction this means that these eight parallel springs have to be added together to fit the 1 D model.

## 6.2 Model input

This section summarizes the input values of the simplified model.

**Mass properties**

The mass properties are summarized below.

Mass 1 consists of the mass of the barge, barge added mass and DSF. Mass 2 is only the topside. The added mass properties are obtained from the project data and the hydrodynamic data base of the H-851 barge. The added mass is depended on the volume of displaced water these properties differ per direction because the draft and wetted area of the barge are different for the investigated cases.

**Table 6-1 Masses used is the simple model**

| Name | North Sea study | Kasawari | Wheatstone 07 | Arkutun-Dagi 3 |
|---|---|---|---|---|
| Topside mass | 32000 | 28000 | 18500 | 38000 |
| Barge mass | 168609 | 155454 | 133780 | 149968 |
| Barge added mass (surge) | 3192 | 2712 | 4391 | 6242 |
| Barge added mass (sway) | 15375 | 12291 | 31060 | 32613 |
| DSF | Included in barge | 2500 | Included in barge | Included in barge |

**Stiffness properties interface spring topside barge**

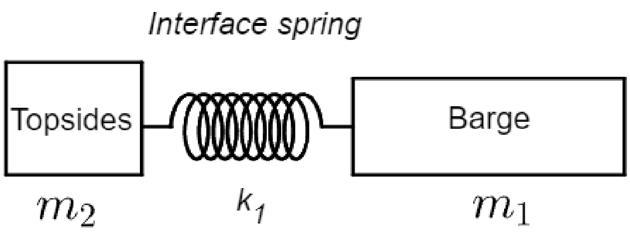


**Figure 6-3 Location interface spring**

The interface spring is built-up via a series of springs where multiple combinations are possible, depending on the design choices. The spring can be built up as the series shown in Figure 6-4 below. However, one or multiple components of this series can be left out. The stiffness of the jacking is set to be the interface spring.

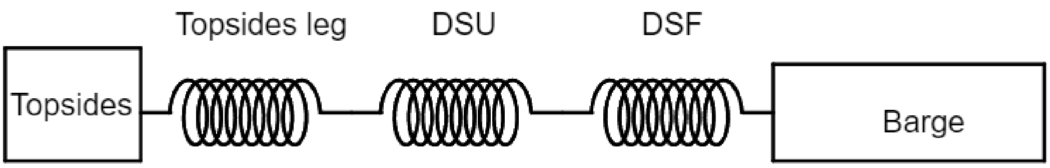


**Figure 6-4 Built-up typical interface spring**

**Stiffness properties LMU**

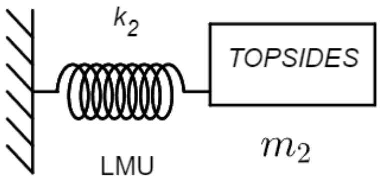


**Figure 6-5 LMU spring**

The stiffness of the LMU spring is like the interface spring built-up via multiple springs in series. These springs do not always have to be activated and there for multiple combinations are possible. A possible combination is shown below.

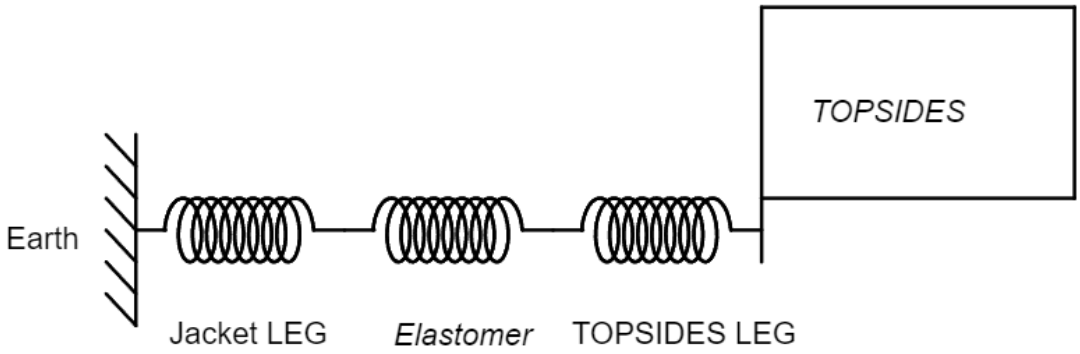


**Figure 6-6 Built up LMU spring**

## 6.3 The calculation

The two-body mass spring system which has been explained and can easily be solved in the frequency domain to obtain the eigenfrequencies or also called mode shapes. First the mass matrix and stiffness matrix are constructed using the displacement method.

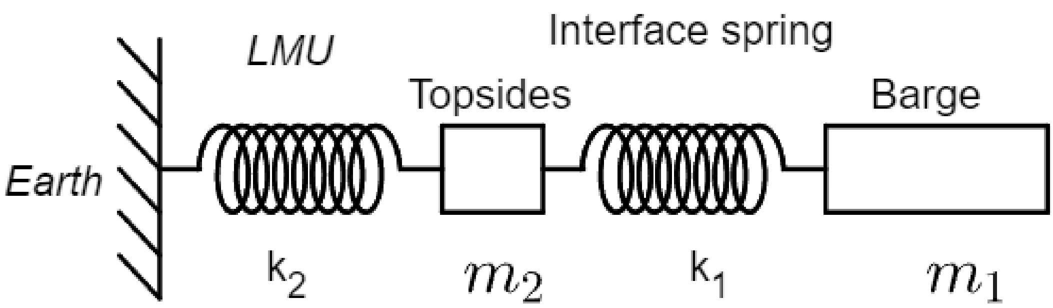


**Figure 6-7 The simple model**

Using the second law of newton with $F = M * a$ the following system of equations can be written down.

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{bmatrix} + \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} F_1 \\ 0 \end{bmatrix}$$

Given that the barge is subjected to a harmonic force in the form of $F_1$ = a cos $(\omega t + \varphi)$

To solve the system $M\ddot{u}(t) + Ku(t) = F(t)$

We use the general solution in the following form:

$$u(t) = \hat{u}\cos(\omega t + \varphi)$$

$$\ddot{u}(t) = -\hat{u}\omega^2\cos(\omega t + \varphi)$$

Substituting the solutions for u into the equations and setting up the characteristic equation.

$$\begin{bmatrix} -\omega^2 m_1 + k_1 & -k_1 \\ -k_1 & -\omega^2 m_2 + k_2 \end{bmatrix} \begin{bmatrix} \widehat{u_1}\cos(\omega t) \\ \widehat{u_2}\cos(\omega t) \end{bmatrix} = \begin{bmatrix} F_1\cos(\omega t \\ 0 \end{bmatrix}$$

The discriminant

$$D = (-\omega^2 m_1 + k_1)(-\omega^2 m_2 + k_2) - k_1^2$$

By using the help variable $\omega^2 = \lambda$ and solving the abc formula we obtain the eigenfrequencies.

$$\begin{bmatrix} \widehat{u_1} \\ \widehat{u_2} \end{bmatrix} = \frac{1}{D} \begin{bmatrix} -\omega^2 m_2 + k_2 & k_1 \\ k_1 & -\omega^2 m_1 + k_1 \end{bmatrix}$$

Which can be written in the form

$$\begin{bmatrix} \widehat{u_1} \\ \widehat{u_2} \end{bmatrix} = \begin{bmatrix} H_{11}(\omega) & H_{12}(\omega) \\ H_{21}(\omega) & H_{22}(\omega) \end{bmatrix} \begin{bmatrix} F_1 \\ 0 \end{bmatrix}$$

Where H is the transfer function of the system which is the ratio between the amplitude of the incoming wave and the displacement of the topside or the barge depending on which transfer function is used.

$$H_{11}(\omega) = \frac{-\omega^2 m_2 + k_2}{D}$$

$$H_{12}(\omega) = \frac{k_1}{D}$$

$$H_{21}(\omega) = \frac{k_1}{D}$$

$$H_{22}(\omega) = \frac{-\omega^2 m_1 + k_1}{D}$$

To get the displacement per frequency for a unit force is this:

The displacement of the barge $\widehat{u_1} = H_{11}(\omega)$
The displacement of the topside $\widehat{u_2} = H_{21}(\omega)$

The transfer function can also be called the Response Amplitude Operator or RAO. A Response Amplitude Operator (RAO) describes the ratio of a ship's motion response amplitude to the wave excitation amplitude, varying with wave frequency and direction, and is a useful tool for predicting vessel behaviour in different sea states. To determine the interface force between the topside and the barge, as well as the load on the LMU, we need to obtain the RAO for these forces. This is achieved by calculating the Force RAO, which involves multiplying the displacement by the stiffness of the relevant spring.

The forces are thus

$$F_1 = \widehat{u_1} * k_1$$
$$F_2 = |\,\widehat{u_1} - \widehat{u_2}| * k_2$$

**Wave spectrum**
As the float-over is performed in the North Sea of the coast of the Netherlands, the waves will not have the same frequency and amplitude the entire time, but the waves will be a spectrum. The wave spectrum used for this research is the JONSWAP spectrum, as is developed for the North Sea and the float-over installation is in the North Sea. The JONSWAP wave spectrum is commonly used for wind waves.

The spectrum is described by DNV-RP-C205 section 3.5.5

The Pierson-Moskowitz spectrum is given by the following formula:

$$S_{PM}(\omega) = \frac{5}{16} * H_S^2 * \omega_p^4 * \omega^{-5} * \exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right)$$
$$\omega_p = \frac{2\pi}{T_p}$$

Then the JONSWAP spectrum is a modified version of the Pierson-Moskowitz spectrum for a developing wind generated sea state in a fetch limited situation.

$$S_J(\omega) = A_\gamma * S_{PM}(\omega)\gamma^{\exp\left(-0.5\left(\left(\frac{\omega-\omega_p}{\sigma\omega_p}\right)^2\right)\right.}$$

Where:

| | |
|---|---|
| $S_{PM}(\omega)$ | = Pierson-Moskowitz spectrum |
| $\gamma$ | = non- dimensional peak shape parameter |
| $\sigma$ | = Spectral width |
| $A_\gamma$ | $= \frac{0.2}{0.065*\gamma^{0.803}+0.135}$ |

Where the average values used are
$\gamma = 3.3$ , $\sigma_a = 0.07\ for\ \omega \leq \omega_p\ and\ \sigma_b = 0.07\ for\ \omega > \omega_p$

With a validity check $3.6 < \frac{T_p}{\sqrt{H_s}} < 5$

**Response spectrum**
It is also possible to get the response spectrum of the RAO with the Jonswap specific wave spectrum. The response spectrum can be calculated according to (Massie, 2001).

$$S_r(\omega) = \lceil RAO^2 \rceil * S_J(\omega)$$

Here is $S_r(\omega)$ the response spectrum and $S_J(\omega)$ is the jonswap wave spectrum for a specific significant wave height and peak period.

The Significant Double Amplitude (SDA) can be calculated with the following formula:

$$SDA = 4 * \sqrt{m_0}$$

The m0 is the $0^{th}$ order moment under the graph.

## 6.4 Results

The method of obtaining the transfer functions (ROA), eigenfrequencies and displacements of the barge and topside is explained in the section above. Using this method and programming it in python, has provided the results in this chapter.

The model properties are split into the surge [x] and sway [y] direction for the different projects however for the North Sea study, horizontal sensitivity is only in the sway direction investigated as based on the previous projects the sway direction was proven to be of the greatest interest on the LMU and interface spring loads.

The table below shows the mass and stiffness properties of all the cases and the resulting eigen periods in seconds.

**Table 6-2 Input properties**

| | **Mass in [mT]** | | **Stiffness in [mT/m]** | | | **Eigen period in [s]** | |
|---|---|---|---|---|---|---|---|
| | m1 | m2 | k1 | k2 | | 1 | 2 |
| **2 GW Jack CASE 1** | 183984 | 32000 | 54078 | 25539 | | 21.3 | 3.8 |
| **2 GW DSF CASE** | 183984 | 32000 | 600000 | 25539 | | 18.6 | 1.3 |
| **2 GW Jack CASE 2** | 183984 | 32000 | 66259 | 25539 | | 20.8 | 3.5 |
| **2 GW Jack CASE 3** | 183984 | 32000 | 160092 | 25539 | | 19.3 | 2.5 |
| **2 GW Jack CASE 4** | 183984 | 32000 | 213099 | 25539 | | 19.1 | 2.2 |
| **2 GW Jack CASE 5** | 183984 | 32000 | 266106 | 25539 | | 18.9 | 1.9 |

By evaluating the eigen periods it becomes clear that if a jacking system would have been used on previous projects, the second eigen period increases from a period of 2 seconds to 4 seconds. In the lower periods there is little to no wave energy present and therefore would the response not be present. Around 4 seconds the wave energy is more present the response is thus more noticeable however still small.

In figure 6-8 the displacement RAO of the topside and barge is shown with JONSWAP wave spectra with a Hs of 1.5 and a Tp of 5 till 8 seconds. This figure shows antiphase behaviour in the movement of the topside and barge which could cause resonance if there is enough energy in the wave spectrum. Looking at the RAO of the (u topside jack case 1) it is clear that the response will be larger for shorter wave periods. This will be calculated later but worth mentioning.

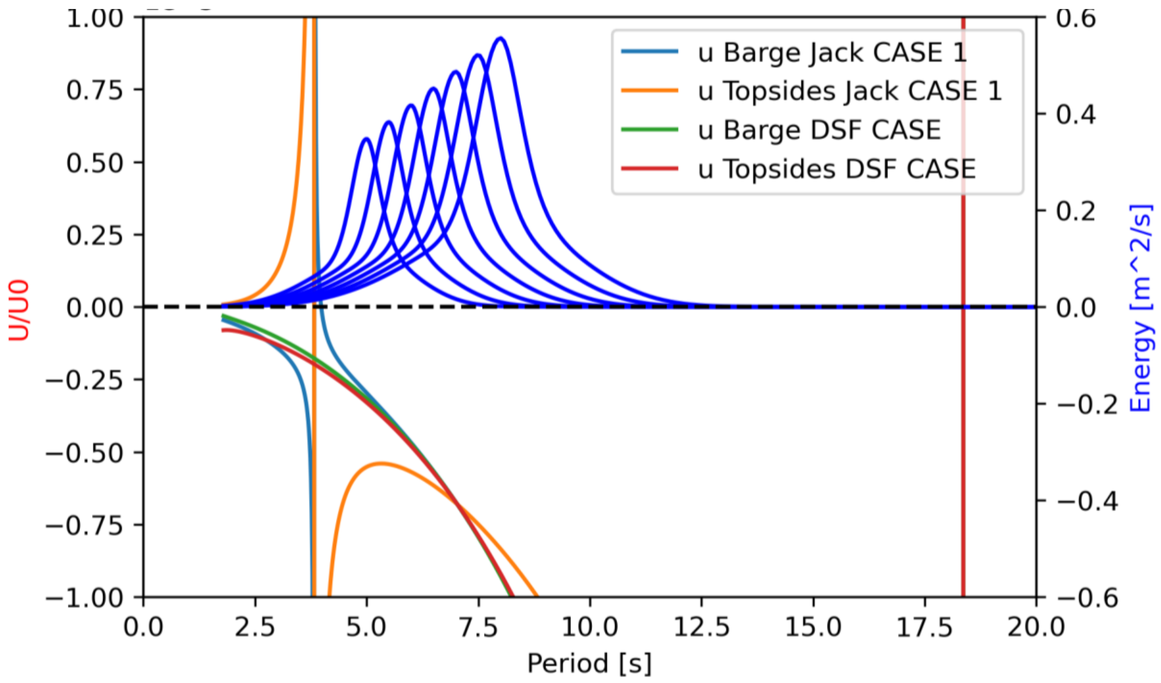


**Figure 6-8 Displacement RAO of topside and barge without damping**

The response spectrum is calculated by the method described in section 6-3. This is done by neglecting damping at first. Figure 6-9 shows a resonance speak, which was mentioned earlier. This peak is only present for the jacking system cases and not for the DSF case. However, this is not correct as the LMU spring also has damping which is not used in this graph and thus damping has to be added to correct the graph.

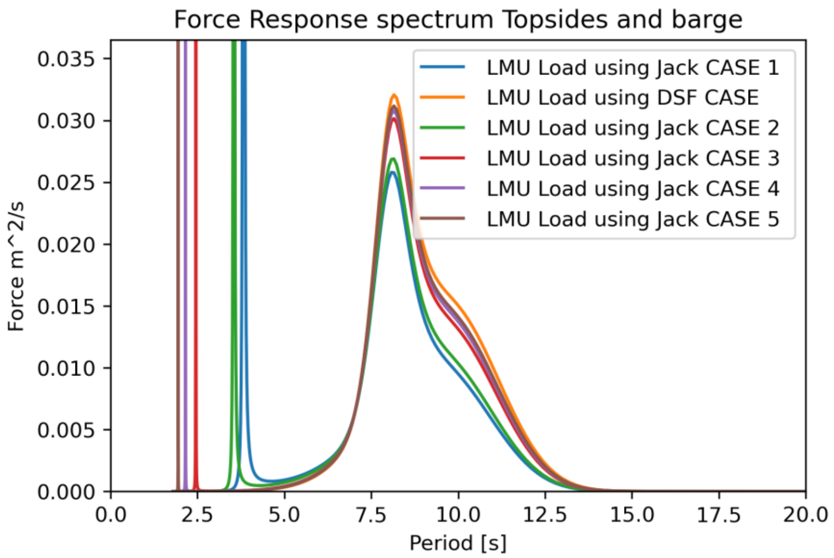


**Figure 6-9 Force response spectrum LMU spring without damping**

For damping 2.5% of the critical damping is used which is a typical value for LMU's based on internal data. By adding damping, the equation of motion changes to $M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F(t)$ . Solving this equation in the same manner as described in section 6-2 the RAO is calculated.

By adding damping, the resonance peak flattened to be almost no noticeable in the response spectrum. This was expected because there is little energy in the lower period range so all this energy will be absorbed by the LMU spring. Including damping shows that the lowest stiffness will result in the lowest peak in the response spectrum. Here the jack case one has the lowest stiffness and the DSF case has the highest stiffness. However, this is only for a significant wave height of 1.5m and a peak period of 8 seconds.

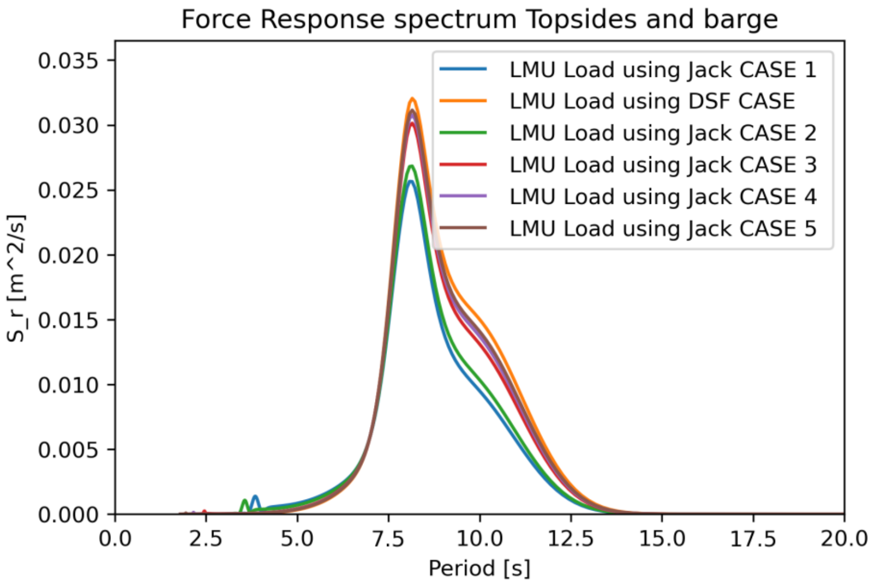


**Figure 6-10 Force Response spectrum LMU spring with damping**

With the response spectrum known, the Significant Double Amplitude can be plotted for multiple peak wave periods for a unit response.

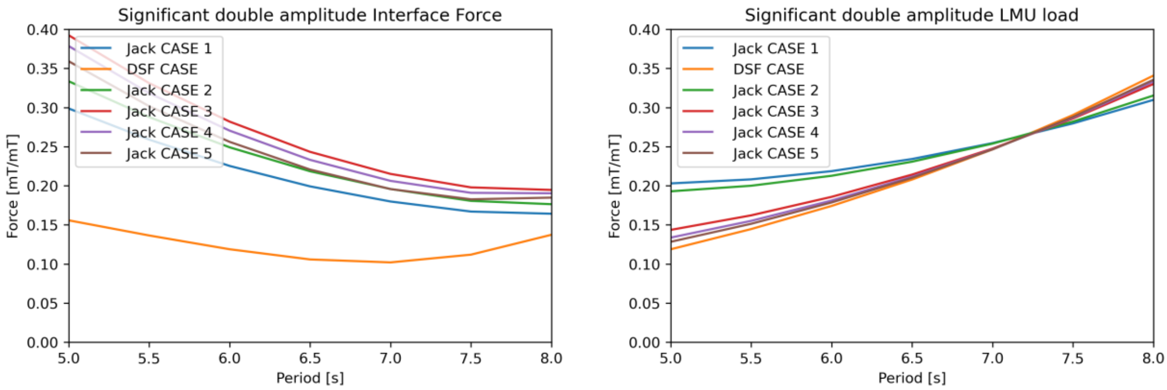


**Figure 6-11 Force response Interface & LMU**

## 6.5 Conclusions frequency domain model

After comparing the equivalent stiffnesses of Table 6-2 it is clear that the equivalent horizontal stiffness of the jacking system is lower than the DSF in combination with a DSU. The factor of difference varies between 6 and 18 in the most extreme case.

The second eigen period becomes higher when the jacking system is used. It increases from 1.3s to 3.8s. This is caused by the lower stiffness of the jacking system. The first eigen period change is not as significant as the second. It changes from 18.6s to 21.3s

Lower stiffness of the interface spring will result in lower LMU loads for higher peak periods with a cross over point of 7.2 seconds. A higher interface spring will result in lower interface spring loads and higher LMU loads for lower peak periods.

## 6.6 Limitations simple frequency domain model

The simplified model has many limitations that are interesting to address in a larger model. The first and most obvious one is that the model only is applied to the transvers or longitudinal movement of the barge and topside. The barge has 6 degrees of freedom, 3 degrees of rotation and 3 degrees of movement, in the model only one degree of freedom is used. The topside has also 6 degrees of freedom where only one is used.

The jacket has eight legs with each a different stiffness depending on location on the jacket, now they are added together and the loading on the jacket is assumed to be equal while it is different.

The difference between the loads on the individual jacks are not visible as the loads are summed up. The stiffness of the jacket legs is averaged rather than the individual jacket leg stiffnesses.

In the simple model it is assumed that all the legs or supports are loaded at the same time while this is highly unlikely to occur in an actual float-over. As the topside is located at the bow meaning that the location of the topside is not included in the simple model.

Non linearities are not considered in the simple model. The stiffness of the LMU is now taken as a constant where in reality it is determined via a compression curve meaning that the stiffness increases after its compressed.

A larger frequency domain model has to be built in order to gain more insight in the influence of the horizontal stiffness and to evaluate the local horizontal loads on the jacking system.

## 6.7 Before steel-to-steel Simple impact model

In the before to steel-to-steel phase of the float over operation there is no long contact between the topside leg and the LMU. The contact that occurs first is an impact load as thus requires a different simple model to gain inside in the behaviour of the system.

Until now the barge and topside are modelled as one body that connected via the DSF. This approach is used internally at HMC and can be read in the multiple papers like (Young Myung Choi, 2014) . The approach has been shown to be valid as proven in model tests. However, this approach is not an option for the jacking system since the stiffness of the jacking system is five till eighteen times less stiff as explained in section 6.5. Splitting the topside barge into two bodies connected via a spring is expected to result in a different behaviour.

The equation of motions set up in section 6.1 are still valid however to predict the motion of the system a different method must be used. Using the state variable z and its derivative d(state)/dt the motion of the masses barge and topside can be plotted.

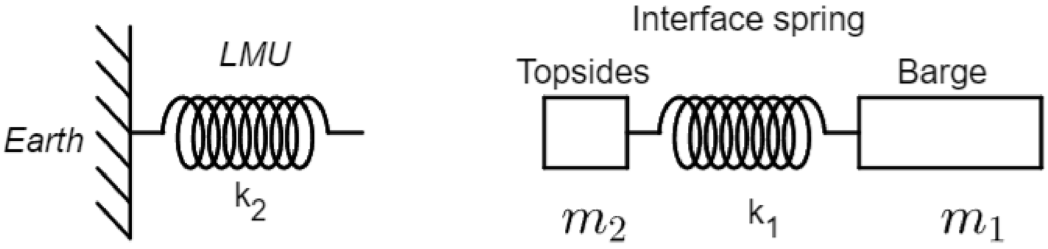


**Figure 6-12 Sketch of model before impact**

The state variable $z = [x_1, x_{2,} \dot{x_1}, \dot{x_2}]$
And its derivative $\dot{z} = [\dot{x_1}, \dot{x_2}, \ddot{x_1}, \ddot{x_2}]$

$\dot{z_1} = z_3$

$\dot{z_2} = z_4$

$\dot{z_3} = -\frac{k_{11}}{m_{11}} z_1 + \frac{k_{12}}{m_{11}} z_2$

$\dot{z_4} = \frac{k_{21}}{m_{22}} z_1 - \frac{k_{22}}{m_{22}} z_2$

With k and m from the in section 6.2 defined matrices.

Now only the initial conditions need to be defined.

Starting with zero displacement because it is assumed that we do not have impact just yet. The initial velocity starts with an assumption which will be updated after the frequency domain calculation with a computer program has been done.

The initial conditions are:
$x_1 = 0m$
$x_2 = 0$m
$\dot{x_1} = 0.40 m/s$ max velocity
$\dot{x_2} = 0.40 m/s$ max velocity

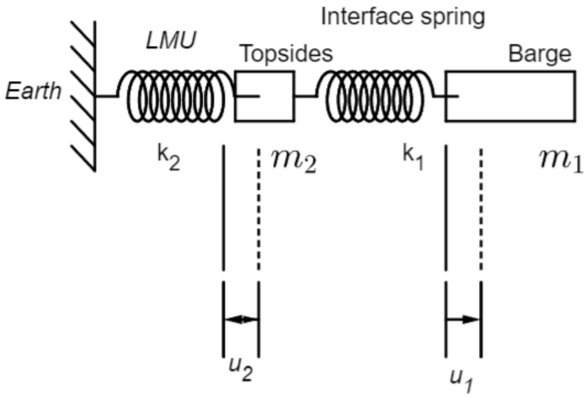


**Figure 6-13 Sketch of time domain model**

In Figure 6-14 it can be seen that while the barge and topside have the same starting velocity the displacement of the barge lags behind the topside after impact. With the displacement of the topside linked to the LMU load meaning a larger displacement of the topside will result in a larger LMU load. It can be seen that the max displacement of the topside is reached around 2 and 6 seconds meaning that the LMU will be loaded multiple times. It makes sense that the barges displacement lags behind the topside as its mass is larger and has an interface spring in between.

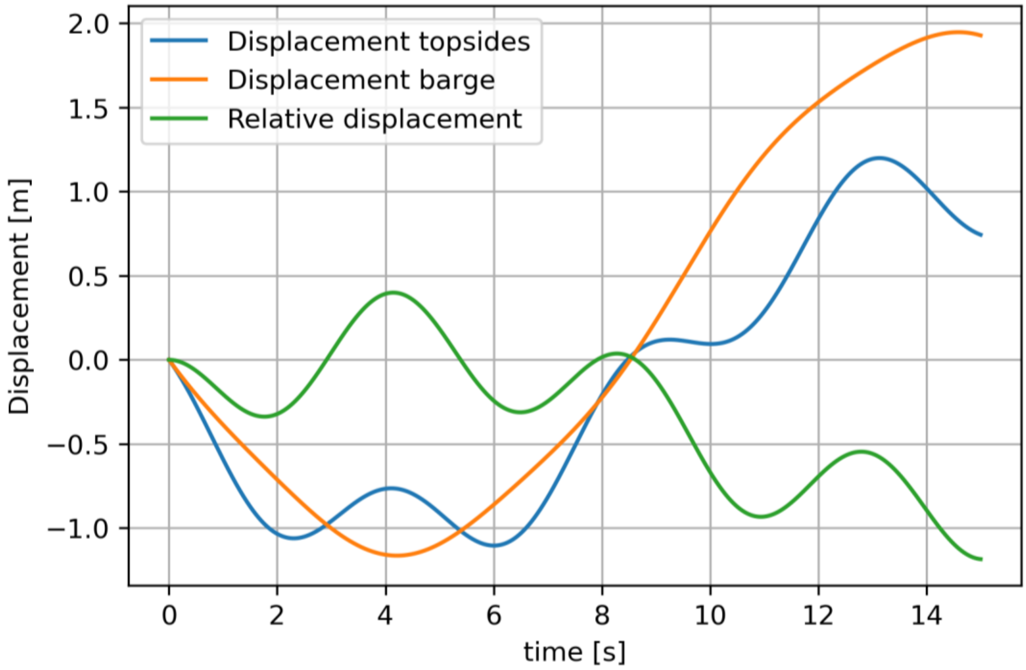


**Figure 6-14 Plot of displacements when a jacking system is used**

When the interface spring is changed to a higher spring stiffness with a factor six the behaviour of the system changes noticeably. The maximum displacement of the topside increases and thus the load on the LMU and the displacement curve change much more in direction. However, the relative displacement of the barge and topside reduces which makes sense as the connection is very stiff. The relative displacement would be non-existent if the stiffness were set to infinity.

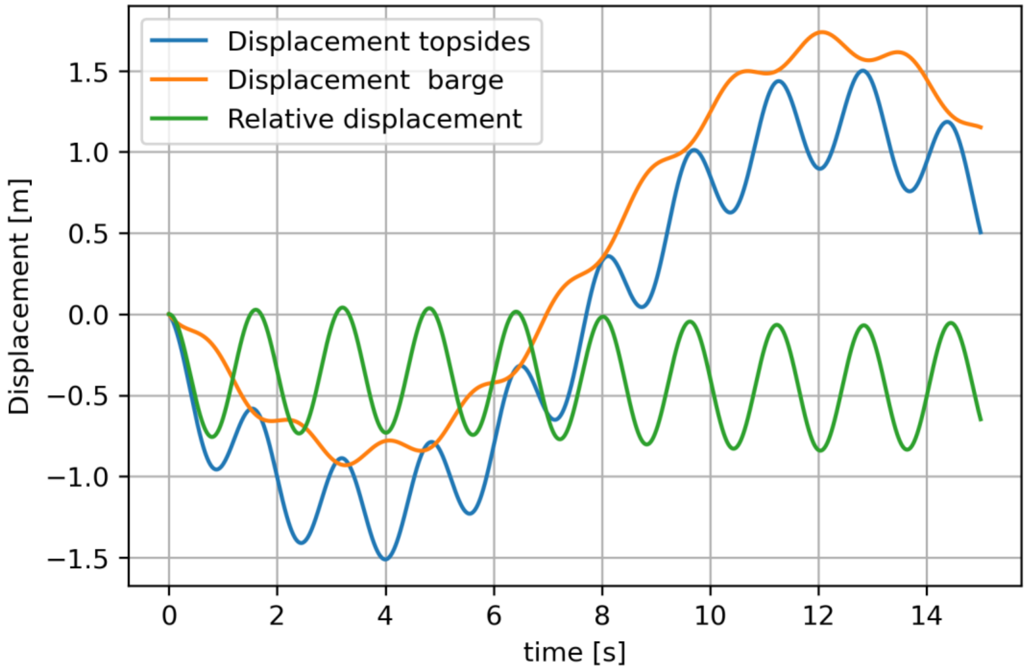


**Figure 6-15 Plot of displacements if a DSF with stiffness is used**

## 6.8 Conclusions and limitations on impact model

The relative displacement of the topsides is larger for a less stiff system. This means that the load on the LMU will be lower for a less stiff system resulting in a possibility to design the LMU for lower loads. The displacement of the barge is larger for a less stiff system which means that the loads on the surge/sway fenders are likely higher. A less stiff system has a slower transition from positive to negative displacement in the axis system. This means that for the same time window, the LMU is less times impacted for a soft system.

The simple time domain model has multiple limitations equal to the discussed limitation in section 6.6. These are: the stiffness of the LMU is linearized and this model does not take the maximum compression of the LMU into account. Furthermore, this model is in 1D rather than 3D and moreover, the model is built on an initial velocity which results the model will end up at a steady state.

## 6.9 Discussion

Based on the following sections, it can be concluded that the stiffness of the jacking system will result in lower LMU loads and higher interface loads. Furthermore, the effect of the horizontal stiffness of the interface spring on the eigen periods is known. This will help understand the change in loads in the 3D model of the next chapters.

## 7.0 3D FLOAT-OVER MODEL FREQUENCY DOMAIN

This chapter will describe the 3D model used to further investigate the jacking system. The investigation is limited for three distinct stages of the float-over operation using the jacking system. This includes the jacking stage and for the two mating stages. First, the model built-up is explained. Thereafter, the analysis is discussed and the results are displayed with the accompanying conclusion. Finally, the limitations of the frequency domain analysis are discussed and how this influences the results.

The research will focus on these three distinct stages as they are key in answering the research question on how the jacking system influences the float-over. The docking stage is a critical stage during a float-over however this is not affected by using a jacking system instead of a DSF and will therefore not be investigated in this research.

It should be noted that a frequency analysis does not provide the actual loads during the mating phase, as established in section 2.4. However, it can be used to study the behaviour of the system and give the eigen periods. These eigen periods in combination with the known wave spectra explain possible changes in load response. However, the jacking phase can fully be modelled in the frequency domain because nonlinearities are not as significant as during the mating phase and thus the results can be accurate.

The investigated stages are the following and will be elaborated more in there respectively section.

- The jacking stages
- Mating before steel-to-steel
- Mating after steel-to-steel

### 7.1 Liftdyn

The 3D float-over model is made in Liftdyn which is an internal tool created by Heerema specifically for resolving equations of motion in the frequency domain. This program effectively manages systems comprising rigid bodies interconnected or anchored to the ground. These connections can be in the form of springs, dampers, or hinges. Although both MOSES and Orcaflex have similar capabilities, within Heerema, Liftdyn stands out as the preferred choice for solving problems in the frequency domain and its simplicity. The methodology Liftdyn uses to solve the equations of motions is the same manner as in Chapter 6. is described which makes a good expansion of the simple model.

The frequency domain model in section 6.0 was in 1D, however each body has 6 degrees of freedom meaning that for a barge and topside there are a total of 12 degrees of freedom. By increasing the number of degrees of freedom it will remove limitations of the simple model. As explained in the section above, liftdyn has the possibility to perform the same calculations as in section 6 but now considering in all degrees of freedom. As the barge is a ship and not a rigid body the effect of coupled motions is taken into account by liftdyn trough the standard equation of motions of a ship and the location of the topside is also added to the model via the mass matrix in the form of inertia. Because liftdyn is in the frequency domain, it makes calculations run very quick compared to time domain solutions which take up to seven hours to complete. The frequency domain analysis allows for quick sensitivity checks and changes. The liftdyn model should provide the answers to limitations posed in section 6.5. It should be noted that liftdyn solves linear equations meaning that the non-linearities are not included in the model.

### 7.2 Model input

This section will describe the input values for the investigated stages taken from the design brief for the North Sea study conceptual mating analysis. Important decisions and theories of the input are explained in this section. The remaining part of the input can be found in attachment 2.

Coordinate system
As the mating operations is built with three components: barge, topside, and jacket with each their own coordinate system an overview with the positive direction given below.

**Table 7-1 Coordinate system overview**

| Axes system | x-axis | y-axis | z-axis |
|---|---|---|---|
| Global | CL jacket towards row three | CL jacket towards row A | MSL upwards |
| Local Barge | CL barge towards bow | CL barge towards PS | Keel upwards |
| Local Topside | Row two towards barge bow | CL row A-E towards barge PS | LAT+21.5m upwards |

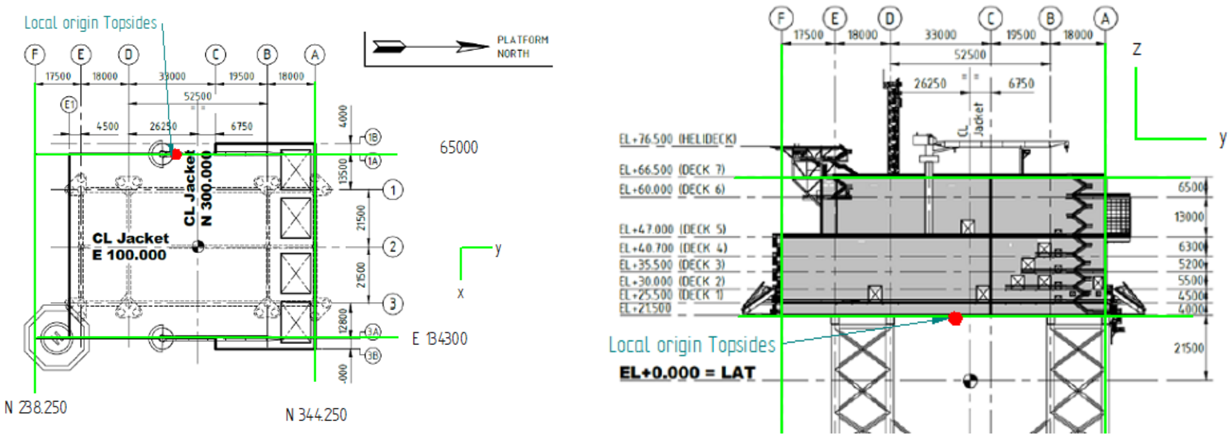


**Figure 7-1 Location CoG Topside**

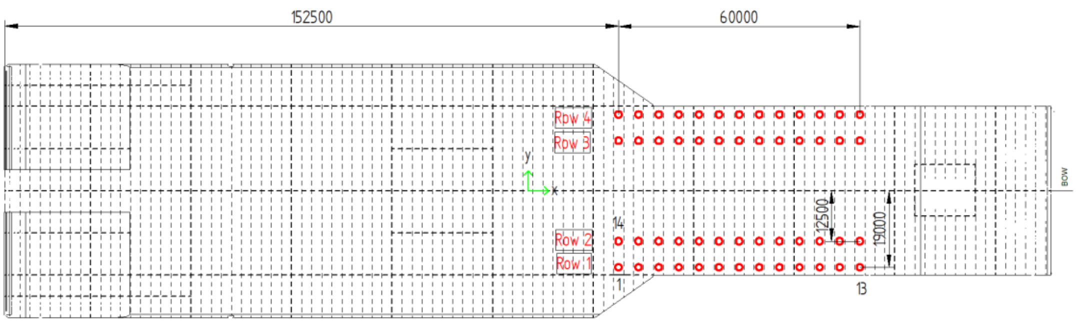


**Figure 7-2 Barge coordinate system with jacks numbered**

**Barge H-851**
As explained above, the analysis is split into three stages. The jacking stage will have a draft suitable for docking the jacket slot while having enough clearance between the topside’s legs and the LMU’s. The first stage of the mating operation has a draft were 0 to 49% of the topside load transfer will occur. The second stage of the mating operation has a draft that covers the 50 to 100% load transfer. The draft of the barge is based on the values used in the design brief.

**Environmental conditions**
The float-over operation is planned to be executed between May and August. The design sea states that have been provided by the North Sea study, for the following months have been summarized in the table below. As the jacking system concept is focused on the North Sea study. It is important that it checked with the design sea states that are used for a float-over installation with a DSF because otherwise comparisons between the jacking system concept and the DSF installation are useless.

**Table 7-2 Design Sea states**

| Direction* | Waves | |
|---|---|---|
| [deg] | Hs | Tp |
| | [m] | [s] |
| 195, 345 | 2.4 | 5, 6, 7, 8 |
| 225, 315 | 2.0 | 5, 6, 7, 8 |
| 270 | 1.25*<br>1.0 | 7<br>8 |

* The sea state of Hs=1.25 for a heading of 270deg will not be used in liftdyn.

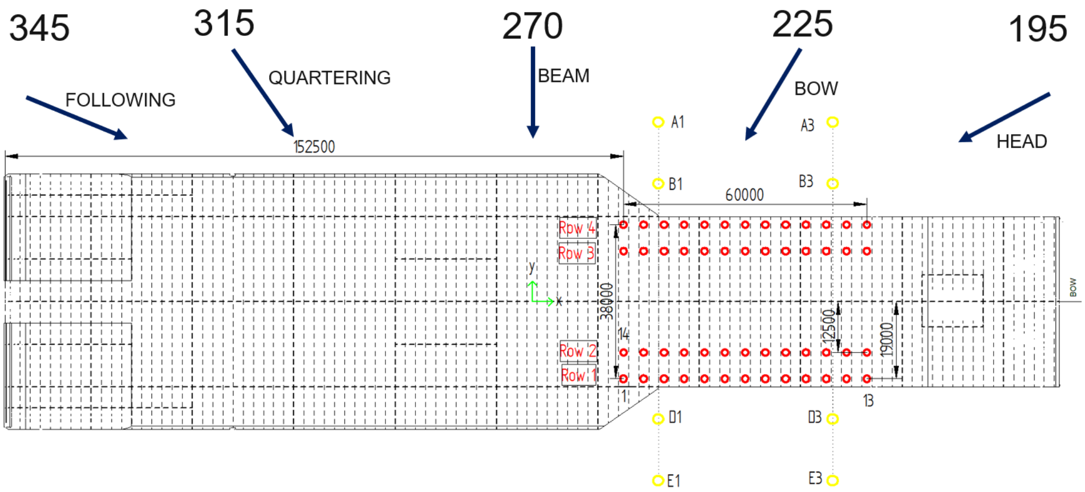


**Figure 7-3 Wave directions and LMU locations with respect to the barge**

**Hydrodynamic properties**
A diffraction analysis will be performed to obtain hydrodynamic databases for the H-851 entrance and exit draught. The hydrodynamic databases will be obtained using the computer program WAMIT and contain added mass, potential damping and first order and second order wave forcing as function of the wave frequency. WAMIT, which stands for "Wave Analysis MIT," is a software package developed by the Massachusetts Institute of Technology (MIT). It is widely used in the maritime and offshore engineering industries for the analysis of floating structures and ships in the presence of waves.

For the hydrodynamic analysis, the jacket will be excluded in the diffraction model because the jacket columns are minor compared to dimensions of H-851. The hydrodynamic data bases are constructed for the three draft cases of 8.7m, 11.3m and 12.05m

Experimental data of the H-851 has shown that not all the calculated damping in WAMIT is not fully accurate. The four damping values must be corrected according with a Heerema internal formula to the damping listed in the table below.

**Table 7-3 Corrected damping values of H-851**

| | Value | Unit |
|---|---|---|
| Surge | 1.2 * 10^3 | kNs/m |
| Sway | 1.5 * 10^3 | kNs/m |
| Roll | 5.4 *10^6 | kNms/rad |
| Yaw | 5.7 * 10^6 | kNms/rad |

In the liftdyn model the mooring arrangement is simplified to a single line connector with a stiffness matrix. Along the diagonal the following values are used. To obtain realistic natural periods of the free-floating barge it needs to be moored. Previous analysis with Heerema Marine Contractors found that a simple mooring line with the following properties result in realistic periods.

**Table 7-4 Mooring line properties**

| Location along Diagonal | Value | Unit |
|---|---|---|
| $c_{11}$ | 100 | kN/m |
| $c_{22}$ | 100 | kN/m |
| $c_{66}$ | 100000 | kNm/rad |

**Topside properties**
The topside is modelled as a rectangular box with the properties defined in this section. The horizontal topside stiffness is not used in this model as the jacking system will support the topside under the beams instead of its support. The Topside legs are at 17.6m from the barge deck and thus will this be the elevation of the underside of the topside in the model.

**Table 7-5 Topside properties**

| | **Units** | **Topside** |
|---|---|---|
| Mass | [mT] | 32,000 |
| CoG X | [m] | 99.55 |
| CoG Y | [m] | 301.42 |
| CoG Z | [m] | 42.44 |
| RoG $K_{xx}$ | [m] | 34.2 |
| RoG $K_{yy}$ | [m] | 26.9 |
| RoG $K_{zz}$ | [m] | 37.7 |

Vertical Stiffness (Z-axis)
The vertical stiffness of the topside has been provided by the manufacturer. The topside has 8 legs by applying a unit load in the z-direction, these legs deform by using the deformation and load, the stiffness along this axis is determined. The stiffness is specified for the eight supports; however, the jacking system does not use these supports but instead relies on the horizontal support beams of the topside. Therefore, the equivalent stiffness for this loading scenario needs to be calculated. This is done by summing the stiffness of the eight supports and dividing it by the number of jacks. This also means that there is no difference in stiffness in the topsides.

**DSU**
Vertical DSU stiffness (Z-Axis)
For the liftdyn model the following assumptions have been made based on the basis of design taken from the North Sea study. The basis of design has 8 DSU's with a maximum compression of 200mm and a maximum load of 2000mT for all supports. This is based on the static load of the topside weight on the DSF supports before the mating. Based on this data, a linear spring has been constructed. Which has been recalculated to accommodate the 52 supports instead of the 8 DSU's.

**Horizontal DSU stiffness:**
No concept design is available yet for the horizontal Seafastening of the Topside. So, for this model the horizontal stiffness will not be considered.

**Jacking system properties**
For the jacking system the base case scenario is used. This is a round tubular with a diameter of 1.7 meters and a wall thickness of 50mm. The horizontal stiffness is determined as explained in section 6.1. The vertical stiffness is not used because a DSU pad is used which is generally in the order of 10 lower. The connection to deck is assumed to be fixed this is not the case however for the purposes of this research this is neglected. The stiffness of the deck could be added as a spring in parallel to the jack stiffness. However, by varying the jack stiffness the different deck stiffness is covered as well. Differences in the rows are not considered and have to be investigated in future research.

**LMU properties**
The design brief of the North Sea study project proposes the following properties for the LMU. The LMU will have a maximum compression of 500mm and a maximum load of 1300mT for the outer legs and 2600mT for the inner legs. The LMU has stiffness in three directions longitudinally, transverse, and vertical. The stiffness of the LMU is not linear however the liftdyn model only uses linear stiffness. Therefore, the stiffness of the LMU is linearized in the same manner as chapter 6.

**Jacket**
The stiffness of the jacket legs has been provided by the manufacturer as a preliminary data. Only the stiffness of the jacket legs in horizontal direction are given. They are split into the stiffness used before steel to steel and after steel to steel. The difference between these phases is that before steel to steel the jacket legs work independently and after steel to steel, they work together and are thus stiffer. The stiffness properties can be found in Attachment 3 Liftdyn input

**Interface spring**
This spring is explained in section 6.2 and will be equal to the horizontal stiffness of the sensitivity case. This spring could be the jacking system or the DSF. This is dependent on the analysis. The vertical stiffness of the interface spring will be equal to the vertical DSU stiffness described in this section.

**LMU spring**
This spring is also explained in section 6.2 and will be the combination of the stiffness of the Jacket, LMU and topside leg both for the vertical and horizontal stiffness.

## 7.3 The jacking stage

This stage is assumed to be at sea at the float-over location after all the mooring lines are connected to the barge and before the docking starts. This entire stage is aimed to be no longer than 2 hours.

The aim of this stage is to gain insight into the loads on the driving system of the jacking system. This will be done for the design sea states of the North Sea study which are summarized in Table 7-4 Design Sea states. For the environmental conditions not all sea states are checked. Only the sea states with a peak period up to 8 seconds as is compares best to the alternatives given in the literature and the competitor research in chapter 2. This will be done for the design base case of the jack stiffness and for four other stiffness variations. This is done to evaluate the base case design and to gain knowledge in case the design needs to be changed later.

In the jacking stage, the model is made with the following situation. The topside is already at the largest elevation as the highest loads will occur in this situation.

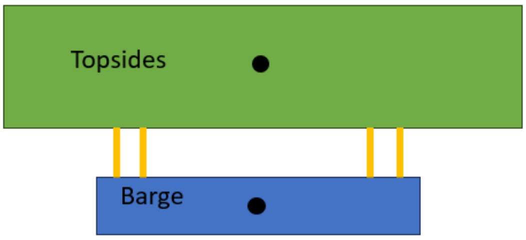


**Figure 7-4 Visualization of jacking stage model**

First the model is run with a fixed interface spring between the barge and topside. This is equal to an analysis where the topside is placed on a DSF. The fixed connection is to check the modes shapes of the model which can be checked via the hand calculation of section 5. Thereafter the model is updated with a stiffness relation between the barge and topside to model the jacking system. The stiffness relations follow from the horizontal stiffness of the jacking system and the vertical stiffness of the DSU. The loads will be calculated using the acceleration of the topside CoG in the first model. In the second model the loads are extracted from the model at the top locations of the jack and calculated with the topside CoG. These loads on top of the jacks are called the interface loads and will be the red wire of the study.

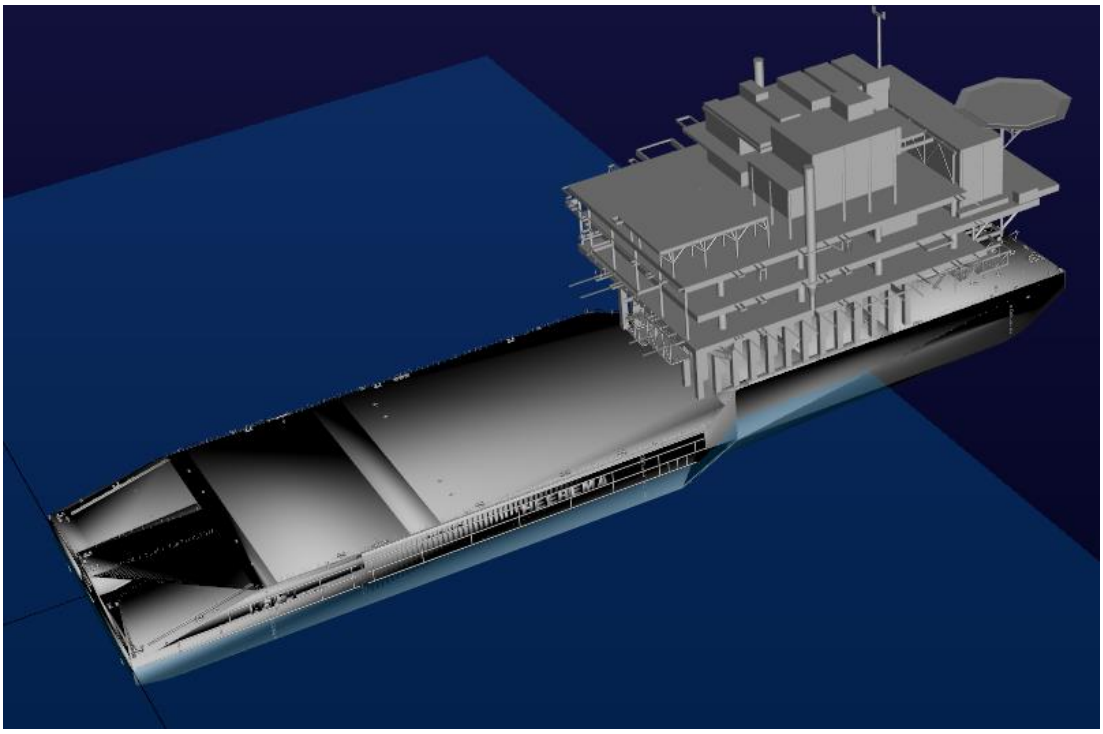

**Figure 7-5 Visual a topside on barge (not from the North Sea study)**

For the jacking stage a draft of 8.7m is used as this will give the required clearance of the topside above the jacket in the docking stage.

**Table 7-6 Jacking system stiffness cases (Interface spring)**

| Case / Stiffness [kNm] | X (Jack only) | Y (Jack only) | Z (DSU only) |
|---|---|---|---|
| 00 (DSF Fixed) | inf | inf | inf |
| 01 (Base case Jack) | 10202 | 10202 | 14889 |
| 02 | 20202 | 20202 | 14889 |
| 03 | 30202 | 30202 | 14889 |
| 04 | 40202 | 40202 | 14889 |
| 05 | 50202 | 50202 | 14889 |

**Results**

Before running the sea states the mode shapes are calculated. These mode shapes help explain and validate the results. As mentioned above the mode shapes of the fixed connection can easily be checked with a hand calculation as it is just a floating barge with 6 degrees of freedom and thus six mode shapes. Table 7-9 gives the mode shapes obtained with the frequency domain solver liftdyn. The cases where a stiffness relation between the topside and the barge is present has twelve mode shapes because the barge has 6 DOF's and the topside as well. However, the dominant mode shapes of the barge can still be seen. A selection of mode can be seen below where the remaining mode shapes can be found in Attachment 4 Results Liftdyn Jacking stage

**Table 7-7 Mode Shapes for the jacking stage**

| Mode shape | Dominant motion | Period [s] | | |
|---|---|---|---|---|
| | | DSF Case (fixed connection) | Jacking Case 1 | Jacking Case 5 |
| 1 | YAW | 559.98 | 477.86 | 477.37 |
| 2 | SWAY | 255.74 | 254.04 | 254.03 |
| 3 | SURGE | 226.15 | 226.15 | 226.15 |
| 4 | ROLL | 15.77 | 15.68 | 15.66 |
| 5 | HEAVE | 10.57 | 10.57 | 10.57 |
| 6 | PITCH | 9.24 | 9.27 | 9.27 |
| 7 | | | 2.33 | 2.20 |
| 8 | | | 2.23 | 2.03 |
| 9 | | | 2.03 | 1.17 |
| 10 | | | 1.17 | 1.01 |
| 11 | | | 1.03 | 0.49 |
| 12 | | | 0.91 | 0.41 |

From Table 7-7 it is clear that the period of the mode shapes of the jacking cases does not change much if the horizontal stiffness changes. This does make sense as the motion of the topside is only caused by the movement of the barge. It is also logical that the mode shapes caused by a rotational degree of freedom change more than the translational as the spring connection allows the barge to rotate with respect to the barge however this in the order of 0.01deg.

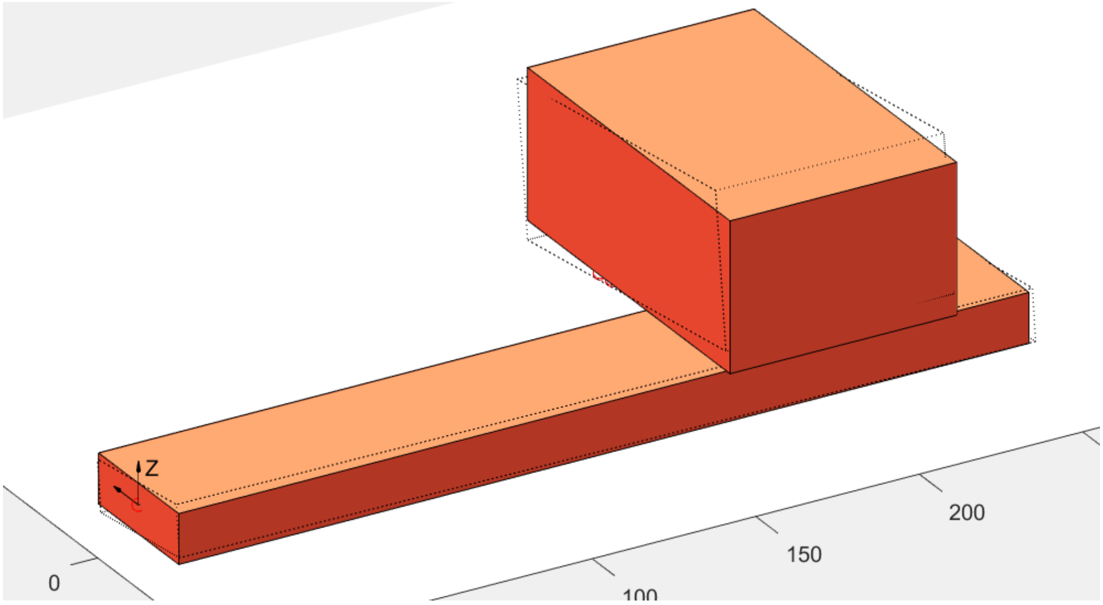


**Figure 7-6 Mode shape 4 with dominant motion roll**

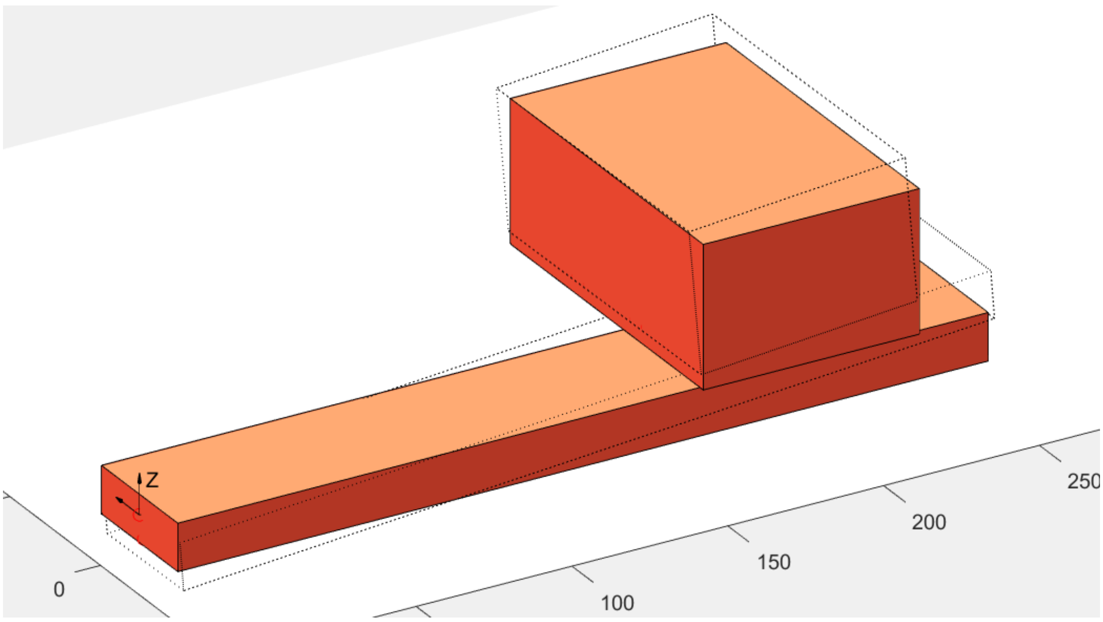


**Figure 7-7 The mode shape 6 with dominant motion Pitch**

From liftdyn the following results are obtained and processed. The results for the force in Longitudinal direction (X) and the transverse direction (Y) are used to get the total horizontal force on the jack in any direction. The forces of the individual Fx and Fy can be found in Attachment 3. The maximum local horizontal force is calculated as follows: by $F_h = \sqrt{F_x^2 + F_y^2}$ . This is the maximum horizontal force on any jack in any direction. The concept calculation in Attachment 1 considered a maximum horizontal design load of 31 mT.

Table 7-8 Maximum horizontal load on a single Jack [mT] in any direction

| | Incoming wave heading in [deg] | | | | |
|---|---|---|---|---|---|
| | 195 | 345 | 210 | 315 | 270 |
| Case 1 | 9 | 13 | 13 | 18 | 22 |
| Case 2 | 8 | 12 | 13 | 19 | 21 |
| Case 3 | 7 | 12 | 15 | 20 | 21 |
| Case 4 | 7 | 12 | 17 | 22 | 22 |
| Case 5 | 8 | 12 | 19 | 24 | 22 |

The maximum local horizontal force on a single jack is found to be of 22mT. This is for the jack base case (case1) and under 270 degree incoming waves. This is lower than the considered 31mT in the design. Meaning that the driving system of the jacks has sufficient capacity or that higher sea states could be an option for jacking.

The design was based on a global horizontal load equally distributed over the jacks as a percentage of topside weight. To make a comparison with the assumed design, the total global horizontal load at the interface is also calculated to make a comparison. Using the maximum local horizontal force to calculate the total global horizontal force results in a total global horizontal force of $22mT * 52 = 1145mT$ .This results in a total global horizontal force on the total system $\frac{1145mT}{32000mT} * 100 = 3.6\%$ of the topside weight. This found by calculation the maximum load on a jack in both x and y direction as explained above. When the local horizontal loads per jack are summed, the total global horizontal force is only 832mT which is equal to 2.6% of the topside weight.

Further investigation led to the conclusion that dividing the total horizontal load equally over the jacks is not right as a design load. As it does not take the load difference per jack into account. The figure below visualises the different loads in the jacks in row one for beam seas (270-degree).

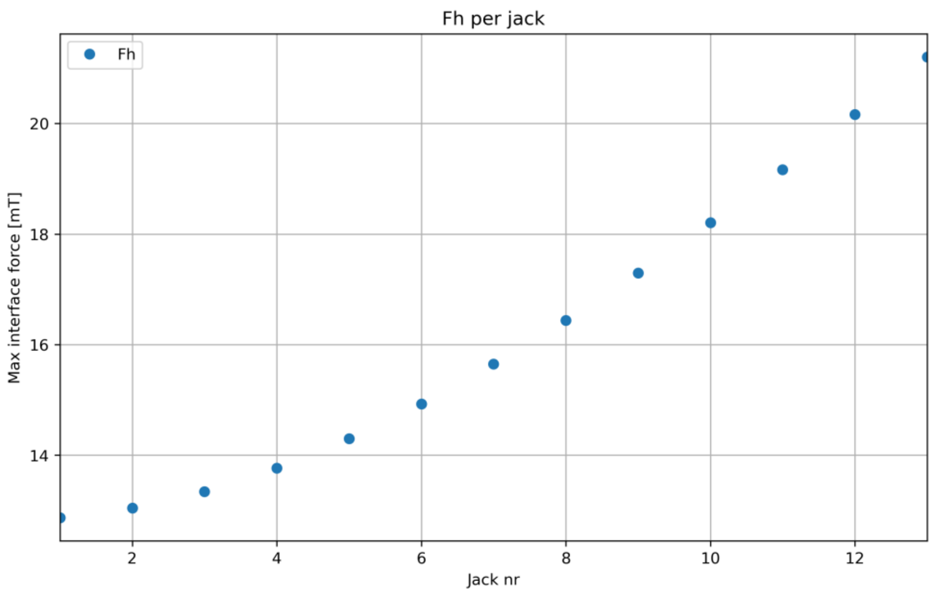


Figure 7-8 Horizontal load on jacks in row 1 for a 270-degree wave heading (case 1)

The graph clearly shows that the local load on the jack increases towards the bow. This can be explained by the mode shapes that causes the load. Which is for this wave direction primary roll. In Figure 7-7, here the barge rotates around its centre and since the topside is not located above the barge's centre, the rotation of the topside is not equal to rotation of the barge. The difference in rotation between the topside and barge results in a different elongation of the springs that have been modelled as the connection between the barge the topside.

By comparing Figure 7-8 and Figure 7-9, it can be concluded that the making the jacking system stiffer will result in a less distributed loading of the system depending on the incoming direction of the waves. Where less distributed means a higher difference in loading between the most inner and most outer jack. In Figure 7-8 Fh has difference of factor 1.7 between the outer jacks, Figure 7-9 has a load difference of 1.8 between the outer jacks. This is because the rotation of the topside is more synchronized with the rotation of the barge and the eigen period of this mode shape decreases, moving it more into the wave spectrum. Increasing the horizontal stiffness also results in a higher load on the jacking system for the investigated cases. This was expected following section 6.4.

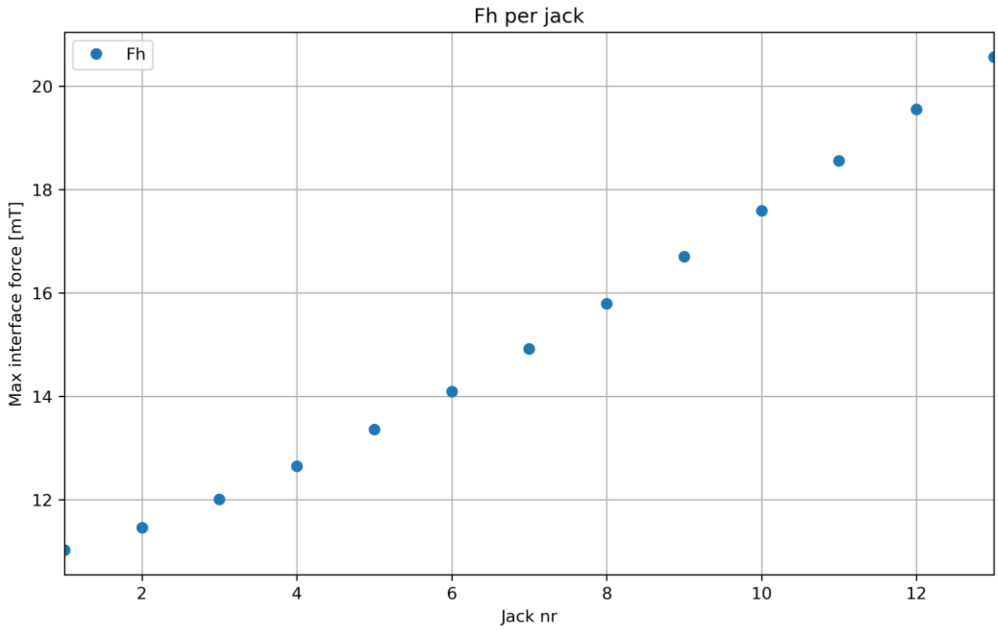


**Figure 7-9 Horizontal load on jacks in row 1 for a 270-degree wave heading (case 5)**

A summary of the horizontal loads on the system is displayed below.

**Table 7-9 Horizontal loads on driving system**

| Draft at 8.7m | Maximum local horizontal load | Total summed horizontal load at interface | | Max local * number of jacks | |
|---|---|---|---|---|---|
| Case | mT | mT | % of topsides weight | mT | % of topsides weight |
| Jacking system | 22 | 832 | 2.6 | 1145 | 3.6% |
| DSF* | 14 | 728 | 2.3 | N.A. | N.A |
| Designed* | 31 | 1600 | 5 | 1600 | 5 |

*Equal distribution assumed

## 7.4 Mating before steel to steel

After barge is moved into the jacket slot as visualised in the figure below, the mating of the topside and jacket starts by ballasting the barge to a shallower draft. The float-over is split into stages of percentage of load transfer or in before steel-to-steel and after steel-to-steel. This section will be about the before steel-to-steel phase which is from 0 to 50% load transfer.

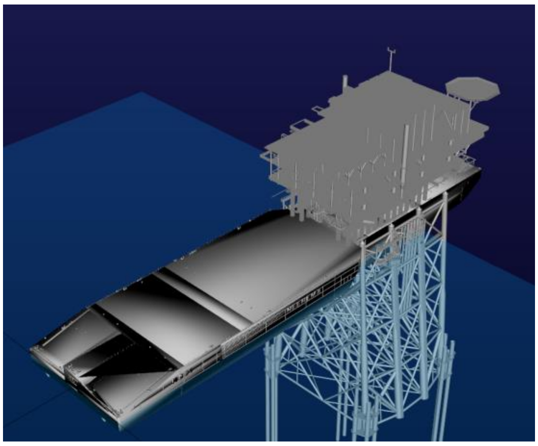

**Figure 7-10 Visualization of the barge in the jacket slot (not from the North Sea study)**

For the before steel-to-steel phase the existing model of the jacking stages is expanded with POI's (points of interest) at the location of the topside legs and the barge is ballasted down to the draft 11.3m.

The aim of the model is to get a first estimate of the behaviour of impact loads on the LMU's. These are not modelled as liftdyn is a frequency domain solver so the impact on the LMU cannot be calculated directly. However, an estimate of the behaviour can be made by using the velocities in the POI's and post process this to a load on the LMU.

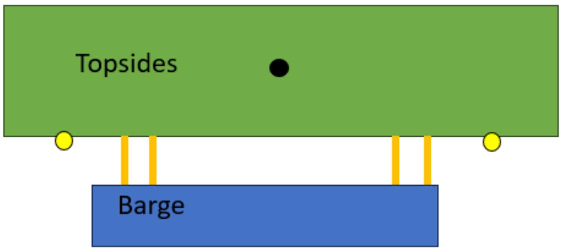


**Figure 7-11 visualization of the liftdyn model before steel to steel**

In this stage the supports of the topside above the jacket are added as points of interest. These POIs are used to extract the velocity of these points. The velocity can be used to estimate the impact on the LMU. The same stiffness relation between the topside and barge as stated in Table 7-6 are used for the BSTS analysis.

**Table 7-10 Mode shapes Before steel-to-steel**

| Mode shape | Dominant motion | Period [s] | | |
|---|---|---|---|---|
| | | Fixed Case | Jacking Case 1 | Jacking Case 5 |
| 1 | YAW | 690.81 | 653.65 | 653.63 |
| 2 | SWAY | 319.22 | 312.76 | 312.77 |
| 3 | SURGE | 262.86 | 262.86 | 262.86 |
| 4 | ROLL | 28.18 | 17.45 | 17.44 |
| 5 | HEAVE | 11.25 | 11.90 | 11.90 |
| 6 | PITCH | 3.20 | 9.74 | 9.75 |
| 7 | | | 2.38 | 2.24 |
| 8 | | | 2.26 | 2.14 |
| 9 | | | 2.14 | 1.19 |
| 10 | | | 1.19 | 1.02 |
| 11 | | | 1.06 | 0.51 |
| 12 | | | 1.01 | 0.46 |

**Results**
The results of the forces on the jacking system before contact with the LMU can be found in Attachment 5 Liftdyn results Before steel to steel. The maximum local horizontal load on the jacking system before contact were overall 10% lower across all sea states. A summary of the maxima is displayed below. The lower loads were expected because the model is almost the same as in the jacking stage (section 7.3) except for the deeper draft,11.3m instead of the 8.7m. The velocity in the POI's did not change significantly during the stiffness cases. The change was only 3% lower velocity if the stiffness increased with a factor five. The velocity is not used to calculate an impact load in this section.

The table below shows the max horizontal loads on the jacking system for a lower draft than Table 7-9 Horizontal loads on driving system.

**Table 7-11 Horizontal loads on driving system before contact**

| Draft at 11.3m | Maximum local horizontal load | Total horizontal load at interface | | Max local * number of jacks | |
|---|---|---|---|---|---|
| | mT | mT | % of topsides weight | mT | % of topsides weight |
| Jacking system | 21 | 801 | 2.5 | 1092 | 3.4 |
| DSF (fixed)* | 13 | 676 | 2.1 | N.A. | N.A |
| Designed* | 31 | 1600 | 5 | 1600 | 5 |

*Equal distribution assumed

The maximum average velocity is used to reiterate the time domain model of chapter 6. As stated, before the before steel-to-steel phase is highly nonlinear and will therefore be modelled in a time domain model in chapter 8.

## 7.5 Mating after steel-to-steel

This stage starts after 50% of the topside weight is transferred from the barge to the jacket. The same model as before steel-to-steel and the jacking stage is used but expanded. During this stage, the model is expanded even more by connecting the topside to the jacket with a stiffness relation this stiffness relation represents the LMU as explained in chapter 6. The jacket is fixed to the earth. The topside has made steel-to-steel contact with the jacket therefore are impact loads not possible anymore and thus is the frequency domain solver sufficient. The aim of the model is to extract the loads on the LMU at the jacket legs and to extract the loads at the connection between the topside and the jacking system. The analysis is done for the same three sea states and the same stiffness relation variation from Table 7-6

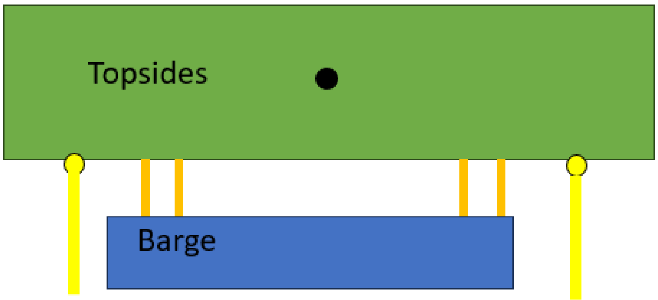


**Figure 7-12 Visualization of the liftdyn model ASTS**

As this stage focuses on the mating after 50% load has been transferred. The 50% load transfer on the 8 LMU's is equal to $\frac{32000mT}{8} * 50\% = 2000mT = 19620kN$ pretension in the LMU's in vertical direction. With the LMU modelled as a vertical spring of 37943 kN/m the compression of the spring becomes 0.5m. In this stage the barge is ballasted to a draft of 12.05m. Furthermore, the POIs of the topside supports are removed because the there are no impact forces expected anymore so the velocity of these points is no longer needed. The LMU, jacket leg and topside leg are added as a spring with vertical, horizontal, and transverse stiffness.

**Results**

The period of the pitch motion does not change when the horizontal stiffness changes. This makes sense and is logical since it does not affect the motion in that plane.

**Table 7-12 Mode shape after steel to steel**

| Mode shape | Dominant motion | Period [s] | | |
|---|---|---|---|---|
| | | Case 0 (Fixed) | Case one | Case five |
| 1 | YAW | 6.95(heave) | 23.21 | 16.75 |
| 2 | PITCH | 5.77 Yaw | 12.22 | 12.22 |
| 3 | ROLL | 4.50 (SURGE) | 5.93 | 5.63 |
| 4 | HEAVE | 3.22 (Roll) | 5.75 | 5.57 |
| 5 | SURGE | 1.02(Pitch) | 5.17 | 4.63 |
| 6 | SWAY | 0.03 | 3.35 | 3.15 |
| 7 | | | 2.00 | 1.85 |
| 8 | | | 1.69 | 1.59 |
| 9 | | | 1.39 | 1.04 |
| 10 | | | 1.05 | 0.89 |
| 11 | | | 0.90 | 0.48 |
| 12 | | | 0.86 | 0.47 |

It should be noted that the mode shape with the dominant motion Sway was already found in section 6.4. The mode shapes lower than 2 seconds will not contribute to the force response as there is no energy in the wave spectrum. The illustrations of the mode shapes can be found in Attachment 6 Liftdyn results After steel to steel. The maximum horizontal loads on the connection between the topside and barge are displayed below.

**Table 7-13 Maximum interface spring loads [mT]**

| | Fh heading 195 | Fh heading 345 | Fh heading 210 | Fh heading 315 | Fh heading 270 |
|---|---|---|---|---|---|
| Case 1 | 40 | 77 | 50 | 72 | 102 |
| Case 2 | 47 | 75 | 66 | 80 | 119 |
| Case 3 | 53 | 75 | 78 | 85 | 128 |
| Case 4 | 57 | 75 | 85 | 89 | 134 |
| Case 5 | 59 | 75 | 90 | 91 | 143 |

As the base case jacking system design of chapter 4 is equal to case one, the maximum local horizontal force of 102mT is found for a wave heading of 270 degrees. This is lower than the considered 123mT in the concept design. However, these loads are calculated in the frequency domain and only for comparison.

Using the local maximum which is calculated as follows: $F_h = \sqrt{F_x^2 + F_y^2}$ and multiplying it by the number of jacks results in a total global horizontal force on the jacking system of 5304mT. This is equal to $\frac{5304mT}{32000mT} * 100 = 16.5\%$ of the topside weight. This is based on taking the maximum load in x direction and in y direction and taking superimposing it to Fh of one jack. If the total horizontal force is calculated based on the sum of the local horizontal force is only 11% of the topside weight. This is because as found in the jacking case the horizontal force on the jacks is not equal over the rows and columns.

In the figure below are the maximum forces in x direction per row per horizontal sensitivity case plotted. The sides which encounter the waves first take the most load and results in higher loads for following waves than for head waves. This can be explained via the location of the rows on the barge and that fact the mode shapes with a natural period (ROLL, HEAVE AND SURGE) are close to each other within the high energy range of a wave with a peak period of 8 seconds.

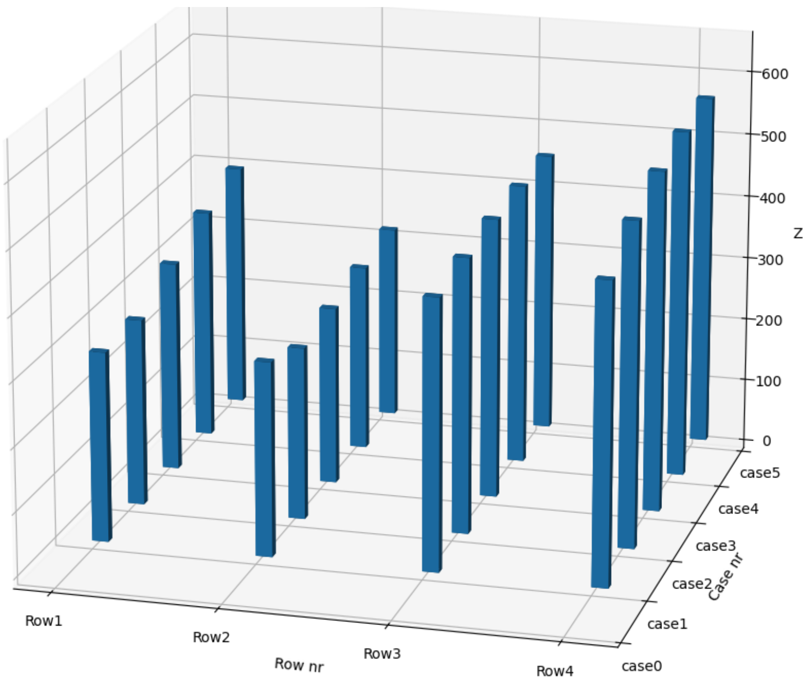


**Figure 7-13 Max Fx for wave heading 315deg per jack case**

The difference maximum local Fh force over the row does show a minimum around a jack (4 in this case) this is because the barge still wants to roll and pitch around its centre but is now restrained by the LMU's shifting its centre of rotation for pitch forwards resulting in a pitch movement around a rotation centre which is between the centre of the barge and the middle of the topside.

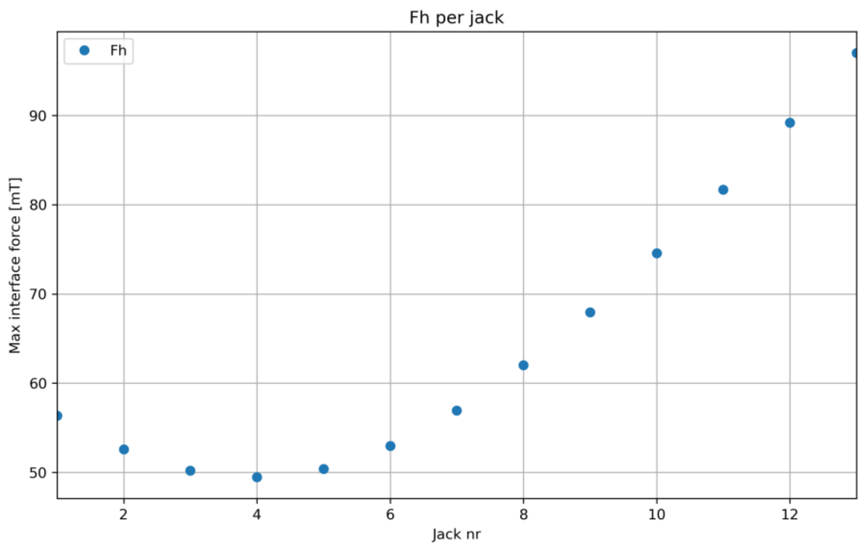


**Figure 7-14 Maximum Fh force in the interface spring for row one for 270 deg, case 1**

Increasing the horizontal stiffness of the interface spring with factor five results in a shift in this midpoint. This point could be referred to as a torsion centre. Increasing the horizontal stiffness also leads to the need to increase the horizontal design loads. This shift in torsion centre is very noticeable in a moving visualisation of the first mode shape. A sketch with the shift of this torsion centre can be found in Figure 7-16.

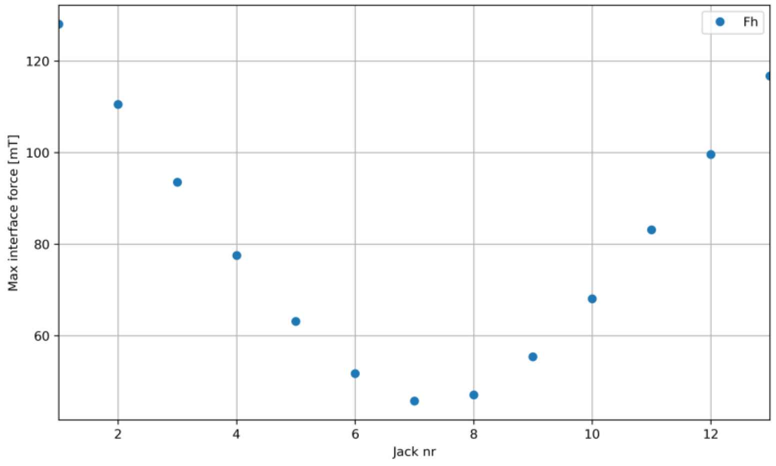


**Figure 7-15 Maximum local Fh force in the interface spring for row one for 270 deg, case 5**

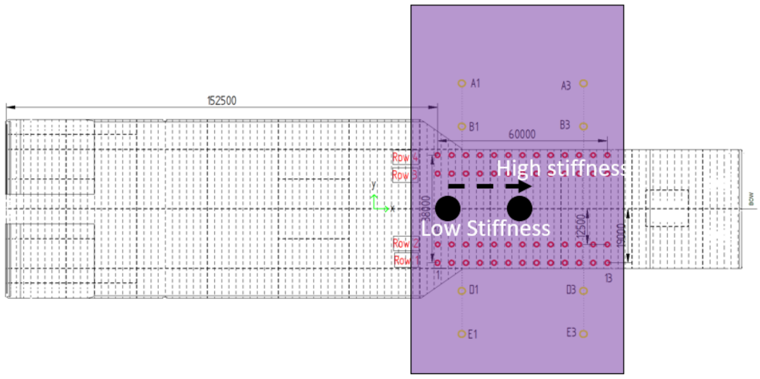


**Figure 7-16 Sketch shift torsion centre**

**LMU**

The results of the horizontal LMU loads are displayed below.

**Table 7-14 LMU loads in [mT]**

| | Fh heading 195 | Fh heading 345 | Fh heading 210 | Fh heading 315 | Fh heading 270 |
|---|---|---|---|---|---|
| Case 0 | 191 | 333 | 204 | 347 | 554 |
| Case 1 | 229 | 491 | 361 | 589 | 443 |
| Case 2 | 228 | 459 | 511 | 701 | 473 |
| Case 3 | 237 | 452 | 604 | 757 | 498 |
| Case 4 | 243 | 447 | 649 | 778 | 524 |
| Case 5 | 248 | 444 | 671 | 785 | 556 |

For case one the loads on the LMU are lower in all wave directions. Increasing the stiffness of the jacking system will increase the loads on the LMU. The load increase is the highest for beam waves.

A summary of the maximum horizontal loads on the interface between topside and barge are displayed below. The global horizontal load is calculated to compare with literature.

**Table 7-15 Horizontal loads on interface( topsides and barge) ASTS**

| Draft at 12.05m | Maximum local horizontal load | | Total summed horizontal load at interface | | | Max local * number of jacks | |
|---|---|---|---|---|---|---|---|
| | Heading | mT | Heading | mT | % of topsides weight | mT | % of topsides weight |
| Jacking system | 270 | 102 | 345 | 3544 | 11 | 5304 | 16.5 |
| DSF(fixed)* | N.A | 31 | 270 | 2965 | 9 | N.A. | N.A |
| Designed* | N.A | 123 | N.A | N.A. | N.A | 6400 | 20 |

*Equal distribution assumed

## 7.6 Conclusions and limitations

**The jacking stage**

The horizontal design load for the driving system of 5% of the topside weight is conservative as analysis showed that the total horizonal load on the system is only 3.6% if the highest local load is multiplied by the total number of jacks. This number reduces to a total horizontal load of 2.6% of the topside weight if the sum of the local horizontal loads is taken which is explained in section 7.3. The horizontal sensitivity cases showed that increasing the horizontal stiffness of the jacking system increased the horizontal loads on the jacking system.

The linear model can be regarded as sufficiently accurate to determine the design loads on the driving system as non-linear behaviour of the interface spring is not wanted and the barge being in open water also means that the linearised waves can be regarded as accurate as there is no interaction between the barge and structures. And thus, for the concept a maximum horizontal load of 22mT can be used as design load for the jacking system driving system.

**Before steel to steel**

The model being the same as the jacking stage and a deeper draft showed that the horizontal loads on the jacking system decreased compared to the previous stage. The maximum velocity in the topside leg decreased if the horizontal stiffness of the jacking system increased.

The impact loads on the LMU's in the before steel-to-steel phase are still unknown and as explained before these can only be calculated in a time domain analysis. However, the impact loads could also be not governing because the compression force on the LMU could be higher. The maximum compression force on the LMU is calculated in section 7.5 for the after steel-to-steel phase. Furthermore, nonlinear behaviour of the LMU spring is not considered. Which could result in under or over estimation of the LMU loads.

**After steel to steel**

The global horizontal load for the jacking system was found to be a maximum of 16.5% of the topside weight if the local maximum horizontal load was multiplied with the total number of jacks. Using the sum of the local horizontal loads resulted in a lower total horizontal load of 11% of the topside weight. A interesting finding is the torsion centre explained in section 7.5 as this influenced the local loads on the jacks.

A lower stiffness of the jacking system resulted in a lower horizontal load on the jacking system and lower loads on the LMU. This was in line with the findings of section 6.5 for the LMU's however section 6.5 suggested that a stiffer jacking system resulted in a marginal lower interface force. The addition of more degrees of freedom gave insight in the horizontal force in different jacks which was an unknown in the hand calculation. With the simple model in chapter 6, a sensitivity analysis in the sway direction of the barge was done. It showed a decrease in natural period in this direction when comparing the DSF to a jacking system. The same behaviour is found in the liftdyn model created in this chapter.

The analysis is done for only one draft meaning that it does not cover the full after steel-to-steel phase. The non-linear behaviour of the LMU is not taken into account which could result in under or over estimation of the LMU load. Furthermore, the barge is now effectively moored to the jacket meaning that the system is non-linear (Massie, 2001) this also means that the symmetric motions can result in non-symmetric motions. Non-linearities cannot be solved in this liftdyn model and have to evaluated in a time domain model. As the literature study showed the highest loads on the system occur during the before steel-to-steel phase therefore only this phase will be investigated in time domain.

## 7.7 Discussion

It can be concluded that the jacking stage, in terms of design loads, is not critical. Local horizontal design loads are lower than those considered in the concept design. This means that higher sea states can be investigated.

For the mating phase, the interface loads were found to be higher for a jacking system compared to a DSF. The higher interface loads are a result of a larger relative movement between the barge and topside caused by a change in eigen periods of the system. This change causes out of phase behaviour. The LMU loads are lower for a jacking system compared to a DSF, which is due to a smaller maximum displacement of the topsides being a result of the mentioned antiphase behaviour.

Increasing the stiffness of the jacking system increased both the interface loads and the LMU loads as the out of phase behaviour remained present. This trend continued until a turnover point at which the movement of the barge and topsides synchronised, leading to same system behaviour as with a DSF. Passing this turnover point sets a trend of decreasing interface loads. Following these findings, it can be concluded that early assessment of the eigen periods of a soft system is important. For design purposes, it is crucial to determine which side of the turnover point the system is on, as the relationship between stiffness and interface loads depends on the system's position relative to this turnover point.

An interesting finding is the presence of a torsional moment at the interface between the topside and the barge, causing a difference in horizontal interface loading from the centre of the barge increasing toward the bow. More accurate loads of a mating analysis can only be done in the time domain.

# 8.0 3D TIME DOMAIN FLOAT-OVER MODEL

To make the study of a jacking system float-over more concrete for its intended purpose, more precise interface(connection topside and barge) and LMU loads need to be determined. This can only be achieved through a time-domain analysis for the mating phase. This modelling is done in the program aNySIM.

In Chapter 7 the before steel-to-steel phase was touched upon and analyst in the inhouse frequency domain solver. However, the before steel-to-steel phase is highly nonlinear due to impact loading therefore is this phase analysed in a time domain solver. The time domain solver used is aNySIM. Another option was Orcaflex, however within the company and in literature little to no information was available regarding float-overs in these programs. Since they all had the same functionalities, the choice was made for ANySIM since previous float- over have been analysed in ANySIM as well, therefore previous float overs could be used as reference to compare the Jacking system with a DSF.

aNySIM allows engineers and naval architects to conduct simulations related to ship performance, seakeeping, manoeuvring, and structural analysis. It provides valuable insights into how vessels and marine structures will behave in different maritime environments.

The aim of the model is to analyse the influence of a jacking system on the float-over. This is done by varying the stiffness of the interface spring. After the analysis, the impact forces on the LMU's, Sway fenders and interface spring (Joint) are post processed.

## 8.1 Input

The Input for the ANySIM model is more detailed than the liftdyn model as it changes over time. This requires a more detailed mooring analysis and surge and sway fenders. As the model changes over time the draft has to change as well.

Mooring analysis

The mooring line arrangement is added in more detail as can be seen in the figure below. The mooring should prevent the barge from rotating in the jacket slot and keeping the topside supports aligned with the LMUs on the jacket. The mooring lines are modelled as a "tautline" here the elongation is added as a table taking the nonlinear behaviour of the mooring lines into account. Due to the catenary shape an initial pretension is present in the cable which is calculated beforehand.

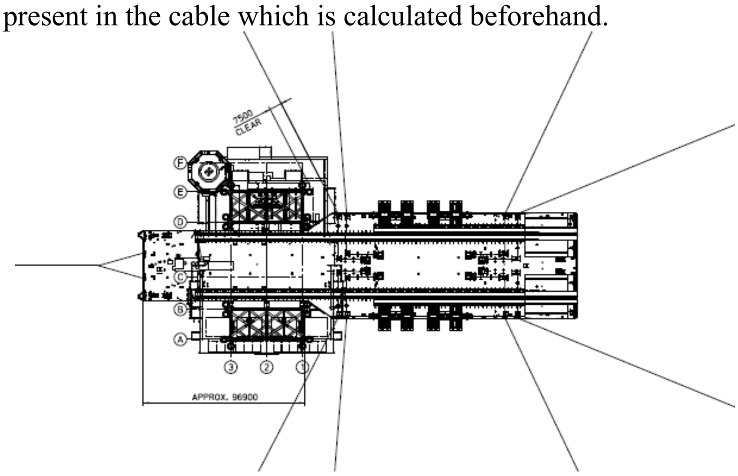


**Figure 8-1 Mooring line arrangement**

Fenders

The jacket and barge are a tight fit through fenders which prevent the barge from moving around in the jacket slot. The fenders are modelled with vertical and horizontal friction coefficients to take the effects of the fenders on the mating analysis into account by having barge fender interactions. Furthermore, the non-linearities are incorporated via a compression table. The stiffness curve used for the analysis is based on the compression – reaction curves from a sway fender design used for a previous float-over project. The sway fenders have a non-linear stiffness. Hysteresis damping in the fenders is considered by modelling both the loading and the unloading curve. An energy loss of 25% will be applied as a typical load curve. The fender stiffness has been combined with the jacket stiffness to get the loading / unloading curve for the combined system.

LMU
The function of a LMU is dampening the impact load. In the program it is modelled as a fender ball with a nonlinear compression curve which is different compared to the linearisation which has been used in chapter 7. Furthermore, a LMU also has damping which is equal to 2.5% of the critical damping based on previous projects within the company.

The interface spring is modelled as eight joints to compare with the DSF case of the North Sea study and previous projects. The joint has a stiffness in X and Y direction in the horizontal plane. Furthermore, a bilinear damping is used. For the DSF case the joint stiffness is set to 1*1010 N/m and for the jack stiffness cases, the recalculated stiffness of the jack is used. The detailed stiffness calculation is explained in section 8.2 below.

Ballast
As mating operation spans the load transfer from 0 till 50% the barge must be ballasted down. This is done by a force series that after a calculated amount of time is added to the model. The ballast plan is made before hand and linearised for model input.

## 8.1 Analysis

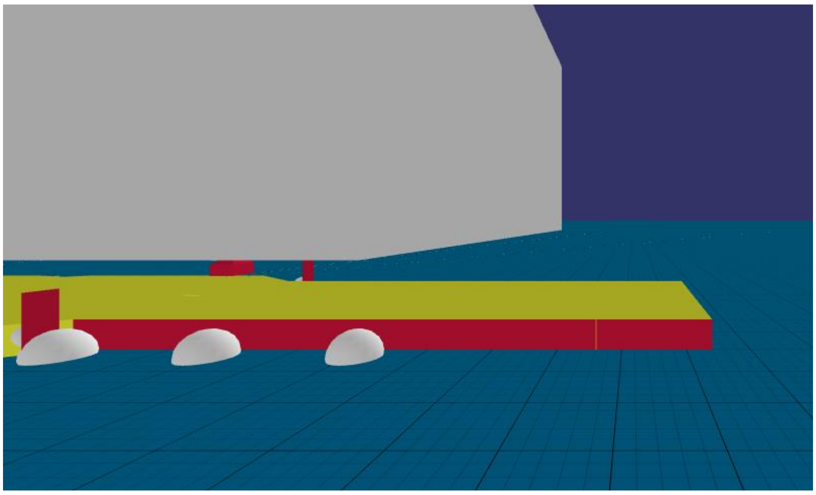

**Figure 8-2 ANySIM model visual**

In the conventional way of modelling the interface connection between the DSF and topside a horizontal stiffness of $1*10^{10}$ N/m is applied per Interface spring point. Using the table section 6.2 it is already clear that the horizontal stiffness using a jacking system is in the order of $10^6$ smaller.

For one individual jack a horizontal stiffness of 10202 kN/m is used in chapter 7. To recalculate the stiffness for eight jacks we multiply this number by fifty-two and divide by eight. Only the linear stiffness is used since plastic deformation of the jacks is not wanted as deformation of the jacks means end of life. This results in a stiffness of 66313 kN/m per support for the analysis as only eight jacks are used. aNySIM uses newtons so the stiffness for case 1 is 6.6*10^7 N/m. In a DSF case this stiffness is $1*10^{10}$ so $10^3$ larger.

**Table 8-1 Horizontal stiffness cases**

| CASE | STIFFNESS C11 [N/m] | STIFFNESS C22 [N/m] | TOTAL (8JOINTS) |
|---|---|---|---|
| DSF | $1*10^{10}$ | $1*10^{10}$ | 8*10^10 |
| JACK1 | $6.6 * 10^7$ | $6.6 * 10^7$ | $5.3 * 10^8$ |
| JACK2 | $13.1 * 10^7$ | $13.1 * 10^7$ | $1.0 * 10^9$ |
| JACK3 | $19.6 * 10^7$ | $19.6 * 10^7$ | $1.6 * 10^9$ |
| JACK4 | $26.1 * 10^7$ | $26.1 * 10^7$ | $2.0 * 10^9$ |
| JACK5 | $32.6 * 10^7$ | $32.6 * 10^7$ | $2.6 * 10^9$ |

For every sensitivity case the environmental cases of Table 8-2 are used. It should be noted that the significant wave hight is remarkably height compared to previous float-overs performed by the company and alternative float over methods in chapter 2. However, the float-over for the North Sea study will be performed in the North Sea where these sea states have a high likelihood of occurrence based on a weather assessment done by the company.

**Table 8-2 Environmental cases**

| case_id | n_seeds | Hs_swell | Tp_swell | Direction_swell | gamma |
|---|---|---|---|---|---|
| SS04 | 10 | 2.4 | 8 | 195 | 3.3 |
| SS08 | 10 | 2.4 | 8 | 345 | 3.3 |
| SS12 | 10 | 2.00 | 8 | 225 | 3.3 |
| SS16 | 10 | 2.00 | 8 | 315 | 3.3 |
| SS17 | 10 | 1.25 | 7 | 270 | 3.3 |
| SS18 | 10 | 1.00 | 8 | 270 | 3.3 |

## 8.2 Results

The results of the time domain simulation are presented in this chapter. It should be noted that in order to reduce the calculation time the jacking system is represented by 8 spring connection and in the frequency domain it was done with 52 springs.

**Interface spring (Load on jacking system or DSF)**

In Table 2-1,The force in the joint (Interface spring) between the topside and the barge show in the time domain the same trends as in the frequency domain. For beam waves the difference in maximum load is significant and the reduction in force stays large for all jacking cases. For head waves the reduction in loads is significant for the softest jacking case stiffness but the reduction of force becomes less after 2 stiffness cases (JACK4). The results in the time domain also show higher loads for following waves as for head waves. This was already found and explained in the frequency domain analysis of the after steel-to-steel phase in section 7.5.

The maximum total horizontal force is calculated by calculation the resultant of local max Fx and Fy force however these forces do not have to have to occur at the same time as the force varies over time. The maximum horizontal force per spring is calculated as follows: The max force in x and y direction are combined in the following manner $F_h = \sqrt{F_x^2 + F_y^2}$ the force in any direction follows from the relative displacement between the topside and barge times the spring stiffness.

**Table 8-3 Maximum local horizontal force [mT] in the interface spring***

| **Hs** | 2.40 | 2.40 | 2.00 | 2.00 | 1.25 | 1.00 |
|---|---|---|---|---|---|---|
| **Tp** | 8.0 | 8.0 | 8.0 | 8.0 | 7.0 | 8.0 |
| **Heading** | 195deg | 345deg | 225deg | 315deg | 270deg | 270deg |
| | | | | | | |
| **DSF** | 1591 | 1880 | 1018 | 1093 | 1288 | 1476 |
| **JACK1** | 1242 | 1824 | 771 | 1096 | 920 | 1070 |
| **JACK2** | 1352 | 1863 | 936 | 1128 | 1058 | 1183 |
| **JACK3** | 1389 | 1800 | 911 | 1100 | 1145 | 1374 |
| **JACK4** | 1381 | 2016 | 866 | 1113 | 1179 | 1354 |
| **JACK5** | 1471 | 1988 | 937 | 1092 | 1079 | 1391 |

*To compare the horizontal loads of this figure with the figures of section 7, the forces in this figure need to be divided by 6.5

Simple multiplying the worst-case local load by 8 to calculate the total global horizontal load on the system is not accurate as shown in chapter 7.5. Therefore, the sum of loads at the interface is taken at every timestep from which the maximum combination is taken. For the worst case ,the maximum summed load of is 9811mT for the jacking system base case1 and 9910 mT for the DSF. This is for the governing sea state of Hs = 2.40m and Tp= 8.0 seconds. The summed Fh of other cases can be found in attachment 7. By summation of the local loads the direction of the forces is lost which discards a reason to perform a time domain analysis.

It can be concluded that a flexible interface spring in the of the jacking system results in equal or lower loads compared to the DSF. However, this is dependent on the wave heading and wave period. It should be noted that the design sea states (Hs) are higher than the reference float-over technologies in chapter 2 and this will result in high local horizontal design loads for the jacks or DSF. The DSF case is modelled with a stiffness so not fully fixed as the assumption is. This means that following the results from table 8-3 the mentioned turnover point of section 7.7 has not been reached. This explains why the maximum local interface loads for jacks are more favourable in these cases.

**LMU**

The loads on the LMU's are generally the most interest as they are an expensive consumable component in the float-over operation where its price is driven by the design load. Meaning reducing the LMU load results in a lower cost of this consumable. Additionally, failure of the LMU also means that the jacket will be damaged. The LMUs are the first object to be contact with the topsides during mating. This means that at first the topsides leg will impact the LMU. After further ballasting the LMU is constantly loaded, and the load will become a horizontal compression force. This means that the LMU has two different types of loading that are interesting namely horizontal impact loading and horizontal compression.

The maximum LMU load is determined by using the load in x and y direction and calculating the resultant force. The table below gives an overview of the loads for different cases, starting with the DSF case followed by the jacking system sensitivity cases starting with the lowest stiffness.

**Table 8-4 Maximum horizontal compression force LMU**

| **Hs** | 2.40 | 2.40 | 2.00 | 2.00 | 1.25 | 1.00 |
|---|---|---|---|---|---|---|
| **Tp** | 8.0 | 8.0 | 8.0 | 8.0 | 7.0 | 8.0 |
| **Heading** | 195deg | 345deg | 225deg | 315deg | 270deg | 270deg |
| | | | | | | |
| **DSF** | 1979 | 2506 | 1195 | 1350 | 1803 | 1756 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **JACK1** | 1535 | 2575 | 889 | 1303 | 1162 | 1172 |
| **JACK2** | 1567 | 2103 | 1049 | 1344 | 1371 | 1450 |
| **JACK3** | 1706 | 2160 | 1056 | 1387 | 1565 | 1554 |
| **JACK4** | 1584 | 2555 | 951 | 1309 | 1451 | 1623 |
| **JACK5** | 1732 | 2569 | 1069 | 1256 | 1308 | 1679 |

For beam waves a lower stiffness resulted in significant lower horizontal loads, a reduction up to 30%. For other cases, the difference in horizontal force between a jacking system and DSF was not as significant as can be seen in the table above however the compression force was still lower or equal for a jacking system compared to the DSF.

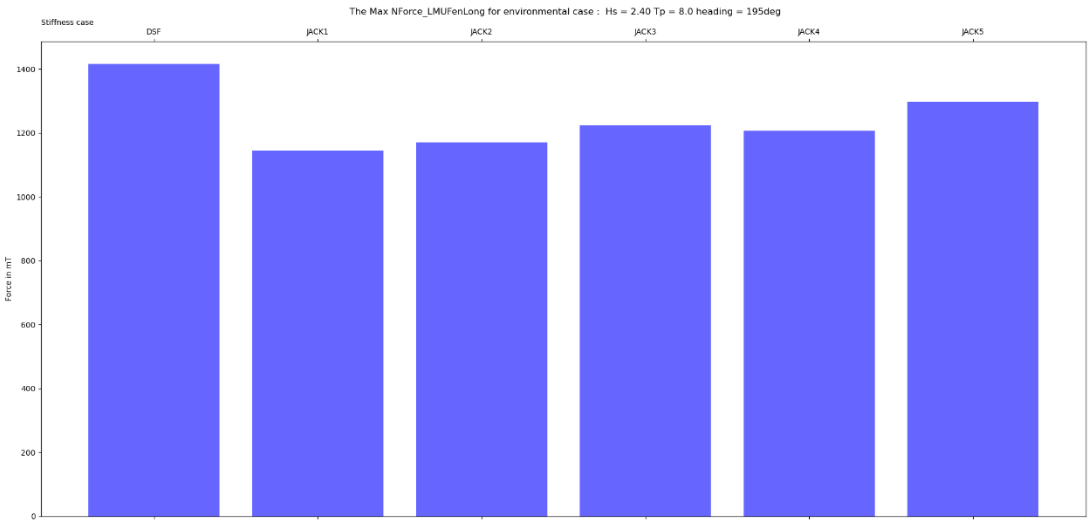


**Figure 8-3 Impact loads on LMU in x direction**

The unknown impact loads on the LMU were a reason to move from frequency domain calculations to a time domain analysis. The analysis showed that for head waves there was a reduction in impact load on the LMU however this reduction did not flatten as fast as for beam waves. The horizontal stiffness cases kept an impact load between 1100 and 1200mT where the DSF case was almost 1400mT this is a minimum reduction of 200mT by having a stiffness difference of order 10^3.

**Table 8-5 Impact load LMU head waves (195deg)**

| Case | Impact load [mT] |
|---|---|
| DSF | 1399 |
| JACK1 | 1086 |
| JACK2 | 1108 |
| JACK3 | 1207 |
| JACK4 | 1120 |
| JACK5 | 1224 |

Only for beam waves, a significant reduction in impact loading due to the lower horizontal interface stiffness is visible. The difference was varied between a reduction for the lowest stiffness of impact force of 2% till 5%. The remaining impact loads can be found in attachment 7.

**Sway fender**

The sway fenders located on the port and starboard side between the jacket and barge are also loaded during the mating operation. These sway fenders were not in the frequency domain model as its effects on the loads during the after steel-to-steel phase are considered small. These seem only be affected for following waves this is expected as the barge wants to rotate around its centre but is at the bow restrained by sway fenders and the topside connected with the supports in the LMU's. As the waves approach the barge from the stern, the effect on the stern is the largest. However, the effect of the lower stiffness on the sway fender loads disappears after two cases. For this direction, the highest horizontal forces in the interface spring are found.

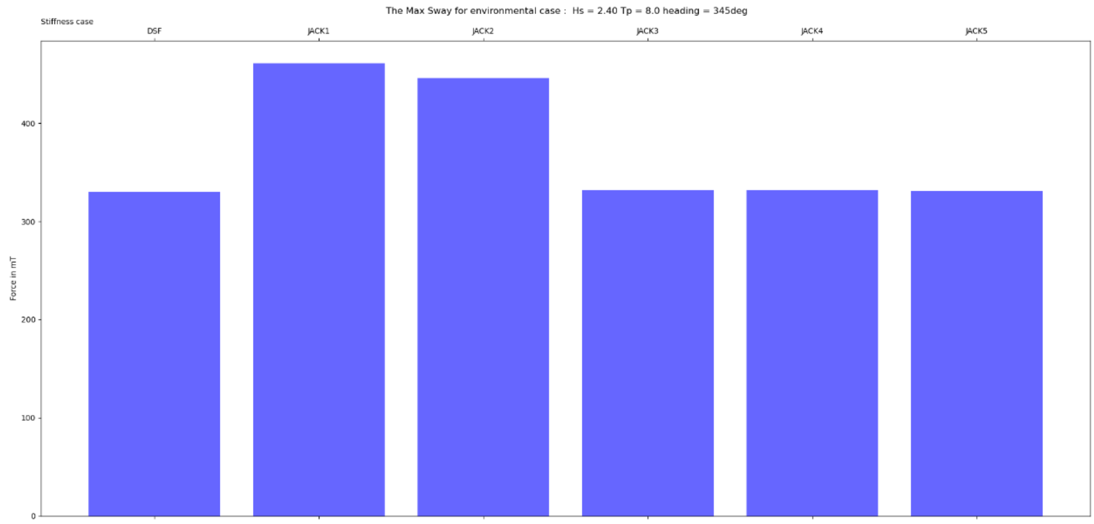


**Figure 8-4 Impact loads on the Sway fender**

The maximum force in the mooring lines is not affected by the change in stiffness as it only deviated 1% across all cases with no trend. The 1% can be regarded as caused by the time domain simulation in which no run is identical because it requires a generated wave record in which each record is different.

## 8.3 Conclusions and limitations

The Time domain model showed that a lower horizontal stiffness reduces the impact loading on the LMU for all investigated wave headings and peak periods with 2 till 5%. The horizontal compression force on the LMU's showed to be lower or equal for the base case jacking system compared to a DSF. As found in the frequency domain analysis, a lower horizontal stiffness of the jacking system results in a lower local horizontal force on the jacking system and the LMU's. The before steel-to-steel phase float-over can be modelled using the stiffness relation described in this chapter.

The sensitivity cases have been run with a seed of 10 meaning that each case in simulated over ten runs. This is accurate enough for investigating the behaviour of the system. However, the number of seeds have to be increased to 100 to accurately retrieve the local loads based on a probability. Furthermore, wind and current are not included in this model as they are static loads of the preparation phase. After the mating starts, the wind and current will not influence the loads of the jacking system and LMU's. However, these two factors should be included to obtain the accurate loads. The local maximum is determined by the mean max of the ten seeds as no seed is equal in the time domain. In a frequency domain analysis the maximum is calculated based on the variance of the response spectrum which is approximately the mean of the 1/3 of the response values. This already explains why the loads are higher in the time domain.

There are limitations in the calculation of the total global horizontal load. The stiffness of the barge deck is not considered, no DSU is used for the jacking system. It should be noted that the global interface loads found the time domain model of chapter 8 are higher than in section 7.5. This makes sense since the LMU's are not loaded in vertical direction in chapter 8, the draft of the barge is 0.8m shallower and nonlinear effect such as second order wave forcing are included. Second order wave forces are known to have a large effect on moored vessels this is not included in the frequency domain calculation. Earlier this thesis it was concluded that a shallower draft resulted in higher loads.

A maximum of the horizontal loads can be found below. Here the local maximum is for the 8 supports instead of the 52 which were used in chapter 7.

**Table 8-6 Interface force BSTS***

| Draft at 11.3m | Maximum local horizontal load | | Total global horizontal load at interface | | | Max local * number of jacks | |
|---|---|---|---|---|---|---|---|
| | Heading | mT | Heading | mT | % of topsides weight | mT | % of topsides weight |
| Jacking system | 345 | 1824 | 345 | 9811 | 30 | 14592 | 46 |
| DSF (fixed) | 345 | 1880 | 345 | 9910 | 31 | 15040 | 47 |
| Designed | N.A. | 800 | N.A | N.A | N.A | 6400 | 20 |

*Maximum local loads needs to be divided by 6.5 to compare with chapter 7

## 9.0 CONCLUSION AND RECOMMENDATION

This chapter presents the conclusions drawn from the literature review, concept design, and the frequency and time domain models. The conclusion is split in the jacking stage and the mating of the float-over operation. Additionally, recommendations for further research and modifications to the conceptual design are provided.

### 9.1 Conclusions

This thesis investigated a barge-integrated topside jacking system. The literature review in Chapter 2.3 indicated that the jacking system should be compared to the HIDECK and UNIDECK float-over techniques. Since this thesis does not address the financial aspects of these techniques, the jacking system must have equivalent or better installation limits to remain competitive.

The following research questions were defined after the literature review.
*How does the jacking system influence the float-over operation?*
With the following sub questions:

- What happens during the jacking stage to the barge's stability?
- Can the design loads of the jacking system be determined through a simple model?
- How does the horizontal stiffness of the jacking system influence the loads during the mating operation?
- What is the difference in between the float-over with a DSF and with the jacking system?

The research focused on the jacking stage and the mating phase.

**Jacking stage**
*Stability*
The stability of the barge is analysed in chapter 5.0 which investigated the behaviour of jacking without ballasting. Jacking of the topsides without ballasting was proven to be of no concern for the barge's stability. The GM stayed far above the required 0.15m stated by Noble Denton for transport and even above the advised 1.0m for positioning before float-over. In the worst case scenario, the GM reduced from 17m to 11m. So, this makes the GM of no concern for the investigated cases in section 5.3.

Furthermore, the heeling due to jacking was identified as a potential issue as the deck of the barge immerses at 9 degrees and the advised freeboard reduced the maximum heel to 6 degrees. This was proven to be of no concern given an initial heeling angle of 0.1deg or a wind speed of 10m/s in section 5.4 & 5.5. An initial heeling angle will result in a larger heeling angle after the topside has been jacked up to height. In the worst case of a 45000mT topside, starting with a heeling angle of 0.10 degrees resulting in a heeling angle of 0.13 degrees. This means that due to rotation, the topside CoG will shift only 0.03m in the horizontal plane with respect to its original position. Attention should be paid to the ballast plan to make sure that the initial heel will not result in a to large heeling angle as the investigated cases had an increase of 30%.

The wind will generate a heeling angle which increases after jacking the topside. For the heaviest topside investigated, the heeling angle increases with about 0.3 degrees which is double the heel with zero jacking height. This will result in a horizontal offset of only 0.08 m over a height of fifteen meters. It could be advantageous to start with a heeling angle opposite of the wind direction to compensate for the additional heel due to wind loading after jacking.

The non concerns for a positive GM also means that shallower drafts can be used in case a larger float-over height is required. The initial heel in combination of heel due to wind loading is of no concern for the investigated cases but the heeling angle increases rapidly after jacking so care should be taken with ballasting before jacking. This should prevent intermediate or after jacking ballasting.

The natural roll period of the barge was also investigated. However, it was shown that the period increased and thus it moved farther away from the peak period of the incoming waves. The roll period of the barge increases when the topside will be jacked up to height. This means that the motions of the barge will be more favourable after the barge is jacked up. This is independent of the weight of the investigated topside. As for the float-over location in the North Sea, long swell waves with a peak period of 17 seconds are almost non-existent. Due to the large initial roll period and the increase in period after jacking this is also not a concern.

*Loads jacking system driving system*
The total global horizontal design load and the local maximum design load for the driving system were investigated in section 7.3. The global horizontal load was expressed as % of vertical topsides weight. This was done in two ways: one by summing the local horizontal loads and two by multiplying the local maximum by the number of jacks. The two methods resulted in a significant difference. Further investigation showed that this difference in horizontal load is caused by a difference in local horizontal load on the jacks. Meaning that the jack at the bow has a higher horizontal load than the jack closer to the stern. This difference is caused by the location of the topside on the barge and the heave roll pitch movement of the barge. The barge wants to pitch and roll around its centre and the topside is not above this centre. Because the connection is modelled as springs the resulting horizontal force follows from the elongation or compression of the spring.

Increasing the stiffness of the jacking system showed that the local horizontal loads increased due to a reduction in eigen period for the dominant motion. The reduction in loads was the most for following seas. However, these wave heading were not governing for the jacking stage, the beam seas were governing for the jacking system driving systems. The assumed 5% of vertical topside weight used as total global horizontal load on the interface was more than sufficient for the investigated sea states. As the driving system was only subjected to a local load of 22mT where it was designed for 31mT. This means that higher sea states can be investigated for the jacking stage or the design could be changed with lower design loads.

The jacking stage can be accurately modelled in the frequency domain as non-linearities are of small interest in free floating condition.

Mating (float-over)
The design loads on the jacks itself are investigated for the mating operation, BSTS which was done in the time domain and ASTS which was done in the frequency domain. The maximum local horizontal load on the jack was found for stern quartering (345 degree) waves. This could be explained by the topside located at the bow and connected to the jacket while the stern is subjected to incoming waves creating a moment around the jacket. The maximum local load on the jack was more than twice its design load. The sea state under which this maximum local horizontal load is found is far higher than the competing float-over technologies in chapter 2. The HIDECK normally has a limit of 1.5m for head seas as can be read in chapter 2. Where for the North Sea study float-over sea states with a Hs of 2.4m are applicable. This makes it impossible to compare technologies as the loads are very dependent on the sea sates, topsides weight and barge.

**Table 9-1 Overview horizontal loads**

| BSTS Time domain | | | | | | | |
|---|---|---|---|---|---|---|---|
| Draft at 11.3m | Maximum local horizontal load | | Total global horizontal load at interface | | | Max local * number of jacks | |
| | Heading | mT | Heading | mT | % of topsides weight | mT | % of topsides weight |
| Jacking system | 345 | 1824 | 345 | 9811 | 30 | 14592 | 46 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| DSF (stiff) | 345 | 1880 | 345 | 9910 | 31 | 15040 | 47 |
| | | | | | | | |
| ASTS Frequency domain | | | | | | | |
| Draft at 12.05m | | | | | | | |
| Jacking system | 270 | 102 | 345 | 3544 | 11 | 5304 | 16.5% |
| DSF (stiff) | N.A. | N.A. | 270 | 2965 | 9 | N.A. | N.A |

The global horizontal load on the interface is calculated in the same manner as for the driving system. This is done to compare with literature as it states the global horizontal load as percentage of topsides weight. As can be seen in the table above the difference between the methodologies is significant. For the jacking system 30% or 46% of topsides weight is found as global horizontal load. In section 7.5 it was concluded to be caused by the presence of a torsional moment which caused large differences in loads per jack.

The presence of the torsional moment means that current design methods for interface connections in float-overs are deemed not accurate. Designing based on the local sum of Fh or local max. Fh times the number of jacks will result in under-designing or over-designing the jacking system. The same holds true for LMU and DSU design loads. I have observed that although time-domain analyses are necessary, the results from these analyses are often simplified to such an extent that it neglects the reason for conducting time-domain analyses in the first place. This is because the torsional moment is neglected, and directionality of the local load is lost due to calculation $F_h = \sqrt{F_x^2 + F_y^2}$ .The torsional moment is shown to be more important for low horizontal stiffness connections such as a jacking system. The absence of the torsional component in other papers makes it difficult or even impossible to compare the results of this study to other studies as it is heavily reliant on vessel properties. The amount of over or under-estimation of loads has not been studied further in more detail and considered a main advice for further study.

Increasing the horizontal stiffness of the jacking system led to a shift of this torsional centre from close to centre of the barge for a low stiffness towards the middle of the jacket footprint for the high stiffness which was visualised in section 7.5. This led to higher horizontal loads on the jack as well as higher LMU loads caused by a decrease in eigen period for this dominant mode shape. This trend continued until a turnover point was reached and the system started to behave as a DSF float-over. It should be noted that a higher stiffness led to decrease in eigen period for this mode shape. This led to the increase in loads for the investigated sea states. It is likely that for very long swell waves (Tp = 19s) this relationship does not hold and will be inverted.

The float-over with jacking system compared to a DSF float-over led to an increase of a maximum local horizontal load on the jack. This was visualised in section 7.5. The jacking system led to a decrease in compression loads on the LMU and lower impact loads on the LMU. Typically the impact loads are the most of interest but because of the high sea states, the compression loads were found to be more important.

Concluding the analysis in the frequency domain program liftdyn and the time domain program aNySIM. The jacking system can be modelled accurately by a two-body system with an interface spring in between like a DSF but now with a low stiffness. Chapter 6 showed that a 1D model is helps to gain understanding in behaviour of the jacking system during a float-over. However, it also showed that a simple 1D model does not give all the information needed to determine the design loads on the jacking system. The mating operation should be done in time domain as the frequency domain analysis only was usable for investigating behaviour trends and eigen periods which proved to be helpful. Non-linearities in the second order wave loading and the non-linear compression curve of the LMU's are not captured in the frequency domain.

## 9.2 Recommendations

Following the finding on the so called torsion centre causing a moment at the interface between topside and barge. The location of this torsion centre should be investigated for the float-over as this influence the local horizontal loads resulting in under or over design. The percentage of over design could be interesting to investigate.

The relation between a lower horizontal stiffness and the loads on the LMU were investigated in this thesis. In this relation a turnover point was found. It would be interesting to know how this point is dependent on the weight of the topsides or barge as this could give additional insight.

A recommendation for further concept design is to reduce the number of jacks in the jacking system to reduce the percentage difference in horizontal loading for the driving system of the jacking system following section 7.3. Reducing the difference in local horizontal load on the jacking systems optimizes the design. It can also be interesting to variate the location of the jacks, IE closer to each other at the sides of the topside and further apart in the middle.

The exceedance of the design capacity of the jacking system during the mating phase could be solved by either lowering the sea sates or by adding a horizontal DSU. The DSU should only be active in the mating stages and not during the jacking stage to not cause misalignments. Using a friction pad with a horizontal elastomer would be an option to use at the interface between the jacking system and the topside.

Another option would be investigating possibilities to reduce the moment on the barge generated during incoming waves from stern quartering seas. This could possibly be achieved by keeping the barge in place with tugs in the transverse direction or adding thrusters with dynamic positioning to the H-851.

A recommendation for future research is investigating the float over with a jacking system but now with a shorter barge. From both models followed that the H-851 did not favour incoming waves of a 345-degree angle. Performing the float-over with a shorter barge could result in more favourable loads as a shorter barge has more of its length between the jacket slots. By this the arm of the barge reduces. However, this likely influences the stability and float-over weight capacity because the hydrostatics change due to shortening of the barge. Placing the topside further to the centre of H-851 is not possible since only part of the barge is narrowed.

The design sea states for head and quartering waves are high compared to reference float-overs described in chapter 2. These chosen design sea states give may give great operability however they also require remarkably high design loads. Reducing these sea states would still bring the design cost down but it would increase the waiting on weather time.

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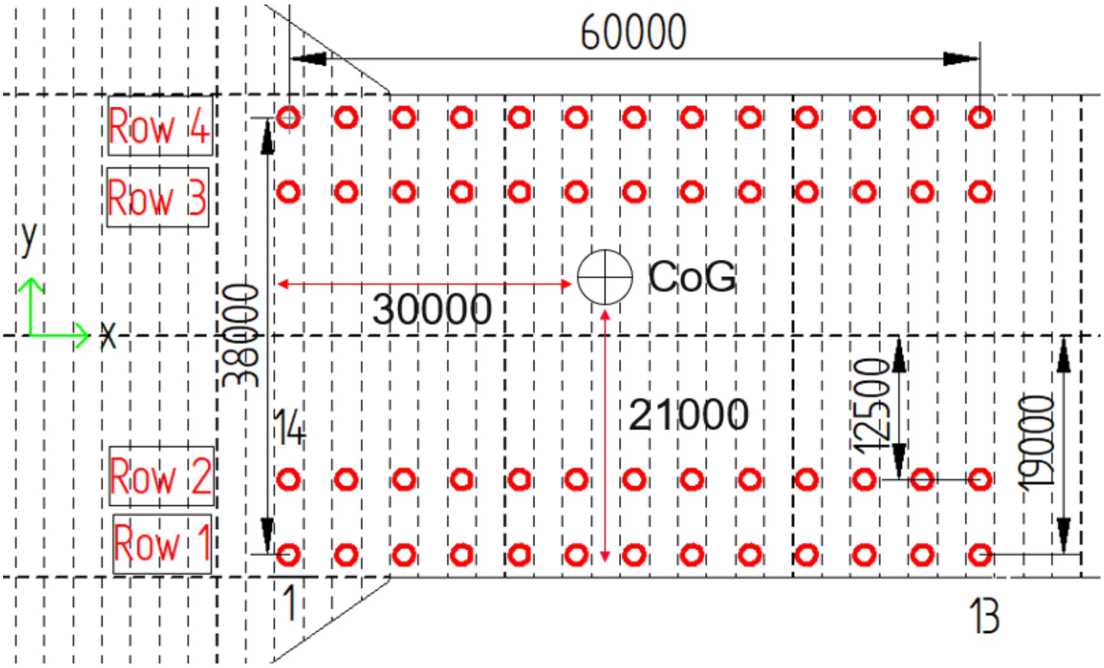
**ATTACHMENT 1 DETAILED CALCULATION JACKING SYSTEM**

This attachment describes the structural calculations for determining the conceptual design loads on the jacks.

The vertical load on the jacks is not equally distributed but depend on their distance from the topside CoG. The vertical design load for the jacks will be calculated based on the bolt theory with a safety factor.

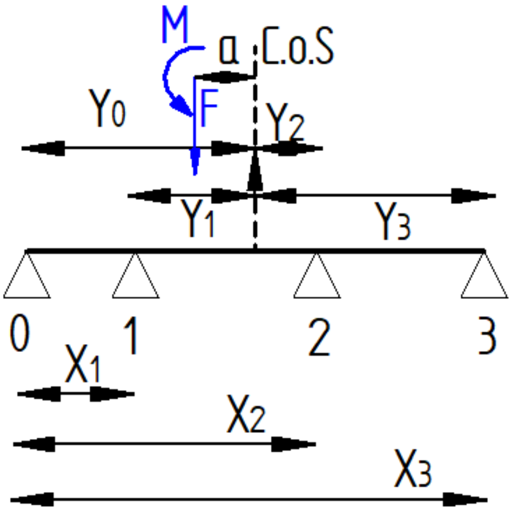
For the calculation of the vertical design loads the following footprint of the jacking system and the location of the topside CoG are used.

The topside has a design weight of 32000mT




The forces are calculated in the program python.

The calculation starts by calculation the loads in the X-direction and there after the distribution over the rows which is the Y-direction.




First the Centre of supports is calculated CoS

$X_{C.o.S} = \frac{X_0+X_1...+X_n}{n}$ with n = 13

Then the polar moment

$I_p = Y_0^2 + Y_1^2 \ldots .+Y_n^2$ with n = 13

Then the moment around the centre of supports
$M_{C.oS} = F_v * a$ with fv the weight of the topside and the distance between CoS and CoG

And finally, the reaction loads on the supports

$F_i = M_{C.o.S} * \frac{Y_i}{I_p} + \frac{F_v}{n}$ with i being a number 0 till 12

Applying the same method over the rows we obtain the following distribution in metric ton.

| | Row 4 | Row 3 | Row 2 | Row 1 |
|---|---|---|---|---|
| **0** | 752 | 728 | 705 | 681 |
| **1** | 752 | 728 | 705 | 681 |
| **2** | 752 | 728 | 705 | 681 |
| **3** | 752 | 728 | 705 | 681 |
| **4** | 752 | 728 | 705 | 681 |
| **5** | 752 | 728 | 705 | 681 |
| **6** | 752 | 728 | 705 | 681 |
| **7** | 752 | 728 | 705 | 681 |
| **8** | 752 | 728 | 705 | 681 |
| **9** | 752 | 728 | 705 | 681 |
| **10** | 752 | 728 | 705 | 681 |
| **11** | 752 | 728 | 705 | 681 |
| **12** | 752 | 728 | 705 | 681 |

An additional 25% of topside weight is distributed over the jacks to account for vertical accelerations

For the horizontal force, 20% of the topside weight is used which is equally distributed over the jacks. Here the force is equally distributed as 20% is twice the recommended load so a simplification is justified.

This results in a design load of $F_h = 0.2 * 32000mT = 6400mT$ equally divided over 52 jacks is 123mT per jack.

The jack was chosen to be a tubular with a Diameter of 1700mm and a wall thickness of 50mm.

First the tubular itself is checked.

## Structural check jack

**Input**

Vertical Design load $F_v := 752\ \boldsymbol{mT} \cdot 1.25 \cdot g = 9218\ \boldsymbol{kN}$

Horizontal Design load $F_h := 123\ \boldsymbol{mT} \cdot g = 1206.2\ \boldsymbol{kN}$

Yield strength $F_y := 325\ \boldsymbol{MPa}$

Diameter pipe $D := 1700\ \boldsymbol{mm}$

Wall thickness $WT := 55\ \boldsymbol{mm}$ $\quad t := WT$

Area Pipe $A_P := \frac{\pi}{4} \cdot \left(D^2 - (D - 2 \cdot WT)^2\right) = 284236\ \boldsymbol{mm}^2$

Maximum unsupported length $l_{brace} := 17600\ \boldsymbol{mm}$ $\quad \frac{D}{WT} = 30.9$

Weight pipe $A_P \cdot 7850\ \frac{\boldsymbol{kg}}{\boldsymbol{m}^3} \cdot l_{brace} = 39.3\ \boldsymbol{mT}$

Axial stress $\sigma_{ax} := \frac{F_v}{A_P} = 32\ \boldsymbol{MPa}$

Buckling check brace

Moment of inertia $I_{zz} := \frac{\pi}{64} \cdot \left(D^4 - (D - 2 \cdot WT)^4\right) = 96251054942\ \boldsymbol{mm}^4$

Radius of Gyration $rz := \sqrt{\frac{I_{zz}}{A_P}} = 582\ \boldsymbol{mm}$

Effective length $K := 2$

Buckling length $l_{buck} := l_{brace} \cdot K = 35200\ \boldsymbol{mm}$

Parameter Cc $C_c := \sqrt{\frac{2\ \pi^2 \cdot E}{F_y}} = 110$

Buckling length/ radius of gyration $\lambda := \frac{l_{buck}}{rz} = 60$

Allowable compressive stress

$$F_a := \begin{cases} \dfrac{\left(1 - \dfrac{\lambda^2}{2 \cdot C_c^2}\right) \cdot F_y}{\dfrac{5}{3} + \dfrac{3 \cdot \lambda}{8 \cdot C_c} - \dfrac{\lambda^3}{8 \cdot C_c^3}} & \text{if } \lambda < C_c \\ \dfrac{12 \cdot \pi^2 \cdot E}{23 \cdot \lambda^2} & \text{else} \end{cases} = 149\ \boldsymbol{MPa}$$

Euler stress $F'_e := \frac{12 \cdot \pi^2 \cdot E}{23 \cdot \lambda^2} = 281.5\ \boldsymbol{MPa}$

Unity check $UC := \frac{\sigma_{ax}}{F_a} = 0.22$

**Axial + Bending check**

Bending moment $M := l_{brace} \cdot F_h = 21229\ \boldsymbol{kNm}$

$$F_b := \begin{cases} 0.75 \cdot F_y & \text{if } \frac{D}{t} \le \frac{10340\ \boldsymbol{MPa}}{F_y} \\ \left(0.84 - 1.74 \cdot \frac{F_y \cdot D}{E \cdot t}\right) \cdot F_y & \text{if } \frac{10340\ \boldsymbol{MPa}}{F_y} \le \frac{D}{t} \le \frac{20680\ \boldsymbol{MPa}}{F_y} \\ \left(0.72 - 0.58 \cdot \frac{F_y \cdot D}{E \cdot t}\right) \cdot F_y & \text{if } \frac{D}{t} > \frac{20680\ \boldsymbol{MPa}}{F_y} \end{cases} = 244\ \boldsymbol{MPa}$$

Bending stress $f_b := \frac{M \cdot 0.5\ D}{I_{zz}} = 187.5\ \boldsymbol{MPa}$

Axial stress $f_a := \sigma_{ax} = 32.4\ \boldsymbol{MPa}$

Cm factor $C_m := 0.85$

Unity check $\frac{f_a}{F_a} + \frac{C_m \cdot f_b}{\left(1 - \frac{f_a}{F'_e}\right) \cdot F_b} = 0.96$

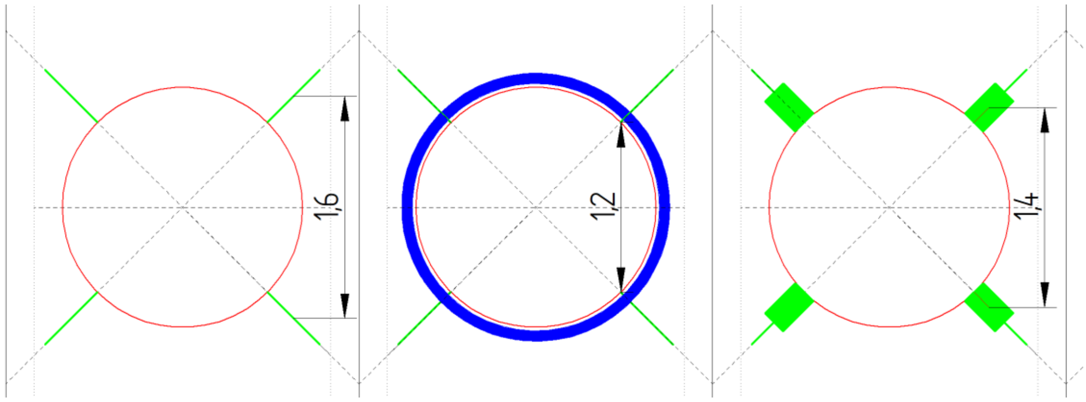
Unity check $\frac{f_a}{0.6 \cdot F_y} + \frac{f_b}{F_b} = 0.94$

For the driving system a lower horizontal load is used namely 5% of the topside weight

$$F_h = 0.05 * \frac{32000mT}{52} = \frac{1600}{52} mT = 31mT$$

$$M = F_h * 17.6m = 304mTm$$

| Concept | 1 | 2 | 3 |
| --- | --- | --- | --- |
| Vertical load | 940mT | 940mT | 940mT |
| Moment | 340mTm | 340mTm | 340mTm |
| Decoupling's arm | 1.6m | 1.2m | 1.4m |
| Vertical load due to decoupled moment | 213mT | 283mT | 243mT |
| Load driving system | 1152mT | 1223mT | 1183mT |
| Per driving per jack | 288mT | 305mT | 296mT |

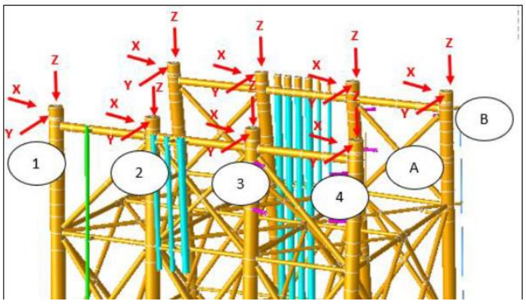


**ATTACHMENT 2 INPUT SIMPLE MODEL**

The stiffnesses of the interface spring and LMU spring have been calculated differently in the past. Therefore, the superposition of these springs is for each project different. The following pages will explain the methodology used to calculate the equivalent stiffness.

**Spring stiffness Methodology Kasawari**

The jacket is eight legged as can be seen in the figure below. For the model we are only interested in the stiffness in x and y direction. The figure below shows that the stiffnesses of the legs all work in parallel.




At every leg there is a Leg mating unit present (LMU) with a linearized stiffness of 3800 mT/m which is in series with the jacket leg.

The Topside is not rigid and has a stiffness. The stiffness is divided in the stiffness at the LMU location and at the DSU location. So, the topside split the two combined springs.

Summarizing: The LMU spring is constructed by calculating the equivalent spring stiffness of the jacket leg, LMU and topside support in series and thereafter adding the eight springs in parallel.

The Interface spring for the DSF case is constructed by calculating the equivalent spring stiffness of the DSF, DSU and topside support and thereafter adding them in parallel.

The Interface spring for the jacking case is constructed by adding the eight stiffnesses of the DSU and then dividing them by the number of jacks (52). The same is done for the topside. Now the stiffness of the jack, DSU and topside are added in series and finally multiplied by the number of jacks.

**Methodology Wheatstone**

The substructure of Wheatstone is having four supports. The combined stiffness of the Topside LMU and SGS has been provided by the report. The LMU spring is constructed by adding the four parallel springs.

The stiffness of the DSU has been provided by the report. Is should be noted that four provide stiffness in longitudinal direction and four in transverse direction. The DSF and topside stiffness at the DSU location is not considered. The spring interface will be the parallel added DSU stiffness for the DSF case.

The Interface spring for the jacking case is calculated by dividing the total DSU stiffness by fifty-two, calculating the equivalent stiffness per jack and there after multiplying by fifty-two.

**Methodology ARKUTUN DAGI**

The LMU spring is constructed by adding the stiffness of the GBS, LMU and topside in series and there after adding this in parallel.

The spring Interface spring for the DSF case is constructed by using the topside stiffness at DSU location and adding it in parallel.

The Interface spring for the jacking case is constructed by using the topside stiffness at DSU location and adding it in parallel then dividing it by the number of jacks. Then adding the stiffness of the jacks and the topside stiffness at DSU location. Finally multiply this stiffness by the number of jacks.

| | **Mass in [mT]** | | **Stiffness in [mT/m]** | | | **Eigen period in [s]** | |
|---|---|---|---|---|---|---|---|
| | m1 | m2 | k1 | k2 | | 1 | 2 |
| **KASAWARI TRANSVERSE JACK CASE** | 167745 | 28000 | 51245 | 13715 | | 26.0 | 3.9 |
| **KASAWARI TRANSVERSE DSF CASE** | 167745 | 28000 | 338211 | 13715 | | 24.1 | 1.6 |
| **KASAWARI LONGITUDINAL JACK CASE** | 158166 | 28000 | 48721 | 23334 | | 20.7 | 3.8 |
| **KASAWARI LONGITUDINAL DSF CASE** | 158166 | 28000 | 324336 | 23334 | | 18.2 | 1.7 |
| **WHEAT STONE TRANSVERSE JACK CASE** | 146762 | 18500 | 51205 | 37440 | | 16.7 | 2.8 |
| **WHEAT STONE TRANSVERSE DSF CASE** | 146762 | 18500 | 964000 | 37440 | | 13.4 | 0.8 |
| **WHEAT STONE LONGITUDINAL JACK CASE** | 137034 | 18500 | 45345 | 37440 | | 16.6 | 2.9 |
| **WHEAT STONE LONGITUDINAL DSF** | 137034 | 18500 | 280800 | 37440 | | 13.5 | 1.4 |
| **Arkutun-Dagi TRANSVERSE JACK CASE** | 168468 | 38000 | 50549 | 28129 | | 20.1 | 4.2 |
| **Arkutun-Dagi TRANSVERSE DSF CASE** | 168468 | 38000 | 774547 | 28129 | | 17.2 | 1.2 |
| **Arkutun-Dagi LONGITUDINAL JACK CASE** | 153768 | 38000 | 44796 | 25539 | | 20.3 | 4.4 |
| **Arkutun-Dagi LONGITUDINAL DSF** | 153768 | 38000 | 261005 | 25539 | | 17.8 | 2.1 |

## ATTACHMENT 3 LIFTDYN INPUT

Liftdyn requires properties of the bodies and connections between the bodies. The first body is light weight mass is determined and the location of the CoG.

**The weight properties of the H-851**
Mating ballast conditions will be calculated with UM to obtain the ballast plan and related mass properties. UM is an internal python tool which has an internal numerical solver. The solver is used to ballast the barge.

The CoG is in local barge coordinates.

| **Items** | **Weight** | **CoG** | | |
|---|---|---|---|---|
| | [mT] | X [m] | Y [m] | Z [m] |
| BILGEWTR | 6619 | -14.6 | 0 | 0.2 |
| DIESLOIL | 98 | 95.1 | 5.1 | 0.7 |
| Jacking system | 4000 | 52.5 | 0 | 5.5 |
| F2F Skidding Track | 310 | -82 | 0 | 17.1 |
| Float-over Equipment | 1707 | -28.5 | 0 | 16.7 |
| FRESHWTR | 353 | 95 | 15.8 | 11.3 |
| FUELTANK | 516 | 108.1 | 14.6 | 11.3 |
| INFILLPC | 840 | -118 | 0 | 14.2 |
| Additional Infill Pieces | 840 | -118 | 0 | 14.2 |
| LIGHTSHP | 35081 | -12.9 | -0.1 | 8.1 |
| Stern Mooring | 60 | -131 | 0 | 15 |
| Additional Skidbeams | 925 | -53.8 | 0 | 16.2 |
| Seafastening | 440 | 55.9 | 0 | 22.5 |
| SKIDBEAM | 2352 | 14.5 | 0.2 | 16.2 |
| | | | | |
| **Total** | **54141** | **-9.5** | **0.2** | **8.1** |

**The location of the LMU’s**

| LMU | X[m] | Y[m] | Z[m] |
|---|---|---|---|
| A1 | -21.5 | 44.25 | EL+16.0 w.r.t. LAT |
| B1 | -21.5 | 26.25 | EL+16.0 w.r.t. LAT |
| D1 | -21.5 | -26.25 | EL+16.0 w.r.t. LAT |
| E1 | -21.5 | -44.25 | EL+16.0 w.r.t. LAT |
| A3 | 21.5 | 44.25 | EL+16.0 w.r.t. LAT |
| B3 | 21.5 | 26.25 | EL+16.0 w.r.t. LAT |
| D3 | 21.5 | -26.25 | EL+16.0 w.r.t. LAT |
| E3 | 21.5 | -44.25 | EL+16.0 w.r.t. LAT |

## ATTACHMENT 4 RESULTS LIFTDYN JACKING STAGE

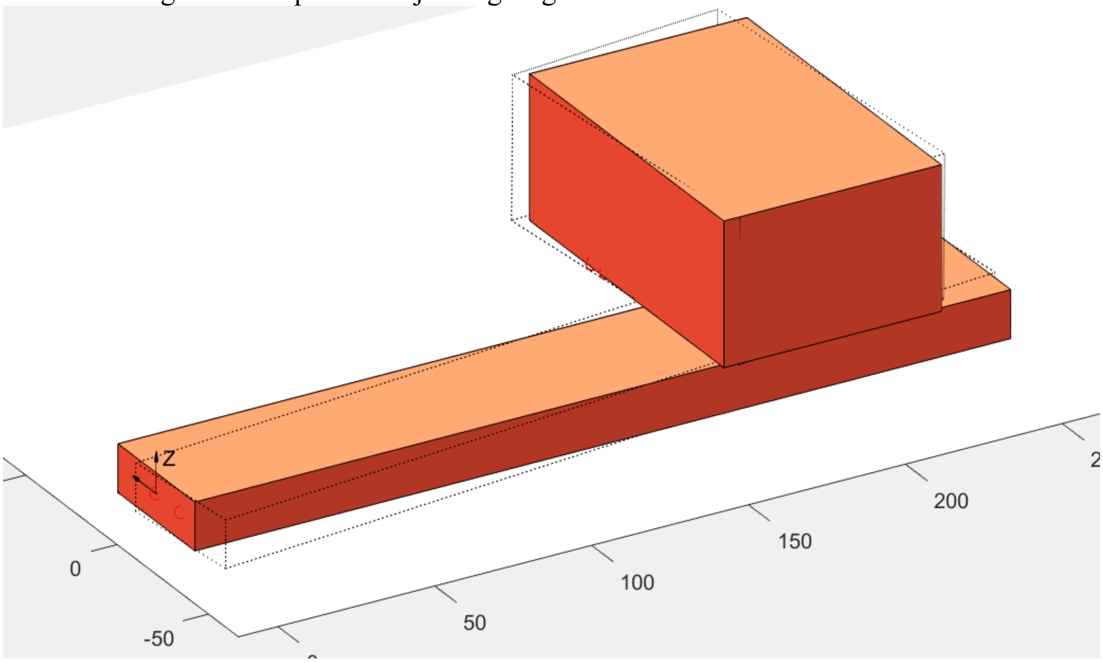
The remaining results from the frequency domain analysis can be found in this attachment.

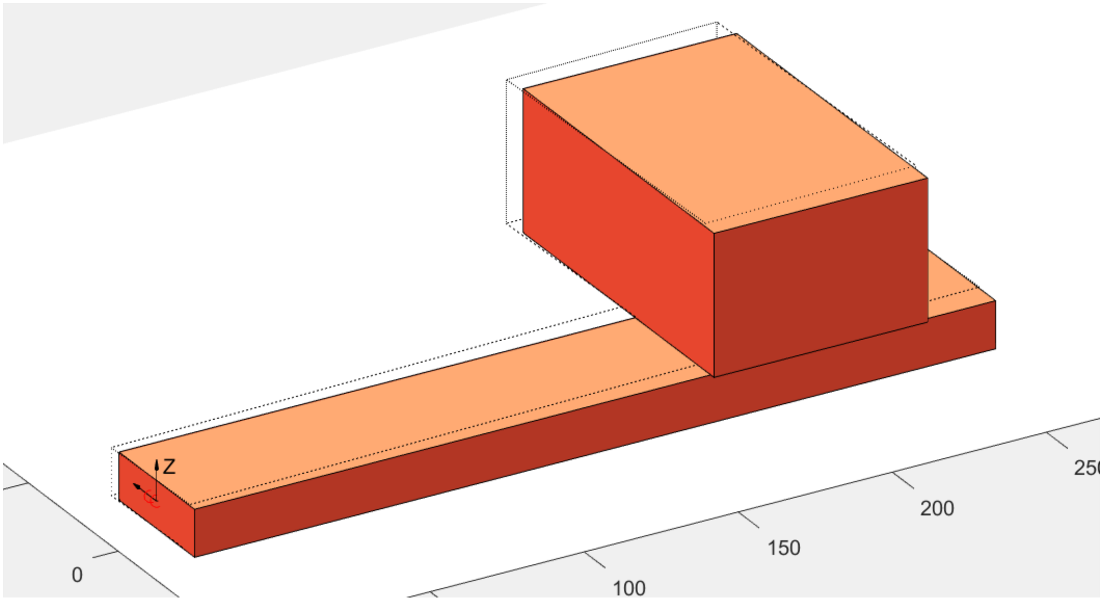
| Local maximum horizontal jacking loads in X direction [mT] | | | | | |
|---|---|---|---|---|---|
| **Heading** | 195 | 345 | 219 | 315 | 270 |
| Case 0 | 7 | 11 | 5 | 7 | 3 |
| Case 1 | 7 | 11 | 7 | 10 | 8 |
| Case 2 | 6 | 10 | 6 | 9 | 7 |
| Case 3 | 5 | 9 | 6 | 8 | 6 |
| Case 4 | 4 | 8 | 8 | 8 | 6 |
| Case 5 | 5 | 8 | 10 | 9 | 6 |
| Local maximum horizontal jacking loads in Y direction [mT] | | | | | |
| Case 0 | 2 | 2 | 3 | 4 | 14 |
| Case 1 | 5 | 7 | 11 | 15 | 20 |
| Case 2 | 5 | 7 | 12 | 16 | 20 |
| Case 3 | 6 | 8 | 13 | 18 | 20 |
| Case 4 | 6 | 9 | 15 | 20 | 21 |
| Case 5 | 7 | 9 | 17 | 23 | 21 |

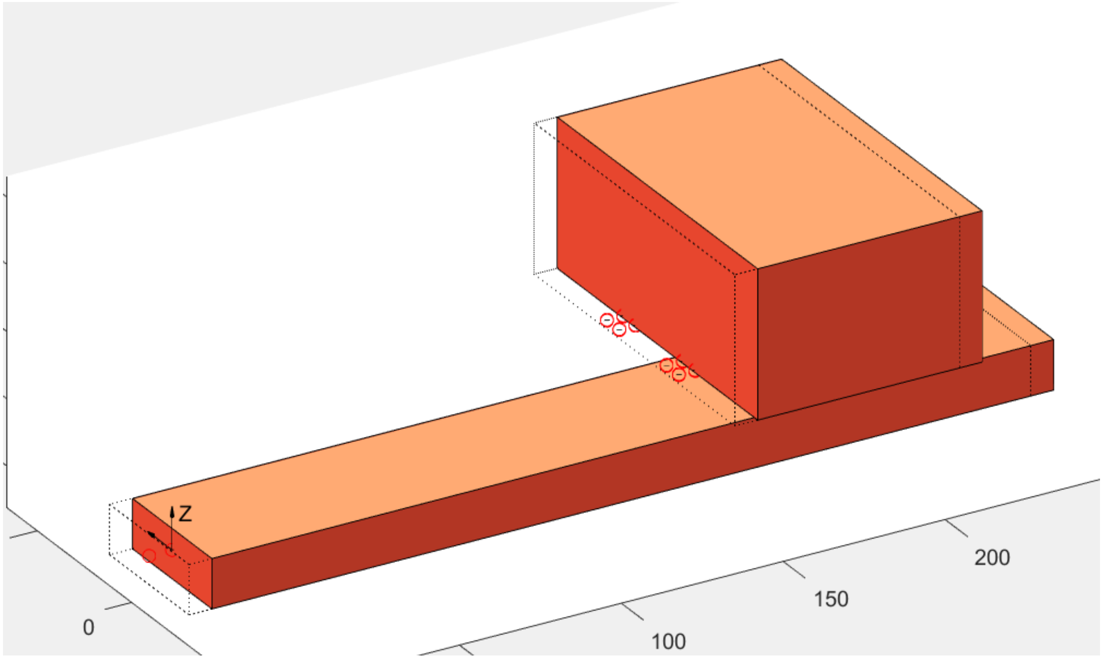
| Maximum local horizontal load based on adding the x and y together [mT] | | | | | |
|---|---|---|---|---|---|
| | **Fh heading 195** | **Fh heading 345** | **Fh heading 210** | **Fh heading 315** | **Fh heading 270** |
| Case 0 | 8 | 11 | 6 | 8 | 14 |
| Case 1 | 7 | 11 | 8 | 10 | 16 |
| Case 2 | 6 | 10 | 8 | 10 | 16 |
| Case 3 | 5 | 9 | 9 | 11 | 15 |
| Case 4 | 5 | 8 | 10 | 13 | 15 |
| Case 5 | 5 | 8 | 12 | 15 | 16 |

When taking the sum over the jacks rather than taking the maximum the local horizontal load the total horizontal loads is lower. However, this difference is not significant. The difference is only 1% in the total horizontal load.

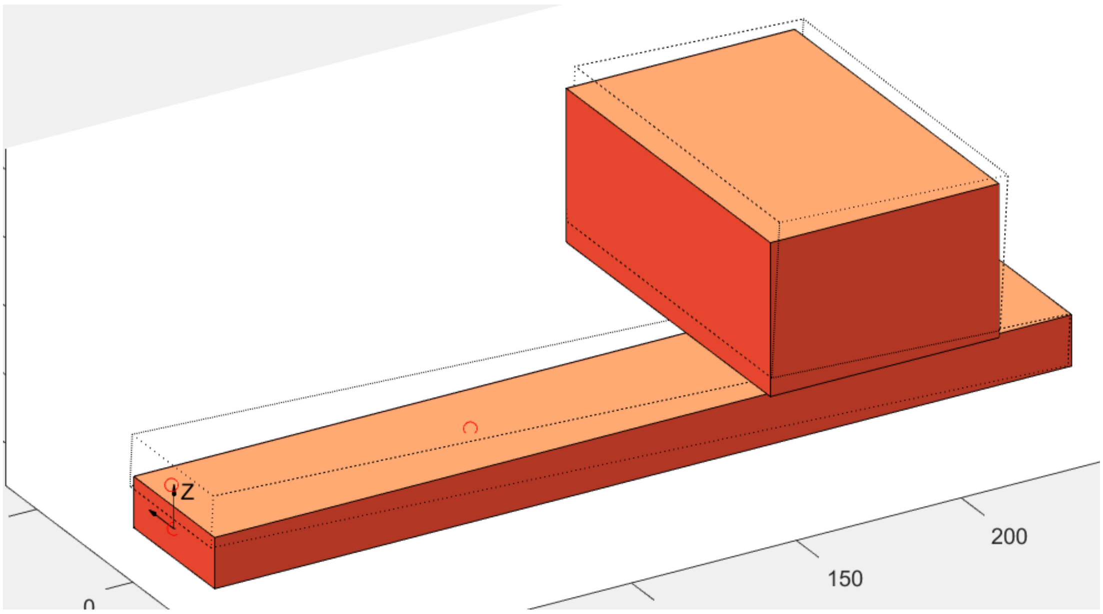
The remaining mode shapes of the jacking stage



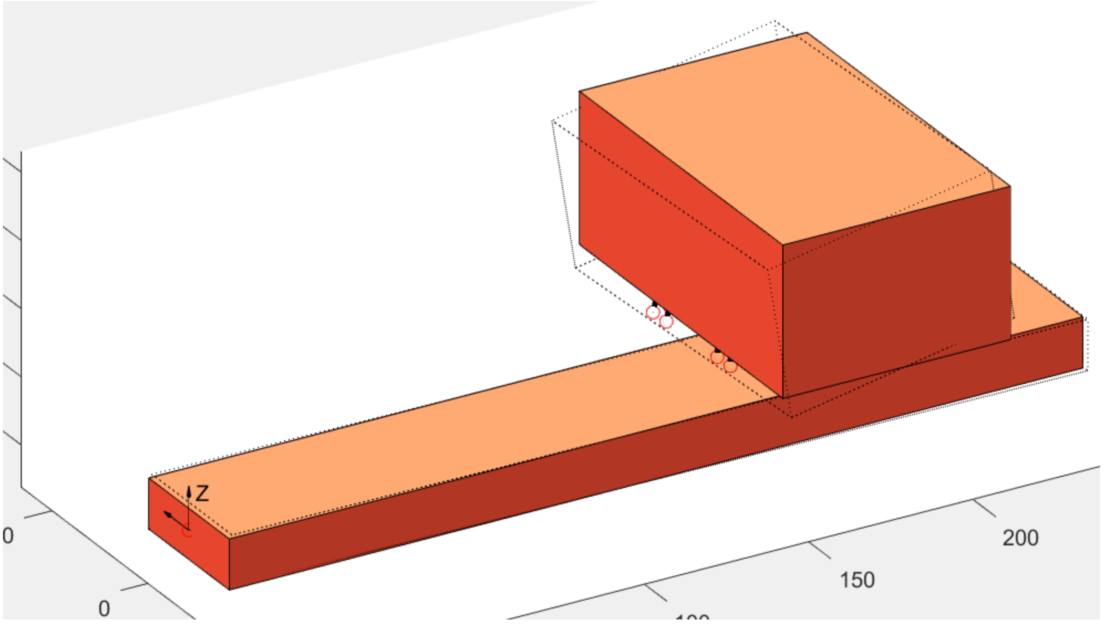



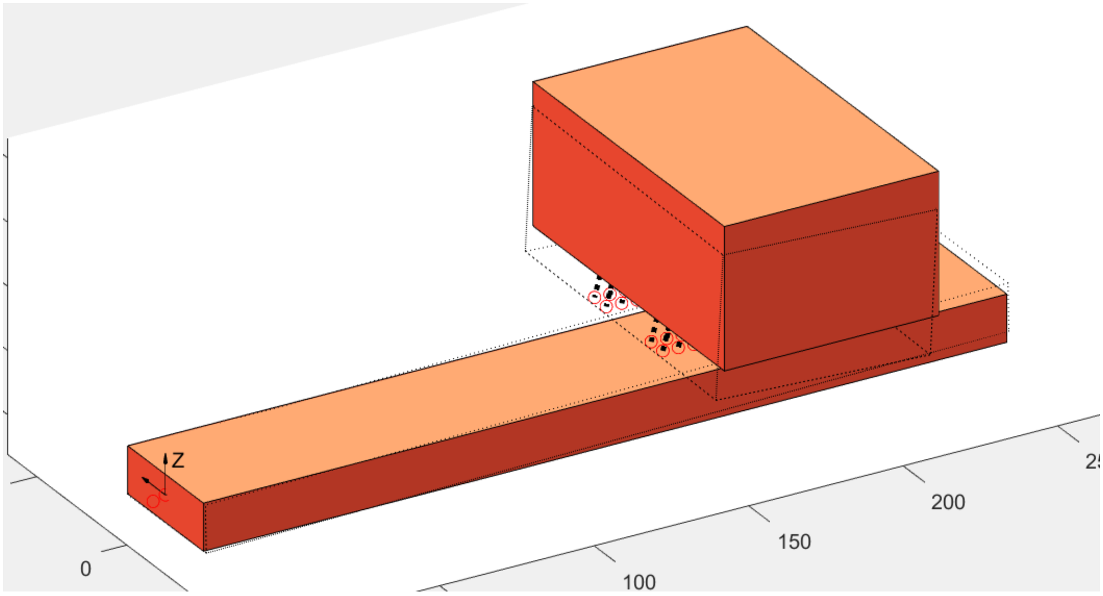


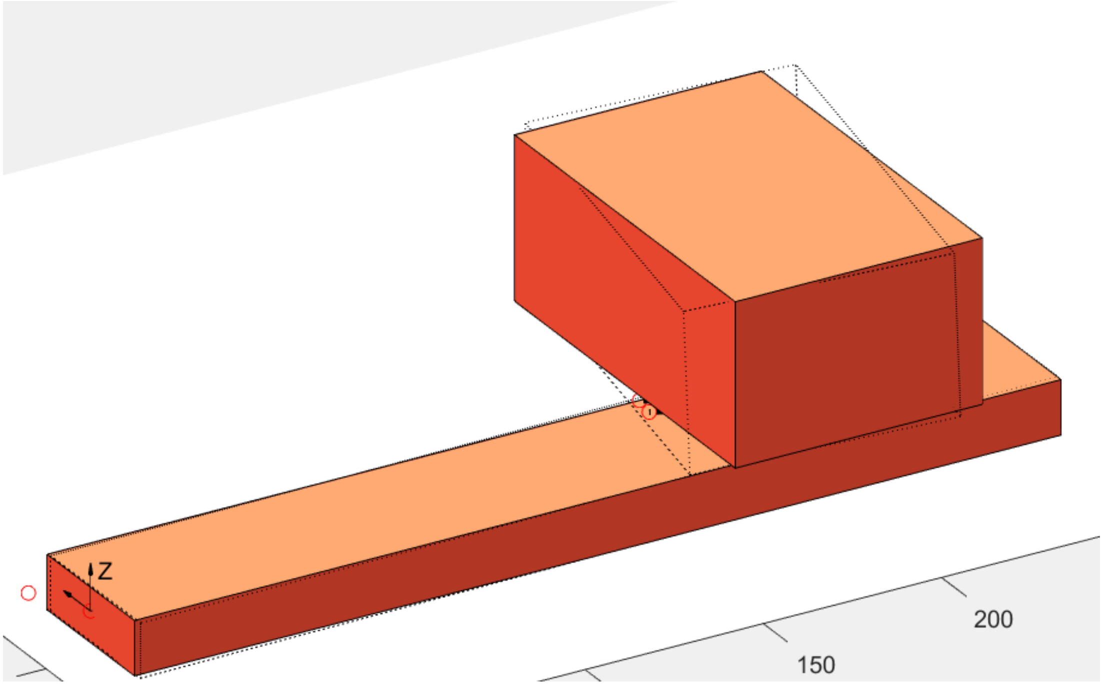
Z
0
100
150
200

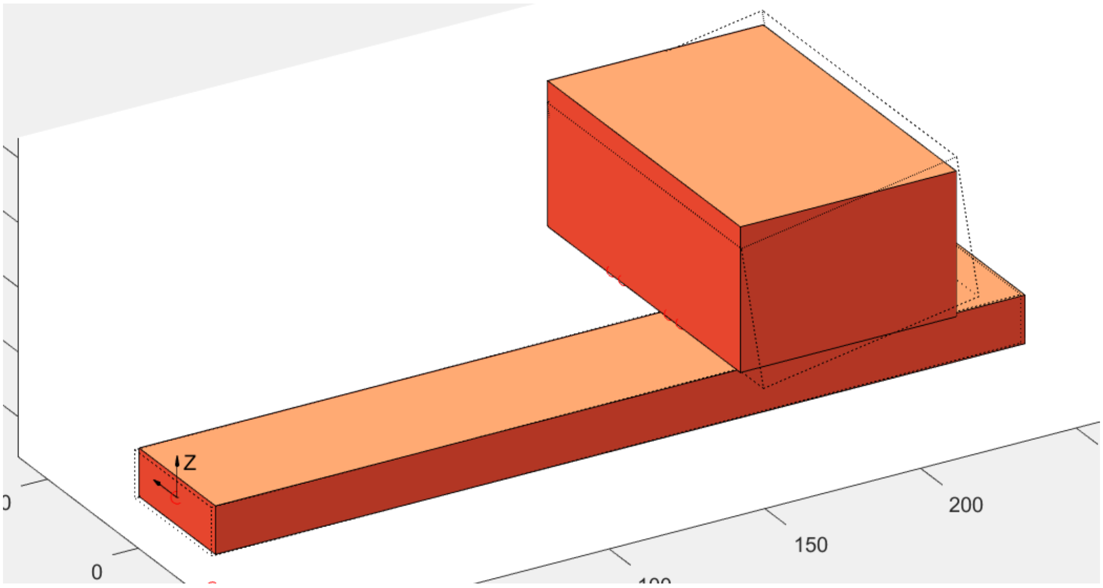



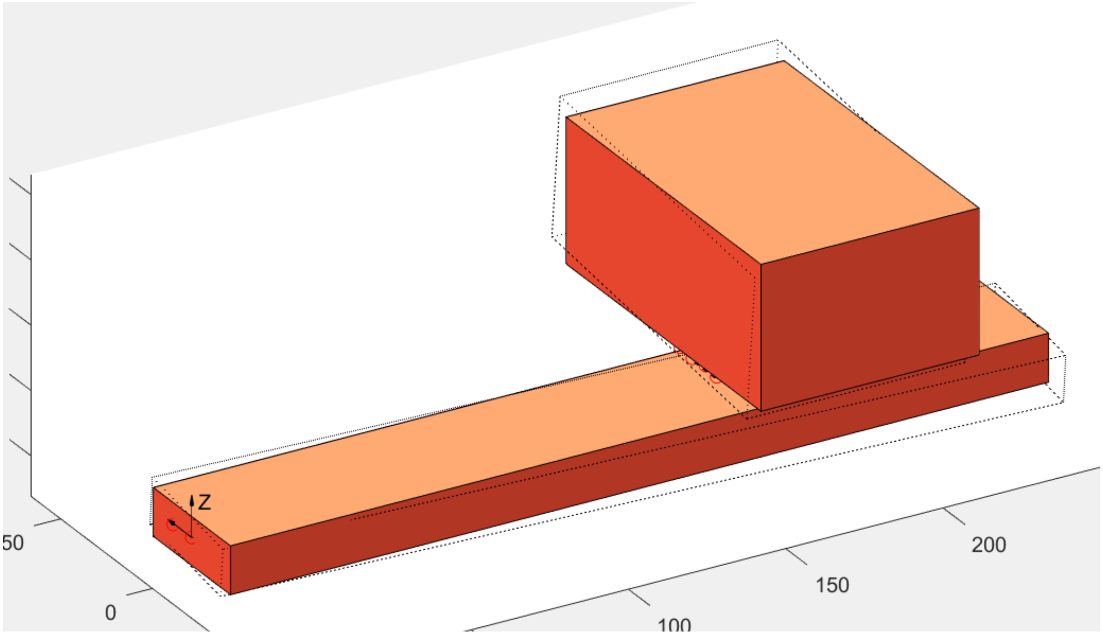
Z
0
150
200


Z
0
0
150
200


Z
0
100
150
200


Z
150
200


Z
0
150
200



Z
50
0
100
150
200

## ATTACHMENT 5 LIFTDYN RESULTS BEFORE STEEL TO STEEL

The remaining results from the frequency domain analysis can be found in this attachment.

Local maximum horizontal jacking loads in X direction [mT]

| Heading | 195 | 345 | 219 | 315 | 270 |
|---|---|---|---|---|---|
| Case 0 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| Case 1 | 8 | 11 | 7 | 10 | 7 |
| Case 2 | 7 | 10 | 6 | 9 | 6 |
| Case 3 | 6 | 9 | 6 | 8 | 6 |
| Case 4 | 5 | 9 | 8 | 7 | 5 |
| Case 5 | 5 | 8 | 9 | 8 | 6 |
| | | | | | |
| Local maximum horizontal jacking loads in X direction [mT] | | | | | |
| Case 0 | 0.1 | 0.1 | 0.1 | 0.2 | 0.3 |
| Case 1 | 5 | 7 | 10 | 15 | 19 |
| Case 2 | 5 | 7 | 11 | 16 | 19 |
| Case 3 | 6 | 8 | 12 | 18 | 19 |
| Case 4 | 6 | 9 | 14 | 20 | 19 |
| Case 5 | 7 | 10 | 15 | 21 | 19 |

| Maximum local horizontal load based on adding the x and y together [mT]. | | | | | |
|---|---|---|---|---|---|
| | **Fh heading 195** | **Fh heading 345** | **Fh heading 210** | **Fh heading 315** | **Fh heading 270** |
| Case 0 | 11 | 11 | 12 | 9 | 13 |
| Case 1 | 9 | 13 | 12 | 18 | 21 |
| Case 2 | 8 | 13 | 13 | 18 | 20 |
| Case 3 | 8 | 12 | 14 | 20 | 20 |
| Case 4 | 8 | 12 | 16 | 21 | 20 |
| Case 5 | 9 | 12 | 18 | 23 | 20 |

The maximum velocity in the POI's (topside legs above LMU) are displayed in the table below.

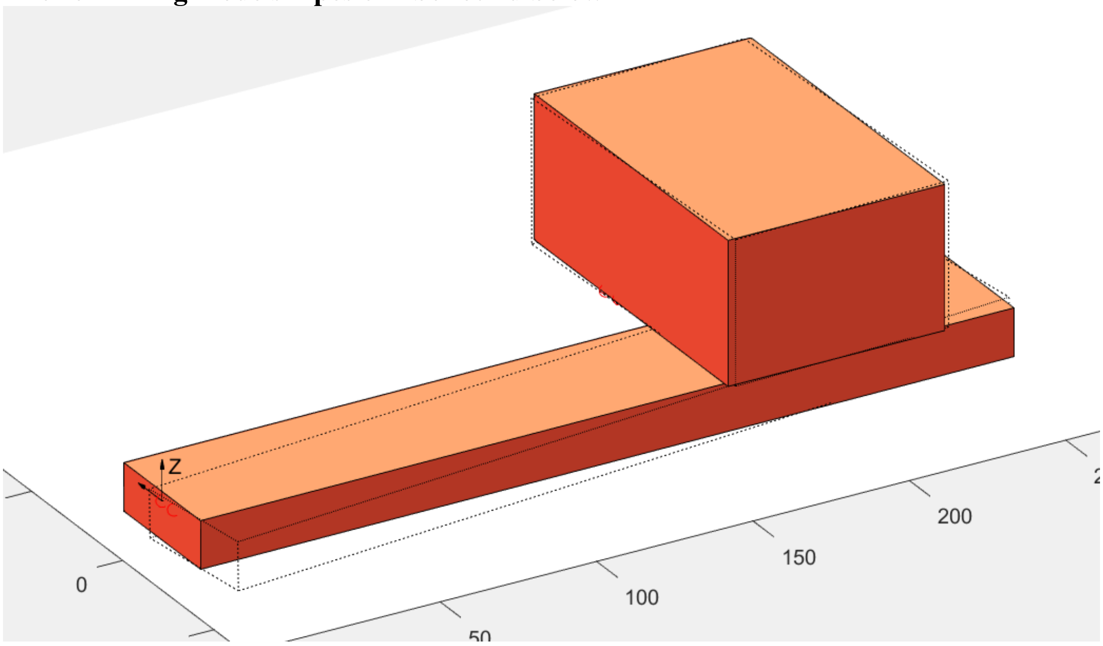
| **in m/s** | **v heading 195** | **v heading 345** | **v heading 210** | **v heading 315** | **v heading 270** |
|---|---|---|---|---|---|
| Case 0 | 0.002 | 0.004 | 0.003 | 0.004 | 0.005 |
| Case 1 | 0.134 | 0.225 | 0.171 | 0.271 | 0.312 |
| Case 2 | 0.130 | 0.220 | 0.166 | 0.265 | 0.306 |
| Case 3 | 0.129 | 0.219 | 0.165 | 0.263 | 0.304 |
| Case 4 | 0.129 | 0.218 | 0.164 | 0.262 | 0.303 |
| Case 5 | 0.128 | 0.217 | 0.164 | 0.262 | 0.303 |

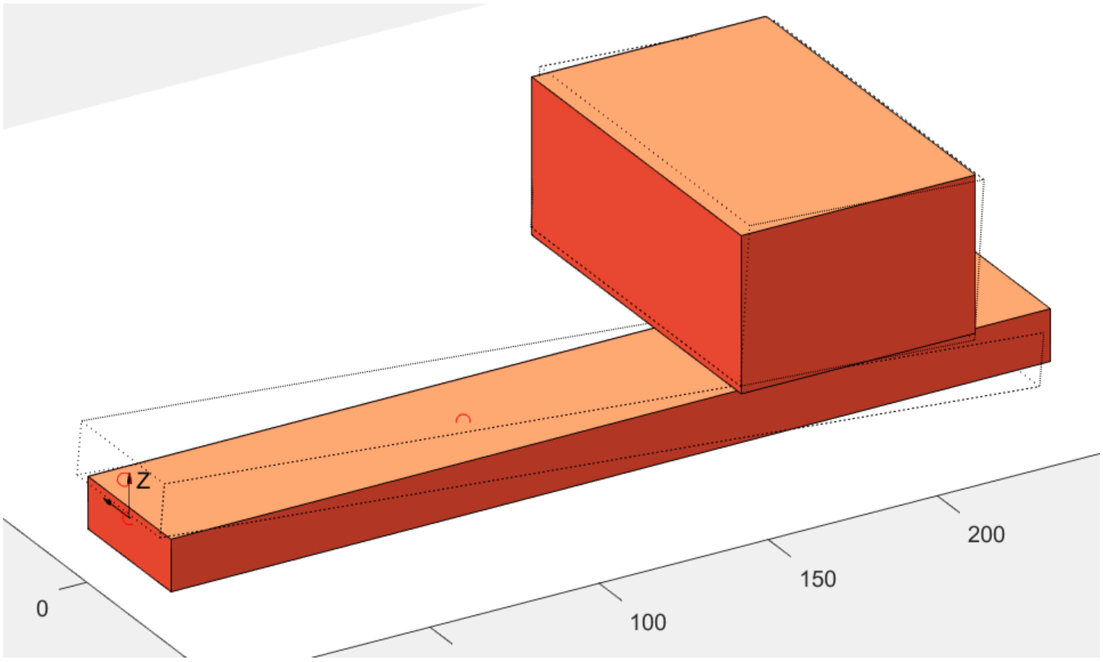
## ATTACHMENT 6 LIFTDYN RESULTS AFTER STEEL TO STEEL

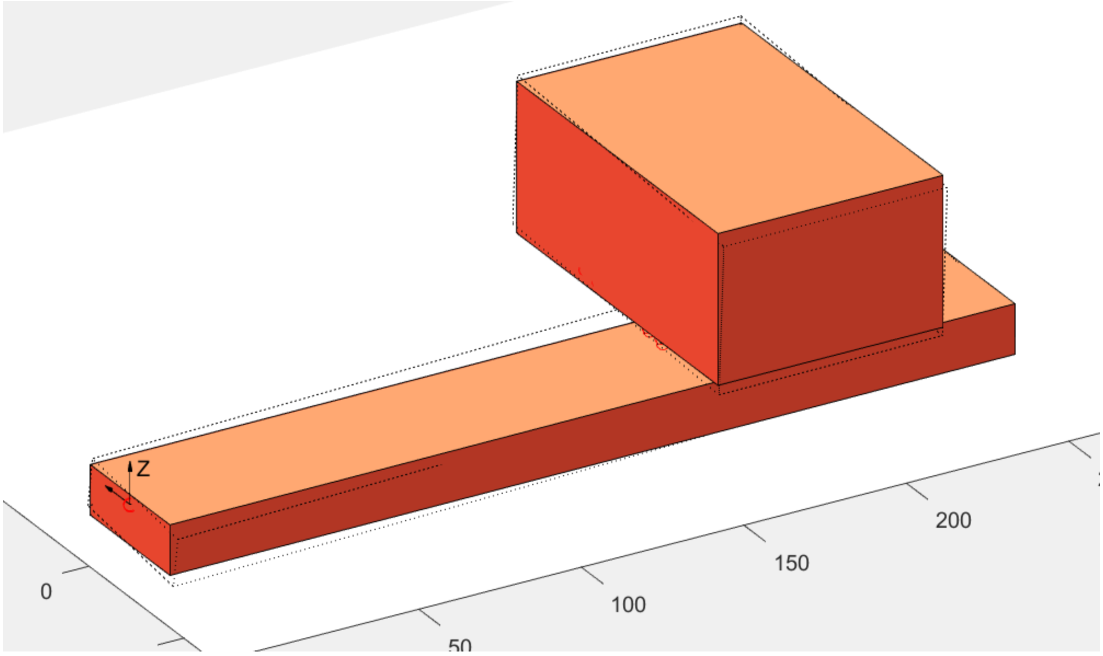
| The local maximum horizontal force X direction [mT] | | | | | |
|---|---|---|---|---|---|
| Heading | 195 | 345 | 219 | 315 | 270 |
| Case 0 | 837 | 1610 | 706 | 1391 | 2551 |
| Case 1 | 33 | 72 | 28 | 48 | 38 |
| Case 2 | 33 | 68 | 36 | 52 | 54 |
| Case 3 | 35 | 66 | 42 | 54 | 63 |
| Case 4 | 36 | 66 | 45 | 56 | 68 |
| Case 5 | 37 | 65 | 48 | 57 | 72 |
| The local maximum horizontal force Y direction [mT] | | | | | |
| Case 0 | 21 | 20 | 34 | 32 | 52 |
| Case 1 | 22 | 28 | 42 | 54 | 95 |
| Case 2 | 33 | 32 | 55 | 60 | 106 |
| Case 3 | 40 | 35 | 66 | 66 | 112 |
| Case 4 | 44 | 36 | 72 | 69 | 115 |
| Case 5 | 47 | 38 | 77 | 72 | 124 |

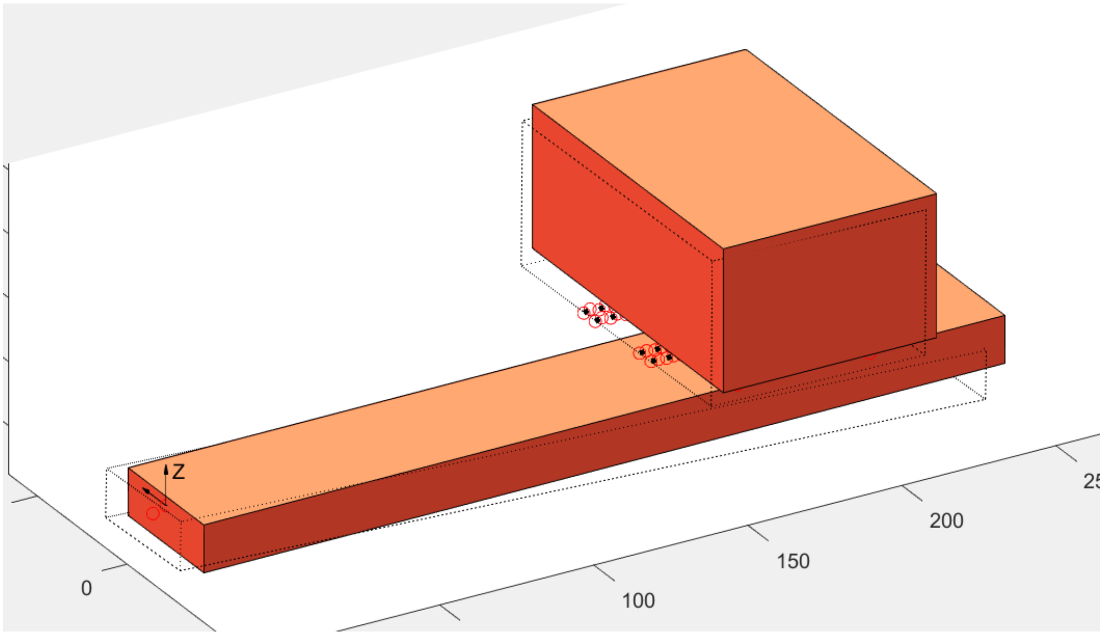
| Maximum local horizontal load based on adding the x and y together. | | | | | |
|---|---|---|---|---|---|
| in mT | **Fh heading 195** | **Fh heading 345** | **Fh heading 210** | **Fh heading 315** | **Fh heading 270** |
| Case 0 | 0 | 0 | 0 | 0 | 0 |
| Case 1 | 9 | 13 | 12 | 18 | 21 |
| Case 2 | 8 | 13 | 13 | 18 | 20 |
| Case 3 | 8 | 12 | 14 | 20 | 20 |
| Case 4 | 8 | 12 | 16 | 21 | 20 |
| Case 5 | 9 | 12 | 18 | 23 | 20 |

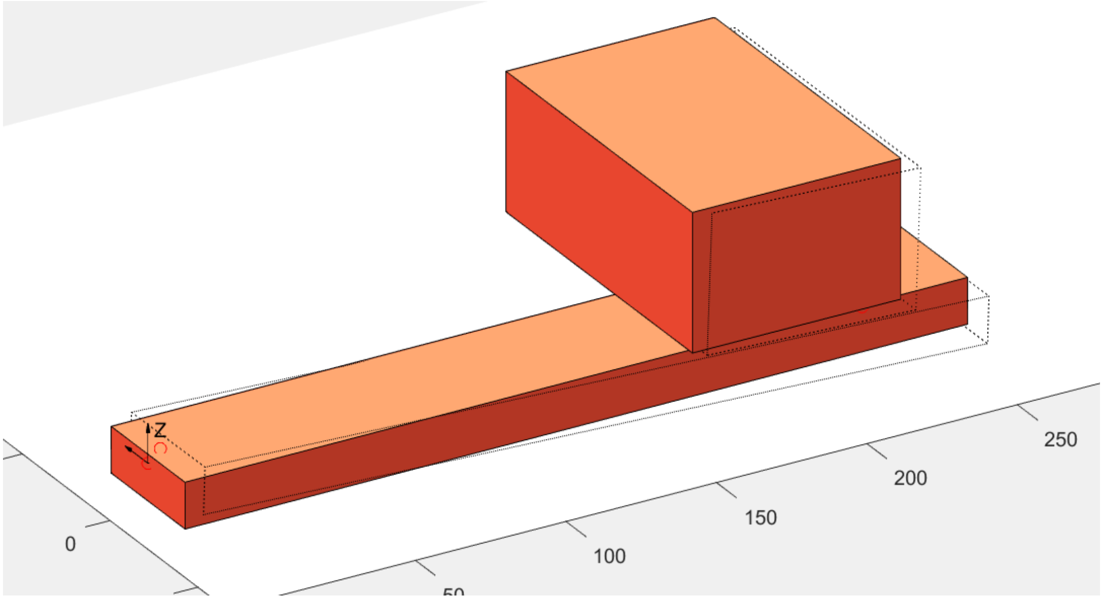
**The remaining mode shapes can be found below**

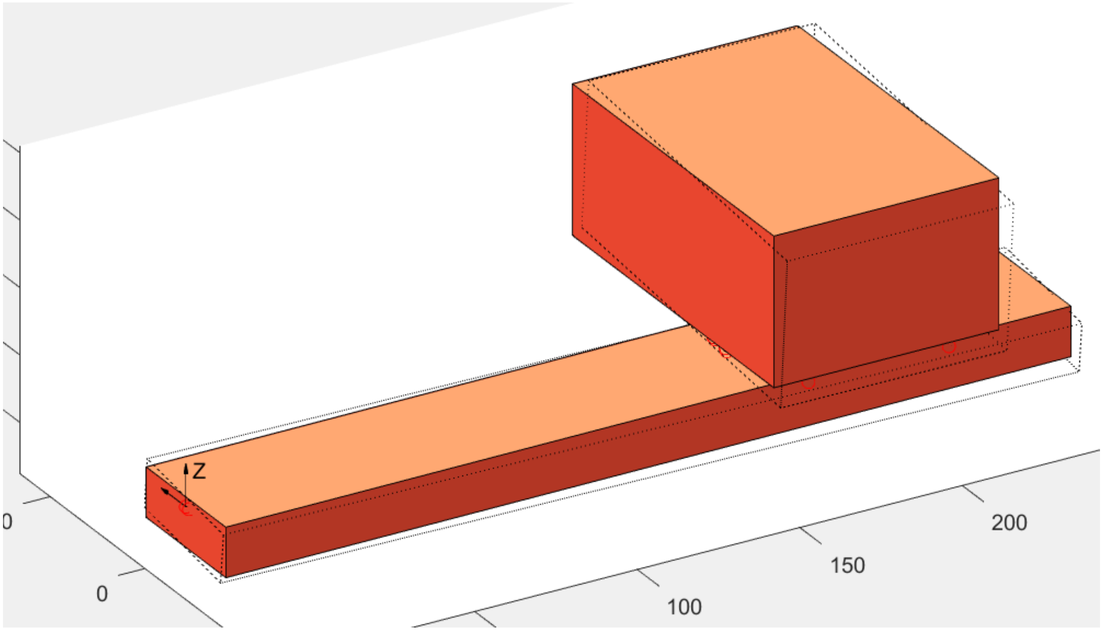


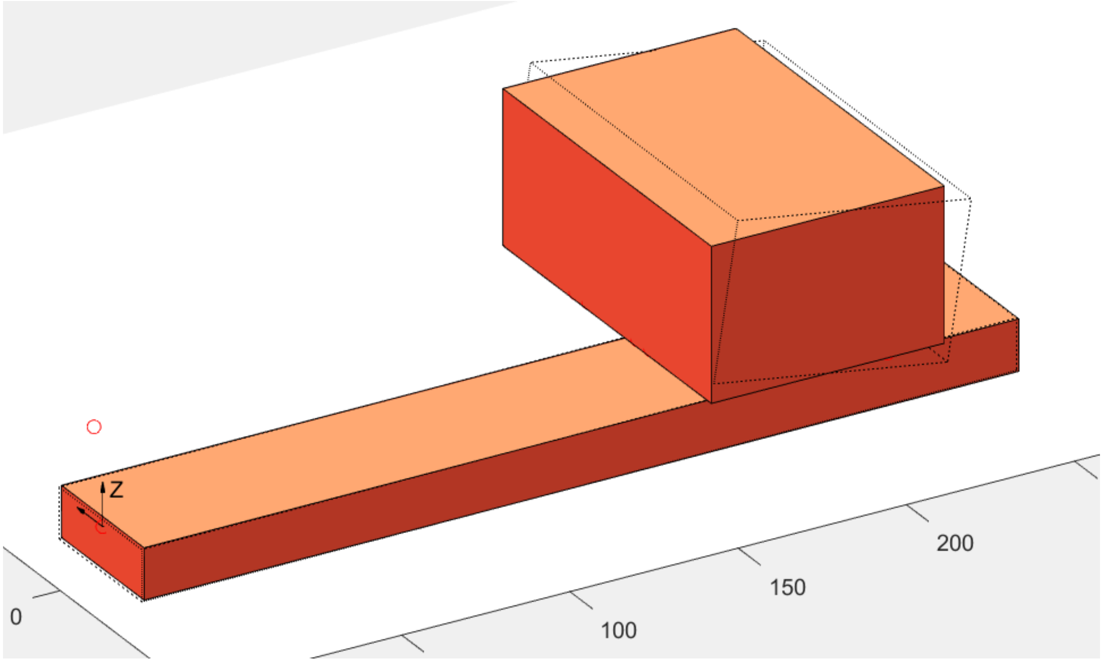



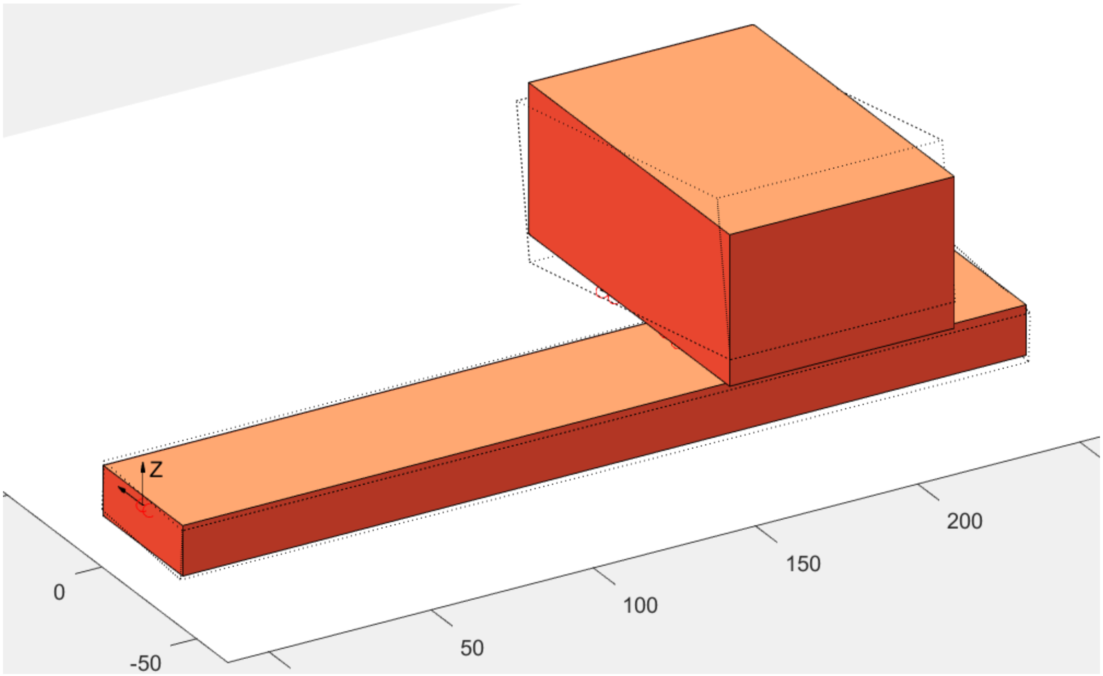

Z
0
50
100
150
200

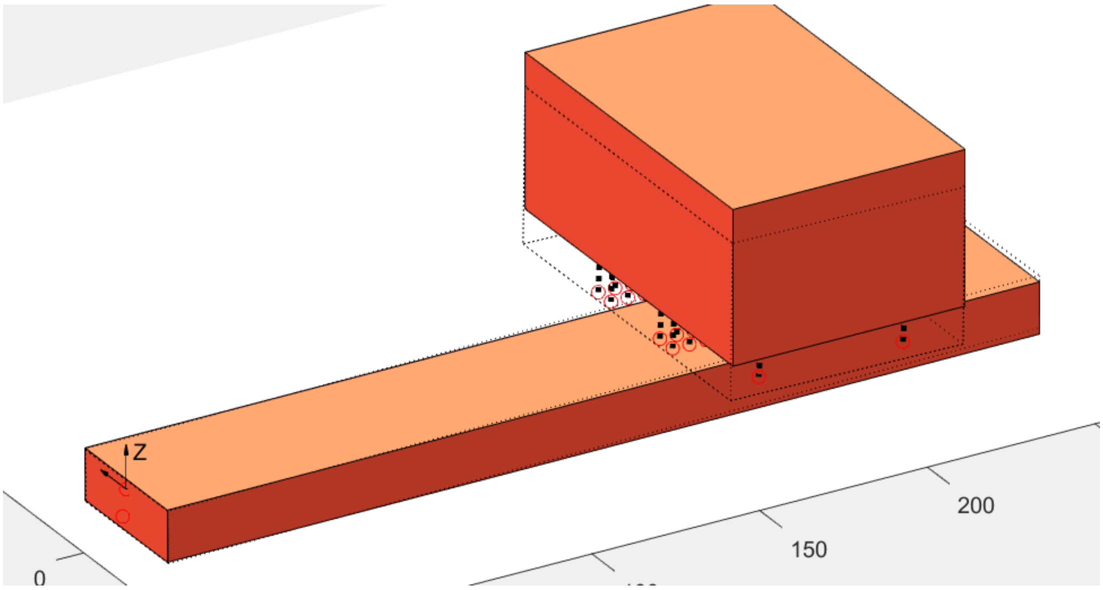
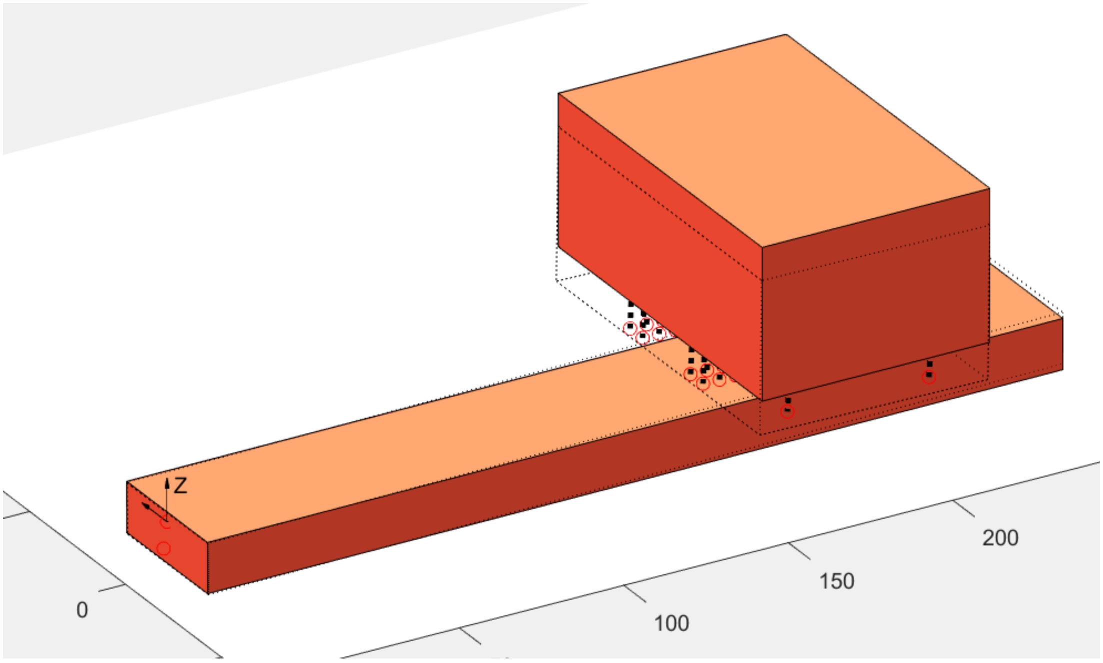

Z
0
100
150
200

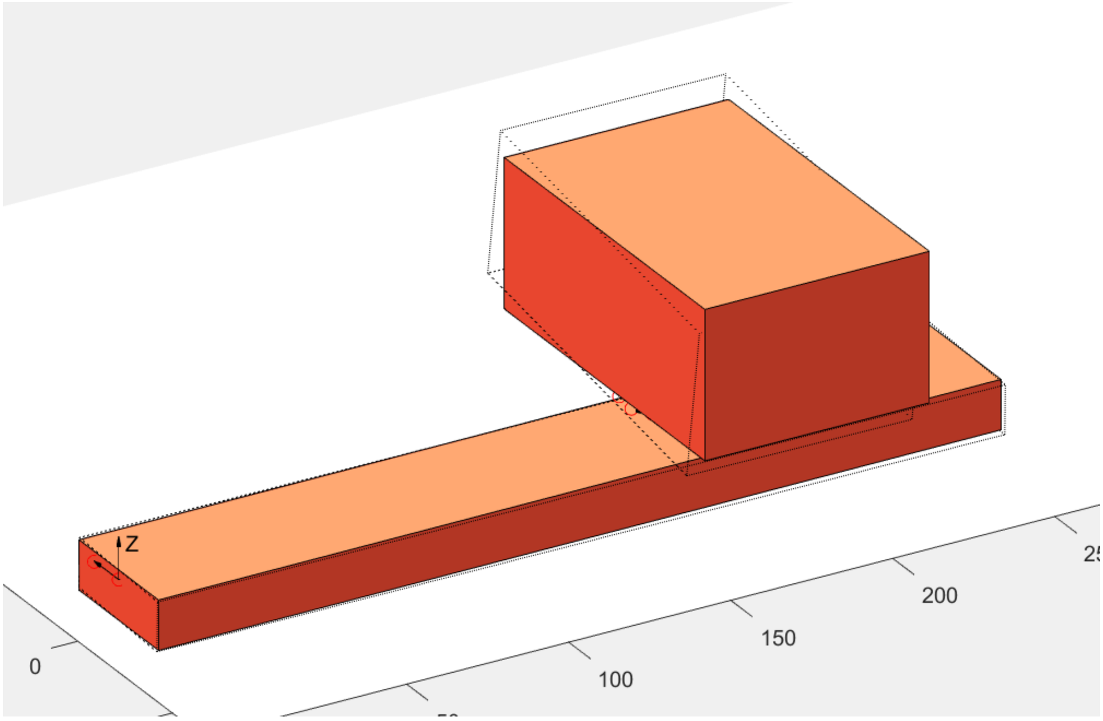

Z
0
50
100
150
200
250

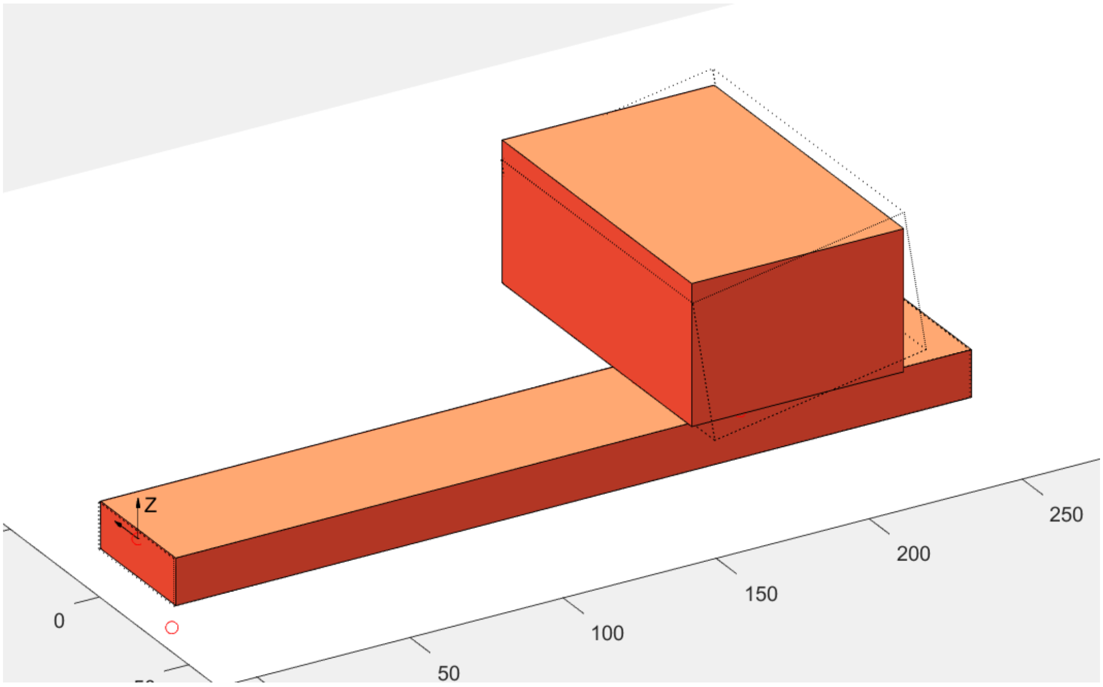

Z
0
0
100
150
200


Z
0
100
150
200


Z
0
-50
50
100
150
200


Z
0
150
200

Z
0
100
150
200


Z
0
100
150
200

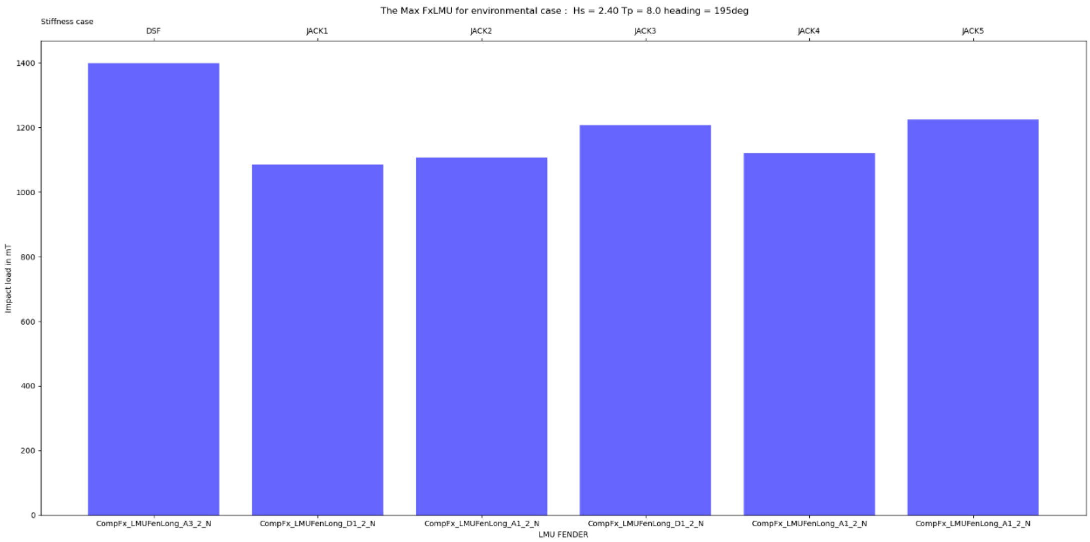

Z
0
50
100
150
200
250

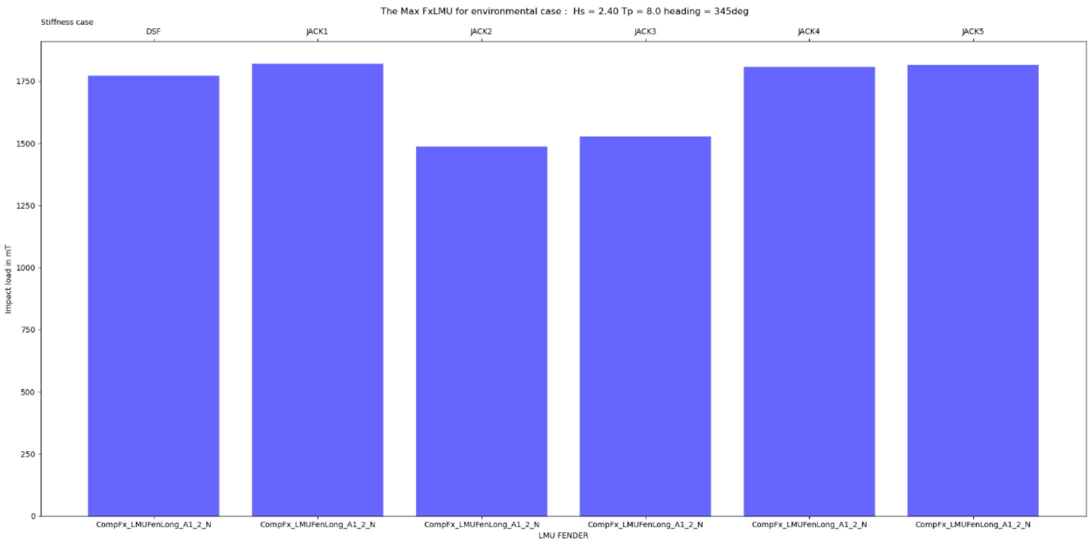
## ATTACHMENT 7 ANYSIM RESULTS

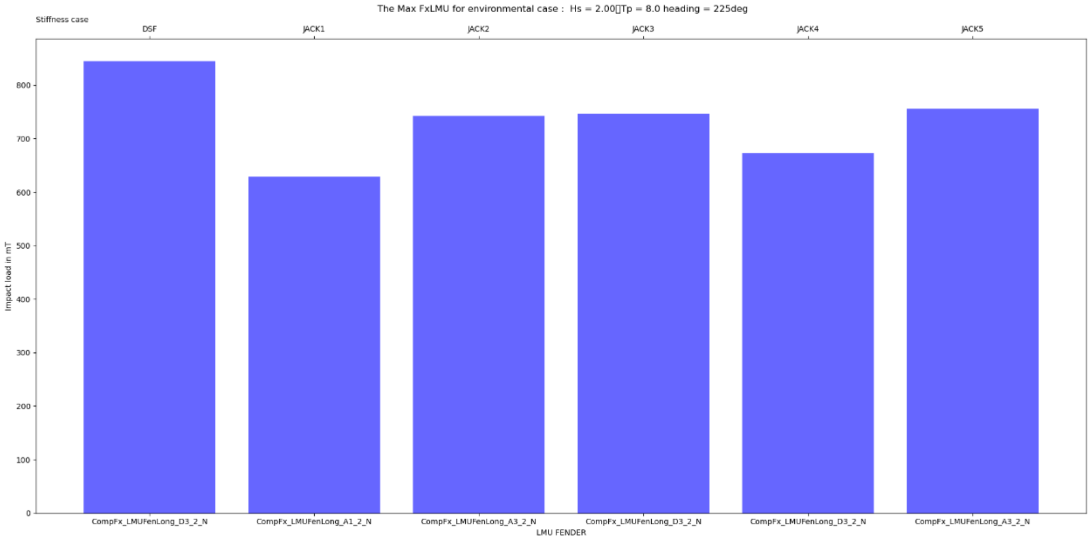
In this attachment all the post processed results can be found.
The loads are displayed in x or y direction. Distinction is made between compression forces and impact loads.

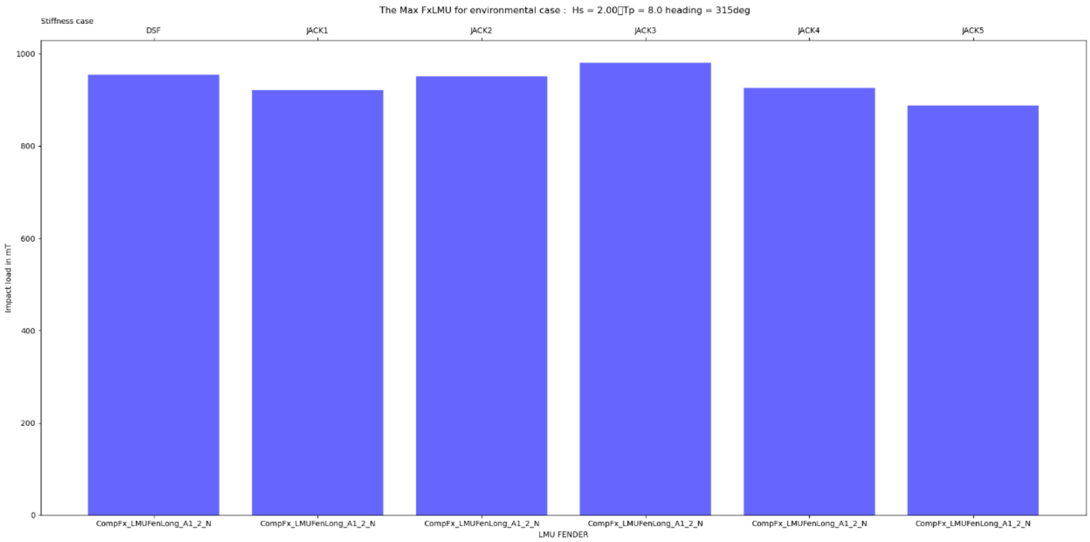
The results are visualized in a bar plot.

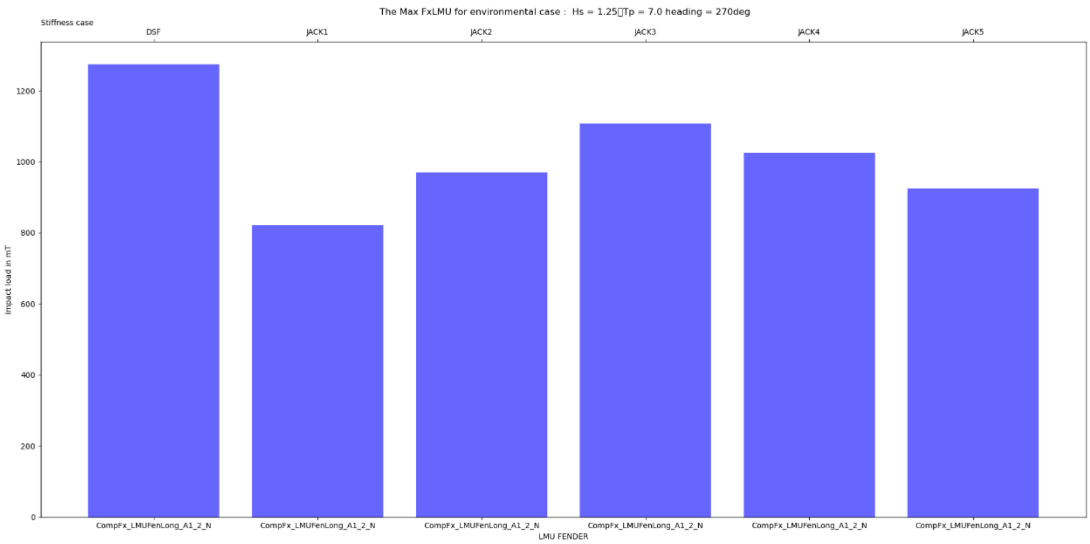
**The results of the maximum compression load on the LMU in X direction (Longitudinal)**

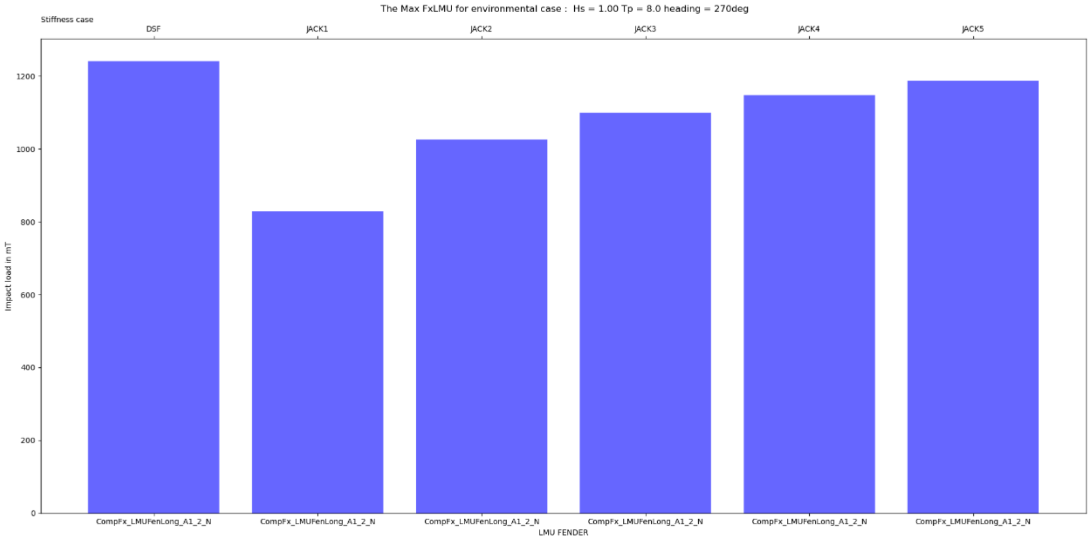


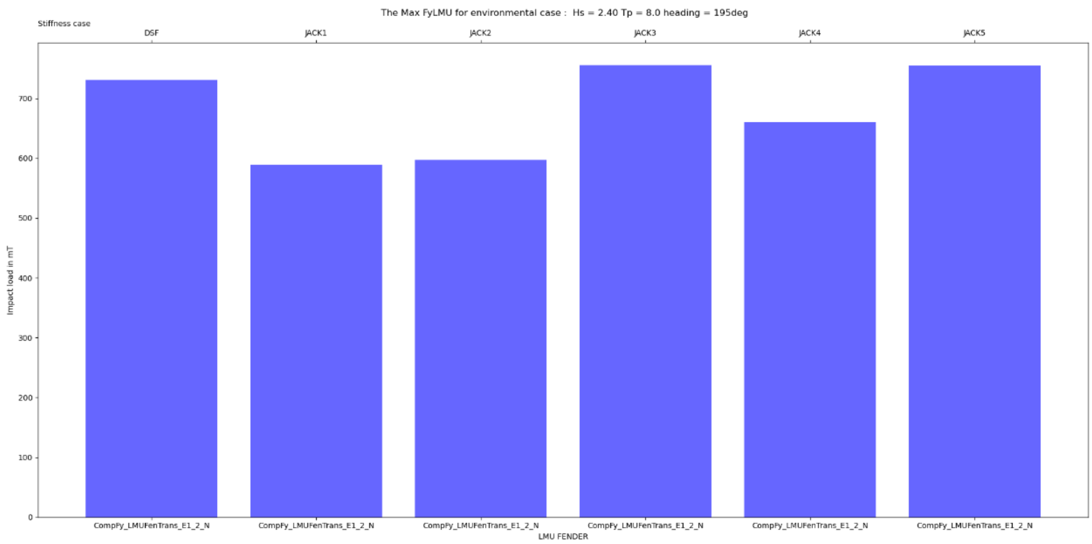

The Max FxLMU for environmental case : Hs = 2.00□Tp = 8.0 heading = 225deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Impact load in mT
0
100
200
300
400
500
600
700
800
CompFx_LMUFenLong_D3_2_N
CompFx_LMUFenLong_A1_2_N
CompFx_LMUFenLong_A3_2_N
CompFx_LMUFenLong_D3_2_N
CompFx_LMUFenLong_D3_2_N
CompFx_LMUFenLong_A3_2_N
LMU FENDER

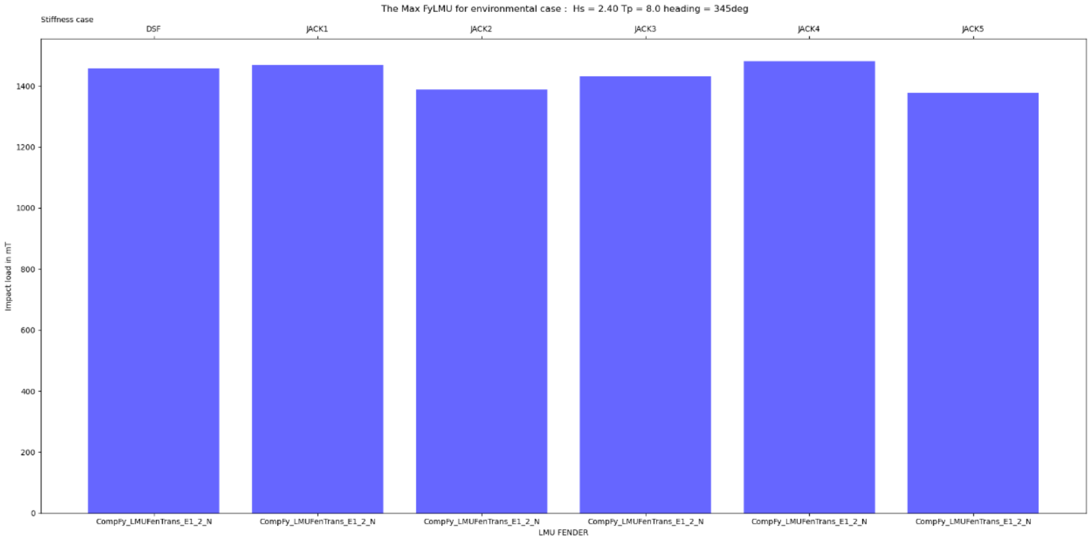

The Max FxLMU for environmental case : Hs = 2.00□Tp = 8.0 heading = 315deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Impact load in mT
0
200
400
600
800
1000
CompFx_LMUFenLong_A1_2_N
CompFx_LMUFenLong_A1_2_N
CompFx_LMUFenLong_A1_2_N
CompFx_LMUFenLong_A1_2_N
CompFx_LMUFenLong_A1_2_N
CompFx_LMUFenLong_A1_2_N
LMU FENDER


The Max FxLMU for environmental case : Hs = 1.25□Tp = 7.0 heading = 270deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Impact load in mT
0
200
400
600
800
1000
1200
CompFx_LMUFenLong_A1_2_N
CompFx_LMUFenLong_A1_2_N
CompFx_LMUFenLong_A1_2_N
CompFx_LMUFenLong_A1_2_N
CompFx_LMUFenLong_A1_2_N
CompFx_LMUFenLong_A1_2_N
LMU FENDER

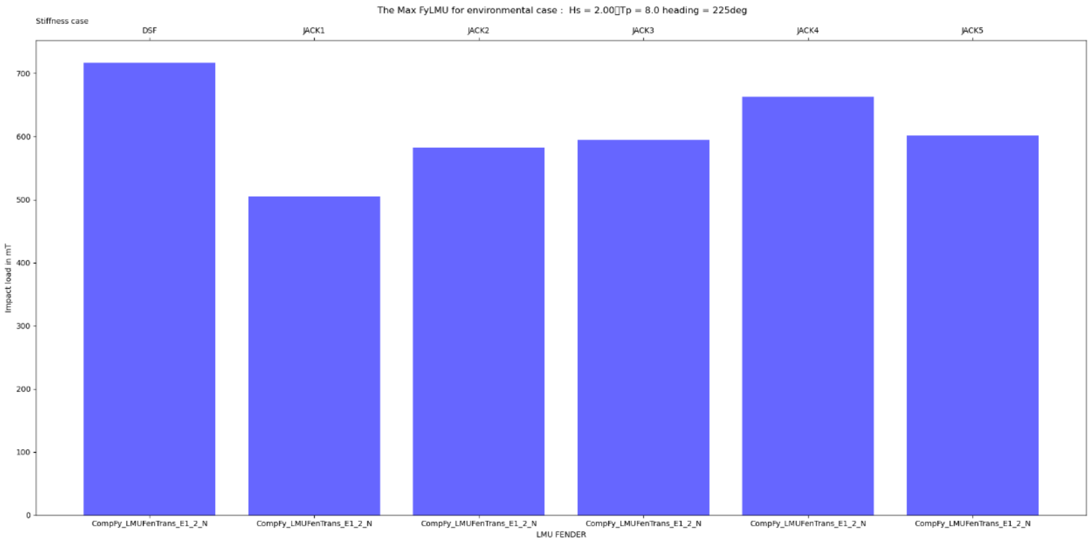



## The maximum compression load on the LMU in Y direction (Transverse)

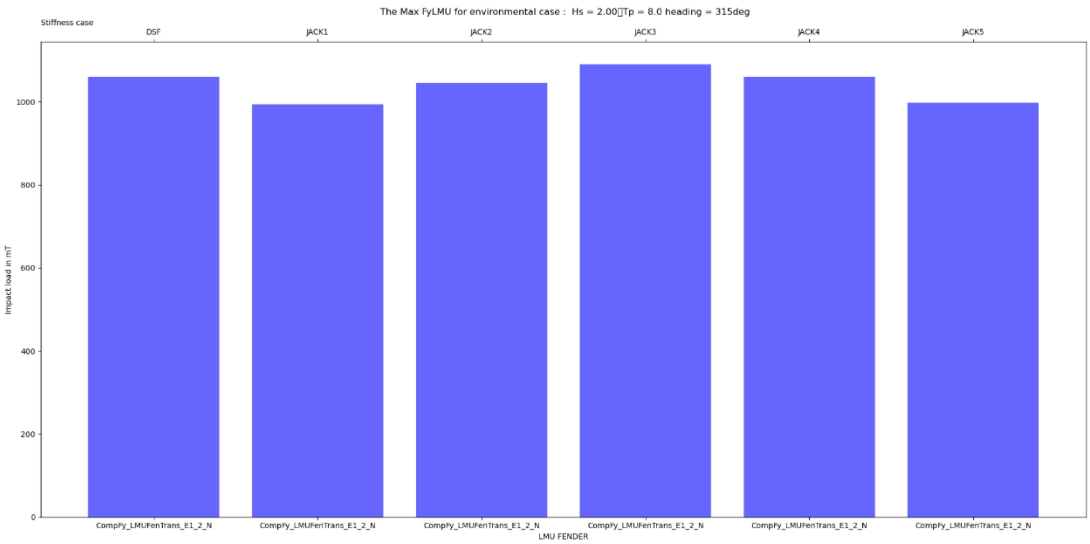




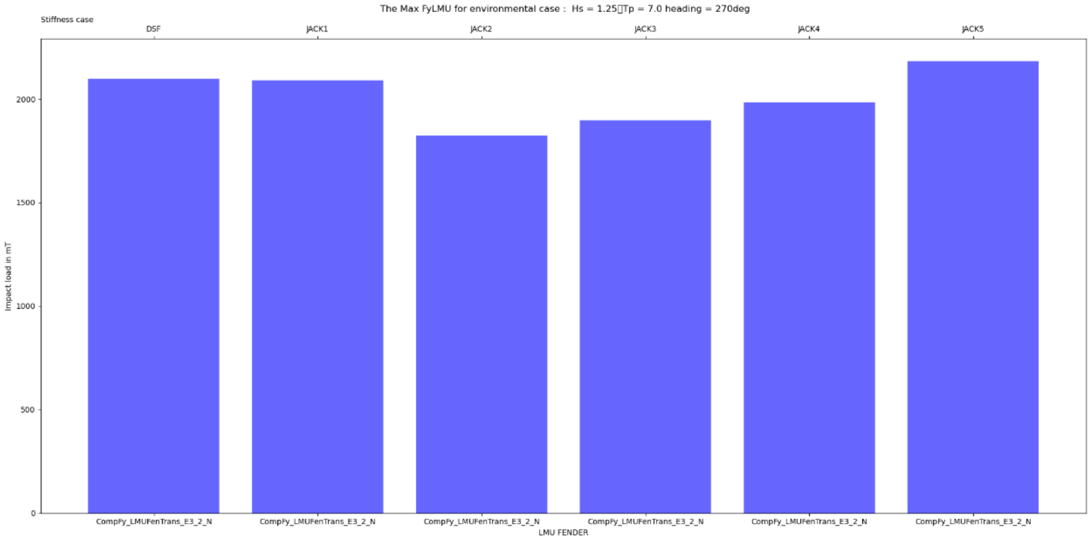
The Max FyLMU for environmental case : Hs = 2.40 Tp = 8.0 heading = 345deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Impact load in mT
0
200
400
600
800
1000
1200
1400
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
LMU FENDER

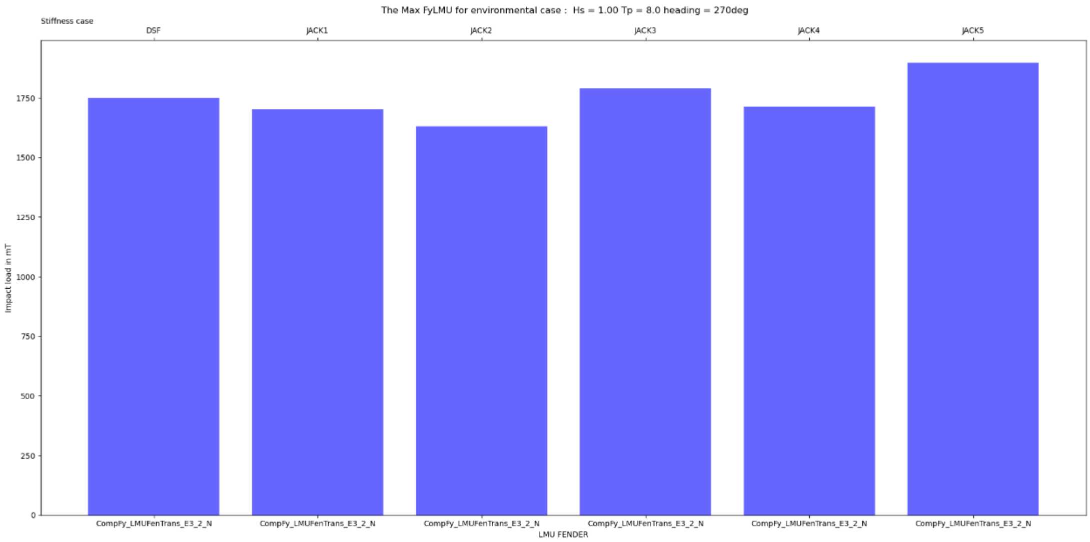



The Max FyLMU for environmental case : Hs = 2.00 Tp = 8.0 heading = 225deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Impact load in mT
0
100
200
300
400
500
600
700
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
LMU FENDER

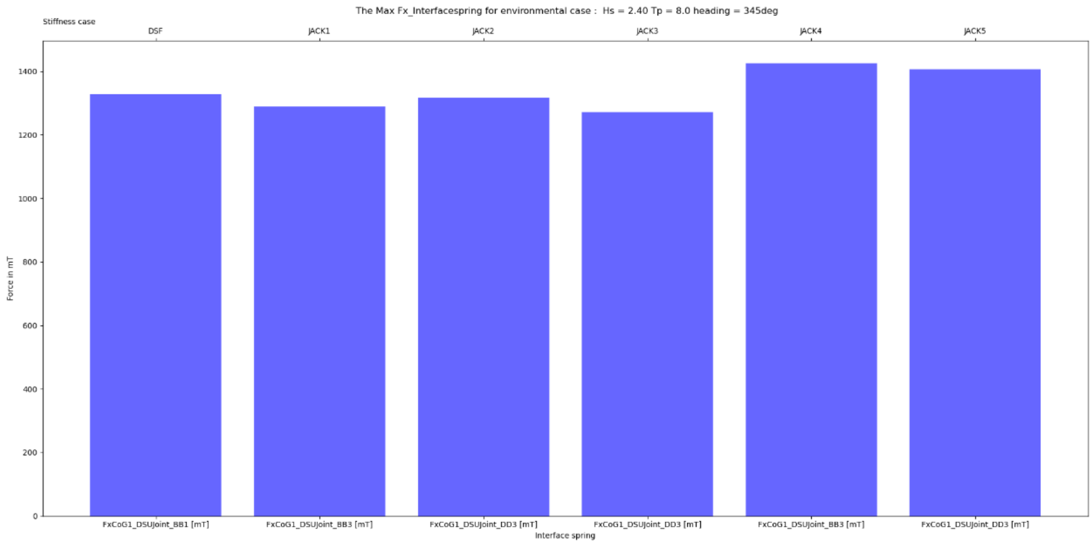
The Max FyLMU for environmental case : Hs = 2.00 Tp = 8.0 heading = 315deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Impact load in mT
0
200
400
600
800
1000
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
CompFy_LMUFenTrans_E1_2_N
LMU FENDER

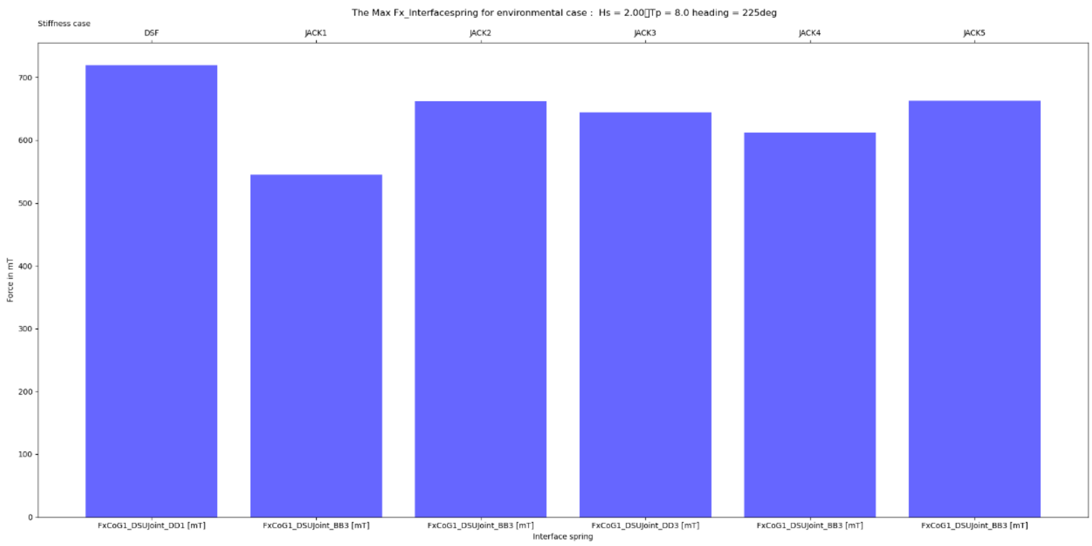

The Max FyLMU for environmental case : Hs = 1.25 Tp = 7.0 heading = 270deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Impact load in mT
0
500
1000
1500
2000
CompFy_LMUFenTrans_E3_2_N
LMU FENDER

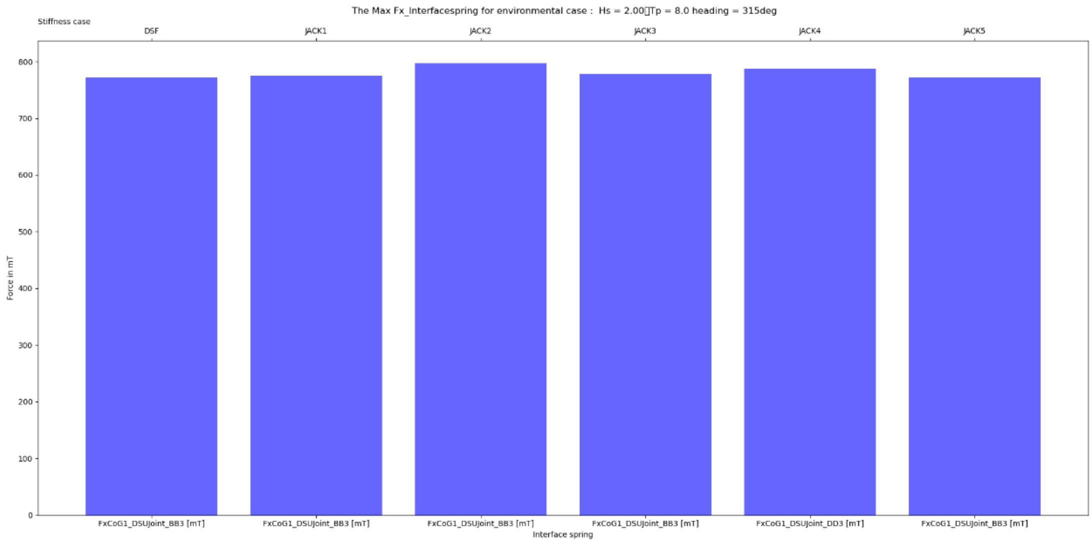

The Max FyLMU for environmental case : Hs = 1.00 Tp = 8.0 heading = 270deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Impact load in mT
0
250
500
750
1000
1250
1500
1750
CompFy_LMUFenTrans_E3_2_N
LMU FENDER

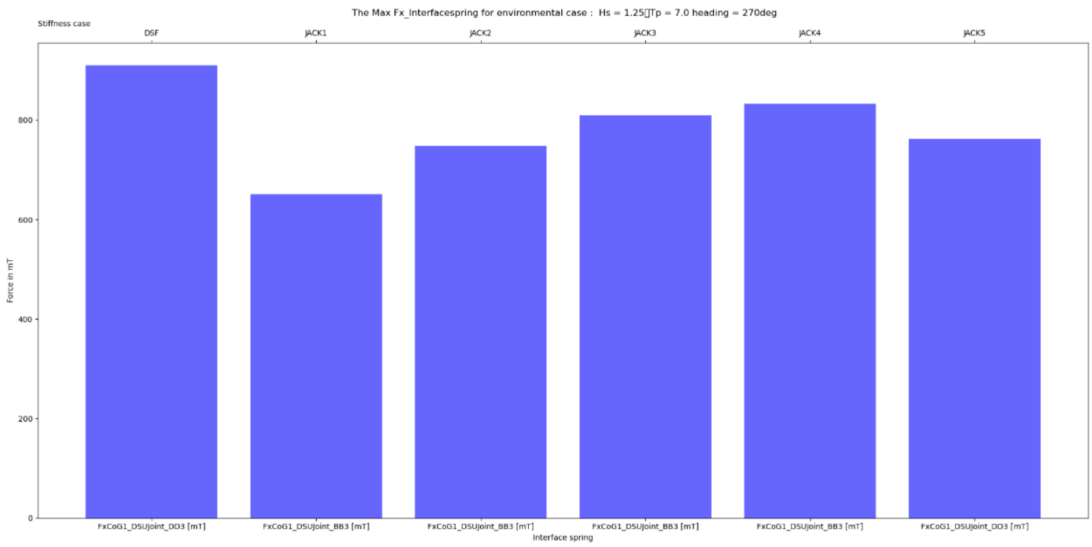
**The maximum interface force in x direction**

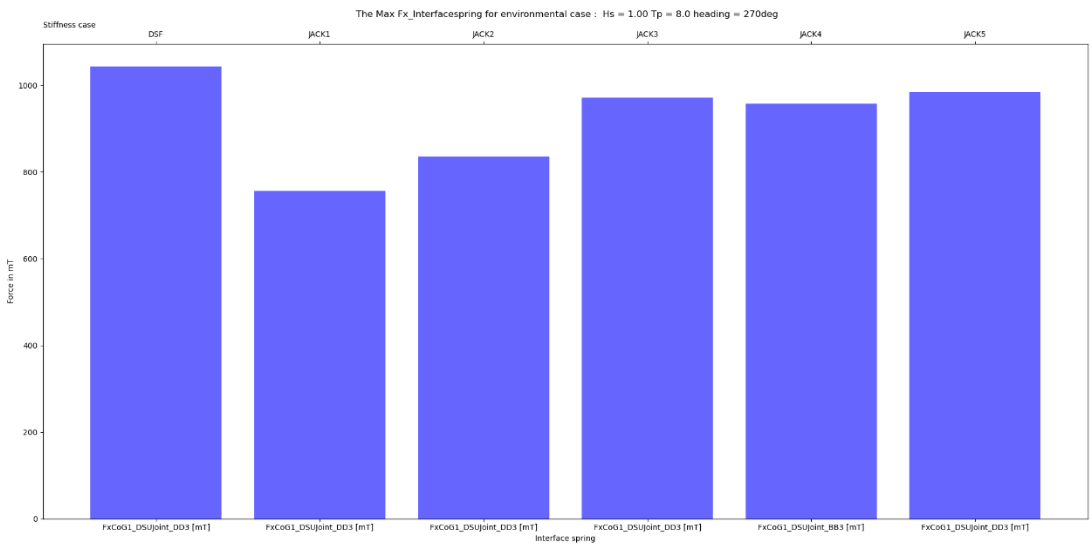
The maximum load in the interface spring is not an impact load but a force. The results for the load in x direction is plotted below. It should be noted that the spring is called a joint.



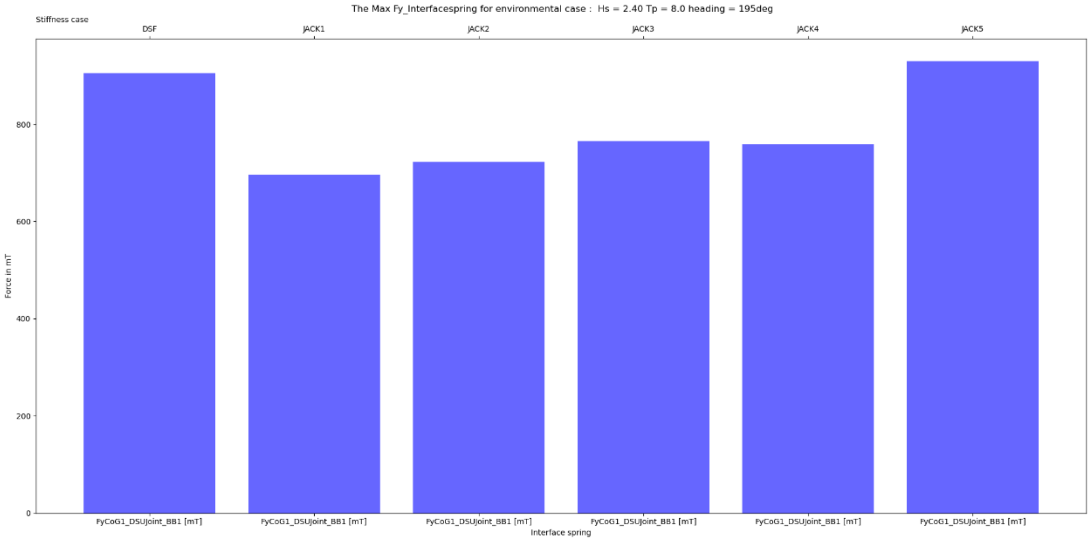





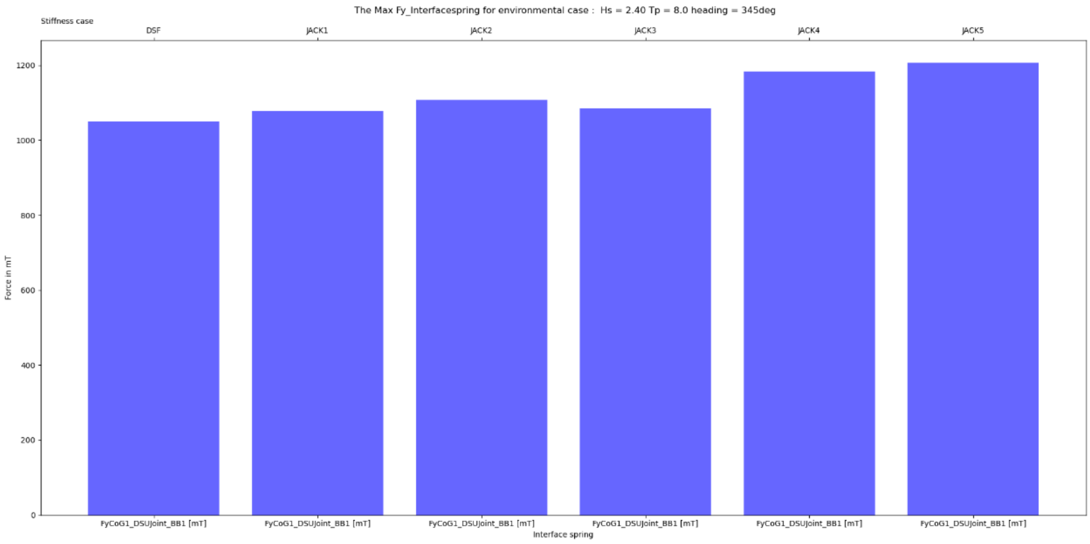



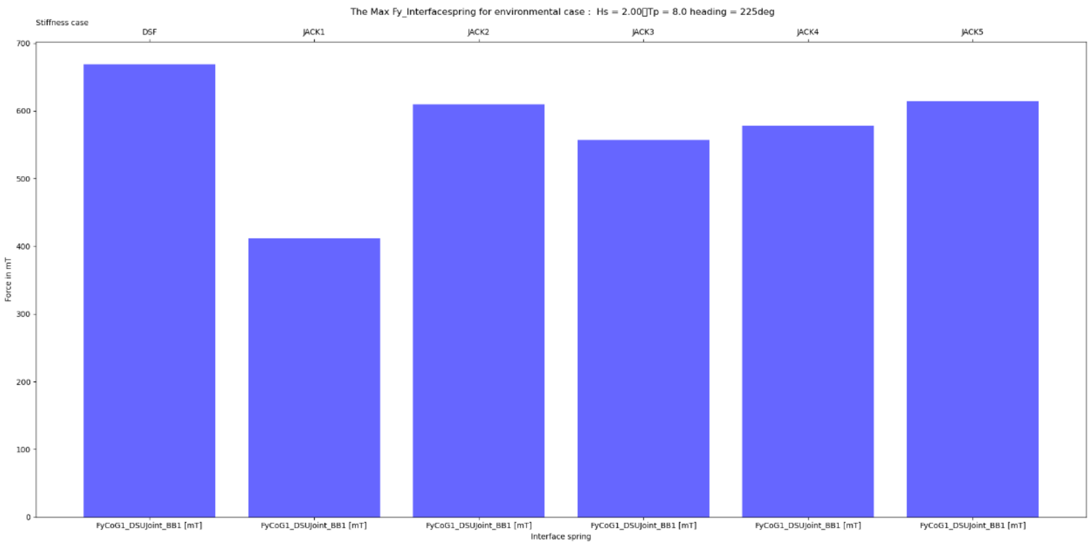

**The maximum interface force in y direction is plotted below**



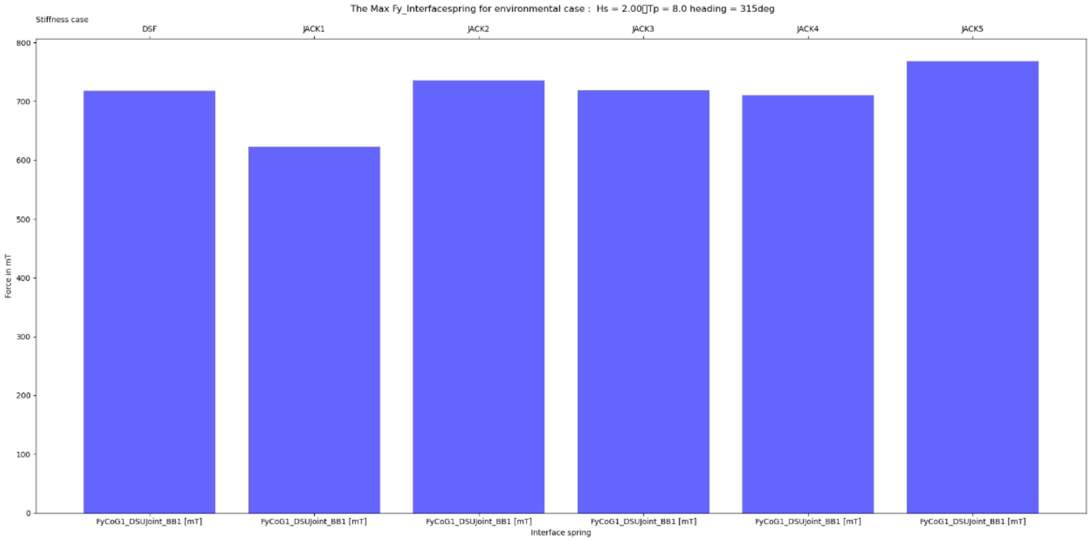
The Max Fy_Interfacespring for environmental case : Hs = 2.40 Tp = 8.0 heading = 195deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Force in mT
Interface spring
FyCoG1_DSUJoint_BB1 [mT]

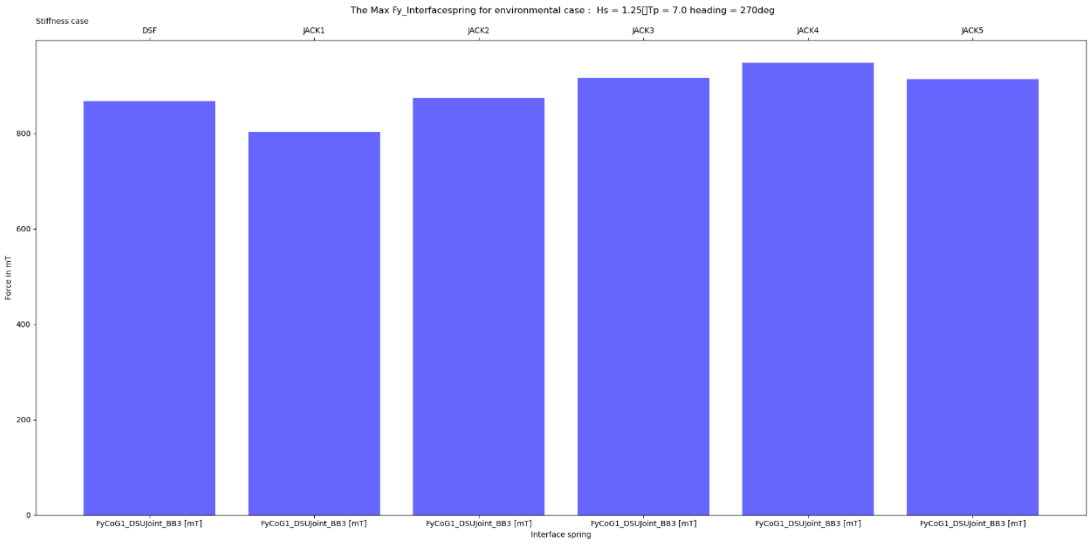
The Max Fy_Interfacespring for environmental case : Hs = 2.40 Tp = 8.0 heading = 345deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Force in mT
Interface spring
FyCoG1_DSUJoint_BB1 [mT]

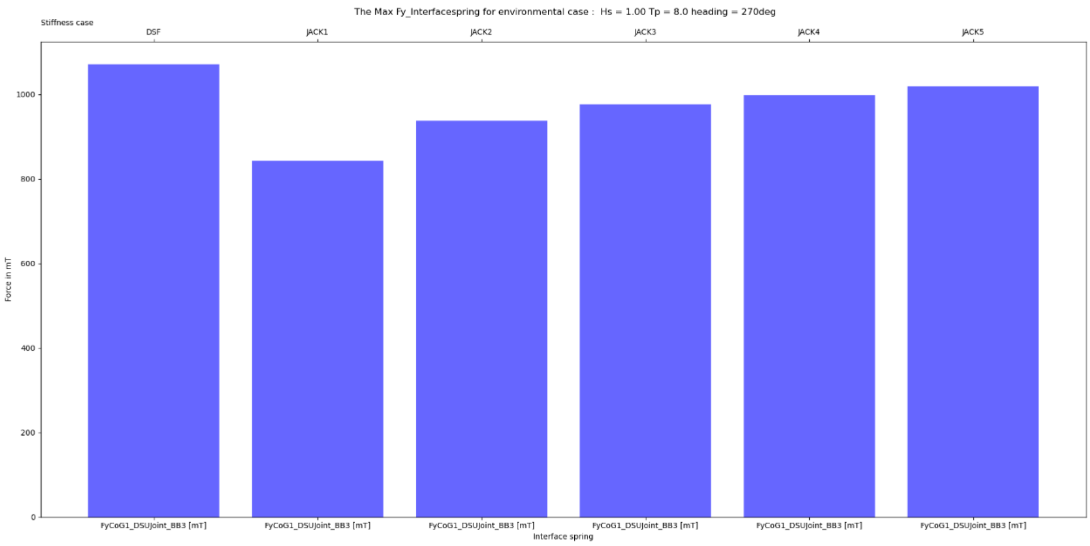
The Max Fy_Interfacespring for environmental case : Hs = 2.00 Tp = 8.0 heading = 225deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Force in mT
Interface spring
FyCoG1_DSUJoint_BB1 [mT]



The Max Fy_Interfacespring for environmental case : Hs = 2.00 Tp = 8.0 heading = 315deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Force in mT
FyCoG1_DSUJoint_BB1 [mT]
Interface spring

The Max Fy_Interfacespring for environmental case : Hs = 1.25 Tp = 7.0 heading = 270deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Force in mT
FyCoG1_DSUJoint_BB3 [mT]
Interface spring

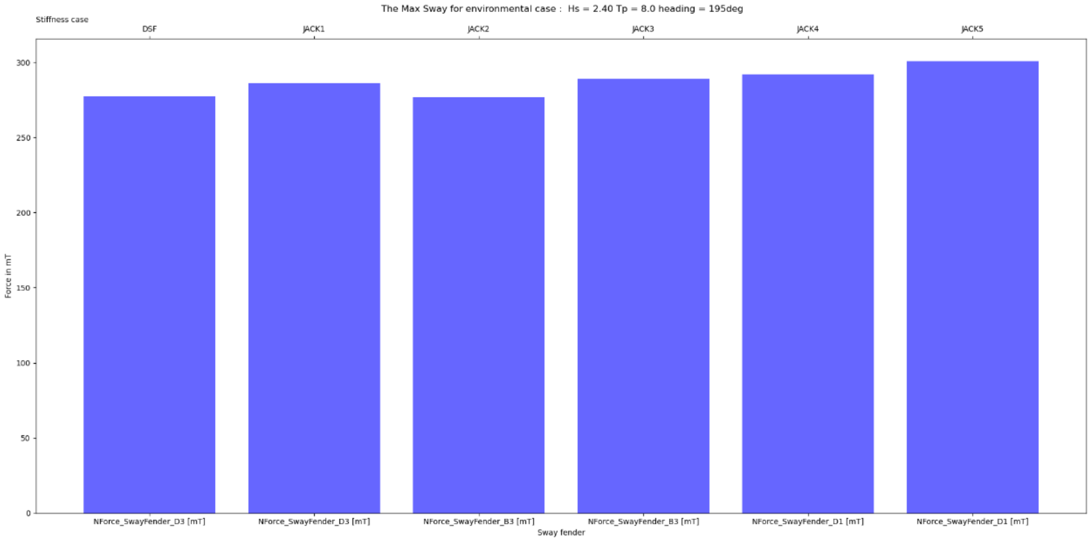



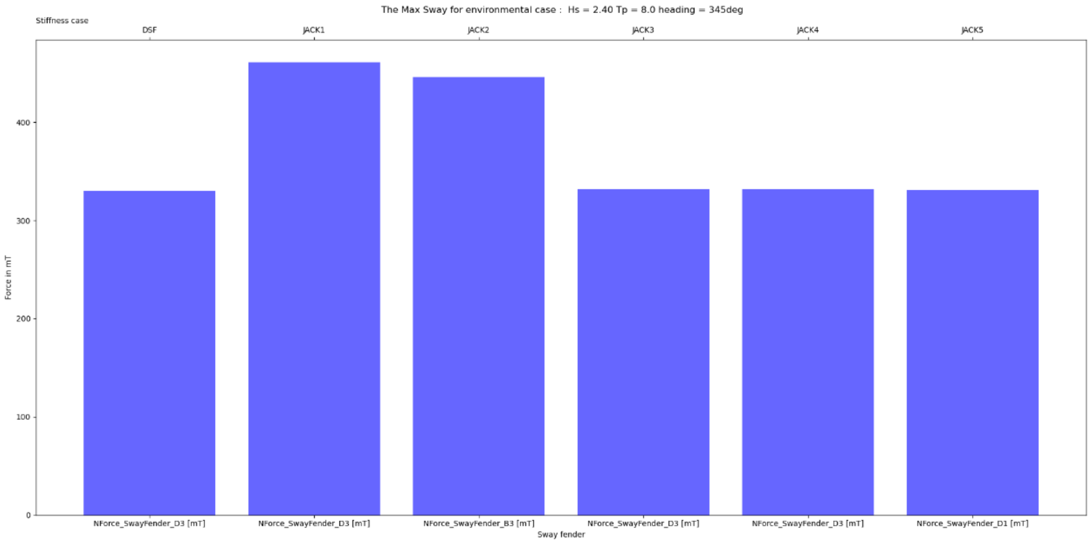
The Max Fy_Interfacespring for environmental case : Hs = 1.00 Tp = 8.0 heading = 270deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Force in mT
FyCoG1_DSUJoint_BB3 [mT]
Interface spring

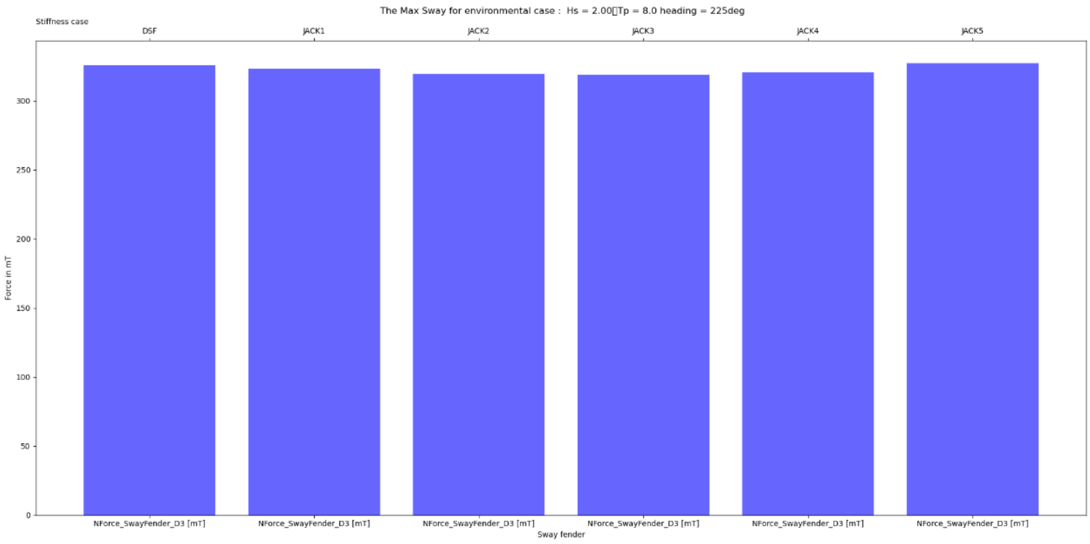
**The summed interface load of Fh**

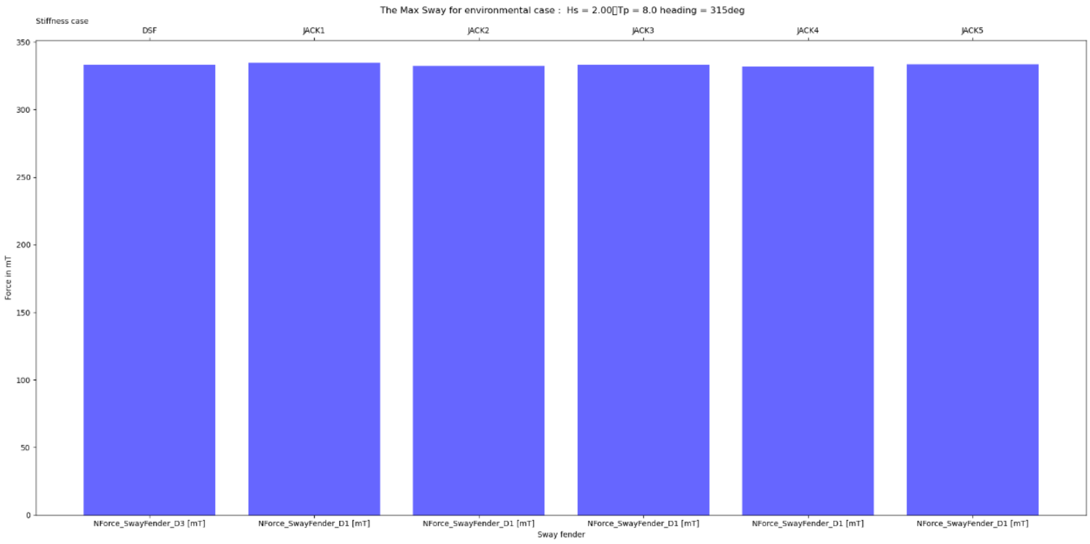
| **Hs** | 2.40 | 2.40 | 2.00 | 2.00 | 1.25 | 1.00 |
|---|---|---|---|---|---|---|
| **Tp** | 8.0 | 8.0 | 8.0 | 8.0 | 7.0 | 8.0 |
| **Heading** | 195deg | 345deg | 225deg | 315deg | 270deg | 270deg |
| | | | | | | |
| **DSF** | 5730 | 9910 | 5466 | 4450 | 5760 | 5806 |
| **JACK1** | 7732 | 9811 | 4657 | 5528 | 5924 | 5977 |

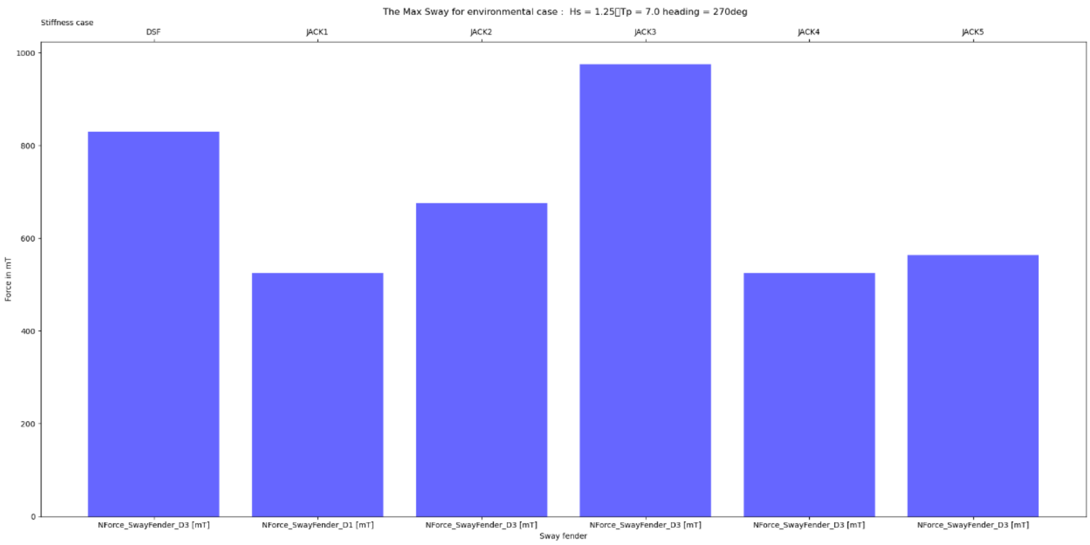
**The sway fender results can be found below.**

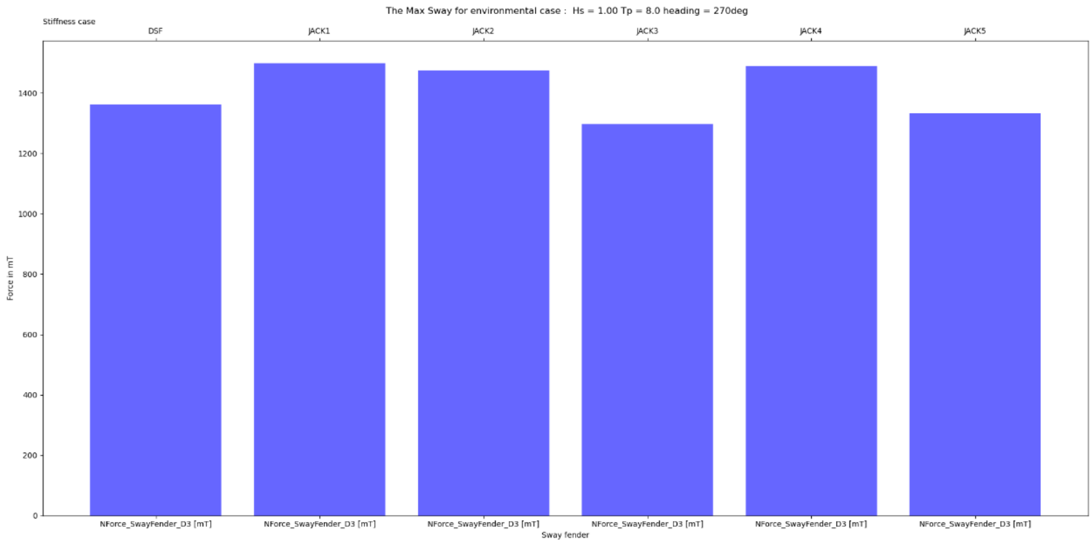


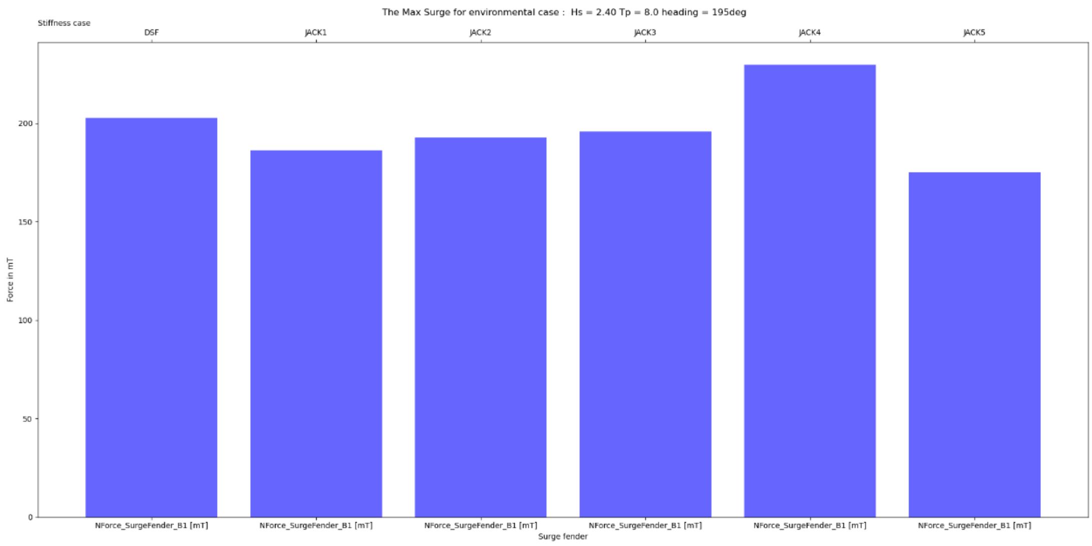

The Max Sway for environmental case : Hs = 2.00 Tp = 8.0 heading = 225deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Force in mT
0
50
100
150
200
250
300
NForce_SwayFender_D3 [mT]
NForce_SwayFender_D3 [mT]
NForce_SwayFender_D3 [mT]
NForce_SwayFender_D3 [mT]
NForce_SwayFender_D3 [mT]
NForce_SwayFender_D3 [mT]
Sway fender

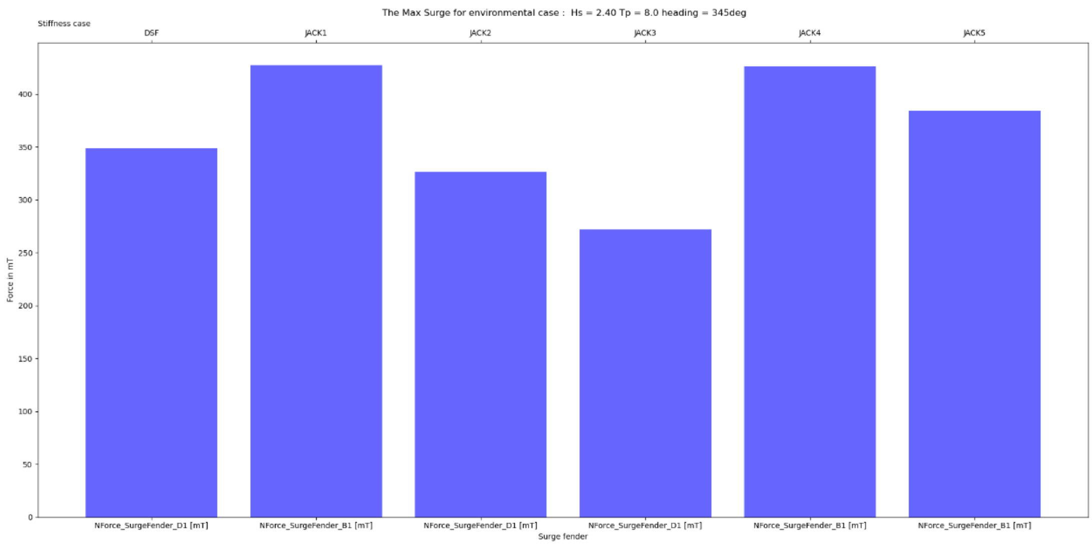

The Max Sway for environmental case : Hs = 2.00 Tp = 8.0 heading = 315deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Force in mT
0
50
100
150
200
250
300
350
NForce_SwayFender_D3 [mT]
NForce_SwayFender_D1 [mT]
NForce_SwayFender_D1 [mT]
NForce_SwayFender_D1 [mT]
NForce_SwayFender_D1 [mT]
NForce_SwayFender_D1 [mT]
Sway fender

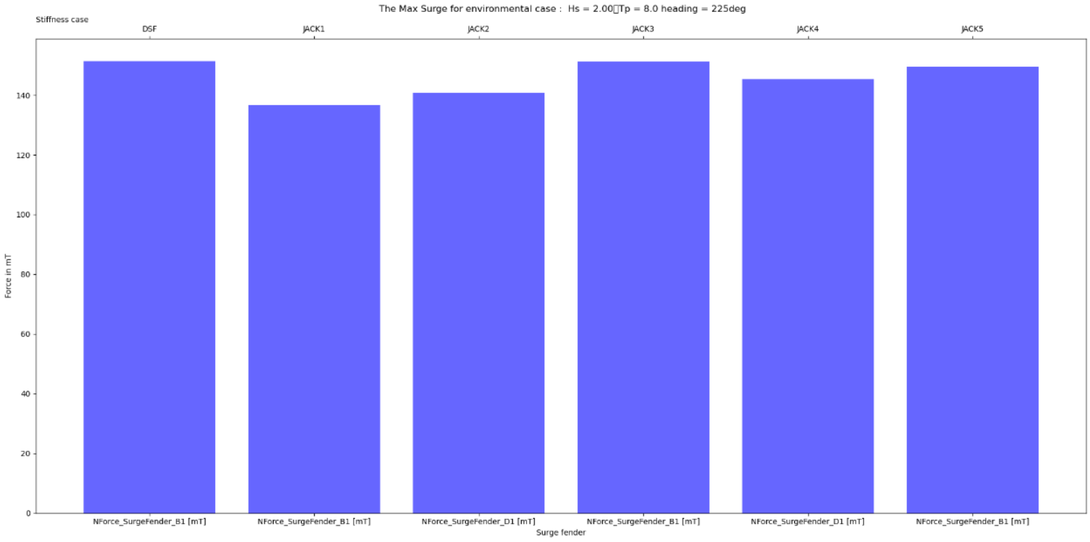

The Max Sway for environmental case : Hs = 1.25 Tp = 7.0 heading = 270deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Force in mT
0
200
400
600
800
1000
NForce_SwayFender_D3 [mT]
NForce_SwayFender_D1 [mT]
NForce_SwayFender_D3 [mT]
NForce_SwayFender_D3 [mT]
NForce_SwayFender_D3 [mT]
NForce_SwayFender_D3 [mT]
Sway fender

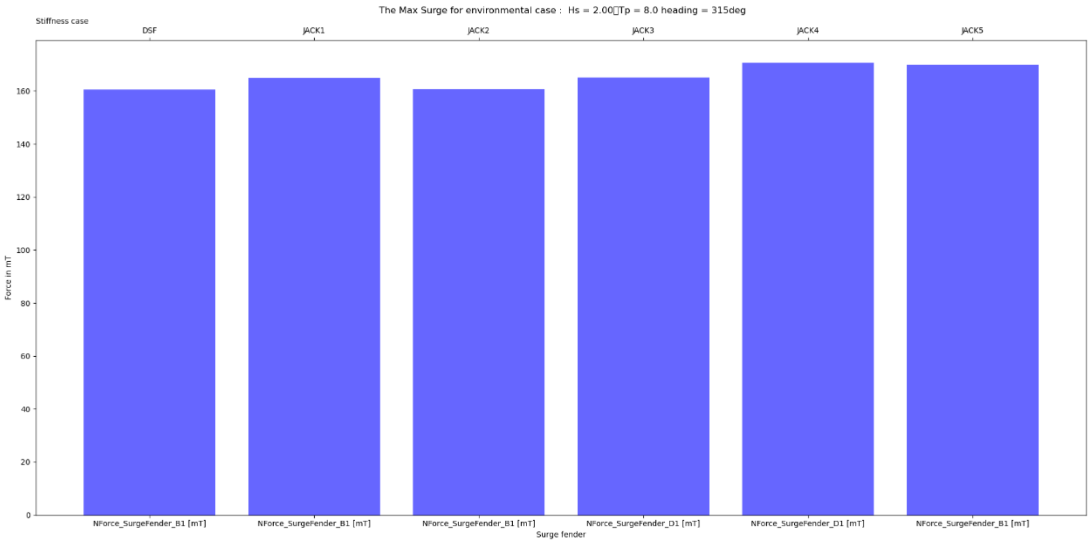


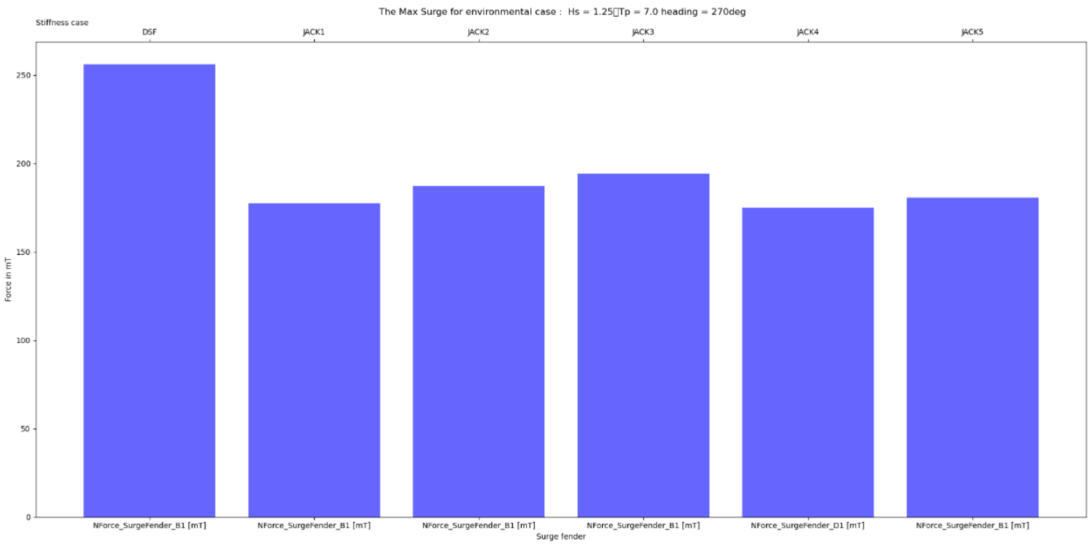

## The maximum surge fender loads can be found below




The Max Surge for environmental case : Hs = 2.00 Tp = 8.0 heading = 225deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Force in mT
0
20
40
60
80
100
120
140
NForce_SurgeFender_B1 [mT]
NForce_SurgeFender_B1 [mT]
NForce_SurgeFender_D1 [mT]
NForce_SurgeFender_B1 [mT]
NForce_SurgeFender_D1 [mT]
NForce_SurgeFender_B1 [mT]
Surge fender


The Max Surge for environmental case : Hs = 2.00 Tp = 8.0 heading = 315deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Force in mT
0
20
40
60
80
100
120
140
160
NForce_SurgeFender_B1 [mT]
NForce_SurgeFender_B1 [mT]
NForce_SurgeFender_B1 [mT]
NForce_SurgeFender_D1 [mT]
NForce_SurgeFender_D1 [mT]
NForce_SurgeFender_B1 [mT]
Surge fender


The Max Surge for environmental case : Hs = 1.25 Tp = 7.0 heading = 270deg
Stiffness case
DSF
JACK1
JACK2
JACK3
JACK4
JACK5
Force in mT
0
50
100
150
200
250
NForce_SurgeFender_B1 [mT]
NForce_SurgeFender_B1 [mT]
NForce_SurgeFender_B1 [mT]
NForce_SurgeFender_B1 [mT]
NForce_SurgeFender_D1 [mT]
NForce_SurgeFender_B1 [mT]
Surge fender