Pioneering Spirit's Jacket Lift System

Feasibility and Favourability Study: Upend/Tilt-over Mechanism of Pioneering Spirit's Jacket Lift System

Pioneering Spirit's Jacket Lift System

Feasibility and Favourability Study: Upend/Tilt-over Mechanism of Pioneering Spirit's Jacket Lift System

By

M.A.D. Wouterse

To obtain the degree of Master in Science
At the Delft University of Technology
To be defended publicly on Thursday October 18, 2018 at 14:30

Document name:	Feasibility and Favourability Study: Upend/Tilt-over Mechanism of Pioneering Spirit's Jacket Lift System
Date:	8 October 2018
Author:	Mark Wouterse 4238389
Master program:	Offshore and Dredging Engineering Bottom Founded Structures, Arctic and Wind
Graduation committee:	
Prof. dr. A.V. Metrikine	Delft University of Technology
Ir. C. Keijdener	Delft University of Technology
Additional committee Member	Delft University of Technology
Ir. M. Dijk	Allseas Engineering B.V.

This thesis is confidential and cannot be made public until October 2023
This material is property of Allseas and may not be wholly or partly disclosed, copied, duplicated or in any way made use of without explicit written consent of Allseas' PR Department
A digital version of this thesis report is uploaded to http://repository.tudelft.nl

Preface

This report is the result of my graduation project for the completion of my master's program Offshore and Dredging Engineering at the Delft University of Technology. The graduation assignment represents 45 ECTS in a total of 120 ECTS. The course of the period went completely different than I had imagined. A textbook example that proves that studying is more than just attending lectures and acquiring knowledge. It is also a period of personal development in any way. I have learned more than I could imagine.

I want to thank Allseas for receiving me and facilitating my graduation project. My supervisors Marijn Dijk and Niels Mallon have guided me carefully and with great patience during my graduation assignment. In addition, the other graduates, working students and employees at Allseas were indispensable in the wonderful time I had at Allseas. My special thanks go to my fellow students and friends with whom I have spent many years. I had a lot of fun and received support where necessary. Finally, my parents. No words do justice to what my parents mean to me. Thank you

Mark Wouterse
Delft, 8 October 2018

Abstract

Allseas Group S.A. is a leading offshore contractor in the field of pipeline installation, heavy lifting and subsea construction. One of Allseas' vessels is Pioneering Spirit. The main activities of Pioneering Spirit can be subdivided into pipeline installation, topside installation/removal and jacket installation/removal. The equipment of the first two activities has been successfully put into operation. The equipment to install and remove jackets (Jacket Lift System (JLS)) is currently under development. The mechanism to upend/tilt-over the Jacket Lift System is the subject of this graduation project.

The design challenge of Pioneering Spirit's Jacket Lift System is to install or remove a jacket with a height of at least 70 meters and a mass of up to 20 000 mt (in air) in a single lift/operation. In this thesis project, an additional design solution has been investigated and developed. The objective was to investigate the feasibility and favourability of various principles and concepts to upend/tilt-over a jacket using Pioneering Spirit. Key topics in the development of the design solution were the controllability of the operation, the compatibility of the system in the current appearance of Pioneering Spirit's, the complexity of the operation and the investments costs to construct, operate and maintain the system.

The design solution found in this graduation project consists of a tilting system that rotates over the stern of Pioneering Spirit. The system is driven by a pushing system installed on the reinforced transverse frames on the aftdeck of Pioneering Spirit. The system must be movable to relocate the centre of gravity before upending or after tilting-over of the system. The system is controlled by two winch systems, one attached to the tip of the tilting lift beams (Derrick Hoist system, consisting of 10 winches) and the other to the upper pivot point of the pushing system (Upend/Tilt-over Mechanism, consisting of 8 winches). The system can be controlled in both rotational directions with the two winch systems. The tilting lift beams and pushing system are connected by means of a roller/slider connection.

The maximum forces, stability and controllability of the system were checked with a coarse dynamic mathematical model. The natural frequency of the system with and without jacket appeared to be in the same frequency range as the excitation response spectra. This was solved by stiffening the system by increasing the effective diameter of the winch systems and by applying pre-tension. Subsequently, the system appeared to be possibly instable during the first/last 18 degrees of the tilting operation. This was solved by applying an auxiliary construction during the first/last 30 degrees of the tilting process. The maximum response amplitude of the system was calculated by means of a calculation of the maximum excitation in the frequency domain (regular waves) and for time series (irregular waves) for the positions in which the Jacket Lift System can be positioned and all incoming wave directions. The maximum response amplitude of the system occurs in beam waves when the system is positioned vertically. Although the maximum response amplitude of the system is small, mainly because of the stiffness, the maximum forces in the system are exorbitantly large. To give an indication, the maximum tension in the Derrick Hoist System is 4125 mt. At a certain moment in the tilting procedure, the entire mass of the Jacket Lift System (15 000 mt) and Jacket (20 000 mt) is applied to the pivot points at the stern of Pioneering Spirit. In general, the static forces deliver the greatest contribution to the total force. The maximum loads are considered feasible, although strengthening measures must be taken.

Abbreviations and Nomenclature

Units:

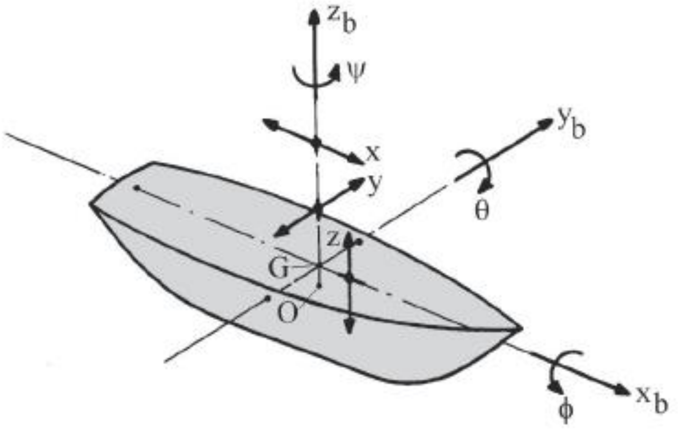
g	-	gram
k	-	kilo
m	-	meter
m^2	-	square meter
m^3	-	cubic meter
mm	-	millimetre
mt	-	metric tonne
N	-	newton
Nm	-	newton meter
Rad	-	radial
s	-	second
W	-	watt
°	-	degree

Symbols:

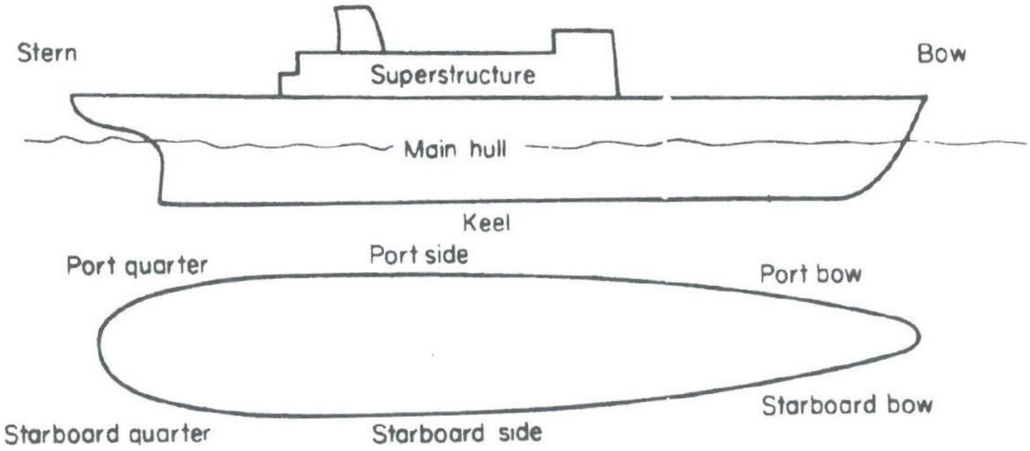
The symbols are explained in the text throughout the report

Vessel motions:

x	-	surge	[m]	Translation in the longitudinal x-direction, positive forward
y	-	sway	[m]	Translation in the lateral y-direction, positive to port side
z	-	heave	[m]	Translation in the vertical z-direction, positive upwards
θ	-	roll	[rad]	Rotation about the x-axis, positive right turning
ϕ	-	pitch	[rad]	Rotation about the y-axis, positive right turning
ψ	-	yaw	[rad]	Rotation about the z-axis, positive right turning



Vessel Terminology:



Pioneering Spirit and Equipment:

PS - Pioneering Spirit
JLS - Jacket Lift System
TLS - Topside Lift System
TLB - Tilting Lift Beams
DHS - Derrick Hoist System
MHS - Main Hoist System
HOF - Hang of Frame
SF - Support Frames/Sledges
HUS - Hydraulic Upend System
SPMT’s - Self-Propelled Modular Transporters
ROV - Remote Operated Vehicle
PLET - Pipeline End Termination
CoG - Centre of Gravity

Miscellaneous:

OSPAR - OsloParis Commission
ULS - Ultimate Limit State
ULC - Ultimate Limit Capacity
MBL - Minimum Breaking Load
MBS - minimum Breaking Strength
SWL - Safe Work Load
RAO - Response Amplitude Factor
ODE - Ordinary Differential Equation
CFD - Computational Fluid Dynamics

List of Figure

Numerous figures are included in this report. To keep overview, the list of figures is included in Appendix K.

List of Tables

Table of Content

1 Introduction

1.1 Introduction

Allseas Group S.A. is a leading offshore contractor in the field of pipeline installation, heavy lifting and subsea construction. Allseas has a versatile fleet to complete, within those working fields, all kind of projects. One of Allseas' vessels is Pioneering Spirit. Pioneering Spirit was taken into operation in 2016 after years of development and construction. It is the largest construction vessel ever built and is in all her disciplines record-breaking. Pioneering Spirit's main activities can be subdivided into pipeline installation, topside installation/removal and jacket installation/removal.

The equipment of all three types of operations is and will be semi-permanently installed on Pioneering Spirit. The equipment is and will be designed to keep the adjustment time between two types of operations to a minimum. Pipelines are installed by means of the on-board pipeline installation factory, horizontal firing line through the vessel and the stinger with transition piece between the twin bows. Topsides are installed and removed by means of the Topside Lift System located at the double bow of Pioneering Spirit. Finally yet importantly, jackets will be installed and removed by means of the so-called Jacket Lift System. The Jacket Lift System will be installed at the aftdeck of Pioneering Spirit. The Jacket Lift System is the topic of this thesis project.

The equipment to install pipelines and to install/remove topsides is currently in operation. In fact, Pioneering Spirit has already completed her first leading projects. Pioneering Spirit has successfully completed the removal of the Yme and Brent Delta topsides and the installation of the Johan Sverdrup DP topside (22 000 mt), all located in the North Sea Region. The Brent Delta Topside had a mass of 24 000 mt [1], a single lift record. Regarding pipeline installation activities, Pioneering Spirit commenced mid-2017 to install the deepwater sections of the Turk Stream Project [2]. The installation of the first of two pipelines in deepwater was successfully completed at the end of May 2018. The Jacket Lift System, however, is currently under engineering and planned to be operable by the end of 2020.

Figure 1: Impression Pioneering Spirit with Johan Sverdrup DP Topside

1.2 Design Challenge

The design challenge of Pioneering Spirit's Jacket Lift System is to install and remove a jacket with a height of at least 70 meters and a mass up to 15 000 mt (in air) in a single lift/operation. Pertaining to jacket installation, an objective is to achieve a mass reduction by excluding the current violent installation techniques, such as launching, and by supporting the jacket during the installation or removal operation. By doing so, the jacket can be designed with reduced beam diameters and reduced steel thicknesses. This results in a tremendous mass reduction, time and cost savings and a better behaviour and resistance in and to environmental loads. Pertaining to jacket removal, Pioneering Spirit's Jacket Lift System must be able to remove jackets in a single lift. By removing a jacket in a single lift, the number of working hours at the offshore location is reduced to a minimum. For the installation of the Johan Sverdrup DP topside only 10% of the estimated offshore working hours was required in reference to conventional installation techniques. Thus, this results in a more efficient use of Pioneering Spirit, lower costs and a lower risk of accidents.

Relevancy

Besides the optimisation of the jacket installation/removal process, an additional motive to design the Jacket Lift System is the relevance of jacket decommissioning. Spread around the world, an immense amount of field developments with one or more steel piled jackets are in place. Allseas designated the North Sea Region as target area to install and remove jackets by means of Pioneering Spirit's Jacket Lift System [3]. In the North Sea Region, a total of 556 steel piled jackets were installed in the period between 1967 and 2012. Only 52 of those facilities were decommissioned until 2012 [4]. It is, enforced by regulations (the OSPAR Decision 98/3), obliged to remove a structure after it has reached its lifetime or has become redundant. A prediction by Oil & Gas UK mentions 316,272 mt of jacket type substructure to be decommissioned in the UK sector and Norwegian Continental Shelve in the period 2016 to 2025. This is associated with 100 jackets [5]. Considering the total North Sea region, containing the UK, Norwegian, Danish and Dutch Continental Shelves, 510,000 mt of substructure in the range from small/unmanned/steel structures to large/manned/concrete gravity-based structures must be decommissioned until 2025 [5]. Allseas' own survey reports about 150 jackets to be decommissioned in the total North Sea Region that meet Allseas' target dimensions.

Previous Preliminary Design

The first concepts of the Jacket Lift System were composed in 1985 together with the concept of Pioneering Spirit. Since then, many concepts have been developed and investigated. The most important concept was based on a principle of a hydraulic upending system. A double-staged hydraulic system was used to upend the system to a vertical position. Wires were used to tilt-over the system back to a horizontal position. This system, however, had some impermissible disadvantages. The most important disadvantage was the feasibility of the double-staged hydraulic cylinders.

New Preliminary Design
An additional concept design solution, focussed on the upend/tilt-over component of Pioneering Spirit's Jacket Lift System, is being investigated and developed in this graduation project. Even though this thesis is focussed on the upend/tilt-over component, the entire installation and removal process is considered in finding a concept that is further investigated. Superfluous to mention, the design must be able to successfully complete the entire installation and removal process.

The installation and removal process, in rough lines, comprises the load-in or load-out of a jacket at a sheltered location, transportation between the onshore and offshore construction sites and the installation or removal at the offshore location. The jacket is positioned horizontally during the load-in/load-out operation and during transportation between the offshore installation/removal and construction/decommissioning site. At the offshore installation/removal location, the jacket is upended/tilted-over and lowered/lifted to/from the seabed in vertical position. The upend/tilt-over operation will be, given the enormous dimensions and masses, a technical challenge for which it is not clear whether this is feasible or not. In addition to the feasibility, Allseas is interested in possible optimisations of the process.

Key topics in the new design solution are the controllability of the process, the compatibility of the system in Pioneering Spirit's current appearance and the finances to construct, operate and maintain the system. It is essential to keep the current applications and processes on Pioneering Spirit in mind. It is highly unfavourable to make major adjustments to the vessel and current processes. The idea to install and remove jackets using the Jacket Lift System is a completely new concept. There is no experience with this kind of systems at all. Hence, little reference material is available. Therefore, and among other reasons, it is important to investigate different principles to upend/tilt-over de system and to examine the feasibility of the proposed methods first before making a detailed design.

1.3 Objective

The objective in this thesis is to investigate various principles and concepts to upend/tilt-over a jacket using Pioneering Spirit for feasibility and favourability. The examination is based on the compatibility in Pioneering Spirit's current appearance, efficiency pertaining to required forces to upend/tilt-over the system and the controllability of the upend/tilt-over process. This includes a qualitative assessment, an analysis on the static equilibrium of the different concepts and a dynamic analysis of the elaborated concept of the upend/tilt-over component of Pioneering Spirit's Jacket Lift System.

1.4 Design/Research Strategy

This thesis is a design-orientated research. A design-oriented research is characterised by the goal to improve/complement or design a certain product, process or system [6]. The point of interest in this thesis is to provide a concept design solution that can be integrated easily into Pioneering Spirit‘s current appearance, is well controllable and efficient pertaining to forces required to operate the system. It is important to keep the feasibility of the entire jacket installation/removal process in mind throughout the project.

The thesis project is subdivided into four main parts. Important information or important decisions obtained/taken in one part are used in the next part(s):

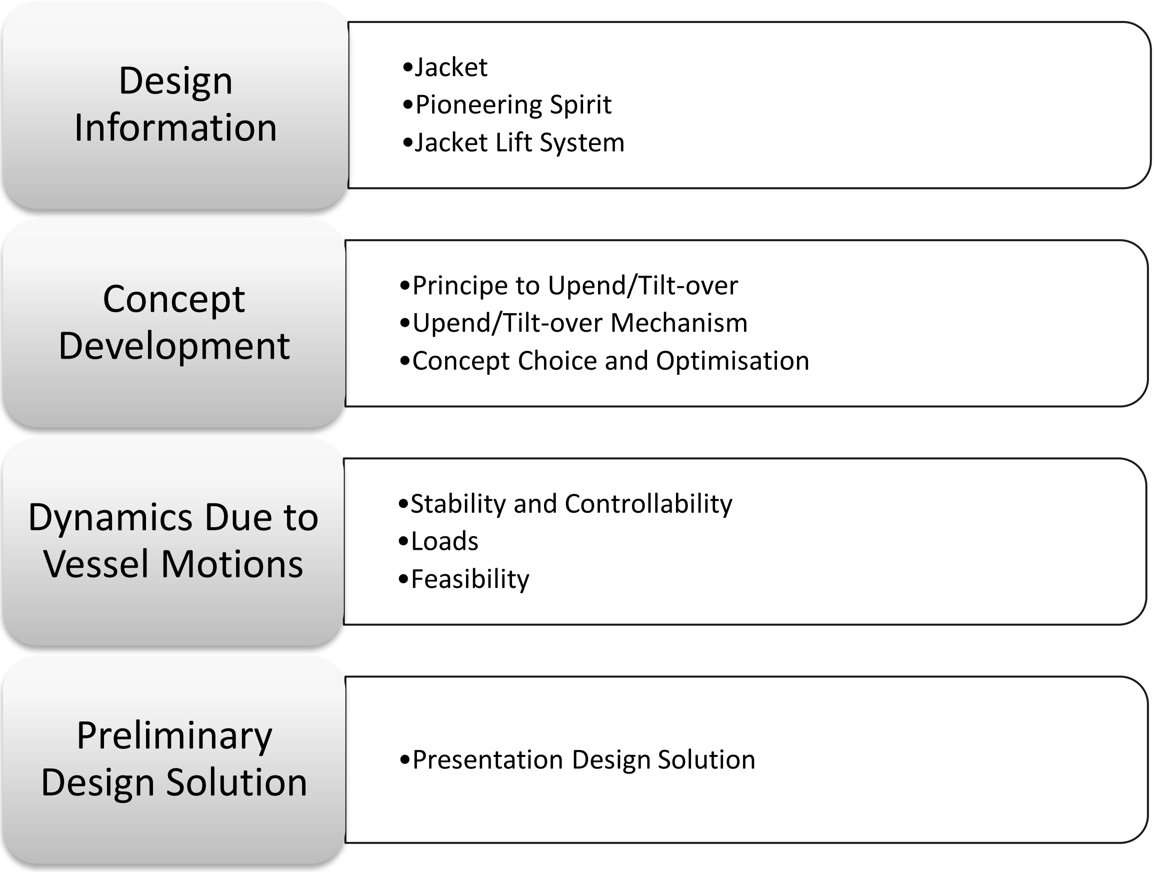


Figure 2: Overview Design/Research Strategy

1.4.1 Design Information (part 1)

The first part, Design Information, consists of a background study on the key subjects in this thesis project. To clarify the situation in which the system must be implemented, and which structure the system must be able to install or remove, a coarse background study is carried-out on a jacket in general and the technical specifications of Pioneering Spirit. The background study is complemented with a function and process description about the upend/tilt-over component/operation of the Jacket Lift System.

1.4.2 Concept Development (part 2)

In the second part, Concept Development, a favourable design solution is developed. A design process is often quite chaotic and time-consuming. In the beginning, the amount of solutions seems to be infinite and, among many other reasons, it is difficult to develop a spot-on concept. The acquired insights and information constantly influence the thoughts about the most critical parameters and aspects. By developing in a coarse manner at the start and adding more and more details, it is possible to implement the acquired insights and information in the design without having to start over and over again. To grow into a favourable design solution in a coherent and thoughtful method, the concept development part is divided into 3 subparts. “Principles to Upend/Tilt-over”, “Upend/Tilt-over Mechanism” and “Concept choice and Optimisation”. The following scheme is used in each subpart:

Figure 3: Approach Scheme Subparts

The first step in the scheme, **brainstorm**, is about generating possible design solutions while keeping the main focus point, for that specific concept development subpart, in mind. The most promising concepts are listed down and a brief elaboration is given in the second step, the **development**. The third step is to **analyse** the concepts that have been elaborated in step 2. This will be done by using pre-determined assessment points. The results are described in the fourth and last step, the **evaluation**.

1. **Concept Development Subpart 1: Principe to Upend/Tilt-over (Chapter 4)**

The objective in this concept development subpart is to compose general principles to upend or tilt-over a jacket. The reference design is ignored in this subpart. Besides the actual installation or removal operation of a jacket, topics such as the load-in and load-out of a jacket are also considered. This is important in developing a design solution that can complete the entire jacket installation or removal operation. The result of this concept development subpart is a qualitative description of which principles have been examined and which principle will be further elaborated in a next subpart. Limitations and other restrictions imposed by the current appearance of Pioneering Spirit have not been considered during the first step of the scheme, brainstorm. Obviously, these topics are included in the later analysis and evaluation steps.

2. **Concept Development Subpart 2: Upend/Tilt-over Mechanism (Chapter 5)**

The focus in the second concept development subpart is on acquiring information about the static forces required to obtain a static equilibrium during the upend or tilt-over operation, to understand what is mechanically desirable and what the most important influencers are during the operation. The main topic in this concept development subpart is the mechanism to initiate the motion to upend or tilt-over the system. The result of this subpart is an analysis of the contributions of the mass of the system, mass of a reference jacket and the buoyancy on the operation and a description of the favourability of the various Upend/Tilt-over Mechanism concepts.

3. **Concept Development Subpart 3: Concept Choice and Optimisation (Chapter 6)**

In the last concept development subpart, the favourable parts of the previous concepts are combined to find the most favourable design solution. At this stage, no new concepts will be introduced. This new design solution is optimised by investigating possible optimisations found during the previous concept development subparts, subpart 2 in particular.

1.4.3 Dynamics Due to Vessel Motions and Feasibility (part 3)

In the third part, Dynamics and Feasibility, the design solution, obtained in part 2, is further elaborated. Time dependent (dynamic) contributions are added to the analysis and the stability of the system is checked. This results in an answer whether or not the system is stable and an estimation of the loads on/in the system. Eventually, this results in the answer whether or not the chosen system is feasible. One of the focus points in this part is the controllability of the system.

1.4.4 Preliminary Design Solution (part 4)

This final part comprises a description of the upend/tilt-over operation. An inventor sketch is added to clarify the design solution pertaining to the upend/tilt-over component of Pioneering Spirit's Jacket Lift System.

1.5 Research/Design Questions

1.5.1 Design Information (part 1)

What are the most critical and important system requirements and aspects regarding the upend/tilt-over component of the Jacket Lift System?

- What are the (technical) specifications and dimensions of normative jackets at this moment and in the future?
- What are the operational conditions and (technical) specifications of Pioneering Spirit?
- What is the general procedure of a jacket installation/removal and what must the system be able to do?

1.5.2 Concept Development (part 2)

What is the favourable (drive) mechanism to upend/tilt-over the system keeping the feasibility, compatibility, controllability, efficiency and the finances in mind?

- Which principles are possible, wide-ranging, to upend/tilt-over a jacket?
- What components in the principles are most favourable?

- Based on the favourable principle, which concepts as (drive) mechanism to upend/tilt-over are possible?
- What are the static forces on the system during the upend or tilt-over operation to obtain a static equilibrium?
- What are (the most) important parameters/influences in the composed concepts?

- What optimisation and combination are possible and what is favourable?

1.5.3 Dynamics Due to Vessel Motions and Feasibility (part 3)

- Is the system dynamically stable?
- What is the response of the system in the designated sea states due to vessel motions?
- What are the most probable maximum dynamic forces due to vessel motions in ocean waves during the upend/tilt-over operation?
- How is the controllability secured during the upend/tilt-over procedure?
- What are the total maximum forces on the system?

1.5.4 Preliminary Design (part 4)

- What are the main parts in the system and how do they (possibly) look like?
- How does to system work?

1.6 Reading Guide

This thesis report requires, partly because of its size, a reading guide. The thesis project is divided into 4 main parts, as explained in this introduction. Within the second main part, the Concept Development, a subdivision has been made again into 3 subparts. The main parts and subparts are the common tread in this thesis report. Each main part and subpart is elaborated in a separate chapter. The chapters are structured in such a way that they can be read independently. If information mentioned or elaborated in another chapter is used, this is mentioned in the text together with a cross-reference to the right place in the report. If one is more deeply interested in the setup and results of each separate part, one is advised to read at least the introduction, the principle and concept descriptions of chapters 4, 5, and 6 and the conclusion of each chapter.

Overview parts and chapters:

• Design Information (part 1)	Chapter 3
• Concept Development (part 2):	Chapter 4, 5 and 6
○ Principe to Upend/Tilt-over	Chapter 4
○ Upend/Tilt-over Mechanism	Chapter 5
○ Concept Choice and Optimisation	Chapter 6
• Dynamics Due to Vessel Motions and Feasibility (part 3)	Chapter 7
• Preliminary Design Solution (part 4)	Chapter Preliminary Design

1.7 Introduction to Allseas

Allseas, “Allseas Group S.A.”, is a Swiss-based company founded in 1985 by Edward Heerema [7]. Allseas is a global leader in offshore pipeline installation, heavy lift operations and subsea structures installation [8]. Allseas employs over 3000 people worldwide and operates a versatile fleet of specialised heavy-lift, pipelay and support vessels. Since Allseas was founded, Allseas has successfully completed all kind of offshore and subsea construction projects worldwide [9].

1.7.1 Activities

The main contractual activities of Allseas can be subdivided into pipelines and subsea installation related activities and heavy-lift operations.

Pipeline and Subsea Installation Activities

Pipeline installation

All Allseas’ pipelay vessels are equipped with pipelay equipment to install pipelines in S-lay configuration. This means that the vessels have a horizontal firing line through the vessel. The pipeline is fed-out horizontally and adjusts to an S-shape while traveling down to the seabed. The S-lay method is characterised by its high installation speed. Allseas can lay pipes with a diameter of 2 inch to 68 inches (0,05 to 1,73 meter) in water depths ranging from shallow water to water depths over 2500 meters.

Subsea installation and pipeline repair operations

A subsea field development may consist, besides pipelines, of many different subsea structures. Allseas has experience installing inline trees, manifolds, jumpers, pipeline termination structures (PLETs) and many more. Some of the operations are complex. Examples are the installation of inline structures and pipeline repair operations. In those cases, it is necessary to retrieve the pipeline to the water surface to safely separate the pipeline section. After installation of the inline structure or replacement of a damaged section, the pipeline is lowered back to the seabed.

Pipeline and subsea structures design and engineering

The pipeline(s) and subsea structures must be designed and engineered prior to installation. The in-house engineers of Allseas mostly do the engineering. This enables Allseas to combine the requirements of the design and user applications with the installation requirements. Examples of topics related to the general design of the pipelines/subsea structures during its operational lifetime are strength, fatigue, environmental influences and user application demands such as the pipeline diameter. Examples of topics related to the installation are environmental loads, such as sea conditions, and other location related difficulties, such as the water depth.

Pipeline protection and specialised pipelay operations

In some situations, the pipelines need to be protected against external influences. Examples of potential threats are objects falling from vessels, pipeline crossings and grounding icebergs. Allseas applies all kind of protections to protect the pipelines from those external influences. Examples of protection measures are mattresses, rock dumping and/or pipeline burial.

Survey and subsea operations

All pipelay and subsea installation vessels are equipped with survey equipment. A Remotely Operated Vehicle (ROV) checks whether the pipeline and structures have been installed correctly. Survey can be used to check and determine which preparations are required prior to the installation of the pipeline(s) or subsea structures.

Heavy-lifting

Allseas' heavy-lift activities comprise the installation/removal of offshore topsides and the installation/removal of offshore jackets. Both types of structures are lifted in a single lift. Regarding the installation activities, the primary goal is to install topsides with a mass of more than 10 000 mt and jackets with a height of more than 70 meters. Pioneering Spirit will of course also be able to install smaller topsides and jackets. The topsides are installed and removed by the horizontal lifting beams, named Topsides Lift System. The Topside Lift System is installed on the double bow of Pioneering Spirit. Jackets will be installed and removed by the Jacket Lift System installed at the stern of Pioneering Spirit.

Source: internet site of Allseas/activities. [10].

1.7.2 Fleet

Allseas has a versatile fleet consisting of pipelay vessels and support vessels. Most of the vessels are (partly) engineered and designed by the in-house engineers of Allseas. Some of the vessels are adjusted from one type of vessel to another. An example is Solitaire.

Pipelay/Heavy Lift Vessels

- **Pioneering Spirit** is the biggest construction vessel ever built. It is designed to install/remove large offshore platforms and to install pipelines. The twin-hulled vessel is 382 meters long and 124 meters wide. The slot at the bow is 122 meters long and 59 meters wide. The maximum lift capacity of the Topsides Lift System is 48 000 mt. The lifting capacity of the Jacket Lift System at the stern of the vessel will be 15 000 mt excluding lifting gear.

- **Lorelay** is a vessel optimised for the installation of small and medium sized pipeline diameters. Lorelay is also suitable for the installation of structures such as risers and subsea protection frames. Lorelay was the first pipelay vessel that was able to fully operate on dynamic positioning. Lorelay is 183 meters (236 meters with stinger) long and 26 meters wide.

- **Solitaire** is a pipelay vessel that was for a long time the standard in the pipelay industry. This was until Pioneering Spirit was taken into operation. Solitaire has a high installation speed and is able to install pipelines in ultra-Deepwater. Back in 2007, Solitaire set the world record laying pipe by installing a pipeline in a water depth of 2775 meters. The length of Solitaire is 300 meters (397 meters with stinger), the breadth is 41 meters.

- **Audacia** is a pipelay vessel optimised to install small to large diameter pipelines. Audacia is also optimised to install specialised subsea structures. Regarding the dimensions and specifications, Audacia can be placed between the Solitaire and Lorelay. Audacia has an overall length of 225 meters (327 meters with stinger) and a width of 32 meters.

- **Tog Mor** is a shallow water pipelay barge that is able install pipelines with a diameter up to 60 inches. Tog Mor has an operation draft of just 2 meters and is equipped with equipment optimised for special activities such as midpoint tie-ins. Tog Mor is an anchored moored barge.

Excluding Tog Mor, Allseas' pipelay vessels are all equipped with a 3-class Dynamic Positioning System.

Support Vessels

- **Iron Lady** is a cargo barge used to transport jackets and topsides from and to Pioneering Spirit. The Iron Lady has a length of 200 meters and a width of 57 meters. The Iron Lady is designed to fit perfectly between the double bows of Pioneering Spirit. The Iron Lady has a relatively small draft to be able to load-out/load-in topsides and jackets in a (shallow) sheltered location.

- The stinger of Pioneering Spirit is removable. The stinger is stored on the **Bumblebee** when removed. Bumblebee is a specially designed cargo barge to store the stinger and transition piece.

- **Calamity Jane** is a trenching support vessel to support Allseas' pipelay vessels. Calamity Jane is specialised in activities such as pre- and post-route survey, crossing preparation and mattress installation. Calamity Jane is equipped for FGT operations (testing operations) to check the integrity of the installed structures.

- **Bright Spark** is Allseas' floating welding training facility. Employees are trained in the facility before going to Allseas' pipelay vessels. The vessel was acquired in 2013 and converted to a welding school. The vessel is 130 meters long and 19 meters wide.

- **Oceanic** is quite recently purchased by Allseas [11]. Oceanic is used for survey activities, the installation of subsea/protection structures and as a support vessel for Pioneering Spirit. Oceanic has a length of 129 meters and a breadth of 30 meters. Oceanic has an ice class and is therefore able to operate in arctic regions.

- **Fortitude** is Allseas' latest purchase. Fortitude will assist on pipelay projects and will support Pioneering Spirit during preparation operations for platform installation/removal activities. Fortitude is a state-of-the-art DP3 vessel with a length of 150 meters. The vessel is equipped with two knuckle boom cranes, one with a lift capacity of 900 mt and another of 200 mt.

- **Alegria, Felicity** and **Havila Fortress** are Allseas' pipe supply vessels.

Source: internet site of Allseas/equipment. [12]

1.7.3 Company Strategy

Allseas is built on technical ingenuity and an entrepreneurial spirit. To remain a sustained frontrunner, Allseas constantly challenges the technical boundaries. Through the development of in-house expertise, Allseas develops new techniques and innovative solutions to meet the fast changing needs of the market.

Allseas can support the client from the beginning of a project, the conceptual design stage, until the decommissioning of the project at the end of its lifetime. Examples of activities are conceptual design, project management, engineering, procurement, installation, and decommissioning. Dynamism, inventiveness, rapid progress and a no-nonsense approach are Allseas' distinguishing qualities.

Allseas' core values [13]:

- Safe, efficient and error-free performance
- Good, long-term relationship with clients
- Innovative and advanced technology
- High-quality service and products
- Integrity
- Skilled and motivated employees
- Maximised profitability in the long term

1.7.4 Allseas Engineering B.V

Allseas has various offices, fabrication sites and yards. Allseas has three engineering offices in the Netherlands. All three offices are located close to the local technical universities. The head office of Allseas Engineering B.V. is seated in Delft. Allseas Engineering B.V. is responsible for all technical "onshore" activities. A few examples are the engineering of the projects, innovations, technical performances of the vessels and research/monitoring. Furthermore, all supporting activities, such as IT, are also located in the office in Delft.

2 Previous Research/Reference Design Solution

This section comprises information about the most important design solution of the Jacket Lift System that Allseas has developed in the past. This design is a reference design with the purpose to provide information about application demands and other requirements. The design of the reference Jacket Lift System is based on a hydraulic upending system. The focus in the description of the reference design is on the upend/tilt-over components. In the second section of the chapter, a photo collage is given about the installation and removal procedure.

2.1 System Components

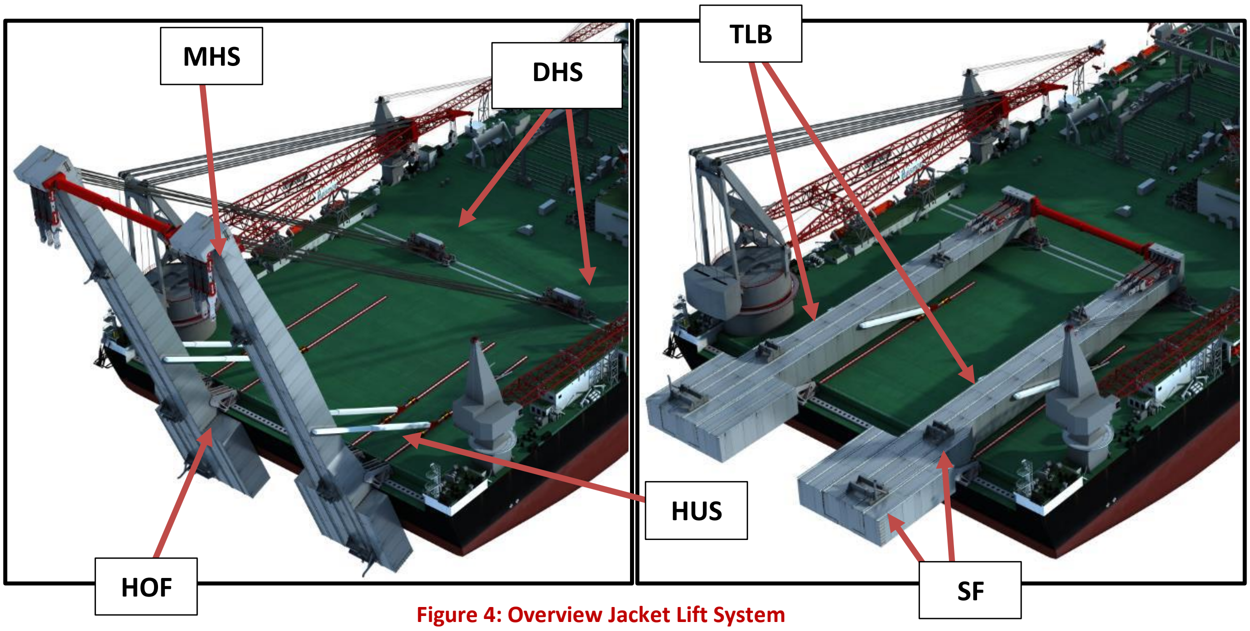


Figure 4: Overview Jacket Lift System

The meaning of the abbreviations is included in the description per component below.

Tilting Lift Beam (TLB):
In the reference design, the Jacket Lift System is equipped with two Tilting Lift Beams. The main functions of the Tilting Lift Beams are to support the jacket during transport, the upend/tilt-over operation and to transfer the loads to the hang of system. The Tilting Lift Beams act as crane booms in upended position. The Tilting Lift Beams provide clearance around Pioneering Spirit and sufficient lift height to lower or lift a jacket from and to the seabed.

The mutual distance between the two Tilting Lift Beams is adjustable. To fully utilise the benefits of the Jacket Lift System, the jackets must be supported at the most critical places. This is done by adjusting the mutual distance between the two Tilting Lift Beams to the mutual distance of the legs of the jacket. Support frames are used to support the jacket into the most favourable positions. The most favourable positions to support a jacket is different for each jacket.

The length of the Tilting Lift Beams at the aftdeck is limited to 110 m. This is the distance between the stern of the vessel and the derrick hoist system. The free hanging length of the Tilting Lift Beams is limited by the keel of the vessel. The system must be able to upend/tilt-over in shallow waters for maintenance and testing purposes. The maximum length of the Tilting Lift Beams in shallow water is restricted to 30 meters. This restriction is less important in deeper waters. The total length of the Tilting Lifting Beams is about 140 meters. A so-called folding tail is used in the reference concept. The folding tail increase the length of the Lifting Lift Beams by 16 meters.

The angle of the Tilting Lift Beams must be adjustable during the upend/tilt-over operation. This is important during the (dis)connection process of a jacket to the Jacket Lift System and is important to obtain sufficient clearance between Pioneering Spirit and the jacket during lifting or lowering.

The angle during connection/disconnection of the hoists to the jacket	≤ 115 degree
The angle during Jacket lifting	≤ 106 degree

Derrick Hoist System (DHS):
The Derrick Hoist system is the controlling system during the upend/tilt-over operation. By taking in or giving out wire, the system rotates around its hinges/hang of frame. The tension in the wires will be of a great magnitude and will also vary during the process. The tension in the wires depends on the position of the system at a certain moment during the upend/tilt-over operation. The Derrick Hoist system is connected to the top of the Tilting Lift Beams. Like the Tilting Lift Beams, the mutual distance between the two hoists systems must be adjustable. The wires of the Derrick Hoist system are attached to the deck of Pioneering Spirit by means of the, transverse movable, derrick hoist skids. An approximation of the skidding speed for a full stroke is 12 hours and is performed in unloaded conditions. The upend/tilt-over operation takes about 12 hours in loaded conditions.

Main Hoist System (MHS):
The Main Hoist System is attached to the top of the Tilting Lift Beams. This system consists of wires, lifting blocks and motion compensators. The Main Hoist system can take in and give out wire to align a jacket with the angle of the Jacket Lift System. This enables the system to attach or detach the jacket to and from the support frames. The main hoist speed in the reference design is 3 m/min.

Support Frames/Sledges (SF):
A jacket must be connected and supported on/to the Tilting Lift Beams. This is done by means of the support frames/sledges on top of the Tilting Lift Beams. The support frames/sledges are positioned in a manner that the jacket is supported at the most critical parts in the jacket. The support frames/sledges also make it possible to load-in and load-out a jacket on/from the Jacket Lift System to/from a cargo barge.

Hang-of frame/Hinge System (HOF):
The hang-of frame or hinge system, together with the derrick hoist system, is the topic where it is initially about in this thesis. The hinge system together with the derrick hoist system makes it possible to upend/tilt-over the Tilting Lift Beams. The system supports the Tilting Lift Beams and transfers the loads from the Tilting Lift Beams to the vessel. The loads in the hinge System are expected to be enormous. It is the only mass carrying component in the system. The Hang-of frame comprises, like the Derrick Hoist systems and the Tilting Lift Beams, of two identical components and must be adjustable in mutual distance.

Hydraulic Upend System (HUS):
In the design of the reference concept, the Jacket Lift System is upended by means of a hydraulic system. A reinforced frame is applied on the aftdeck of Pioneering Spirit.

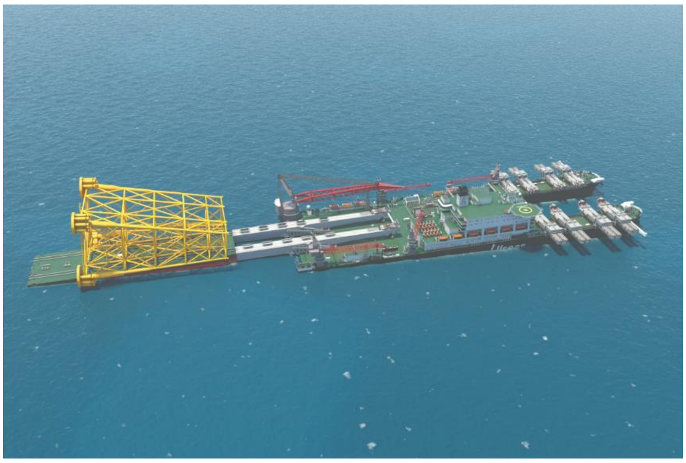
2.2 Jacket Installation/Removal Procedure

The photo collage below provides an impression of the procedure as it was conceived in the reference design. The removal procedure is approximately the same, however, in a reverse sequence. Source Figures: Allseas.

General Procedure

1. The Jacket is loaded out onto a cargo barge and Sea-fastening is applied.

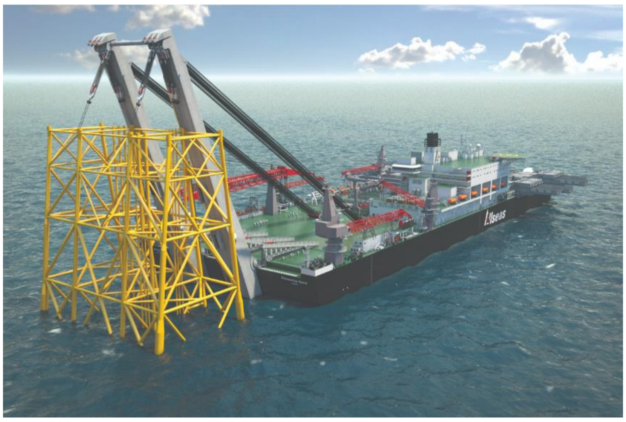
2. The cargo barge is positioned at the stern of the vessel at a sheltered location. The sea feasting on the cargo barge is removed, the jacket transferred from the barge to Pioneering Spirit and the Sea-fastening on Pioneering Spirit applied again.



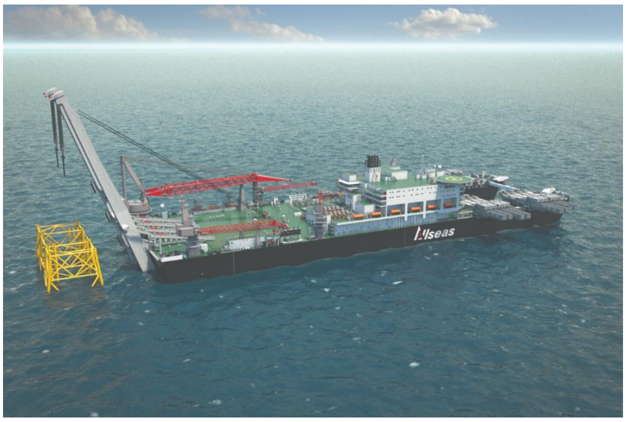
3. Pioneering Spirit sails to the offshore installation site and the Sea-fastening is unlocked/removed.

4. The jacket is upended to a vertical position.

5. The jacket is disconnected from the support sledges/frames. The jacket is now hanging freely.



6. The jacket is lowered to the seabed and the hoisting equipment is then disconnected.



7. The Tilting Lift Beams are tilted-over to a horizontal position and the piling operation commences.

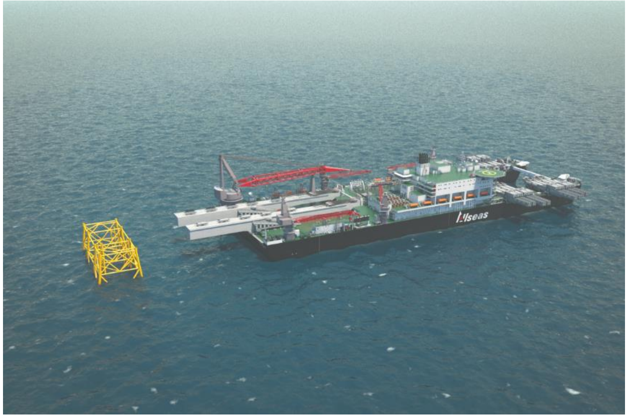


Figure 5: Photo Collage Installation Procedure

3 Design Information

This chapter comprises background information about the key subjects in this thesis report. In the first section (3.1), a general definition of a jacket and specifications about jackets used as input parameters in the concept development process (next main part) is given. The Jacket Lift System must be implemented in Pioneering Spirit's current appearance. Information about Pioneering Spirit and her specifications are given in the second section (3.2). In the last section (3.3), a functional description is given about the Jacket Lift System focussed on the upend/tilt-over component. Information is included in appendix A.

3.1 Jacket

This section provides general information about jackets. First, a general definition and explanation is given about a jacket followed by a selection of important structural topics in the design of a jacket. A jacket can be classified according to installation method. This classification is described in the next paragraph supplemented with a description about regulations concerning the removal of jackets in the North Sea Region. This section is completed with information about reference jackets on which the preliminary design solution is based.

3.1.1 General Definition of a Jackets

A jacket is a steel piled structure that is installed on the seabed for the purpose to accommodate a deck on top [14]. The height of a jacket is determined to prevent waves from hitting the deck in the local most severe environmental conditions. The space between the still water level and the bottom of the deck is called the clearance. The deck installed on top is called a topside. The topside offers space for drilling activities, production activities and crew quarters. A jacket is also named a support structure. A jacket provides structural support and space for equipment such as risers, water intakes and provides load carrying capacity for the topside. [15]. Jackets are applied in water depths up to 450 meters, however most jackets are applied in water depths up to 200 meters. The advantage of using a jacket as support structure is the type of loads that the structure can resist. A jacket has a great resistance against vertical and horizontal static loads and vertical and horizontal dynamic loads. All loads are transferred to the seabed via the foundation piles/arrangements and have proven to be reliable and effective. An example of a static load is the mass of a topside. An example of a dynamic loads is a wave hitting the structure. A picture of a support structure and topside is given in Figure 6. [15].

Figure 6: Support Structure with Topside

In the offshore sector, it is customary to call every steel substructure fixed to the seabed a jacket. However, formally a distinction should be made between a jacket and a tower. A Jacket is a fixed structure with leg piles. Foundation piles are driven through the legs of the jacket. The jacket and the foundation piles are welded together at the top of the piles and the legs of the jacket. The axial force of the structure and topside is transferred at the top of the piles and jacket. The jacket itself provides support for the foundation piles, conductors, risers and other equipment [16]. A Tower is a fixed structure supported by a foundation arrangement at the base. A tower foundation usually consists of clusters of piles that are inserted through and connected to sleeves around the legs at the base of the structure [16]. In this thesis report, just like within Allseas, all support structures are called a jacket. A picture has been added on the next page to clarify the difference between a jacket and a tower. Source Figure 7: [17].

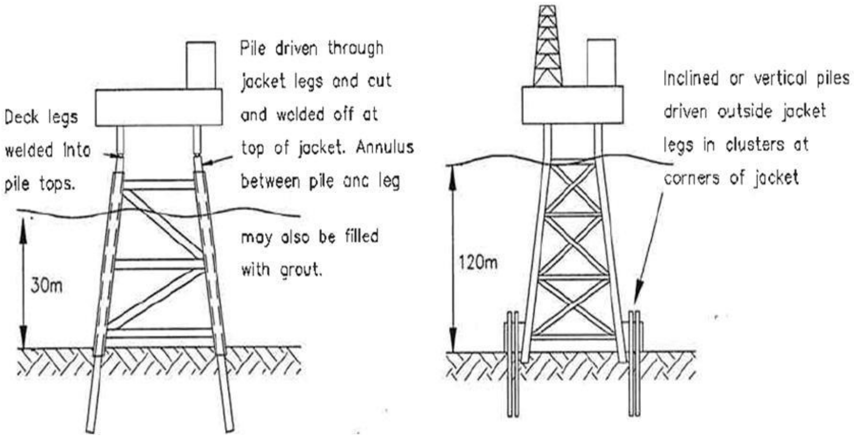


Figure 7: Differences between a Jacket and a Tower

3.1.2 Jacket Structure

Many topics are considered in making a jacket design. Examples of structural topics are the shape of the jacket, the brace pattern of the beams and the dimensions of the beams (diameters and thicknesses). Much depends on the type of jacket (more information in paragraph 3.1.3) and the prevailing conditions and specifications at the offshore installation location. Examples are the water depth and environmental conditions. To conclude, every jacket design is different, and the Jacket Lift System must be able to install/remove all jackets within Allseas' scope.

Allseas has investigated the possibility of reducing the total mass of required steel in a jacket by looking into the installation method. At this moment, violent installation methods are used, an example is launching a jacket from a cargo barge. In case of a launch, it is required to take the forces induced by the jacket entering the water into account in the jacket design. A reduction of mass is obtained by supporting the jacket during the entire upend or tilt-over process. The jacket will be upended and tilted-over in a controlled and gentle manner. It is important to support the jacket during the entire process at the most favourable parts in the jacket. An overview about what type of load is predominant for a certain beam in the jacket is given in Figure 8 [15].

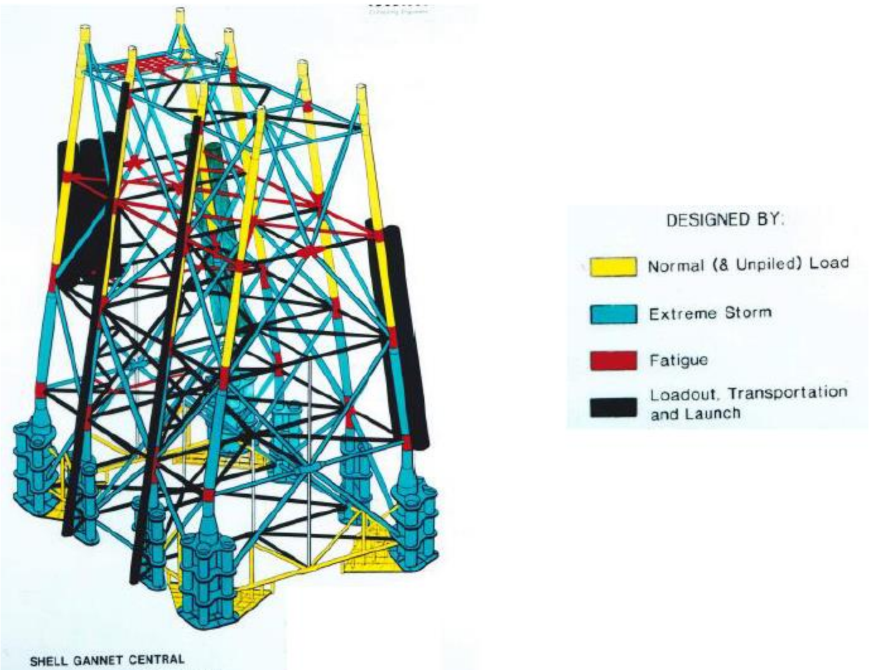


Figure 8: Overview Predominant Source Pertaining to Strength

3.1.3 Jacket Classification to Installation Techniques

As mentioned in the introduction, many Jackets were and have been applied as a support structure in field developments throughout the world. An overview of the most important regions is given below. Allseas designated the North Sea Region as target area for Pioneering Spirit to decommission and install jackets (and topsides). Forecasts about jackets that must be removed, enforced by regulations, in the (near) future and the prevailing environmental conditions in the North Sea Region are examples of topics that Allseas has included in this decision.

Main regions:

- North Sea
- Middle East
- Asia
- Far East
- The Americas (Gulf of Mexico, Alaska, USA West Coast and Brazil)
- Mediterranean Sea
- Africa
- Australia

Different types of installation methods are used in the North Sea Region. As mentioned in section 3.1.2, the installation method has a major influence on the design choices for a jacket. Examples of choices that depend on the installation method are the brace pattern and the dimensions of the beams. This is, among other reasons, why jackets can be classified to installation method. In the North Sea Region, a distinction is made between Self-floater, Barge-launched, lift-installed and shallow water jackets [4]. An overview of the jacket classifications is shown in Figure 9 [4].

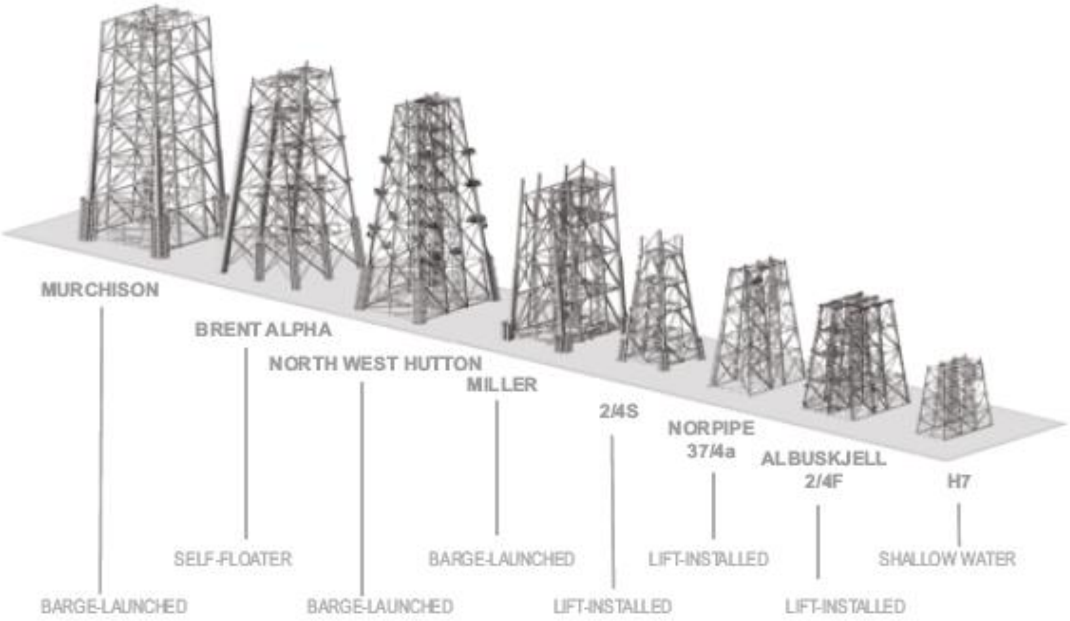


Figure 9: Overview of Jackets to Installation Method

The choice to apply a specific installation method usually depends on the mass and dimensions of the jacket. For instance, there is a strong correlation between the choice for a self-floater and the dimensions of a large jacket. This correlation and the number of how many times a certain type of jacket is applied in the North Sea Region can be observed in Figure 10. This is an overview made by Oil&Gas UK [4].

Type	Countries					Total	Decommissioned To Date (2012)
	UK	Norway	Nether-lands	Denmark	Other		
Self-floater	8	0	0	0	0	8	0
Barge-launched	26	39	0	0	3	68	20
Lift-installed	45	36	0	7	0	88	3
Shallow water	202	2	139	46	3	392	29
Totals	281	77	139	53	6	556	52

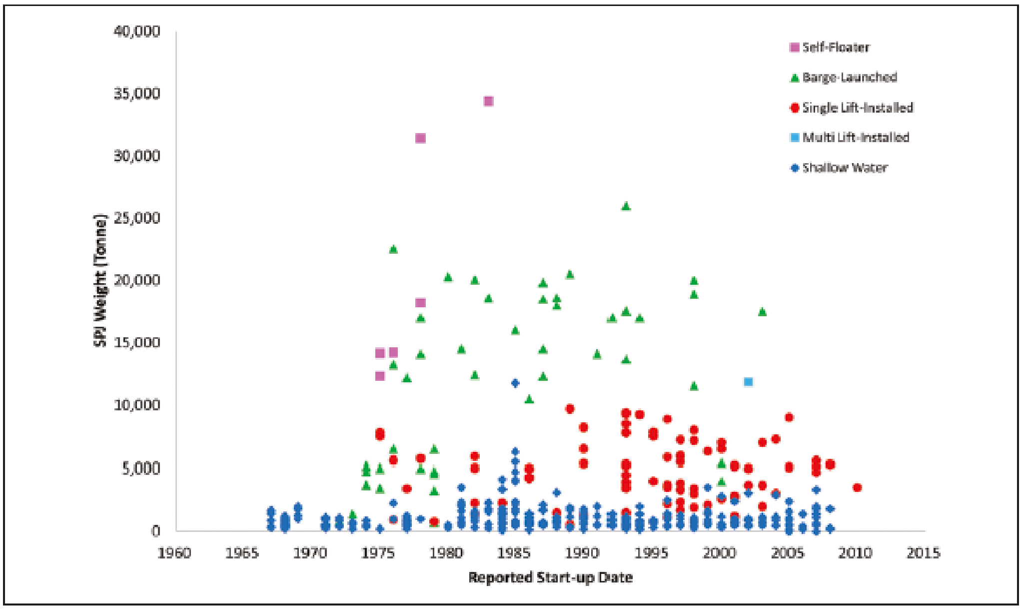


Figure 10: Inventory of Steel Piled Jackets in the North Sea Region

Self-floater

Self-floater jackets are in general the largest jackets applied in the North Sea Region [4]. A self-floater jacket is recognisable by the integrated buoyancy modules in the legs of the jacket. The diameters of the legs are larger. This type of jacket is built on a quay site or in a dry dock. The jacket is towed horizontally floating on its own buoyancy to the offshore construction site. At the offshore construction site, the buoyancy modules are flooded in a controlled manner to upend the jacket. Eventually, the jacket is placed on the seabed with crane assistance. Self-floater jackets in the North Sea Region are applied with a mass of 12 000 mt and more.

Barge-launched

A barge-launched jacket is an often-applied jacket type. A barge-launched jacket is constructed on a quay site and after completion loaded-out to a cargo barge. The cargo barge with jacket is towed to the offshore construction site. The jacket is usually placed horizontally during the construction on the quay site and the transportation between the quay and the offshore construction site. At the offshore field development location, the jacket is launched from the cargo barge. A rocker beam is used during the launch. Once the jacket is in the water, valves are opened to flood the legs in a controlled manner. As a result, the jacket tilts from a horizontal position to a vertical position. The jacket is placed in the right location with crane assistance. Barge-launched jackets usually have a mass between 5 000 mt and 25 000 mt.

Lift-installed

A lift-installed jacket is built horizontally or vertically on a quay site onshore. A lift-installed jacket is usually transferred to a cargo barge using a load-out procedure. Lift-installed jacket are sometimes transferred to a heavy lift vessel or cargo barge using a lift operation. The cargo barge is then transported to the offshore construction site. The lift-installed jacket is lifted from the cargo barge (or heavy lift vessel) and placed in the right location on the seabed. If the jacket is transported horizontally, the jacket is upended in air using cranes. Lift-installed jacket were and are, especially until the nineties, the most commonly applied type of jacket in the North Sea Region [18]. After the nineties, the desire to make lighter jacket designs became increasingly important, as was the desire to design jackets for field developments in deeper waters and locations with more violent environmental conditions. Lift-installed jackets in the North Sea Region have a maximum mass of 10 000 mt.

Shallow water

A shallow water jacket is a collective term for steel structures with a mass of less than 2 000 mt and are usually installed in a water depth until 55 m. Shallow water jackets are barge-launched or lift-installed. This category also includes monopiles, Vierendeel towers and braced caissons. This type of structure is the most commonly applied jacket in the North Sea region, especially in the shallower southern part of the region.

3.1.4 Regulation Disused Jackets/OSPAR Decision 98/3

The largest part of the North Sea Region is included in the OSPAR Maritime area. This can be observed in Figure 11. The OSPAR commission is a commission existing out of representatives from 15 governments (Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom). The commission is established to protect and conserve the North-East Atlantic and its resources [19]. OSPAR was founded in 1972 with the Oslo Convention against marine pollution by land-based sources. The Offshore industry was added during the Paris Convention in 1974. Eventually, the OSPAR Decision 98/3 on the disposal of disused offshore installations was made. The OSPAR Decision 98/3 states that all offshore installations that are no longer in use must be removed.

Many jackets were/have been installed before the OSPAR Decision 98/3 was applicable. These jackets are therefore not constructed in such a way that the removal of the structures is considered. Partly for this reason, agreements have been made to, in some cases, not remove the entire structure after the structure has reached its lifetime or has become redundant. It has been agreed that steel construction with a mass of more than 10 000 mt, in air, installed before February 1999 may remain in full condition, remain partially or that the footing may remain on the seabed. A motive to leave the complete structure in place is when the structure has suffered unforeseen structural damages or has deteriorated to an extent that removal of the structure entails disproportionate difficulties. In the cases were the structure is partially allowed to remain, the upper part must be removed to a water depth of at least 55 meters in reference to the lowest expected astronomical tide. A gravity-based concrete structure may remain completely intact. All structures installed after February 1999 must be fully brought to shore. Source: Oil & Gas UK [4] and [20].

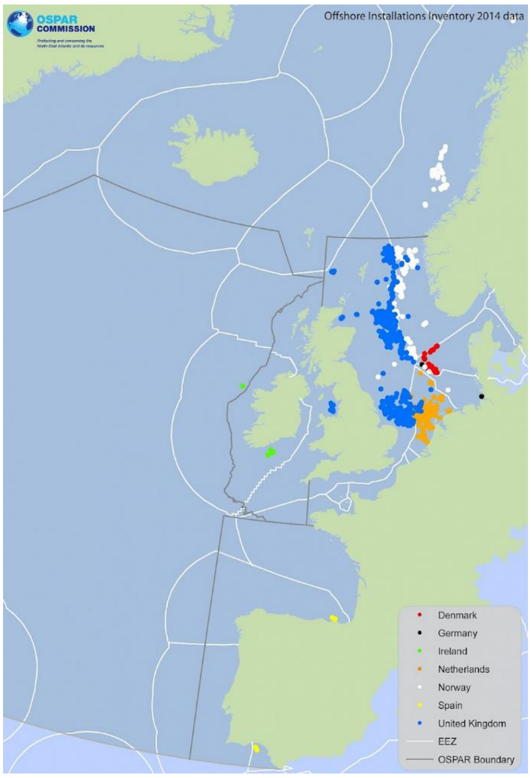


Figure 11: OSPAR Maritime Area

3.1.5 Reference Jackets

The Jacket Lift System must be able to install and remove jackets with a mass up to 15 000 mt. Each jacket is a project specific design, so no jacket will be the same and every lift will be an engineered lift. To assign Design Information, four jackets have been chosen as reference jacket. The reference jackets to be removed are one of the largest installed jackets in the North Sea Region. The reference jackets to be installed are jackets that will be installed in the near future. Specification of the reference jackets about the height, mass and location are included in Table 1.

Name of Jacket:	Height: [m]	Mass: [mt]	Location:
North West Hutton		17 500	North Sea, North - East Shetland Basin (UK)
Brent Alpha	150	14 225	North Sea, East Shetland Basin (UK)
Murchison	166	14 000	North Sea, East Shetland Basin (UK)
Kvitebjørn	215	12 000	North Sea, Norwegian Continental Shelf (NO)
Sverdrup P1	143	17 700	North Sea, Norwegian Continental Shelf (NO)

Table 1: Predominant Reference Jackets

North West Hutton (informative about procedure)

The North West Hutton field is located 140 km North-East of the Shetland Islands in the UK sector. The platform consisted of a steel jacket with 8 legs. The jacket was installed in a water depth of 144 meter in 1981 [21]. The jacket was a barge-launched type jacket. The mass of the jacket was 17 500 mt. The jacket was removed in the summer of 2009. 8 500 mt of the total mass is removed in 54 pieces. The 54 pieces are removed using cutting and lifting techniques. The heaviest lift was 2 250 mt [4].

Brent Alpha (1)

The Brent Alpha platform is a platform that consists of a steel jacket with a mass of approximately 31 500 mt. The platform was installed in 1976. The jacket is a self-floater type jacket and was floated out from the shore of Scotland. Brent Alpha is one of the four platforms in the Brent field development. The Brent Alpha platform is the only platform in the Brent field development that has been applied with a steel jacket. The jacket is installed in a water depth of 140 meters and has 8 legs. Only the upper half of the jacket must be removed. The mass of the upper half is approximate 14 225 mt [22].

Murchison (2)

The Murchison platform was one of the biggest platforms in the North Sea Region. The platform had a topside with a mass of 24 000 mt and a steel 8-legged jacket with a mass of 24 500 mt [23]. The platform was installed in 1982 and removed in 2017. The platform has been removed in modules [24]. The footing of the platform has been left at the offshore site. 14 000 mt of the total mass has been removed.

Kvitebjørn (3)

The Kvitebjørn platform was installed in 2003 in the Norwegian region of the North Sea. The Kvitebjørn platform is an integrated drilling and processing platform. The platform has a 4-legged steel jacket measuring 215 meters in height. The platform is installed in a water depth of 190 meters. The jacket is installed in two parts and is the tallest jacket on the Norwegian Continental shelf [25].

Sverdrup P1 (4)

The Johan Sverdrup field development will be one of the five largest oil field developments on the Norwegian Continental Shelf [26]. The field development will consist of 4 new to build steel jackets. Sverdrup P1 has an 8-legged jacket that will be installed in phase 2 of the development. The platform will be installed in a water depth of 120 meters [27].

To give an impression of the above mentioned jackets, drawings of the platforms are included in Appendix A.

3.2 Pioneering Spirit

This paragraph comprises a summary of technical specifications, limitations regarding the Jacket Lift System and operational procedures/specifications of Pioneering Spirit. The Jacket Lift System will be installed at the stern of Pioneering Spirit. The vessel is already in operation and the aftdeck is also used by other activities. This is one of many examples of topics that must be considered during the design process.

3.2.1 General Technical Specifications

A summary of general technical specification of Pioneering Spirits is given in Table 2. The summery comprises information about vessel dimensions, system capabilities and available facilities such as cranes, generators and other equipment. Not all information is directly applicable to the Jacket Lift System but is still of great relevance to mention as it provides information to get a general overview.

Length overall	382 m (477 m incl. TLB's and stinger)
Length between perpendiculars	370 m
Breadth	124 m
Depth to main deck	30 m
Slot length	122 m
Slot width	59 m
Topsides lift capacity	48 000 mt
Jacket lift capacity	15 000 mt (excl. 2 500 mt hoist equipment)
Maximum draught	27 m
Minimum draught	10.5 m
Maximum speed	14 knots
Displacement	100,000 mt (at maximum draught)
Design life	25 years
Total installed power	95,000 kW
Thrusters	12 x 6050 kW azimuth 6 thrusters at the stern, 6 thrusters at the bow The thrusters do not extend the keel of the vessel
Dynamic positioning system	Fully redundant, class 3 Kongsberg K-Pos DP-22 and 2 x cJoy system
Accommodation	571 persons
Helideck	Maximum take-off weight 12.8 mt, suitable for Sikorsky S-61 and S-92 helicopters
Deck cranes	Special purpose crane 5000 mt Special purpose crane 650 mt 3 x pipe transfer cranes 50 mt
Work stations	Double-joint factory, with 5 line-up stations and 2 stations for combined external/internal welding Firing line with 6 (double joint) welding stations 1 NDT station and 6 coating stations
Installed tension capacity	4 x 500 mt
Pipe cargo capacity on main deck	27,000 mt
Pipe diameters	From 2" to 68" (outer diameter)
Minimum operational temperature	-20 °C

Table 2: General Specification of Pioneering Spirit

3.2.2 Operational Specifications

Operational Category Pioneering Spirit

Previously, in this thesis report, a distinction was made between three main activities of Pioneering Spirit. These activities can be further subdivided into operating modes. An operation mode defines a part in a main activity that is similar or applies in the same environmental conditions. Examples are vessel positioning, preparation work, small lifts, standby or waiting on weather, topside lifting and winter berthing in sheltered waters. These operational categories are directly applicable on the Jacket Lift System and therefore described in paragraph 3.3.2.

Draughts

Pioneering spirit can adjust her draught between 10.5 meter and 27 meters by water ballasting. A typical draught of Pioneering Spirit during a jacket installation/removal operation is 17 meters. However, this may vary between 12 and 27 meters depending on whether this is allowed and/or necessary for a specific project.

Typical draughts per operation:	
Maximum	27.0 m
Minimum	10.5 m
Heavy lifting	17.0 m
Transit	12.0 m
Survival	11.5 m
Pipelay	10.5 m
Load-out/Load-in	27.0 m
In Ice	11.0 m

Table 3: Draught per Operational

Minimum Operational Temperature

Pioneering Spirit will operate in weather conditions of -20 °C or higher. If the temperature drops below this temperature, no lift and special operations will be carried-out.

3.2.3 Equipment Specification

Position Thrusters

Pioneering Spirit is equipped with 12 Azimuth thrusters with a capacity of 5500 kW. 6 thrusters are installed at the aft of Pioneering Spirit and 6 thrusters are installed at the bows. An overview of the positions of the thrusters at the aft of Pioneering Spirit is given in Figure 12.

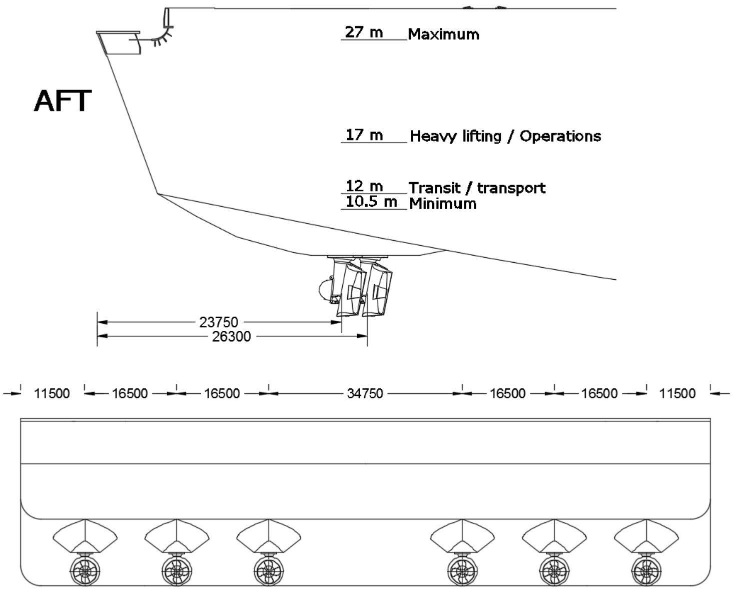


Figure 12: Position Thrusters (upper figure: Side view, lower figure: rear view)

Special Purpose Cranes

Pioneering Spirit is equipped with four special purpose cranes at the aftdeck of the vessel. Especially the Special purpose crane with a lift capacity of 5000 mt and the special purpose crane of 650 mt are able the support jacket installation and removal operations. The positions of the cranes at the aftdeck are shown in Figure 13. Pioneering Spirit is equipped with more cranes than the cranes showed in Figure 13, however those cranes do not have sufficient reach and capability to assist during jacket installation and removal operation.

-	Special purpose crane	Lift capacity:	5000 mt	at 35 m	Max reach: 98 m
				Auxiliary hoist	Max reach: 117,5 m
				Whip hoist	Max reach: 129 m
-	Special purpose crane	Lift capacity	650 mt	at 20 m	Max reach: 58 m
-	2 cranes of	Lift capacity	50 mt	at 33 m	Max reach: 58 m

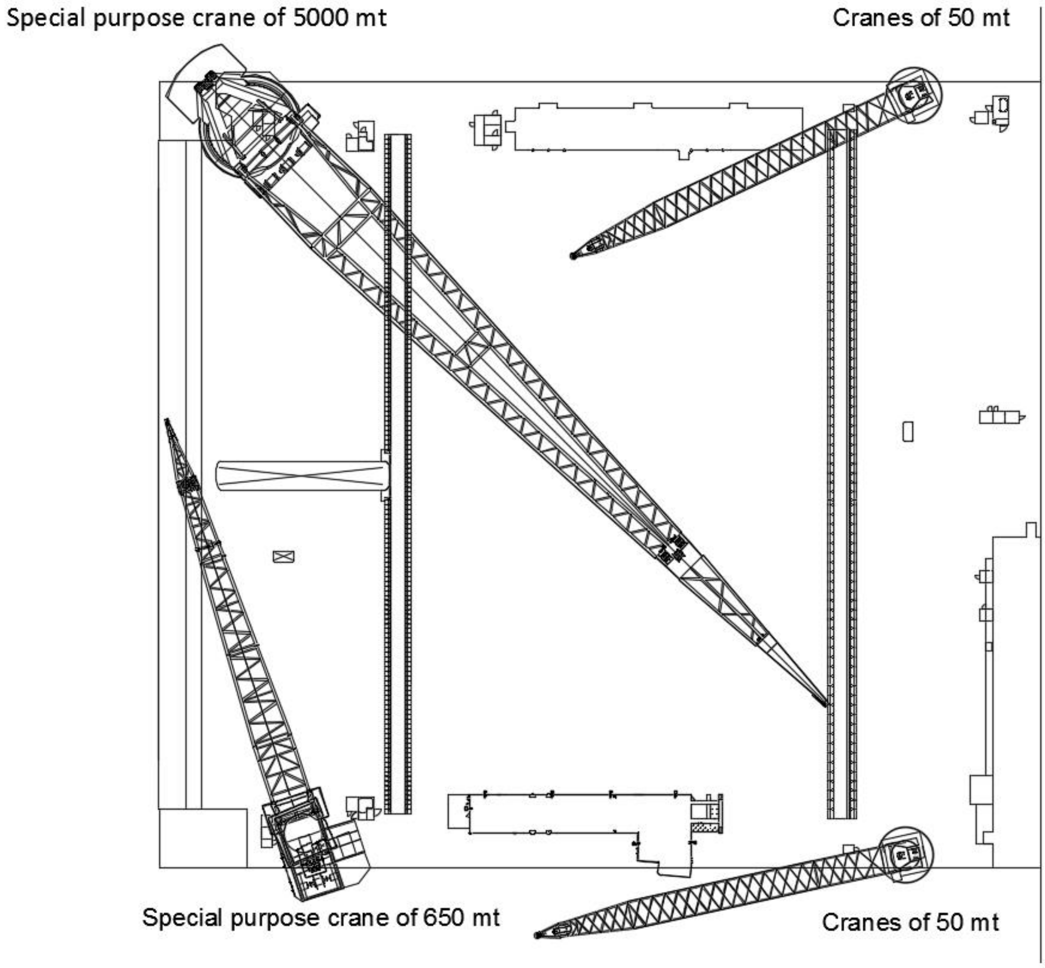


Figure 13: Position Cranes Aftdeck (top view)

Power Generation

Pioneering Spirit has a total installed power of 95 000 kW. The following power generators are responsible for this power capacity:

Diesel Motors	8x 11 000 kW	88 000 kW
Harbour Generator	1x 5 000 kW	5 000 kW
Emergency Generator	2x 1 000 kW	2 000 kW

Table 4: Installed Power

The 12 thrusters using their full capacity have a power use of 6050 kW each.

3.2.4 Structural Specifications

Deck Load Capacity Aftdeck

The stern of Pioneering Spirit is reinforced by a combination of transom and transverse bulkheads. The aftdeck has parts that have been reinforced to the capacities listed down in Table 5. Other deck areas of the vessel have a uniform loading capacity of **12 mt/m^2**. The aftdeck is equipped with two transverse frames. The transverse frames have been specially applied for the Jacket Lift System. The frames are part of the reference design as explained in chapter 2. The transverse frames can be seen in Figure 14. The centre of the frames is at 38 m and 108 meters in reference to the stern of Pioneering Spirit.

Type of load	Deck	Transverse frame	Bulkhead Transverse	Bulkhead Longitudinal	Crossing point Bulkhead
Wheel load [mt]	30	-	-	-	-
Uniform load [mt/m2]	15	10	10	10	-
Line load [mt/m]	-	300 compression 450 tension		800	-
Point load [mt]	-		750	500 (750 if reinforced)	2000 compression 3000 tension

Table 5: Deck Load Capacity

Deck Space

The available deck space for the Jacket Lift System depends on other installed equipment and activities at the aft of the vessel. To give an example, the aftdeck is also used during pipelay operations. The pipe segments are transferred from a supply vessel to the deck of Pioneering Spirit. Subsequently, the pipe segments are transported to the bevelling station at the aftdeck. Equipment used during this process is partly removable. Another example is the minimum space between the top of the Jacket Lift System, in horizontal position, and the accommodations/permanent installed equipment such as the support cranes. The available deck space at the aftdeck for jacket installation/removal purposes is shown in Figure 14.

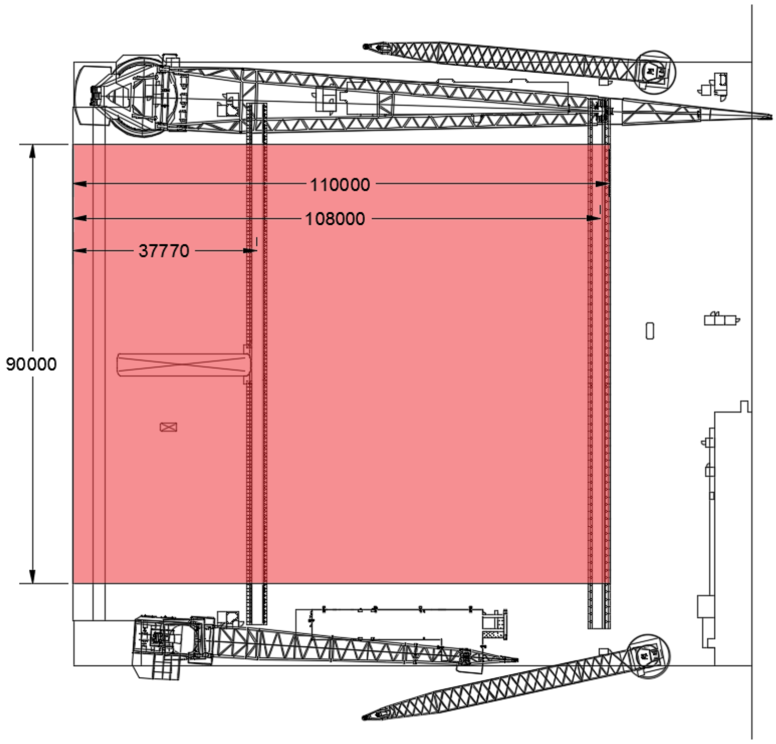


Figure 14: Deck Space for Jacket Installation/Removal Purposes (top view)

3.3 Jacket Lift System

Requirements and Design Information can be separated into functional and non-functional aspects [28]. Functional aspects define what the system must do. Non-functional aspects define how the system should do it [29]. In this section, a functional description is given of the Jacket Lift System. These aspects are considered in the assessment criteria in the analysis of each concept.

The purpose of the description in this paragraph is to provide clarity on the jacket installation and removal process by means of the Jacket Lift System. This description is also written to give information about which parts of the total jacket installation and removal process are considered.

3.3.1 General Installation and Removal Procedure

As the name implies, the main activity “Jacket installation and removal” comprises the installation and removal of a jacket. The installation procedure for a jacket is roughly similar to the removal procedure, but in a reverse order. There are, however, some differences between the two procedures. A general description of the installation and removal procedure is given on the following two pages. A more advanced description about the topics introduced in this paragraph is given in paragraph 3.3.2.

General Installation Procedure

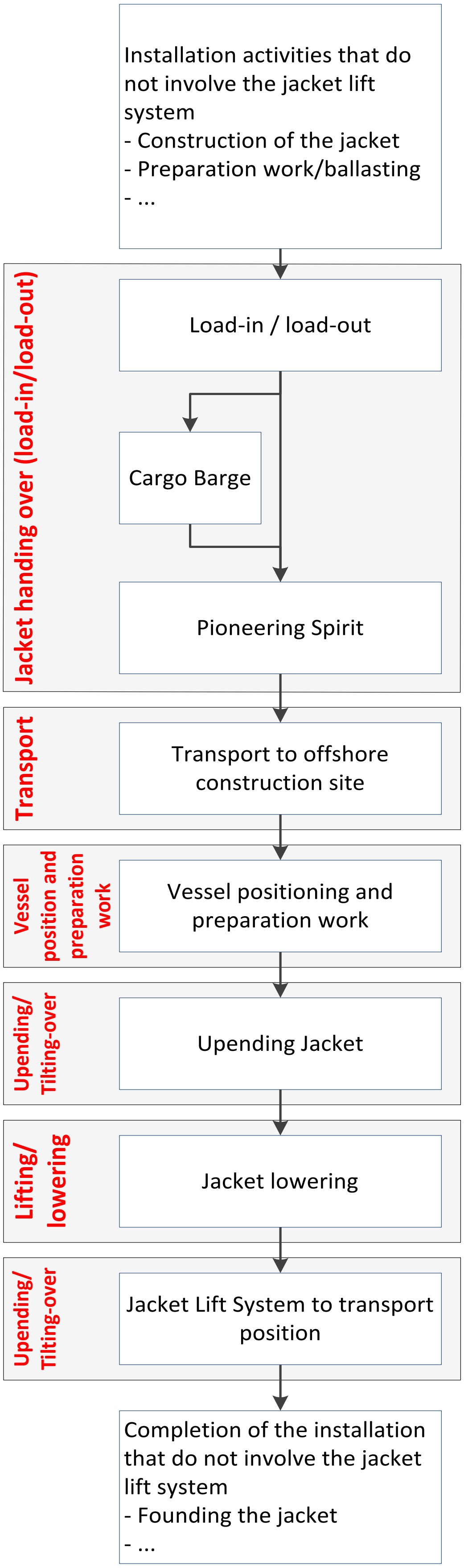


Figure 15: General Installation Procedure

Prior to the offshore installation activities, the jacket is constructed at an onshore construction site. The same applies to other installation activities in which the Jacket Lift System is not involved. Examples are the preparation of the support structures/frames, sailing to the onshore construction site and ballasting the vessel to the right draught. Other preparation work at the offshore location by other vessels is also done is this phase.

The first actual installation activity in which the Jacket Lift System is involved is the load-out/load-in of the jacket from a quay on a cargo barge or on Pioneering spirit. Whether the jacket is loaded on a cargo barge or directly on Pioneering Spirit depends on the circumstances at the quay site. If the location is suitable for Pioneering Spirit to reach and navigate, the jacket is loaded directly on Pioneering Spirit. If the location is not suitable, the jacket is firstly loaded on a cargo barge. Subsequently, Pioneering Spirit and the cargo barge both sail to a sheltered location where the load-in/load-out on Pioneering Spirit happens.

After the jacket and the system are sea-fastened, Pioneering Spirit leaves for the offshore construction site. The jacket is positioned in horizontal position during transport.

Upon arrival at the construction site, Pioneering Spirit is manoeuvred into the right position, the Sea-fastening is removed, and other preparation work is carried out. An example is ballasting Pioneering Spirit to the ideal jacket installation draught.

At this moment, the actual upend/tilt-over operation is carried-out. The jacket is tilted from a horizontal position to a vertical position. The jacket must be supported in such a way that the jacket will not suffer any damage during this operation.

The jacket is lowered in vertical position to the seabed. After the jacket is placed on the seabed, the jacket is disconnected from the hoisting system.

The jacket is now standing freely. The Jacket Lift System is returned to a tilted (horizontal) position.

At this point, activities commence where the upend/tilt-over component of Pioneering Spirits Jacket Lift System is not involved. The jacket is founded together with other completion activities.

General Removal Procedure

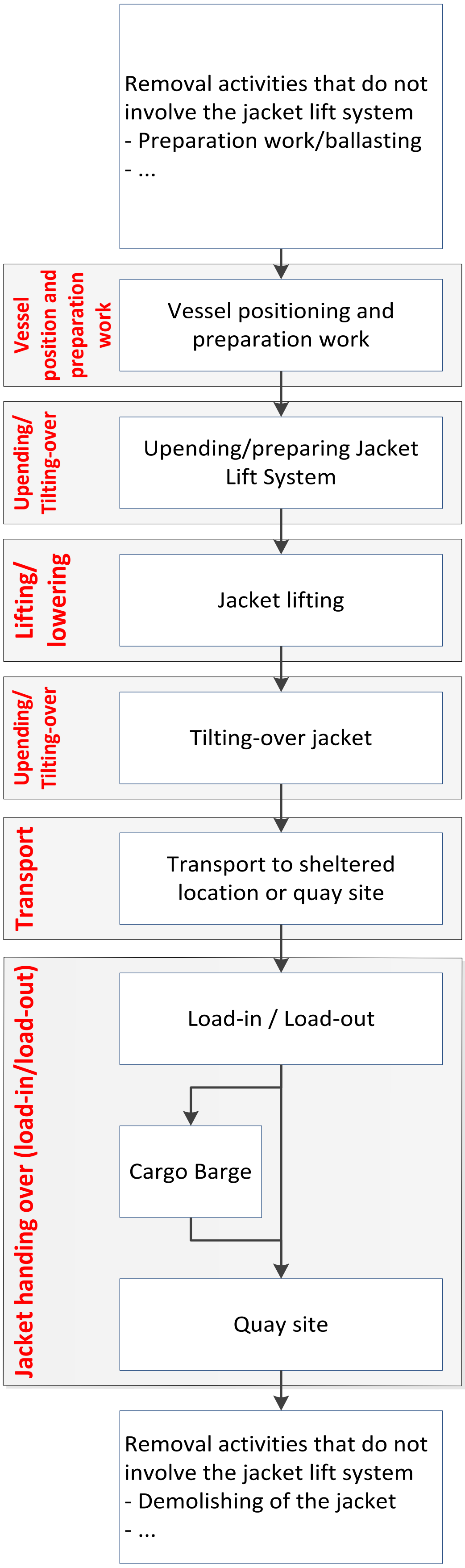


Figure 16: General Removal Procedure

Preparatory activities are carried-out prior to the offshore removal operation. Examples are applying reinforcements to certain parts of the jacket, cutting footings/foundations and general inspections. The Jacket Lift System is not involved in these activities. In addition, preparation work to Pioneering Spirit is being carried out.

Upon arriving at the construction site, Pioneering Spirit is manoeuvred into the right location, support frames are placed in the right positions and other offshore preparation work is carried out. An example is ballasting the vessel to the ideal jacket removal draught.

After all preparation and positioning activities have been carried-out, the Jacket Lift System is upended/prepared.

The hoisting system is connected to the jacket followed by lifting the jacket from the seabed to a pre-determined height.

This phase in the operation involves the actual upend/tilt-over operation. The jacket is tilted-over to a horizontal position. The method of tilting-over is concept dependent. The jacket must be supported in such a way that the jacket will not suffer any damage during this operation.

As soon as the jacket is placed in a horizontal position on the deck of Pioneering Spirit, the jacket is sea-fastened and other transport preparation work is carried-out. After the preparatory work is completed, the jacket is transported to a sheltered location or directly to the quay site where the jacket is demolished.

Whether the jacket is loaded on a cargo barge or directly to a quay at the demolishing site depends on the circumstances at the quay site. If the location is suitable for Pioneering Spirit to reach and navigate, the jacket is directly loaded onto the quay. If the location is not suitable, the jacket is firstly loaded on a cargo barge. Subsequently, Pioneering Spirit and the cargo barge both sail to a sheltered location where the load-in/load-out happens.

Pioneering Spirit leaves to the next job and the jacket is demolished.

3.3.2 Functional Description Jacket Lift System

As already indicated in Figure 15 and Figure 16, the general procedure for installing or removing a jacket can be divided into operation categories. The operation categories have certain function requirements. Examples are the activities that comprise that part of the overall procedure and how this affects the equipment. Another example are the environmental conditions allowable during a certain part of the general procedure. In the figure below, Figure 17, an overview is given of the three main activities of pioneering spirit, the procedural categories and the operation modes. The operation modes are the situations in which the system must be able to work. The system, for example, must also be tested in addition to actual installation and removal activities. A detailed explanation of the operational states and operational categories is given on the following pages.

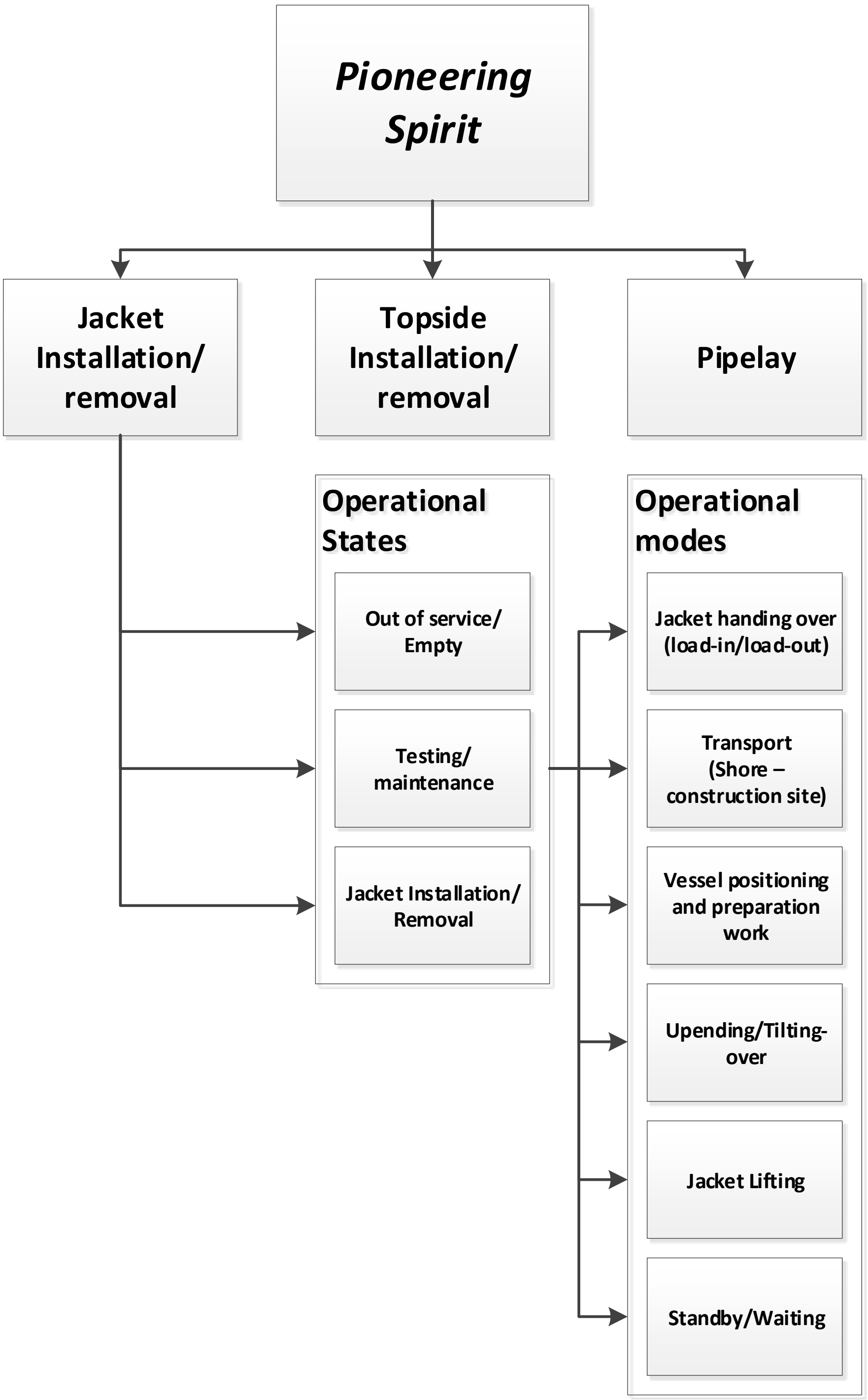


Figure 17: Jacket Lift System Functions Decomposition

Operational States Definition

A distinction is made between operational modes. An operation mode describes the conditions and situations that the Jacket Lift System will encounter during its lifetime. The system must be able to operate in these situations in addition to the actual jacket installation and removal operations. To give an example, the system must also be tested and maintained.

Out of Service/Empty

It is desirable to design a Jacket Lift System with most equipment semi-permanent installed. After the installation or removal activity is complete, the equipment is removed and temporary stored in a convenient storehouse/location. However, some components of the equipment cannot be removed. These components must be placed in a position where it does not interfere with other activities. In addition, the devices that are permanently installed must be designed according to the same conditions and situations of Pioneering Spirit. An example are the environmental conditions.

Testing/Maintaining

One of Allseas' pillars in her mission statement, paragraph 1.7.3, is to work safe, efficient and error-free. After each adjustment to the system or procedure the system and procedure must be tested. This includes the installation of semi-permanent installed equipment, procedure adjustments and maintenance activities. The testing location is preferable close to the installation/maintaining site.

Jacket Installation/Removal

The Jacket installation/removal mode is the situation where a jacket is installed or removed. This mode contains all steps of the installation or removal procedure.

Operational Category Definition

Jacket Handing Over (Load-in/load-out):

The jacket handing over operational category is when the jacket is transferred from a quay site to Pioneering Spirit, or vice versa. This is done at a sheltered location with mild environmental conditions. Whether a jacket is (off)loaded on a cargo barge or directly on Pioneering Spirit depends on the circumstances at the quay site. If the location is suitable for Pioneering Spirit to reach and navigate, the jacket is directly (off)loaded onto Pioneering Spirit. If the location is not suitable, the jacket is firstly (off)loaded onto a cargo barge. Pioneering Spirit and the cargo barge both sail to a sheltered location that is suitable for a load-in/load-out operation. The load-in/load-out takes place at this location. The load-in/load-off is a complicated operation.

Transport (shore – construction site):

The transport operational category is the operation category where the jacket is transported between the quay site and the offshore construction site. The jacket is transported horizontally on the aftdeck of Pioneering Spirit. The system and the jacket are sea-fastened during the transport to prevent slamming and other unwanted movements of the system or parts in the system. The vessel undergoes all sorts of movement and acceleration during transport. An example of a sea-fastening is given in Figure 18 [30].

Figure 18: Example of Sea-Fastening

Vessel Positioning and Preparatory Work:
Upon arriving at the construction site or quay site, preparatory work is carried-out. The systems must be placed in position and tested. This type of operations, including positioning of the vessel, is included in this operational category. Other examples are the removal of the sea-fastening and the ballasting of Pioneering Spirit to the desired draught.

Upending/Tilting-over:
Once all preparatory and positioning activities are carried-out, the system is upended and tilted-over. This process must be executed thoroughly. The mass of the jacket and the mass of the system will be enormous. Errors will almost certainly lead to fatal consequences. It is important to keep, for instance, the motion of Pioneering Spirit due to the local environmental conditions into mind during the upend/tilt-over procedure.

The upend/tilt-over operations are quite similar, however in a reverse order. What is different, is whether the system operates with or without a jacket on top. The possible situations during upending and tilting-over are:

- Upending with jacket
- Upending without jacket
- Tilting-over with jacket
- Tilting-over without jacket
- Transport with jacket
- Transport without jacket

Jacket Lifting:
This operational category includes the hoisting and lowering operation of a jacket from and to the seabed. The jacket is positioned vertically during this operation. The system is maximum loaded during this operation category.

Standby/Waiting:
This operational category includes all time moments in which Pioneering Spirit must wait before an installation or removal operation commences. All sorts of reasons are possible why Pioneering Spirit must wait. The most common reason is waiting for better weather conditions. Although all operations are intensely prepared, the weather conditions are sometimes unpredictability and can easily exceed the maximum capacity of the systems.

3.3.3 Functional Specification Jacket Lift System

Environmental specification per operational category are given in Table 6. These capacities are set for Pioneering Spirit during the design of Pioneering Spirit.

Preparations work and small lifts		
Significant wave height	4	m
Wave period (Centroid Mean)	≤ 10	s
Wind speed	12	m/s (1 hour average, 19 m above sea level)
Current speed	0.5	m/s

Jacket lifting and upending / tilting-over		
Significant wave height	2.5	m
Wave period (Centroid Mean)	≤ 6	S Spectrum type: Pierson-Moskowitz
Wind speed	12	m/s (1 hour average, 19 m above sea level)
Current speed	0.5	m/s

Standby or waiting on weather (survival)		
Significant wave height	14	m
Wave period (Centroid Mean	10.5-15.5	s
Wind speed	51.4	m/s (1 hour average, 19 m above sea level)

Transport (no heading control)		
Significant wave height	6	m
Wave period (Centroid Mean	≤ 11	s
Wind speed	20	m/s (1 hour average, 19 m above sea level)

Transport (heading control)		
Significant wave height	10	m
Wave period (Centroid Mean	≤ 12	s
Wind speed	24	m/s (1 hour average, 19 m above sea level)

Load-out / load-in		
Significant wave height	1	m
Wave period (Centroid Mean	≤ 6	S Spectrum type: Pierson-Moskowitz
Wind speed	12	m/s (1 hour average, 19 m above sea level)
Current speed	0.5	m/s

Table 6: Environmental Specifications per Operational Category

4 Principles to Upend/Tilt-over

The objective in this first subpart of the concept development is to find a favourable principle to upend/tilt-over a jacket. This is done in a qualitative search considering the entire jacket installation/removal operation. The result of this concept development subpart is a qualitatively description of which principles have been examined and which general principle will be further elaborated in the next subpart of the concept development. Limitations and other restrictions imposed by the current appearance of Pioneering Spirit have not been included during the first step of the scheme (see Figure 3 (page 5), brainstorm. Obviously, these topics are included in the later analysis and evaluation steps.

4.1 Introduction Upend/Tilt-over Principles

Innumerable options are possible to upend/tilt-over an object. Therefore, and for many other reasons, it is difficult to develop a spot-on concept at the start of the design process. As a starting point, the definition is taken of upending/tilting-over an object. The upending or tilting-over of an object can be seen as changing its orientation in the Cartesian coordinate system. The object changes, for example, from an orientation in the Y-axis direction to an orientation in the X-axis direction. The object rotates around a certain arbitrary point. The Cartesian coordinate system is shown in Figure 19.

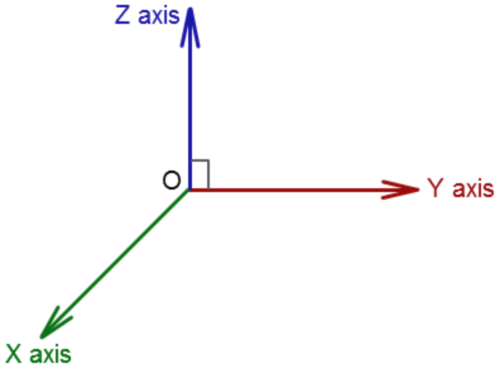


Figure 19: Cartesian Axes System

In this thesis report, only three of the many composed principles to upend/tilt-over are elaborated and included. The elaboration per principle is coarse and merely focused on a qualitative search to find the most favourable principle. The three principles are the result of the narrowing-down during the “brainstorming”. The three principles are the most general principles and therefore, at this stage, the most useful. More details are included in the next concept development subparts, as described in the thesis strategy/approach (paragraph 1.4). An overview of the elaborated principles with assessed concepts is shown in Figure 20:

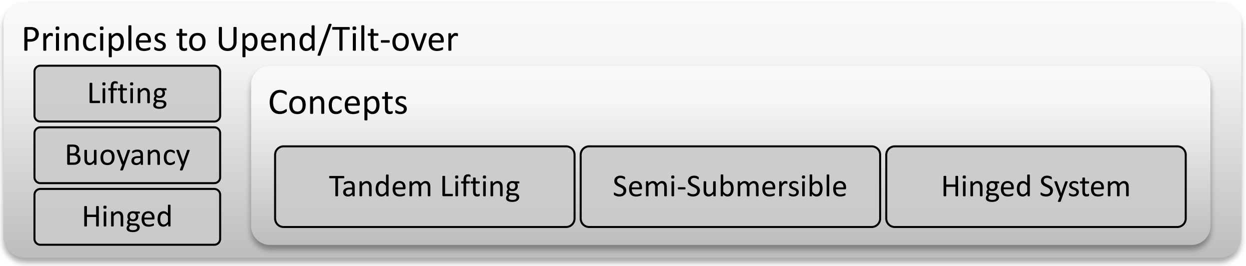


Figure 20: Overview Upend/tilt-over Principles

4.2 Assessment Criteria Upend/Tilt-over Principles

Five topics are considered as the most important assessment criteria in this subpart of the concept development. As mentioned earlier, the assessment consists of a qualitative description and the results are obtained in a reasoning manner. The five assessment points are:

- **Compatibility**
  The compatibility of the Jacket Lift System is about the extent of adjustments needed to the vessel, the equipment and the processes on Pioneering Spirit. It is important that as few adjustments as possible are necessary. Many adjustments result in high investment costs and causes the vessel to be out of service for a long time. Moreover, making many adjustments can lead to earlier investments being lost.

- **Workability**
  Whether or not an Offshore operation can happen is strongly dependent on the prevailing environmental conditions at that time. A design is resistant to environmental influences to a certain extent. Examples of environmental influences are wind, current and waves. At the moment that an operation cannot be performed, due to the occurring environmental conditions, the vessel will go into a standby mode until the conditions are sufficient reduced. It is superfluous to mention that the downtime period should be kept to a minimum. This can be achieved by designing a system that is less sensitive to environmental phenomena. In this phase of the concept development, a quantitative prediction is given per concept.

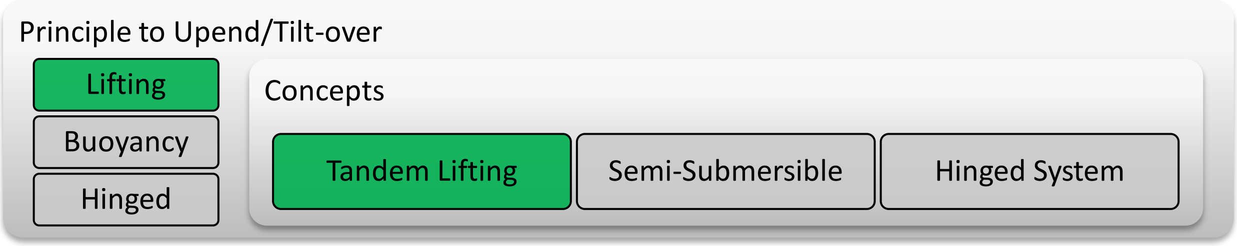
- **New Equipment**
  The Jacket Lift System will consist of new components. One design needs more components than another. The smaller the size of the new system, the less space the system will take and the smaller (likely) the investments costs will be. This assessment point has similarities with the compatibility assessment point. However, the new equipment assessment point concerns the system that will be added. Adjustments to Pioneering Spirit to implement the new system are included in the compatibility assessment point.

- **Complexity**
  The system must be as simple as possible to install, operate and maintain. The more complicated the system, the greater the chance of errors and accidents. The completion of a job failure-free and accident-free is one of Allseas' strategic pillars. The complexity of the system is weighted as important in this assessment. It is important that the process, during the upend/tilt-over operation, can be adjusted to the circumstances at that moment. Thus, the controllably of the process must be high. Furthermore, the process must last as short as possible.

- **Investment Costs**
  In addition to technical assessment points, the investment costs are also essential in deciding whether a design is favourable or not. A concept or principles can be technically favourable, but if it is too expensive to realise, operate and maintain, it is not worth the investment. Even though no quantitative cost estimation can be provided at this stage, it is possible to qualitatively assess whether a concept is expected to require larger investments compared to another.

4.3 Principles Descriptions

4.3.1 Lifting Principle



1. Principle Description

The lifting principle consists of one or more cranes installed on the vessel. The crane(s) perform all moving and lifting operations where Pioneering Spirit is involved. The jacket is placed on pre-positioned support frames at the aftdeck during transport. The positions of the frames are adjustable to the dimensions of the jacket. The jacket is supported at the most favourable places in this way. The installed crane(s) can also be used for other activities besides jacket installation and removal operations. The Jacket Lift System will thus consist of adjustable support frames and one or more special purpose cranes with a (combined) capacity sufficient to install or remove jackets with a maximum mass of 15 000 mt.

2. Reference Applications

This principle, in the basis, is frequently used in the offshore sector. Vessels equipped with a single crane are often used for smaller jackets. This type of jackets, explained in paragraph 3.1.3, can be classified as “shallow water” jackets. Examples of single crane vessels are Subsea 7’s “Seven Borealis” and Seaway Heavy Lifting’s (part of Subsea 7) vessel “Oleg Strashnov”. The maximum installation and removal capacity of these vessels is limited to 5 000 mt. The crane tip usually has a maximum height of 100 m. Another frequently used offshore crane vessel is a semi-submersible crane vessel. This type of vessels is equipped with two cranes and can perform so-called tandem lift operations. This type of vessels is not able to transport a jacket on its own deck. Instead, cargo-barges and other heavy transport vessels are used to transport the jacket. Examples of semi-submersibles crane vessels are the vessels of Heerema Marine Contractors and Saipem. The current maximum capacity, in tandem lift, is 14 000 mt. Lift-installed jackets, explained in paragraph 3.1.3, are often installed using this principle. An example is given in Figure 21 [31]. Buoyancy modules are regularly used to make the tilting process easier and more manageable.

Figure 21: Upending/Tilting-over of a Jacket in Tandem Configuration

3. Concept Description "Tandem Lifting"

The "Tandem Lifting" concept, within the lifting principle, consists of two cranes installed at the stern of Pioneering Spirit. The two cranes perform all activities related to the installation or removal of a jacket involving Pioneering Spirit. Besides the two cranes, no other equipment is used for loading in/out, lifting and upending/tilting-over a jacket. Support frames are positioned on the aftdeck in such a way that the jacket is optimally supported during the transportation between the offshore location and the construction/demolish quay.

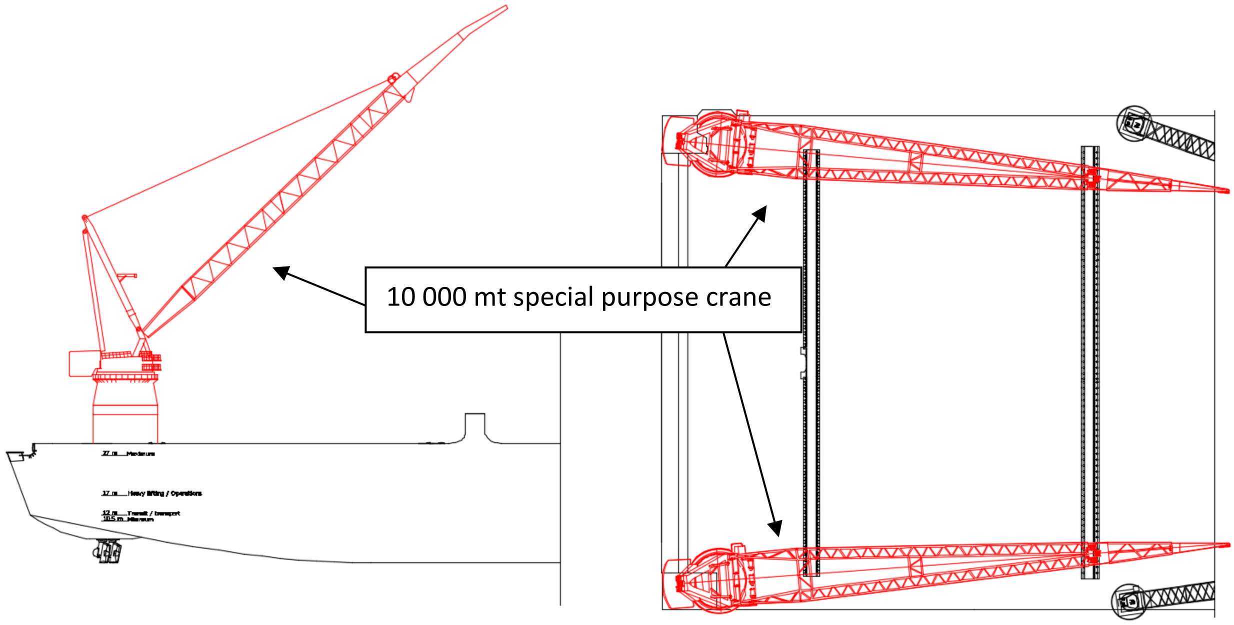


Figure 22: Overview Concept "Tandem Lifting"

Load-out / load-in

The jacket is placed on support frames during transport, as already mentioned. The two cranes at the aftdeck are used to load-in or load-out the jacket on Pioneering Spirit. The jacket does not have to be upended or tilted-over during this process. The jacket is constructed/demolished and transported horizontally. The width of the vessel is considered sufficient to manoeuvre and rotste the jacket between the two cranes. An impression of this operation is given in Figure 23.

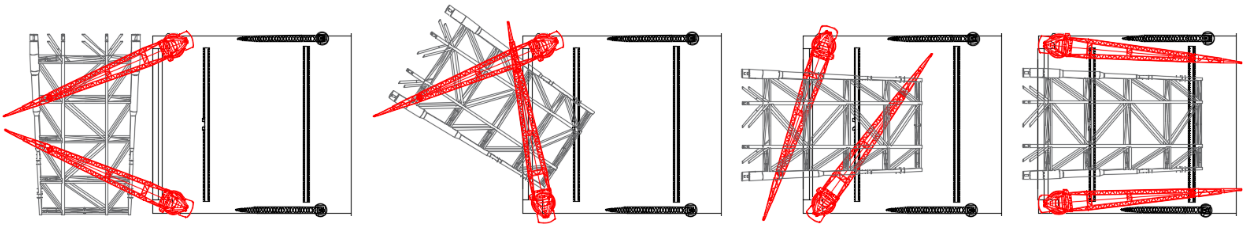


Figure 23: Load-in/Load-out Process "Tandem Lifting"

Transportation between onshore and offshore construction site

As soon as the jacket is placed on the support frames, the sea-fastening is applied. The sea-fastening consists of steel braces welded to the structure. This is to prevent the jacket from moving during transport. The moment that the sea-fastening is applied, and other preparatory work is completed, Pioneering Spirit sails to the offshore construction site or to the demolition site.

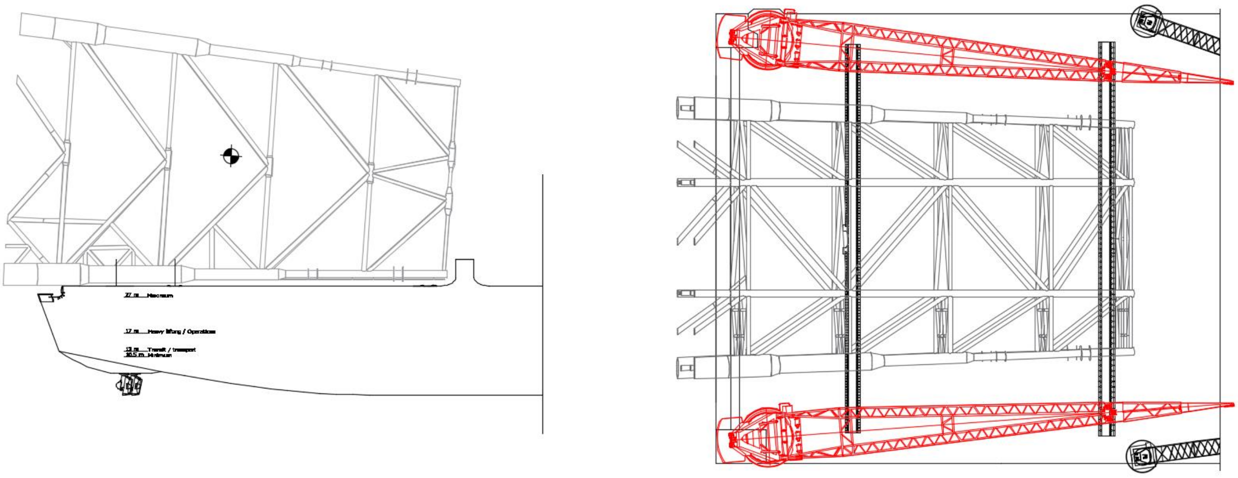
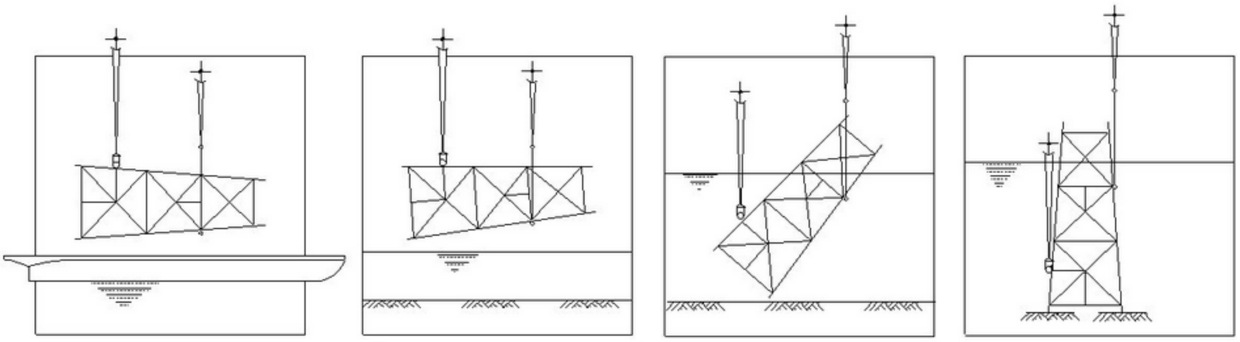


Figure 24: Transportation Situation “Tandem Lifting”

Upending / tilting-over and jacket lifting

The upending/tilting-over and lifting of the jacket is a continuous process in this concept. The two cranes at the stern move the jacket from the aftdeck to the stern of the vessel. This is done in the same way as described for the loading-in and loading-out of a jacket (Figure 23). After the jacket is positioned at the stern of the vessel, the jacket is upended by lowering the bottom part of the jacket. During this process, buoyancy blocks or integrated buoyancy modules/tanks can be used to assist the process. As soon as the jacket is positioned vertically, it is lowered to the seabed. After the jacket is placed in the right position, non-related Jacket Lift System processes commence. An example is the installation of the foundation piles. This description is carried out in a reverse order in case of a jacket removal. The hook-up point of the jacket must be designed that the jacket can rotate around the pick-up points. The procedure of a jacket upending is shown in Figure 25 (Source: [32].



Stage 1 Lifting from barge

Stage 2 Upending : phase 1

Stage 3 Upending : phase 2

Stage 4 Setting in final position

Figure 25: Upending/Tilting-over “Tandem Lifting”

4. Adjustments to the Vessel Construction

Cranes

Currently, a special purpose crane with a lift capacity of 650 mt is installed on the aftdeck of Pioneering Spirit. In 2018, an additional special purpose crane with a capacity of 5000 mt will be installed. The 650 mt special purpose crane is installed on the starboard side and the 5000 mt special purpose crane will be installed on the port side of the vessel. These two cranes must be replaced by special purpose cranes with a larger lift capacity. The goal is to be able to lift a jacket with a mass of 15 000 mt. The mass of the lifting equipment is usually approximately 10% of the total mass to be lifted [33]. In addition, the jacket must also be manoeuvred. This causes the jacket to be in a position, during the manoeuvre, where the cranes do not have their maximum lifting capacity. This is because of the reach of the cranes. Therefore, two cranes with a lift capacity of 10 000 mt each is proposed.

Loads in the hull of the vessel (crane foundation)

A larger crane capacity (in comparison with the currently installed cranes) results usually in larger loads at the base of the crane. The crane's loads are transferred to the construction of the vessel via the base of the crane. It is likely that complex and expensive adjustments are needed to strengthen the structure of the vessel.

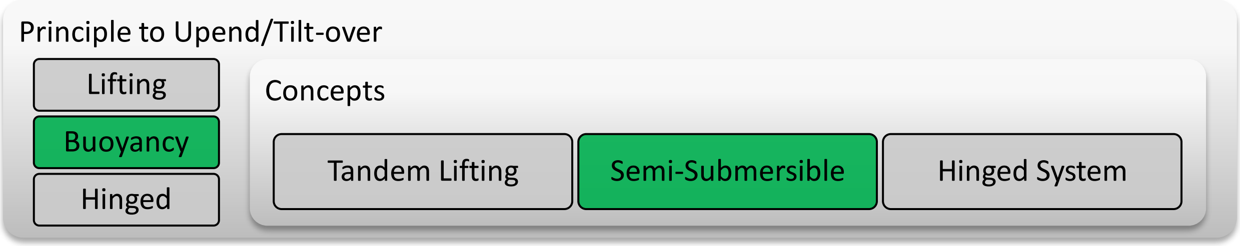
Aftdeck

The jacket is supported during transport by support frames placed on the aftdeck of Pioneering Spirit. The position of the support frames will vary from jacket to jacket. The aftdeck currently has a maximum general deck load capacity of 15 mt/m^2 (see also Paragraph 3.2.4). It may be necessary to make strengthening modifications. Another possibility is to apply a removable support frame that is positioned on the strongest parts of the aftdeck, the reinforced transverse frames.

5. Adjustments to the Processes on-board the Vessel

Besides jackets installation and removal activities, the aftdeck is also used for pipeline installation projects. The path of the pipeline installation factory is party directed over the aftdeck of Pioneering Spirit to the removable bevelling station at the stern of the vessel. The aftdeck is also used for storage purposes. Between pipeline installation projects, topside installation/removal projects and jacket installation/removal projects, the aftdeck needs to be prepared for that certain project. The adjustments between the different activities will not be complicated and the time to make these adjustments will be, by approximation, limited.

4.3.2 Buoyancy Principle



1. Principle Description

The buoyancy of an object is the ability of that object to float in a liquid body [34]. In this buoyancy principle, the buoyancy is influenced by flooding or emptying buoyancy tanks/modules at certain locations in the object. The buoyancy can be influenced in such a way that the jacket will sink/rise and/or will upend/tilt-over in the water. Cranes or other equipment can assist this process. The jacket is placed on support frames on the aftdeck of Pioneering Spirit during transportation. A layout of support frames as described in the first principle (Lifting) can be used, but a cargo-barge like structure can also be used as a support frame. In case a cargo-barge like structure is used, it can also be used in the process of flooding or tank-emptying. The offloading and loading of a jacket on the aftdeck will be done by means of a float-on/float-off principle. The draft of Pioneering Spirit must be adjusted in such a way that the jacket or cargo-barge with jacket can be drifted on and off the aftdeck. This principle excludes violent methods, such as launching, from the process. This is one of the key focus points of the Jacket Lift System. In this principle, no additional equipment is required besides the support frames or cargo-barge like structure.

2. Reference Applications

The principle of installing and removing an object based on buoyancy is already applied in the offshore sector. Launched and self-floater jackets, explained in paragraph 2.1.3, are examples of jackets that are being transported and installed using buoyancy. Launched and self-floater jackets are currently the largest category of jackets applied in the North Sea Region. Buoyancy is also a widely used method to (off)load an object onto a vessel. Example are the Boskalis semi-submersible vessels. The Boskalis vessels can adjust their draft, causing the deck to flood. As soon as the draft between the flooded deck and the water level is sufficient, the object is floated on or off the vessel. Then the water tanks (or a certain number of tanks) in the vessel are emptied and the vessel will return to its original draft. It is advantageous to completely fill or empty a tank to prevent adverse stability effects such as sloshing. The ability to adjust the draft is already integrated into Pioneering Spirit. Pioneering Spirit uses the technique, among many other activities, to adjust the draft of the vessel during topside installation and removal operation. This technique is used to exert pressure on the yokes attached to the bottom of the topside. An impression of a semi-submersible vessel is given in Figure 26 [35].

Figure 26: Boskalis's Semi-Submersible Vessel "Boskalis Vanguard"

3. Concept Description “Semi-Submersible”

The concept “Semi-Submersible” is based on the principle to upend/tilt-over and lower or lift a jacket based on its buoyancy. The aim in this concept is to add as little new equipment as possible to Pioneering Spirit. The jacket is supposed to be designed such that it can float on its own buoyancy. The jacket must be constructed or demolished in a dry-dock. The jacket is loaded and offloaded by floating it on or off Pioneering Spirit in semi-submerged mode. The jacket is thus loaded or offloaded on Pioneering Spirit by adapting the draft to the draft of the jacket, possibly with support of a cargo-barge like structure. The upending or tilting-over and the lifting or lowering of the jacket is done by flooding or emptying buoyancy tanks in the jacket or attached to the jacket. The 5000 mt special purpose crane is used as assistance during this process. The Jacket Lift System will only consist of support frames on the aftdeck or a cargo barge like support structure. Whether a cargo-barge like structure or support frames on the aftdeck are used is investigated if this principle proves to be the most favourable of the three principles.

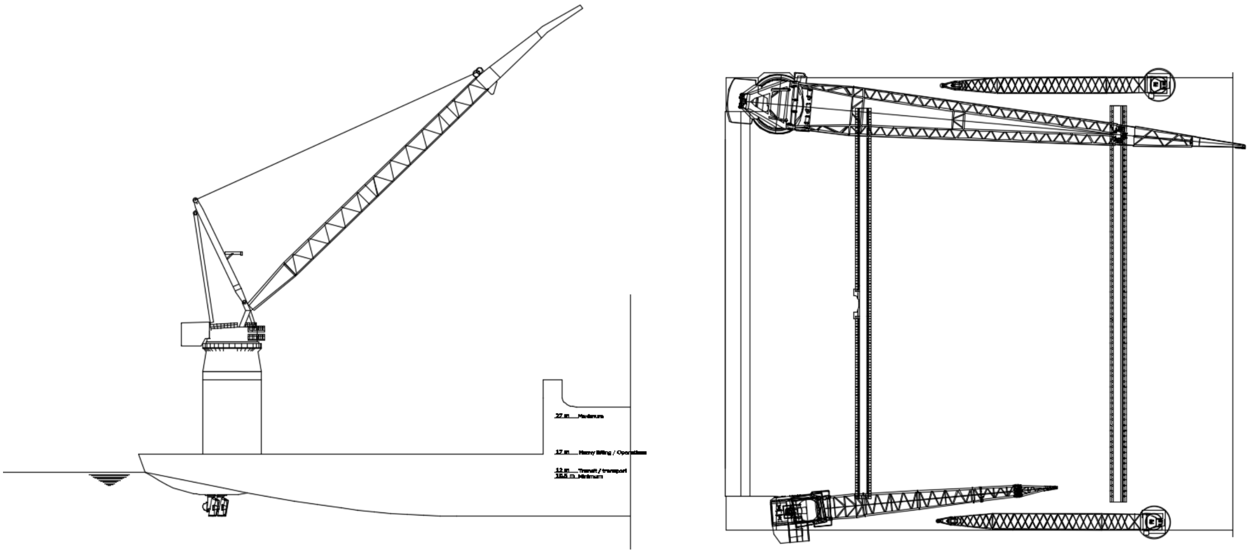


Figure 27: Overview Concept “Semi-Submersible”

Load-out / load-in

As mentioned above, the load-in and load-out is done by ballasting the water tanks of Pioneering Spirit. The jacket is floated out of the dry-dock before Pioneering Spirit arrives at the transfer location. At the construction site, the jacket is water ballasted such that its draft is reduced to a minimum. Pioneering Spirit is ballasted until sufficient water depth has been reached between the deck of Pioneering Spirit and the water level. Then, the jacket is floated onto the aftdeck of Pioneering Spirit. After that, Pioneering Spirit is de-ballasted and returned to the desired transportation draft. In case of a removal project, the above description is done in a reverse order. The positioning of a jacket on and off Pioneering Spirit is done by a winch system on the vessel assisted by tugs.

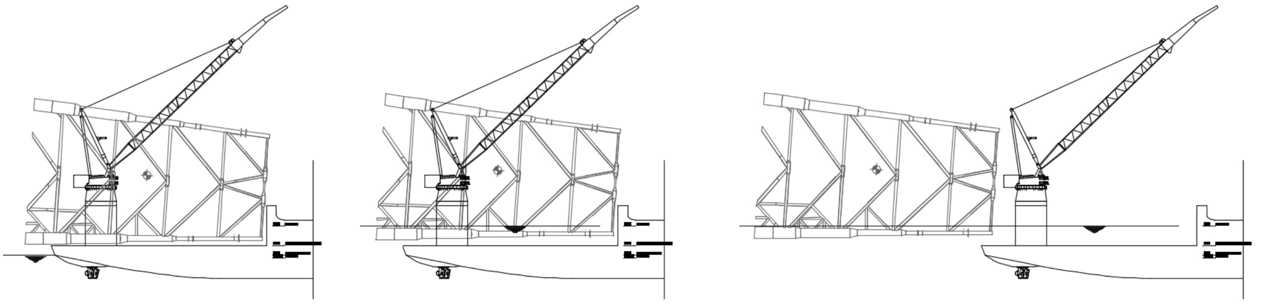


Figure 28: Load-in/Load-out Process “Semi-Submersible”

Transportation between onshore and offshore construction site

As soon as the jacket is loaded onto the aftdeck of Pioneering Spirit, Pioneering Spirit is ballasted to the desired transportation draft. Once the aftdeck is free of water, the sea-fastening is applied. The jacket is placed on support frames that are placed in the ideal position to support the jacket. After the preparatory work for the transportation is completed, Pioneering Spirit departs. In case of an offloading, the sea-fastening is cut and Pioneering Spirit is ballasted to the ideal draft to allow the jacket to float-off.

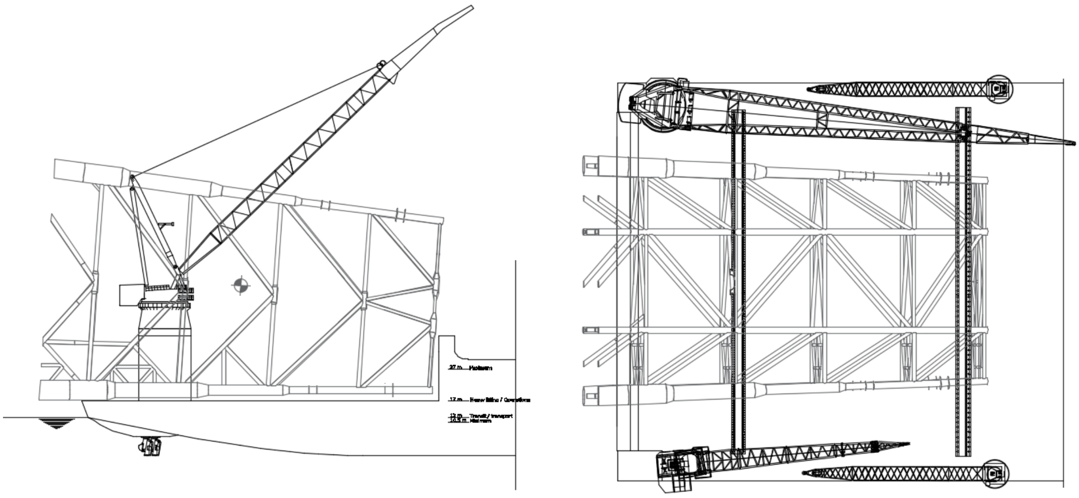


Figure 29: Transportation Situation "Semi-Submersible"

Upending / tilting-over and jacket lifting

The upending or tilting-over and lifting of a jacket is done in a sequential process. Buoyancy modules/tanks are flooded in a sequence such that the jacket will upend and sink in the right orientation and to the right place on the seabed. The 5000 mt special purpose crane is used as assistance during this operation. In the case of a jacket removal, buoyancy tanks are attached to the jacket to obtain sufficient buoyancy to lift and tilt-over the jacket to the water surface and a horizontal orientation. This method is displayed in Figure 30. (Source: [32])

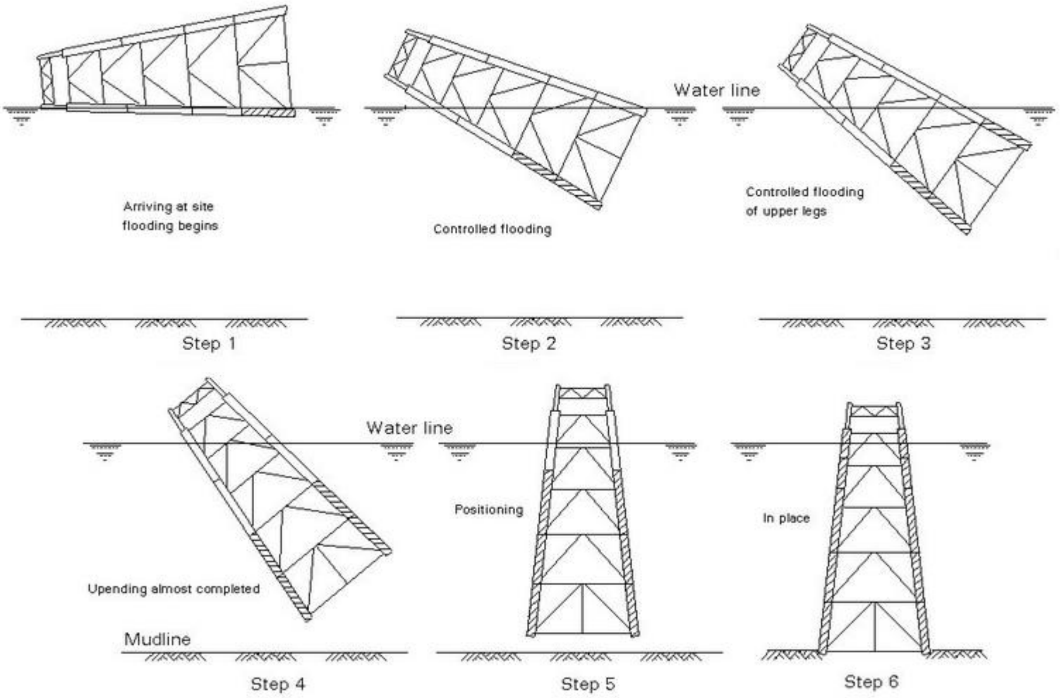


Figure 30: Upending/Tilting-over "Semi-Submersible"

4. Adjustments to the Vessel Construction

Although the new equipment regarding the Jacket Lift System is limited to supporting frames on the aftdeck, the modifications to the construction of the vessel are extremely far-reaching. The maximum draft of the vessel is currently 27 meters, water line to keel. This draft can only be reached if Pioneering Spirit has sufficient load/ballast on board, otherwise a maximum draft of 25 meters from waterline to keel can be reached. The aftdeck of Pioneering Spirit is currently 3 meters above the water line when Pioneering Spirit is ballasted to the maximum draught. Extremely far-reaching adjustments to the aftdeck are necessary to allow the aftdeck to submerge. Large parts of the construction of Pioneering Spirit must be removed from the vessel. This means that all current equipment placed at the aftdeck must be removed or relocated.

5. Adjustments to the Processes on-board the Vessel

Similar to the modifications to the vessel causes this principle extremely far-reaching adjustments to the processes of other main activities. The route of the pipeline segments is located over the aftdeck to the (removable) bevelling station at the stern of the vessel. At the bevelling station, the pipeline segments are lowered to a lower deck. This is where the pipeline installation factory, including the firing line, is located. The ceiling of the firing line is currently 3 meters below the aftdeck. As a result, it will be necessary to remove the pipeline installation factory and to redesign it.

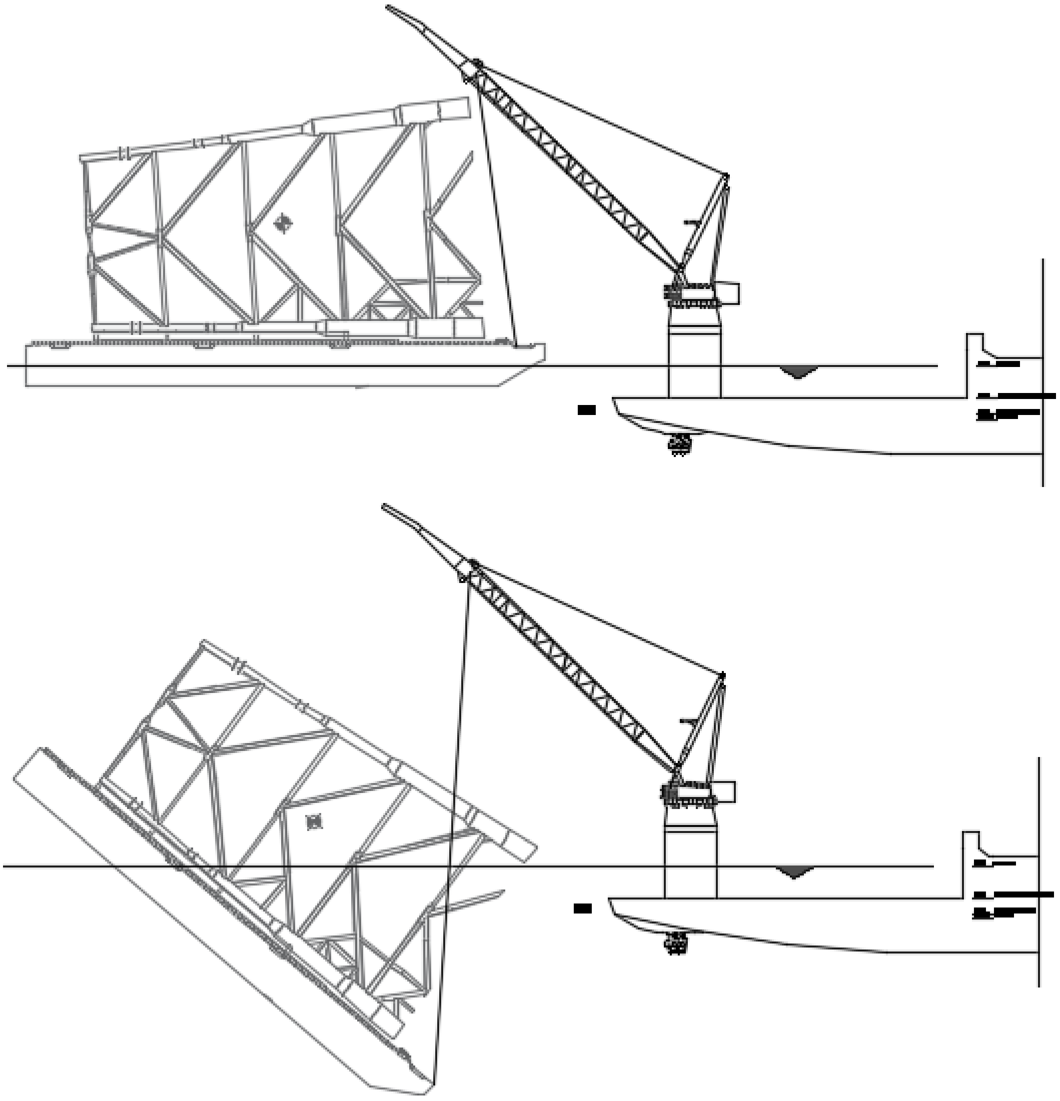
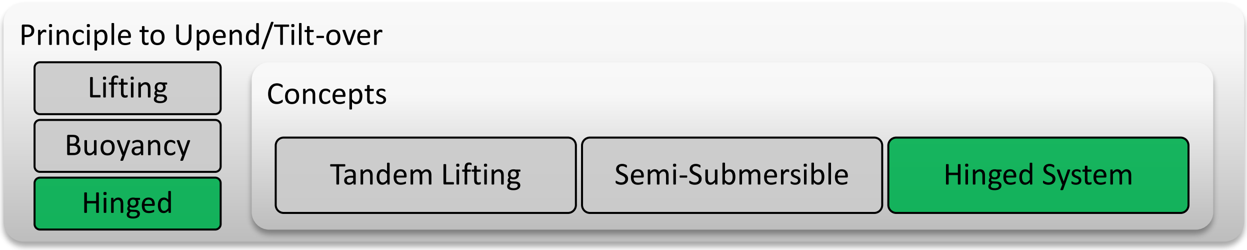


Figure 31: Upending/Tilting-over “Semi-Submersible” with Cargo-barge

4.3.3 Hinged System Principle



1. Principle Description

A hinge generally consists of two parts that can be moved separately from each other. The two parts are interlocked and connected by a pin. The two parts, or one of the two parts, can rotate around the pin to make a hinged movement. Hinge constructions do exist in many different forms, just like the mechanism to initiate the hinged movement. In the principle of a hinged system, Pioneering Spirit is one part of the hinged system and a support frame the second part. The Jacket Lift System will thus consist of a support frame that is connected to the stern of Pioneering Spirit by a hinge system. The previous/reference design of the Jacket Lift System is based on a principle of a hinged system.

2. Reference Applications

There are numerous examples of small sized hinged objects. Examples are doors/windows and entrance ramps of a ferry. In terms of large constructions, a bascule bridge, shown in Figure 32 (Photo taken by Henk Zijderveld), is a good example. In terms of masses and dimensions, large bridges are the best comparison to the application of the Jacket Lift System. There are, as far as the writer’s knowledge, no examples known in the offshore sector where the lifting device also supports the object during the upend or tilt-over process.

Figure 32: An Example of a Hinged Construction

3. Concept Description "Hinged System"

The jacket to be installed or removed in the "Hinged System" concept is supported by a supporting frame during the upend/tilt-over operation. The same system is used to lift and lower the jacket to the seabed. The support frame functions as a crane boom when it is positioned upright. The supporting frame is upended or tilted-over over a hinge point located at the stern of Pioneering Spirit. Reinforcements have already been applied at this location. The support frame also supports the jacket during the transportation between the onshore and offshore construction sites.

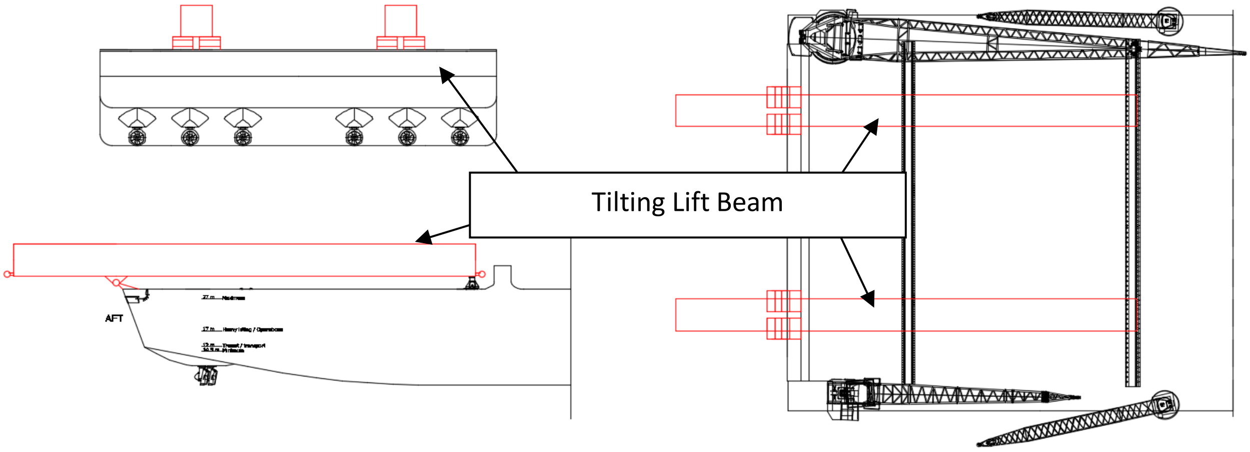


Figure 33: Overview Concept "Hinged System"

Load-out / load-in

The transfer of the jacket to and off Pioneering Spirit will take place at a quay site. In case Pioneering Spirit cannot reach the quay site, the jacket is transferred to a cargo-barge first. Subsequently, the cargo-barge and Pioneering will sail to a suitable location where the transfer between the cargo-barge and Pioneering Spirit will take place. The method to load-in and load-out a jacket is the same as currently used for launched jackets. Skids or Self-Propelled Modular Transporters (SPMT) are used to move the jacket on or off the Jacket Lift System. The ballast procedure is important during this process to prevent unwanted loads on the jacket and vessel by mutual vessel motions. The frame of the Jacket Lift System is adjustable to the width of the jacket. In the assessment of this principle and concept, the Tilting Lift Beams are taken as described in the reference design (chapter 2).

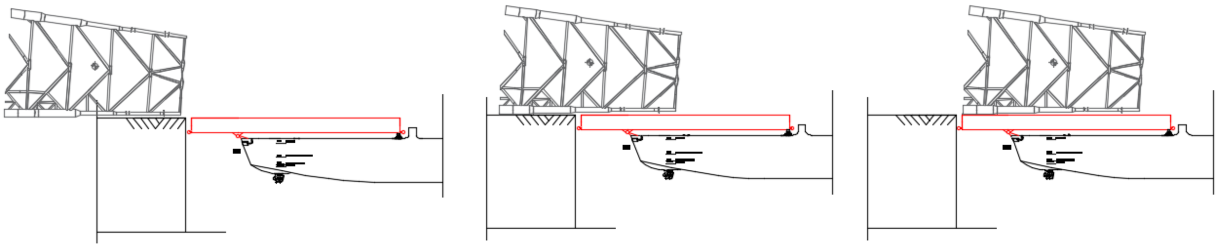


Figure 34: Load-in/Load-out Process "Hinged System"

Transportation between onshore and offshore construction site

The jacket is placed on top of the Tilting Lift Beams during transport. A clamp system on top of the Tilting Lift Beams is used as sea-fastening. The need to apply sea-fastening is previously described. The same clamp system is used in the upend/tilt-over operation described below.

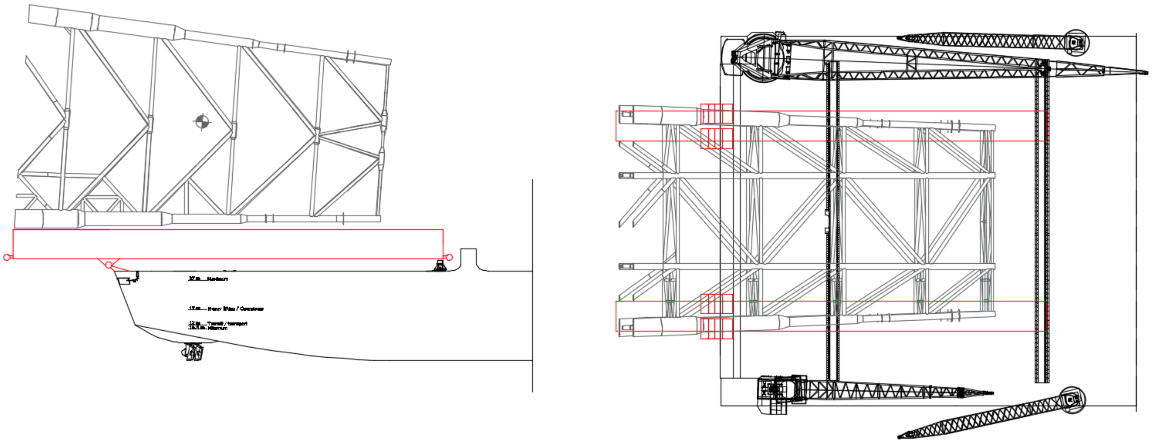


Figure 35: Transportation Situation "Hinged System"

Upending / tilting-over and Jacket lifting

The Tilting Lift Beams are upended after arrival at the offshore location. The jacket is supported by the support frames during this process. When the jacket is upended, the jacket is detached from the support frames and the main hoist system becomes fully responsible for keeping the jacket in place. As earlier mentioned, the Tilting Lift Beams functions as a crane boom during the jacket lifting operation. The jacket is placed on the sea floor by lowering the jacket using the main hoist system attached to the tip of the Tilting Lift Beams. The Tilting Lift Beams are, on their turn, attached to the vessel by a hinge system. The Tilting Lift Beams are returned to a tilted position after the jacket is placed in the right location. This process is carried-out in a reverse order in case of a jacket removal.

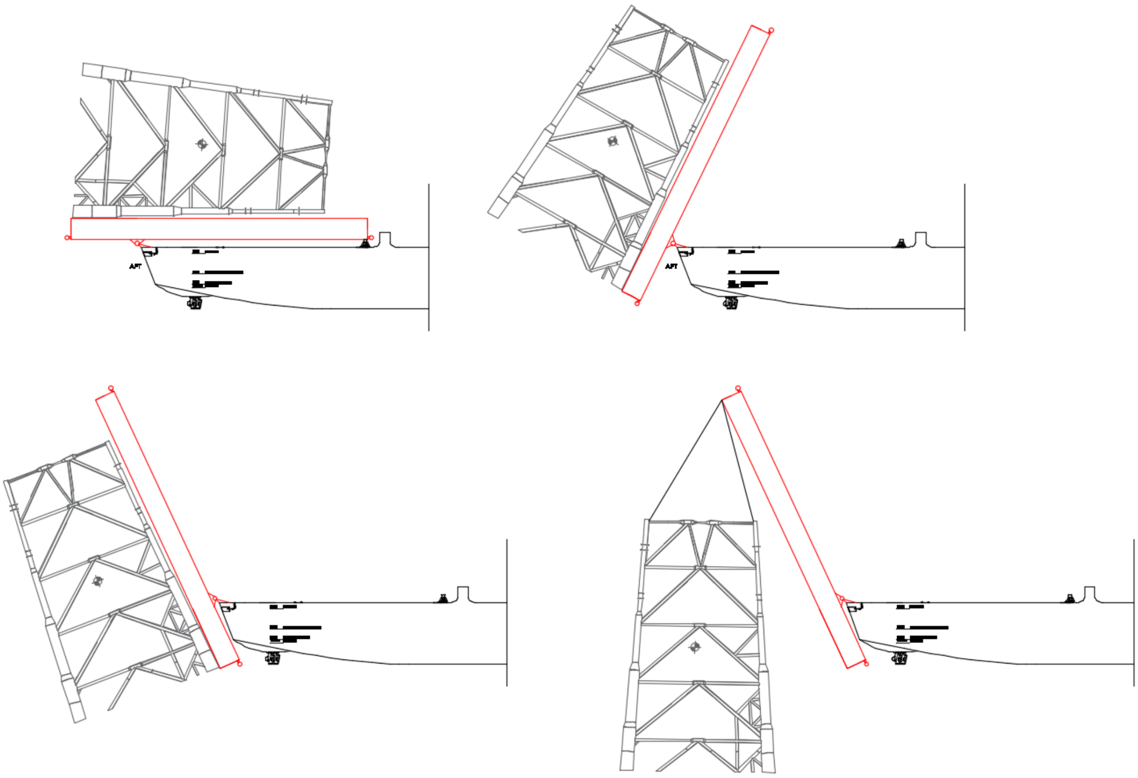


Figure 36: Upending/Tilting-over "Hinged System"

4. Adjustments to the Vessel Construction

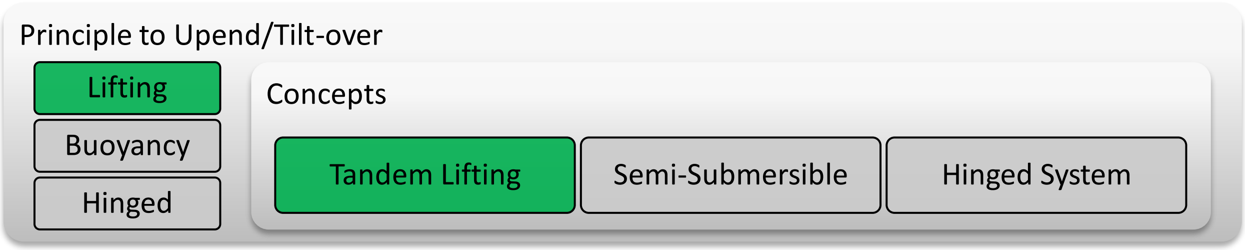
During the construction of Pioneering Spirit facilities have already been installed. The aft of the vessel is reinforced by bulkhead reinforcements and two transverse frames are applied. The specifications of these facilities are included in paragraph 3.2. With these features, the equipment of the Jacket Lift System can be designed such that no major adjustments are necessary to the construction of Pioneering Spirit. This is a design assumption if this principle proves to be the most favourable principle for further elaboration.

5. Adjustments to the Processes on-board the Vessel

The reinforcements and the transverse strips are designed during the engineering of the other main activities. They are a result of an analysis of the applications of Pioneering Spirit by Allseas. This is why the reinforced deck areas and the transverse strips have been considered in placing equipment of other main activities. If only the reinforced areas are used for the Jacket Lift System, no major adjustments to processes of other main activities are required. This is highly desirable.

4.4 Principles Analysis

4.4.1 Lifting Principle "Tandem Lift" Concept



1. Compatibility

Considering the compatibility, this concept scores reasonably well. The new system can be implemented relatively easy in the current situation on Pioneering Spirit. The equipment belonging to the other two main activities on the vessel is relatively easy to remove temporary. This also applies to the components of the Jacket Lift System in this concept. The cranes, once installed and stored in their stand-by positions, do not hinder other processes on the vessel. To be able to install the new cranes, no major adjustments to other equipment are required. However, it will be required to replace some general equipment. The loads of the cranes are transferred to the vessel via the foundation of the cranes. The magnitude of the forces will probably be large. It is likely that the hull of the vessel must undergo a major metamorphosis to be able to accommodate cranes with sufficient lift capacity to install or remove a jacket with a mass up to 15 000 mt. A big advantage of this concept is that the cranes, once installed, can be used as assistance during other operations. To store a jacket on the aftdeck, support frames are placed on the aftdeck. The support frames will be easy to install and remove after the installation or removal work is completed.

Pros and cons overview:

+ Current equipment relatively easy to remove temporary
+ The Jacket Lift System is relatively easy to install, remove or storable in a position where it doesn't disturb other activities
+ No major adjustments required to equipment of other activities to install the system
+ The new cranes can be used during other activities besides jacket installation and removal activities

- Adjustments required to the construction of the vessel at the base of the cranes
- Minor adjustments to general equipment needed to make space for the cranes

2. Workability

Regarding the workability, it is expected that this principle will score fair. Lifting in tandem configuration is a complicated operation, particularly during the process of bringing the jacket from the aftdeck to de stern of the vessel and vice versa. The vessel motions in a certain point of a vessel in wave motions are often known. Using an axes system and a measure point as a reference point, it is possible to determine the motions in any other point of the vessel. This is known as the transfer function of the Response Amplitude Operator (RAO). Since the crane tips are in difference positions during a lifting operation, in reference to the reference point, the motions in those points will be different as well. This results in additional loads on the jacket and possible operational difficulties. The loads and handling difficulties will increase in more severe wave conditions. The expectations are that this concept is sensitive to vessel motions.

Pros and cons overview:

- Tandem lift operations are complicated, especially the operation to bring the jacket to the stern of Pioneering Spirit and vice versa.
- Sensitive to vessel motions

3. New Equipment

Concerning new equipment to be added, regarding the Jacket Lift System, it is likely that major adjustments to Pioneering Spirit are required. The 650 mt crane and the 5000 mt crane must be replaced by two cranes with a lifting capacity of (by approximation) 10 000 mt each. Similar cranes on offshore crane vessels have not yet been installed. Besides the new cranes, no new equipment must be installed on Pioneering Spirit. As mentioned in the compatibility topic, major adjustments to the vessel are required.

Pros and cons overview:

+ Besides the two new cranes, no major other permanently installed equipment required

- 650 mt and the 5000 mt special purpose cranes must be replaced
- Crane capacities that do not exist yet (10 000 mt each)

4. Complexity

As already mentioned, lifting in tandem configuration is complex. The crane tips will be moving separately of each other. A convenient way to look at this is to compare the position of the crane tips in reference to the heave, pitch and roll with the reference point in the vessel. The motions in the crane tips will be different during a lift operation and will induce an additional load on the jacket. The extent of the differences and the effects on the jacket must be investigated. It is likely that the lifting operation will become complex. Detailed calculations and simulations are required to perform an operation in a safe and successful manner.

Pros and cons overview:

- Complex procedure regarding the movements of the crane tips and the corresponding loads on the jacket
- Detailed calculations and simulations required prior to each operation
- Uncertainties in the feasibility of having different crane tips positions in wave motions

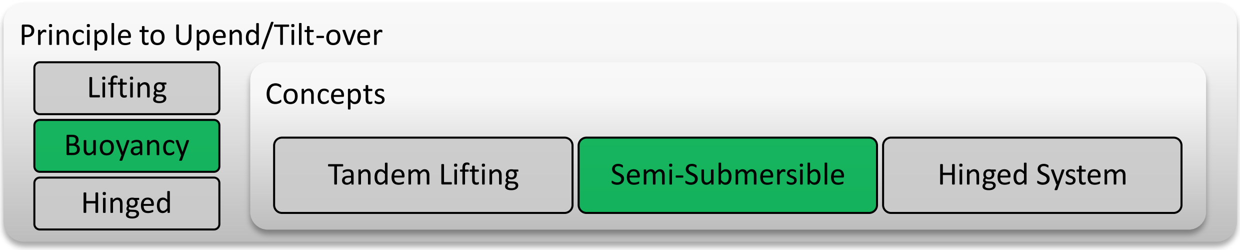
5. Investment Costs

As described earlier, it is likely that radical adjustments to the internal construction of the vessel are required. The costs of these adjustments will be approximately high. This is based on the expectation that the vessel will have to be in a dry dock for a long time. The adjustments to Pioneering Spirit cannot be made during the execution of contracted projects, therefore no income is earned during this period. Before the adjustments can be applied, the modifications first need to be designed and calculated. This will also take a lot of time. It is therefore questionable whether work already contracted can be carried out within the stipulated time. An example is the jacket installation for the Sverdrup field.

Pros and cons overview:

- Major investments required to replace the special purpose cranes
- Major investments required to strengthen the vessel
- The vessel will be out of service for a long time to replace the cranes, no revenue will be earned during this period

4.4.2 Buoyancy Principle “Semi-Submersible” Concept



1. Compatibility

The concept "Semi-Submersible", based on a Buoyancy principle, is extremely difficult to implement in Pioneering Spirits current appearance. The vessel must be redesigned and modified almost completely. Large parts of the aftdeck must be removed. This has consequences for the entire vessel. Examples are the stiffness, strength (resistance) and stability. The current equipment on and below the aftdeck must be removed and redesigned. An example is the equipment regarding pipelay operations. The entire pipeline installation factory must be redesigned and rebuild. Even though Pioneering Spirit is the largest crane vessel in the world, it was difficult to realise an optimally working pipeline installation factory. Adjusting these equipment and processes is therefore not a feasible option. In short, this principle cannot be applied to the current vessel. This principle, however, may be interesting for a next vessel that is likely to be designed and built by Allseas.

Pros and cons overview:

- Extremely poor implementable in Pioneering Spirits current situation
- Necessary to redesign and rebuilt the vessel
- Considered as a non-feasible concept

2. Workability

In this concept, the jacket must be able to float on its own buoyancy. The jacket will be exposed to environmental influences such as current, waves and wind during an installation or removal operation. Approximately, the allowable environmental influences are limited with respect to the stability, manoeuvrability and the manageability of the jacket. One of the objectives of the Jacket Lift System is to make the jacket as light as possible. It must be investigated which additional strength measures are required because of the environmental influences and other forces that arise at the offshore location. Hoisting and tilting-over operations of a jacket based on buoyancy are complicated and it is likely that the workability of this principle is the worst compared to the other principles. This also applies to the load-out/load-in of a jacket onto Pioneering Spirit. Loading-in or out an object onto a semi-submersed vessel is usually carried out at a location with sheltered environmental conditions. In this case, however, the operation must to be performed in the open ocean.

Pros and cons overview:

- Poor workability due to sensitivity to environmental influences

3. New Equipment

For this principle, little new equipment is needed when it comes to the Jacket Lift System. Support frames are used to support the jacket during transport and winch systems must be installed to manoeuvre the jacket off and on the aftdeck of Pioneering Spirit, probably assisted by tugs.

Pros and cons overview:

+ Little new equipment required

- Tug assistance required

4. Complexity

The complex parts in this concept is to upend/tilt-over, lift/lower and manoeuvre a jacket on and off the aftdeck of Pioneering Spirit by means of its own buoyancy. Examples are known of operations where a jacket is installed using buoyancy, but there are no known examples of projects where a jacket has been removed using this principle. Detailed calculations and simulations are required to anticipate on the environmental influences. The mandatory use of a dry-dock to build or demolish a jacket is a disadvantageous restriction.

Pros and cons overview:

- Complex and difficult manageable operation
- No known examples of removal projects using buoyancy
- Detailed calculations and simulations required prior to each operation
- A dry-dock required to build and demolish a jacket

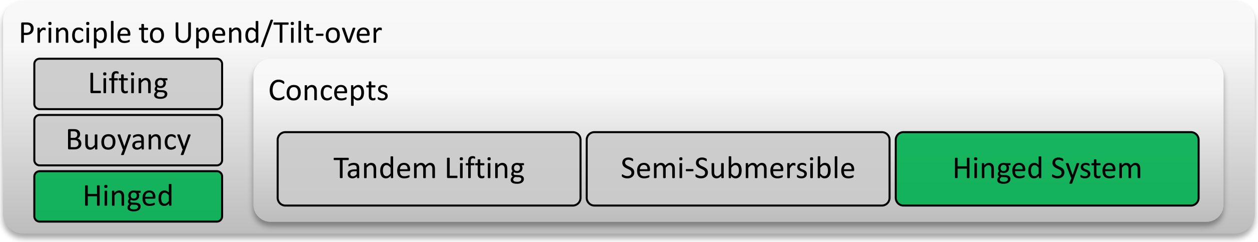
5. Investment Costs

In this principle, it is necessary to redesign and modify the entire vessel. The costs and time to adjust the vessel will be enormous and is considered as non-feasible. This principle is the least favourable in terms of investment costs.

Pros and cons overview:

- Extremely high adjustments cost
- Considered non-feasible in terms of investment costs.

4.4.3 Hinged System Principle “Hinged System” Concept



1. Compatibility

The concept “Hinged System” is well implementable in Pioneering Spirits current appearance. Facilities on the vessel have already been installed. This is because of this principle was used in the design of Pioneering Spirit. The aftdeck and the two transverse frames on the aftdeck are specially reinforced for foundation purposes of the Jacket Lift System. Equipment for other main activities are designed considering the reinforcements to the aftdeck. Hence, the equipment is designed and built with respect to each other. Therefore, using the reinforced parts will be favourable as it minimizes the hindrance to other main activities and requires fewer adjustments to the structure of Pioneering Spirit. The expectation is that the facilities offer sufficient possibilities to make a design solution. This is a design assumption for the next subpart in the concept development, if this principle proves to be most favourable. A disadvantage of the preinstalled foundation reinforcements are the constraints by the locations.

Pros and cons overview:

+ Well implementable on Pioneering Spirit because of the already applied facilities
+ If the facilities already installed are used in the design solution, other processes on board of Pioneering Spirit will be marginally disturbed

- The location of the facilities limits the design freedom

2. Workability

Considering the workability, this principle has some similarities with a tandem lift operation. The Jacket is held by the main hoist by means of two hook-points. With regard to phase differences in wave motions and the RAO’s, the same applies as in the tandem lifting principle. However, because of the fixed mutual position of the hook-points, the hook-points can be considered in sync. Therefore, and among other reasons, it is expected that no major extra measures will be required regarding extra loads on the jacket. A disadvantage of this concept is that the loads at the connection point on the jacket, by its own mass, will change during the upend/tilt-over procedure. A big advantage of keeping the jacket in position by the support frame is that the jackets position is guaranteed during the upend/tilt-over process. The jacket, Jacket Lift System and Pioneering Spirit can be considered as a total system. The combination of this total system is much less sensitive to environmental loads. The workability of this concept is therefore assessed positively in reference to the other principles.

Pros and cons overview:

+ Fixed mutual position hook-points, in sync
+ Jacket is held by the support frames during upending and tilting-over and can be considered as a total system with Pioneering Spirit
+ Workability is expected to be good

3. New Equipment

The hinged support frame will consist of a relatively large amount of new equipment. However, relatively few changes are required to Pioneering Spirit. Reinforcements to the construction of Pioneering Spirit have already been applied. The Jacket Lift System can be designed in such a way it will be removable. This is favourable regarding other main activities.

Pros and cons overview:

- \+ System can be designed in such a way it will be removable
- +/- Relatively large amount of new equipment

4. Complexity

Assuming that the principle of keeping a jacket in place on a supporting frame during the upend/tilt-over operation is possible, this concept is relatively straightforward. The total mass of the Jacket Lift System and the jacket will be enormous. Managing the hinged movement will be a challenge. There must be a drive mechanism to bring the centre of gravity past the pivot point. Subsequently the hinged movement of the system must be controlled. The derrick hoist system, as conceived in the reference design, can be used for this purpose. The influences of current, wind, waves and above all vessel motions are expected to be quite large. These influences must be examined in a subsequent concept development subpart, if this principle turns out to be the most favourable. It is expected that the manageability of this concept is the best in reference to the other concepts. For example, the process does not depend on the buoyancy of the jacket, but can be controlled by, for example, changing the tension in the winches. This concept is considered the least complex.

Pros and cons overview:

- \+ The controllability of the upending and tilting-over concept is expected to be good

- \- The total mass of the jacket and the Jacket Lift System is large. A driving mechanism must be able to upend or tilt-over the system
- \- Environmental influences on the upend/tilt-over process are expected to be large, these influences must be investigated

5. Investment Costs

This concept is a completely new. There is no experience with this kind of systems at all. All parts must be newly designed. The chance of an unexpected setback is therefore quite large. A setback can quickly lead to extra investment costs. The financial risks are therefore quite high. A major advantage of this principle is that already installed facilities can be used. No big modifications to Pioneering Spirit are required to install the Jacket Lift System. Pioneering Spirit does not have to be in a dry dock for a long period. The system can be designed such that the manufacturing of the system can take place while Pioneering Spirit is carrying out contracted projects.

Pros and cons overview:

- \+ The system can be constructed, for most parts, separately from Pioneering Spirit. Pioneering Spirit can continue working on paid projects

- \- Completely new concept, therefore high risks of setbacks and additional investment costs

4.5 Evaluation Principles and Principle Choice

A summary of the analysis per concept is shown in Table 7. The classification positive, neutral and negative is used in the comparison (Table 7).

	Principle		
	Lifting	Buoyancy	Hinged System
Compatibility	+	- [1]	+
Workability	-	-	=
New equipment	-	+	-
Complexity	-	-	+
Investment Costs	=	- [2]	=

Positive
Neutral
Negative

Table 7: Assessment Matrix Principles of Upending/Tilting-over

[1] This concept is not feasible considering the compatibility.

[2] This concept is not feasible considering the investment costs.

The principle **Buoyancy** with the semi-submersible concept is considered non-feasible. Too many modifications are necessary to integrate this principle and concept in Pioneering Spirit current appearance. The investment costs will be exorbitantly high. This concept may be interesting for a new to build vessel, however the removal of a jacket with this principle will still be a big challenge and has not been done before. The current jackets are not designed to be removed with buoyancy tanks/modules. Although none of the jackets installed before 1999 have been especially designed to be removed. In addition, the float-on and float-off operations are usually carried-out in sheltered water conditions. In this principle, the procedure must be performed in offshore conditions.

The offshore sector has experience with **Tandem Lift** type of operations. The specifications of Pioneering Spirit are such that a large gain in capacity can be achieved compared to competing vessels in the Offshore market. The ability to transport a jacket on its own deck complements the concept of installing and removing a jacket using a tandem lift principle with Pioneering Spirit. However, the process to manoeuvre a jacket from the stern of the vessel to the aftdeck and vice versa will be complex. The cranes will have to operate independently, this causes negative influences regarding loads on the jacket and position keeping of the jacket. In addition, the fact that existing cranes must be replaced, the construction of Pioneering Spirit must be strengthened at the base of the cranes and the investment of these cranes are lost is a decisive disadvantage.

The principle based on the **Hinged Support Frame** has been used in the design of Pioneering Spirit. Facilities for this type of system have already been applied. If the design solution is adapted to these facilities, the design can be easily implemented in the current appearance of Pioneering Spirit. No big hindrances to other activities are expected. The workability of this principle is considered favourable. A reason is that the jacket is connected to the support frame during the upend/tilt-over operation. This results in a total system that is less sensitive to environmental effects and easier to control. The biggest disadvantage of this concept is that similar systems do not exist. This means that the level of uncertainty about the feasibility is quite high. However, the hinged system principle proves to be the most favourable principle to apply on Pioneering Spirit, based on the used assessment point.

Conclusion/Recommendation next subpart

The Hinged System principle is chosen for further elaboration.

5 Upend/Tilt-over Mechanism

In this second subpart of the concept development the focus is on acquiring information about the forces required to obtain a static equilibrium during the upend/tilt-over operation, to understand what is mechanically desirable and what the most important influencers are during the operation. The main topic in this concept development subpart is the mechanism to initiate the motion to upend/tilt-over the system. The result of this subpart is an analysis of the contributions of the mass of the system, mass of a reference jacket and the buoyancy to the upend/tilt-over process and a description of the favourability of various Upend/Tilt-over Mechanism concepts. Information is included in appendices B, C, D and E.

To recapitulate, the objective in this concept development subpart is to find or acquire information about:

- Static equilibrium/forces on the system during the upend/tilt-over operation
- Important aspects during the upend/tilt-over operation
- A favourable mechanism to upend/tilt-over the system
- Approximation of the feasibility of the upend/tilt-over components

5.1 Introduction Upend/Tilt-over Mechanism

In this second subpart of the concept development, principles for generating the upend and tilt-over movement are examined. In finding a favourable way to initiate the upend or tilt-over movement, many concepts are conceivable again. In this report, a distinction is made between pushing, pulling and systems based on a movement initiated by its own mass (gravitational force). The focus in this subpart is on the magnitude of the force required to obtain a static equilibrium during upending or tilting-over the system, the magnitude of the force in the pivot points/support points and the influences of the different factors on the upend/tilt-over movement. The principles with concepts studied in this concept development subpart are listed down in Figure 37. The concepts are briefly described in paragraph 5.4. As in the previous concept development subpart, the method described in paragraph 1.4.2 is used in selecting these concepts.

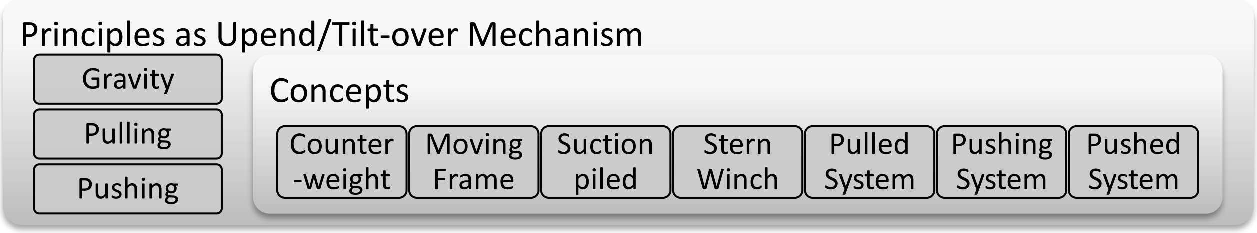


Figure 37: Overview Mechanisms to Upend/tilt-over the System

5.2 Input Information/Assumptions Upend/Tilt-over Mechanism

Based on information collected in chapter 3 “Design Information” and the findings in the first concept development subpart, chapter 4, a few assumptions have been made. The assumptions are uniformed input for the further elaboration of the concept development. Input assumptions:

1. Adjustments to the construction of Pioneering Spirit is highly unfavourable and should be avoided. The already installed facilities, explained in paragraph 3.2, offer sufficient possibilities for further development.
2. The system must be removable. Only the attachment points/hinge points may remain after an installation or removal project has been finished. This is similar to the Stinger of Pioneering Spirit.
3. The Tilting Lift Beams and the Derrick Hoist System are adopted as explained in the reference design, described in paragraph 2.1.
4. The connection between the jacket and the Tilting Lift Beams is considered to be stiff. Effects and interactions between the Tilting Lift Beams and the jacket are not considered.

5.2.1 Main Parts of Upend/Tilt-over Component

1. Tilting Lift Beams

Adopted from the reference design, the Jacket Lift System consists of two identical Tilting Lift Beams. The main functions of the Tilting Lift Beams are supporting the jacket during transport, during upending/tilting-over and to transfer the loads to the hang of system (pivot points). The Tilting Lift Beams figure as crane boom during the lifting and lowering operations. To support a jacket in the most critical places, the mutual distance between the two Tilting Lift Beams will be adjustable.

The length of the Tilting Lift Beams on the aftdeck is limited to 110 m. This is the length between the stern of the vessel and the Derrick Hoist System. The free hanging length of the Tilting Lift Beams is limited by the keel of the vessel. The system must be able to upend/tilt-over in shallow waters for maintenance and testing purposes. The maximum length of the Tilting Lift Beams in shallow water is limited to 30 meters, the distance between the main deck and the keel. This limitation is less important in deep waters.

2. Hinge System

Depending on the upend/tilt-over mechanism, the pivot point is the only mass carrying component in the system. The entire mass of the Tilting Lift Beams and the Jacket is transferred through this point to the structure of Pioneering Spirit. The Jacket Lift System comprises two Tilting Lift Beams, so there will be two hinge points in the Jacket Lift System. Like the Tilting Lift Beams, the mutual position of the hinge points is adaptable to the dimensions of the jacket to be installed or removed. The hinge points may remain on the vessel after completion of a jacket installation or removal project, provided that the hinge points can be placed in a position where it does not interfere with other main activities. The stern of Pioneering Spirit is reinforced. More information about the already applied facilities is given in paragraph 3.2.

3. Driving/Controlling component(s), concept dependent

The driving/controlling system of the Jacket Lift System will consist of at least the mechanism to initiate the upend/tilt-over movement of the Tilting Lift Beams and the Derrick Hoist System adopted from the reference design.

3.1 Derrick Hoist System:

The Derrick Hoist system is used to control the upend process and to initiate the movement in the tilt-over process. This is done by giving in or giving out wire. The wires can also be used to keep tension in the system by adding pre-tension. It is expected that the tension will vary during the upend or tilt-over process due to changing excitation forces and changing forces to obtain a static equilibrium. An example is the buoyancy on the tail of the Tilting Lift Beams. Like the Tilting Lift Beams, the mutual distance between the two hoists systems must be adjustable. The wires of the Derrick Hoist system are attached to the deck of Pioneering Spirit by means of derrick hoist skids. The skidded connection enables the system to adjust in transverse direction.

3.2 Tilting Lift Beam Rotate System:

The Tilting Lift Beam Rotate System is a preliminary name for the system to rotate the Tilting Lift Beams together with the Derrick Hoist System. This system is the main topic in this concept development subpart. Similar to the other components, the system must be able to adjust to the mutual distance for a certain jacket. The facilities that have already been applied on Pioneering Spirit, described in paragraph 3.2. must be used. As mentioned before, an upend or tilt-over duration of 12 hours is acceptable and assumed.

5.3 Assessment Criteria Upend/Tilt-over Mechanism

The assessment points in this second subpart of the concept development are described below. General assessment points initiated by the objective of the thesis project and assessment points initiated in previous steps are still of great importance. These points are party included in the specific assessment point described below and partly included in the assessment description per concept.

Static Forces/Equilibrium

- **Static Forces/Equilibrium**
  This assessment point is about the static forces initiated by the driving component(s) in the Jacket Lift System and on the support points on Pioneering Spirit. Regarding the large masses of the Jacket Lift System and the jacket, the loads must be distributed optimally over the carrying parts in the Jacket Lift System and the support points on Pioneering Spirit. The method to upend/tilt-over has a significant influence on this distribution. An example of a factor is the position where the force to upend/tilt-over the system is applied. In this assessment point, attention is paid to:

    - Forces required to obtain a static equilibrium
    - Tension/Pressure in upend/tilt-over component(s)
    - Reaction forces in the pivot point at the stern
    - Reaction forces in the concept specific support points

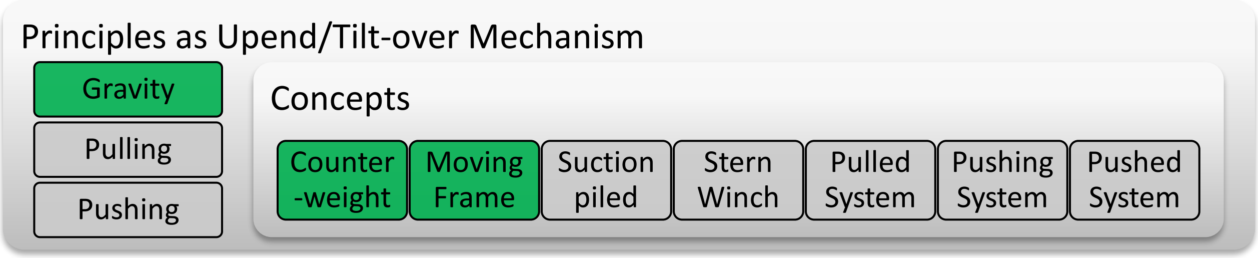
- **Maximum Power Use**
  Depending on the concept, a certain force is required to obtain a static equilibrium during the upend/tilt-over operation of the system. The maximum power requirement depends on the force and the speed at which the system moves. Superfluous to mention, the forces requirement to upend/tilt-over the system must be as small as possible and the point at where the force to upend/tilt-over the Jacket Lift System is applied must be placed in an as advantageously as possible position to initiate a controlled and effective movement. The exact power use cannot be calculated at this stage of the concept development as it depends on many detailed factors. Instead, an estimation is given based on the maximum force and the estimated speed at which the system will (must) move.

Complexity and New Equipment

- **Complexity**
  The complexity of the system and procedure are also of great importance in this concept development subpart. The system must be relatively easy to upend/tilt-over, able to be stopped/paused during the process, return to its initial position (at the start of the process) without having to finish the full procedure and must be fast enough. Finally yet importantly, the system must be able to continue if parts of the system fail without resulting in a total system failure.

- **New Equipment**
  An objective is to implement a system as minimalistic as possible. A large mass has besides the loads on the vessel also disadvantages to other processes. Examples are the already mentioned power requirement to upend/tilt-over the system, the minimum draft of Pioneering Spirit, the available deck space and the investment costs of the construction.

5.4 Upend/Tilt-over Mechanism Concept Descriptions



5.4.1 Gravity Based Concepts

In the gravity-based concepts, the jacket Lift System is upended by means of the mass of the system and/or the jacket. The mass of an object, in general, can be expressed as a lumped force acting on its centre of gravity. The centre of gravity is a geometric property of an object. It is the average location of the weight [36]. This principle can be applied for a group of objects. The objects are taken as a group with one lumped force acting in the joint centre of gravity. For example, the joint mass and joint centre of gravity of the Tilting Lift Beams and the jacket. The principle "gravity" is based on shifting the joint centre of gravity to a position past the pivot point in reference to the stern of Pioneering Spirit. This principle is shown in Figure 38.

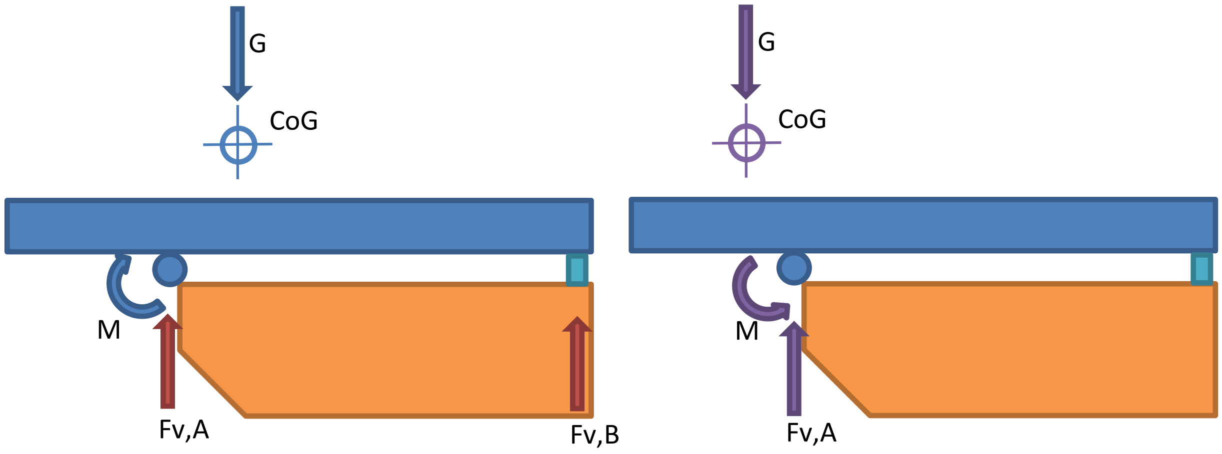


Figure 38: Gravity Principle

Figure 38 is a simplified schematic side view of Pioneering Spirit (orange rectangular). The blue circle represents the pivot point. The blue rectangular represents the Tilting Lift Beams. Finally, the light blue rectangular represents the Derrick Hoist System. Arrows depicted in purple are affected by the upend/tilt-over mechanism.

Two situations are shown in Figure 38. On the left, the initial situation where the centre of gravity of the Tilting Lift Beams and jacket is located to the right of the pivot point. On the right, the situation where the centre of gravity of the Tilting Lift Beams and jacket is located to the left of the pivot point. As can be seen in the figure, the direction of the moment around the pivot point changes when the centre of gravity is shifted past the pivot point. This direction of the moment will cause the Tilting Lift Beams with jacket to upend. Besides gravity, no other forces are used to upend the system, forces to move the Tilting Lift Beams not taken into account. The Derrick Hoist System controls the upending movement. The same Derrick Hoist System tilts the system to a horizontal position.

-	**CoG**	Joint Centre of Gravity of the Tilting Lift Beams and the Jacket
-	**G**	Weight of the Tilting Lift Beams and the Jacket
-	**M**	Moment around the pivot point
-	**Fv,A**	Reaction force in support point A
-	**Fv,B**	Reaction force in support point B

Counterweight Concept

The first concepts within the gravity-based principle is the Counterweight principle. The tail of the Tilting Lift Beams will be ballasted with a pre-applied mass, ballast water or a combination of a pre-applied mass with water ballast. To give two examples, the pre-applied mass can be incorporated in the beams but can also be hung with wires to the tail of the beams. The mass of the ballast must be sufficient to shift the joint centre of gravity past the pivot point in reference to the stern of Pioneering Spirit.

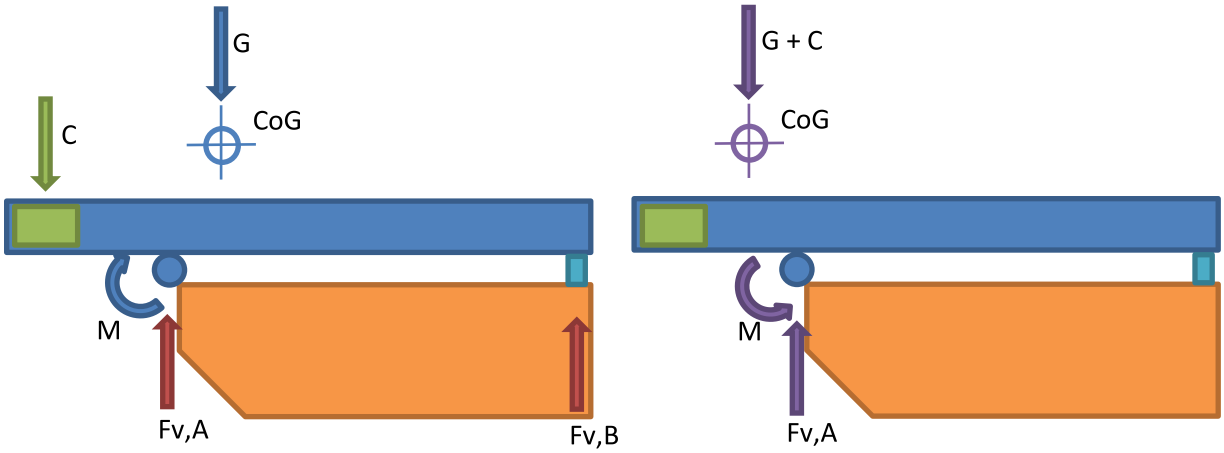


Figure 39: Concept "Counterweight":

The side view shown in Figure 39 is the same as in Figure 38. The objects in the figure have the same meaning as explained in Figure 38. A green rectangular is used to represent the position of the counterweight. The arrow "C" shows the gravitational force of the counterweight. In the right figure, the lumped mass and the position of the joint centre of gravity is depicted. The location of the centre of gravity is shifted past the pivot point in reference to the stern of Pioneering Spirit. The different stages during the upend/tilt-over operation for all concepts are included in Appendix B. Figure 41 is an example of the figures included in Appendix B.

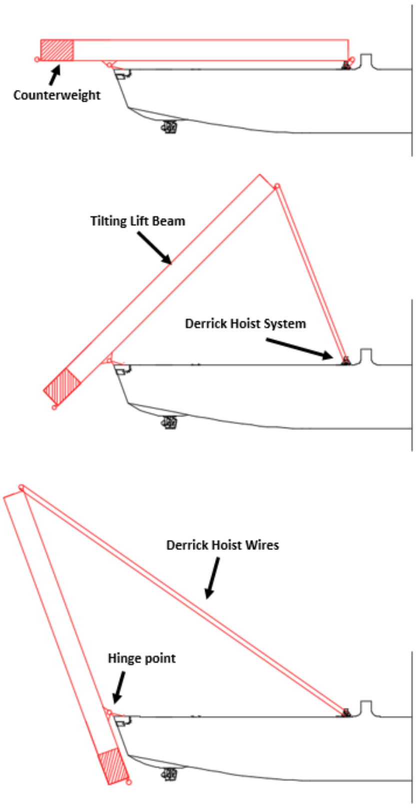


Figure 40: Upend/Tilt-over Stages in Concept "Counterweight"

Moving Frame Concept

The second concept within the gravity principle is the Moving frame concept. The joint centre of gravity of the Tilting Lift Beams and jacket is shifted past the pivot point in reference to the stern of Pioneering Spirit by moving the Tilting Lift Beams in the direction of the pivot point. The Tilting Lift Beams are moved by means of Self-Propelled Modular Transporters (SPMT's) or skids. The SPMT's or skid system are depicted in green in Figure 41. The other objects have the same meaning as described in Figure 38. The different stages during the upend/tilt-over operation are included in Appendix B.

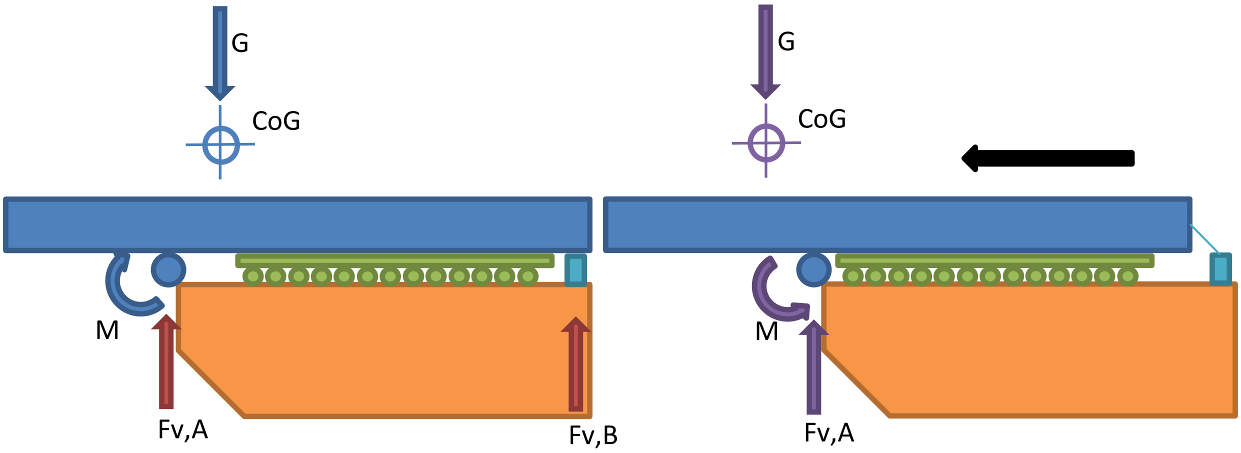
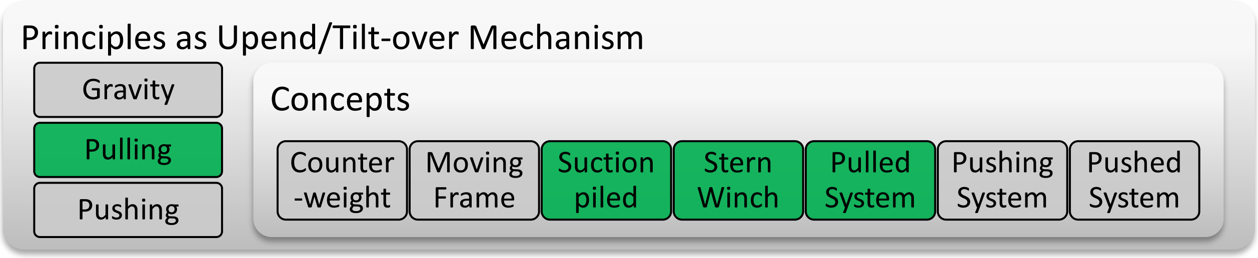


Figure 41: Concept "Moving Frame"

5.4.2 Pulling Based Concepts



In the pulling based concepts, the Tilting Lift Beams are upended/tilted-over by means of pulling on the beams. The pulling force initiates a moment around the pivot in opposite direction of the gravitational moment of the joint mass of the Tilting Lift Beams and jacket. The moment that the joint centre of gravity of the Tilting Lift Beams and jacket is past the pivot point, the derrick hoist system takes over the positioning of the Tilting Lift Beams. The opposite applies when the Jacket Lift System is tilted to a horizontal position.

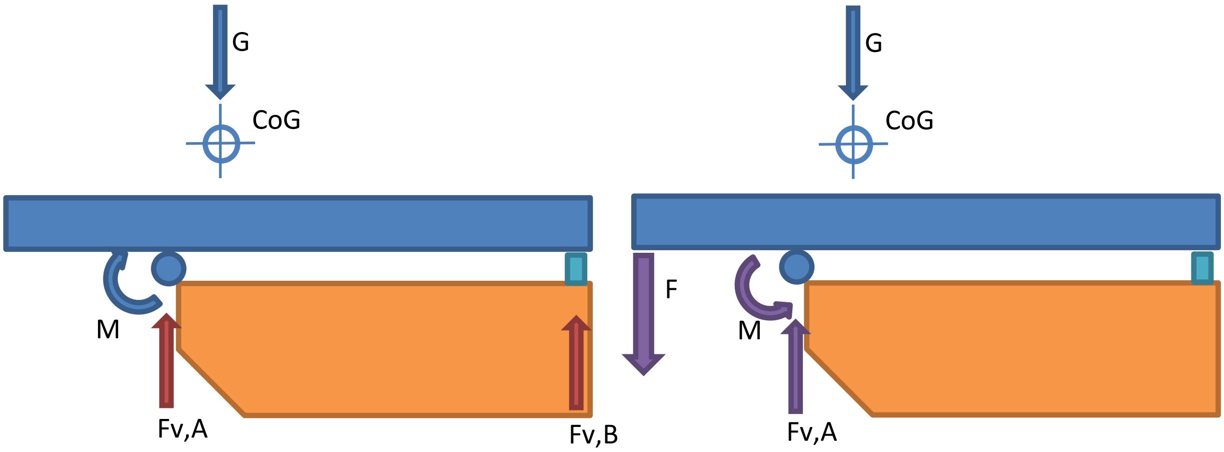


Figure 42: Pulling Principle

The explanation of Figure 42 is similar to the explanation of Figure 38 (page 58). The figure is a simplified schematic side view of Pioneering Spirit (orange rectangular). The blue circle represents the pivot point. The blue rectangular represents the Tilting Lift Beams. Finally, the light blue rectangular represents the Derrick Hoist System. Arrows depicted in purple are affected by the upend/tilt-over mechanism.

Two situations are shown in Figure 42. On the left, the tilted position where no additional forces are applied to the system. On the right, the situation where the pulling force, initiated by upend/tilt-over mechanism, is applied to the system. The direction of the moment changes and causes the Tilting Lift Beams and jacket to upend/tilt-over. The Derrick Hoist System together with the pulling system controls the rotating movement.

- **CoG**	Joint Centre of Gravity of the Tilting Lift Beams and the Jacket
- **G**	Weight of the Tilting Lift Beams and the Jacket
- **M**	Moment around the pivot point
- **Fv,A**	Reaction force in support point A
- **Fv,B**	Reaction force in support point B
- **F**	Pulling force by the upend/tilt-over mechanism

Suction Piled Concept

The first concept within the pulling principle is the Suction Piled Concept. One or more suction piles are installed on the seabed next to the jacket to be removed or next to the position of the jacket to be installed. The suction piles can be installed with the 650 mt or 5000 mt special purpose cranes at the stern of Pioneering Spirit. As soon as the suction piles are installed, a connection is made with the tail of the Tilting Lift Beams by means of a winch system. The system is upended/tilted-over by taking in or giving out wire. The Derrick Hoist System takes in or gives out wire in opposite direction. The winch system connecting the beams and the suction piles are shown in green in Figure 43. The different stages during the upend/tilt-over operation are included in Appendix B.

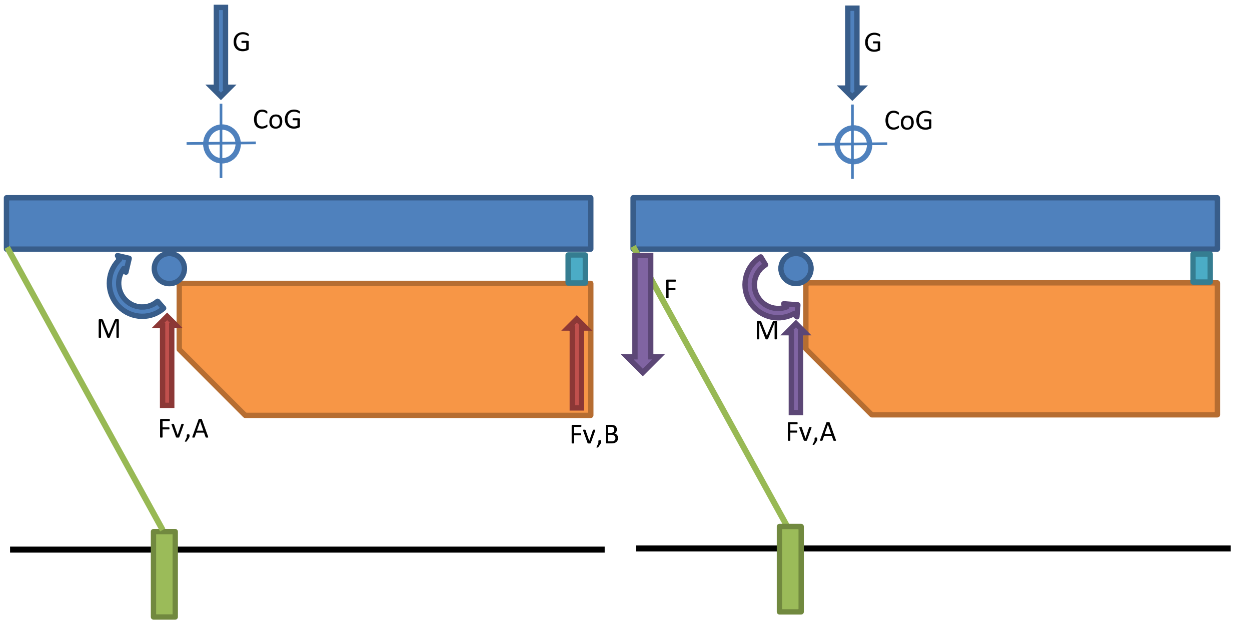


Figure 43: Concept “Suction Piled”

Stern Winch Concept

The second concept within the pulling principle is the Stern Winch Concept. The concept “Stern Winch” works in the same way as described in the concept “Suction Pilled”. However, no suction piles are installed. Instead, a winch connection is made between the stern of Pioneering Spirit and the tail of the Tilting Lift Beams. The winch system connecting the beams and the stern of Pioneering Spirit are shown in green in Figure 44. The different stages during the upend/tilt-over operation are included in Appendix B.

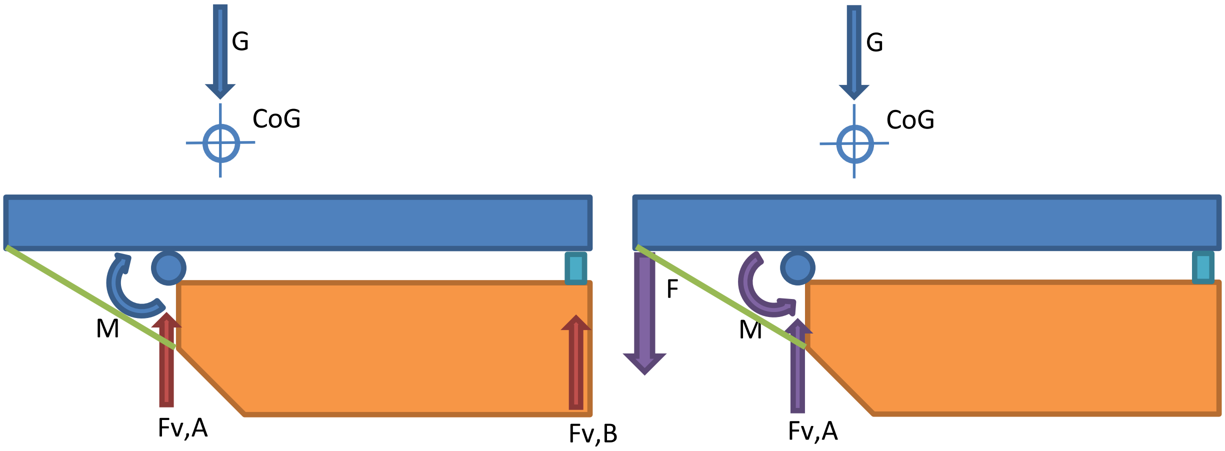


Figure 44: Concept “Stern Winch”

Pulled System Concept

The third and last concept within the pulling principle is the Pulled System Concept. A rigid construction is pulled against the Tilting Lift Beams by means of a winch system that is connected to the rigid construction and the Tilting Lift Beams. By pulling the rigid construction against the Tilting Lift Beams a moment is initiated in opposite direction of the moment caused by the mass of the Tilting Lift Beams and jacket. Just as in the other pulling concepts, once the joint centre of gravity is past the pivot point in reference to the stern of Pioneering Spirit, the Derrick Hoist system takes over the positioning of the beams. The rigid construction and the winch connection are shown in green in Figure 45. The different stages during the upend/tilt-over operation are included in Appendix B.

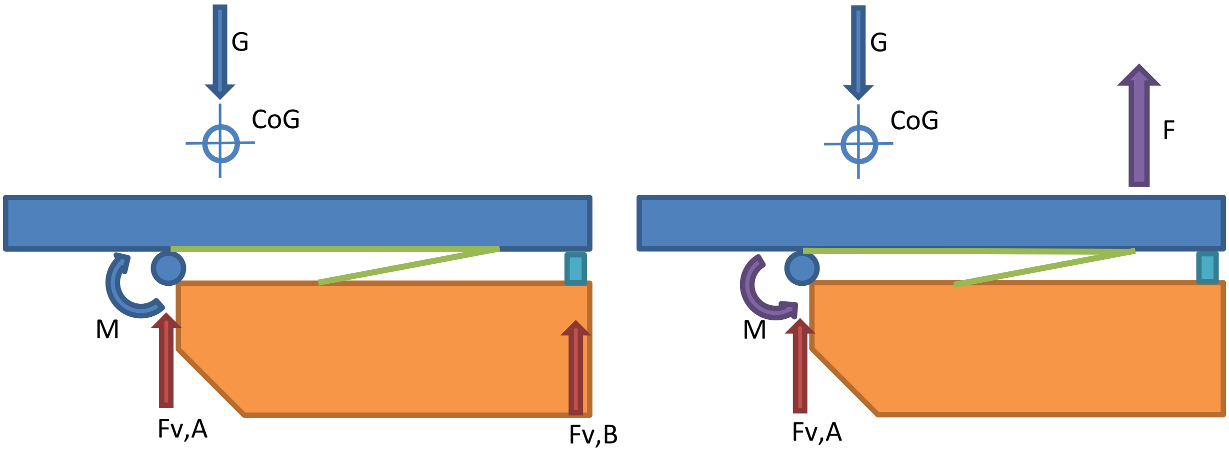
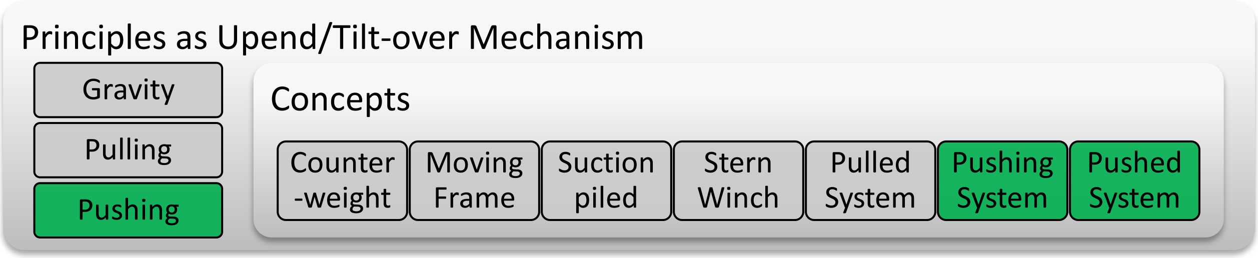


Figure 45: Concept “Pulled System”

5.4.3 Pushing Based Concepts



In the Pushing principle, the rotational movement of the Tilting Lift Beams is initiated by pushing against the Tilting Lift Beams. The direction of the force is in opposite direction to the moment caused by the mass of the Tilting Lift Beams and jacket. The derrick hoist system takes over the positioning of the Tilting Lift Beams as soon as the joint centre of gravity is past the pivot point in reference to the stern of Pioneering Spirit. This is like the pulling principle. This is in every principle and concepts the same.

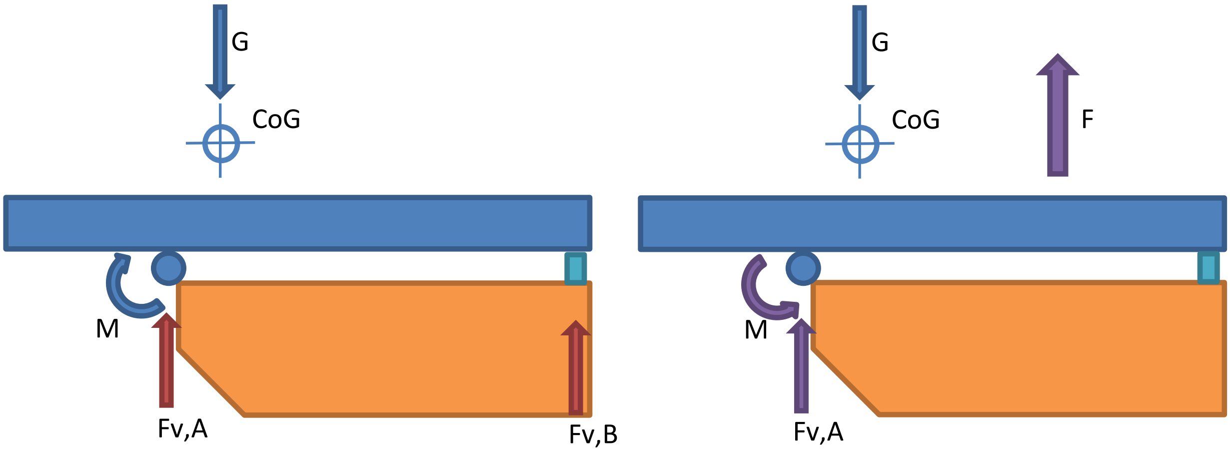


Figure 46: Pushing Principle

Again, the explanation of Figure 46 is similar to the explanation of Figure 38 (page 58). The figure is a simplified schematic side view of Pioneering Spirit (orange rectangular). The blue circle represents the pivot point. The blue rectangular represents the Tilting Lift Beams. Finally, the light blue rectangular represents the Derrick Hoist System. Arrows depicted in purple are affected by the upend/tilt-over mechanism.

Two situations are shown. On the left, the tilted position where no additional forces are applied to the system. On the right, the situation where the pushing force, initiated by upend/tilt-over mechanism, is applied to the system. The direction of the moment changes and causes de Tilting Lift Beams and jacket to upend/tilt-over. The Derrick Hoist System together with the pulling system control the rotating movement.

-	**CoG**	Joint Centre of Gravity of the Tilting Lift Beams and the Jacket
-	**G**	Weight of the Tilting Lift Beams and the Jacket
-	**M**	Moment around the pivot point
-	**Fv,A**	Reaction force in support point A
-	**Fv,B**	Reaction force in support point B
-	**F**	Pulling Force by the upend/tilt-over mechanism

Pushing System Concept

The first concept within the Pushing principle is the Pushing System Concept. The system is upended by means of a system pushing against the Tilting Lift Beams. The pushing system consists of hydraulic segmented cylinders and is installed on the aftdeck of Pioneering Spirit on the already applied transverse reinforced frames. The derrick hoist system takes over the positioning of the beams as soon as the joint centre of gravity of the beams and the jacket is past the pivot point in reference to the stern of Pioneering Spirit. The pushing system is shown in green in Figure 47. The different stages during the upend/tilt-over operation are included in Appendix B.

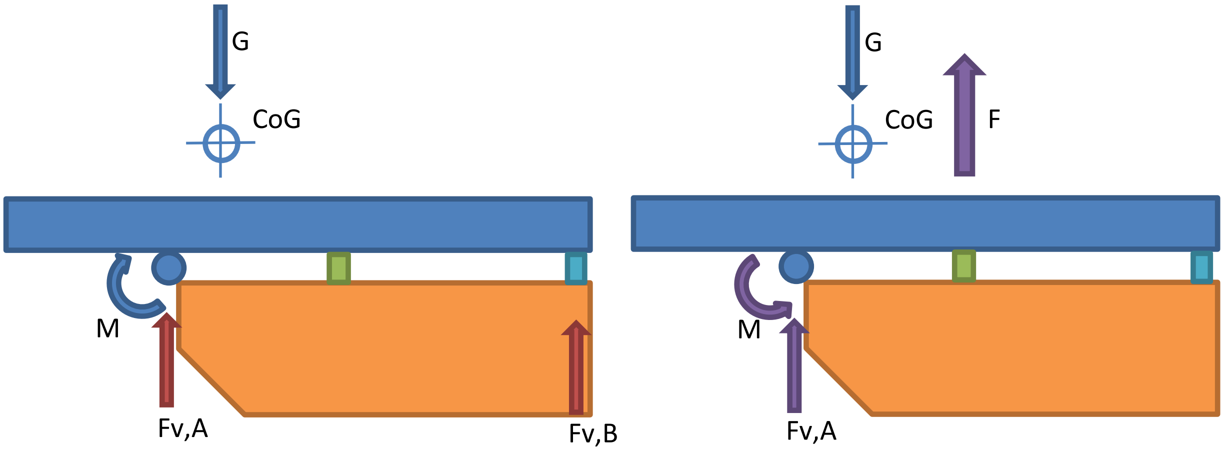


Figure 47: Concept "Pushing System"

Pushed System Concept

The second concept within the Pushing principle is the Pushed System Concept. The pushed System concept is almost the same as the Pulled System concept. The difference is the principle to initiate the rotational movement. The System is not pulled with a winch system against the Tilting Lift Beams. Instead, a hydraulic cylinder is installed between the rigid construction and the Tilting Lift Beams. The rigid construction and the hydraulic system are shown in green in Figure 48. The different stages during the upend/tilt-over operation are included in Appendix B.

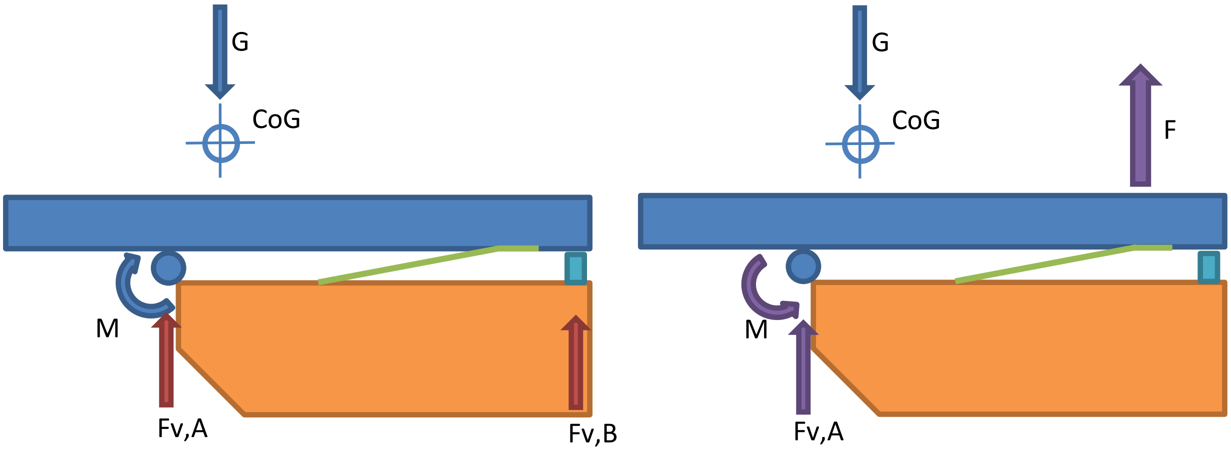


Figure 48: Concept "Pushed System"

5.5 Approach/Calculation Method Static Equilibrium/Forces

In this second subpart of the concept development, the upend and tilt-over movement of the Jacket Lift System is analysed. This includes the equilibrium state of the system during the upend/tilt-over operation. Dynamic forces are not considered (yet). A force is dynamic when the magnitude changes over time. In other words, when the magnitude is time dependent. [37]. An equilibrium state is achieved by the concept dependent upend system together with the Derrick Hoist System.

Static forces considered during this concept development subpart are initiated by:

- Mass of the Jacket Lift System
- Mass of the jacket
- Buoyancy due to the submersion of the tail of the Tilting Lift Beams and jacket
- Mechanism to upend/tilt-over the system

The forces of the above mentioned initiators are all dependent on the angle in which the Jacket Lift System is positioned. In the approach to calculate and analyse the forces during the upend/tilt-over operation, the equilibrium state for the 115 degrees in which the system can be positioned is calculated and analysed.

5.5.1 Schematisation Jacket Lift System Static Analysis

As mentioned before, in this second subpart of the concept development the static equilibrium of the system during the upend/tilt-over operation is analysed. The static equilibrium is controlled by the concept dependent upend system together with the Derrick Hoist System. The system can be schematised as a beam placed on a pivot point. The system is statically determinate (isostatic) [36]. This is also assumed for the Pushing System concept. It has been assumed that the connection in this concept is arranged such that phenomena as shrinkage and creep do no cause additional stresses/forces in the system.

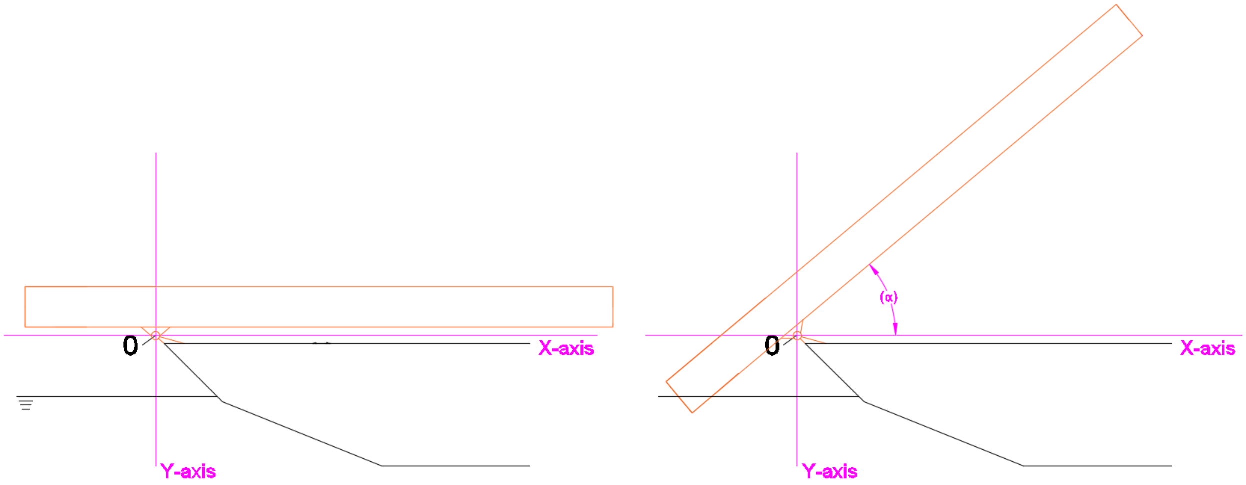


Figure 49: Schematic Overview of the System

An equilibrium state is achieved when the summation of the horizontal, vertical and rotational forces is (individually) zero [38].

$\sum F_v = 0$ Vertical equilibrium
$\sum F_h = 0$ Horizontal equilibrium
$\sum M = 0$ Rotational equilibrium

The positive directions of the horizontal, vertical and rotational forces are given in Figure 50.

The following forces exert, concept dependent, on the system:

- Gravitational force by the mass of the JLS
- Gravitational force by the mass of the rigid construction
- Gravitational force by the mass of the jacket
- Gravitational force by the mass of the counterweight
- Force by the Derrick Hoist System
- Force by buoyancy
- Force by the pulling upending system
- Force by the pushing upending system

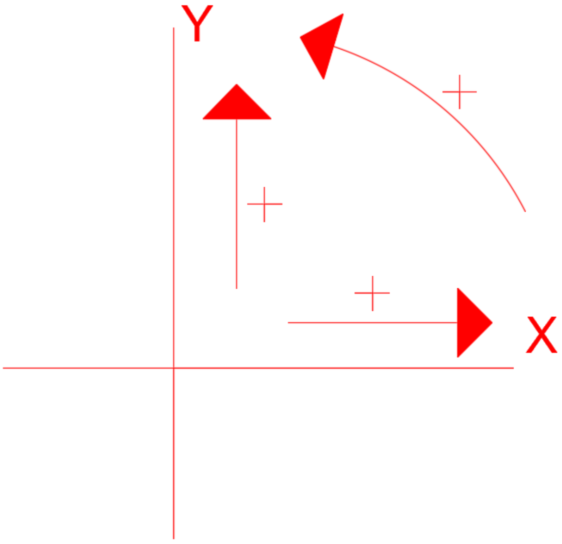


Figure 50: Positive Orientation Forces/Moment

5.5.2 Assumptions, Simplifications and General Parameters

Mass rigid push construction and mass wires

The mass of the wires is assumed to be included in the mass of the Jacket Lift System. No additional mass is added per concept for the wires. Two reasons for this are the fact that all concepts include wires and because of the ratio of the mass of the wires in reference with the total mass of the system with jacket. The exact contribution of the mass of the wires on the static equilibrium is at this stage of the design not known. It is too detailed.

The masses of the pushing systems in the pushing concepts are included in the calculation. The masses of the pushing system are of a magnitude that they cannot be neglected. Another reason to include the masses of the pushing systems is that all concepts contain wires but only the pushing concepts contain a rigid push construction. This mass is extra on top of the wires.

Angular velocity is equal to zero

The duration of the upend/tilt-over operation is adapted from the reference design as described in chapter 2. The upend/tilt-over operation takes approximately 12 hours. Because of the slow angular velocity, the angular velocity is assumed to be zero. The static equilibrium is calculated for 0 – 115 degrees in reference with the aftdeck of Pioneering Spirit (x-axis). The velocity is included when determining the maximum power requirement.

Angular speed:

$$\omega = \frac{\pi \cdot 115}{T \cdot 180}$$ T = 12 hours ~ 720 minutes ~ 42300 seconds

$$\omega = 4.65 \cdot 10^{-5}\ [\mathrm{Rad/s}]$$

Pressure/Tension in upend/tilt-over specific components
A distinction is made in which component is responsible to obtain a static equilibrium at a certain time during the upend/tilt-over operation. The Derrick Hoist System is responsible for the static equilibrium when the system undergoes a positive moment. The upend specific component is responsible for the static equilibrium when the jacket Lift System undergoes a negative moment. The orientation of the positive and negative directions is given in Figure 50 (page 66).

Simplification jacket dimensions
The dimensions of the jacket to be installed or removed are of great importance regarding influences on the static equilibrium (and later dynamic analysis). An example is the contribution of the buoyancy caused by the submersed part of the jacket. However, since this is a feasibility study and only a limited number of influences have been included, the dimensions of the reference jacket have been considerably simplified. A common method to simplify the dimensions of an offshore structure is to apply the stick model [14]. In the stick model, the beam diameters are summed up per unit length. The result is a single lumped beam that varies greatly in diameter over the length. So, the stick model does consider the brace pattern of the jacket design, the orientation of the braces in the water and the beam dimensions. This is, among other reasons, why this model is not used in this thesis. Besides the large variety of jacket dimensions/designs, the angle of the jacket also changes during the upend/tilt-over procedure. This also affects the stick model. Taking this into account turns this thesis in a detailed research about the contribution of (different) jackets placed on the jacket lift system during the upend/tilt-over procedure instead of a feasibility and favourability study about the Upend/Tilt-over Mechanism of Pioneering Spirit's Jacket Lift System. More information about the large variations of jacket designs/dimensions can be found in paragraph 3.1.

Instead of the stick model, the dimensions are simplified by taking uniformed mean dimensions in width and height over the total length of the jacket. The position of the Centre of Gravity is kept as indicated in the original drawings of the reference jackets (Appendix A). By looking at the simplified dimensions of the reference jacket, a representative (representative for this feasibility study) reference jacket is defined that is used in the static and (later) dynamic analysis.

Simplified dimensions per reference jacket

Brent Alpha (1)	Mass of the jacket	$M_{\text{Jacket},1}$	= 14 225	[mt]
	Length of the jacket	$L_{\text{Jacket},1}$	= 84	[m]
	Height of the jacket	$H_{\text{Jacket},1}$	= 15	[m]
	Width of the jacket	$W_{\text{Jacket},1}$	= 30	[m]
	Centre of Gravity TLB	$x_{\text{CoG, Jacket},1}$	= 41	[m] (from bottom)
		$y_{\text{CoG, Jacket},1}$	= 17.5	[m]
Murchison (2)	Mass of the jacket	$M_{\text{Jacket},2}$	= 14 000	[mt]
	Length of the jacket	$L_{\text{Jacket},2}$	= 122	[m]
	Height of the jacket	$H_{\text{Jacket},2}$	= 21	[m]
	Width of the jacket	$W_{\text{Jacket},2}$	= 25	[m]
	Centre of Gravity TLB	$x_{\text{CoG, Jacket},2}$	= 60	[m] (from bottom)
		$y_{\text{CoG, Jacket},2}$	= 22.5	[m]
Kvitebjørn (3)	Mass of the jacket	$M_{\text{Jacket},3}$	= 12 000	[mt]
	Length of the jacket	$L_{\text{Jacket},3}$	= 166	[m]
	Height of the jacket	$H_{\text{Jacket},3}$	= 14	[m]
	Width of the jacket	$W_{\text{Jacket},3}$	= 14	[m]
	Centre of Gravity TLB	$x_{\text{CoG, Jacket},3}$	= 56	[m] (from bottom)
		$y_{\text{CoG, Jacket},3}$	= 30	[m]
Sverdrup P1 (4)	Mass of the jacket	$M_{\text{Jacket},4}$	= 17 700	[mt]
	Length of the jacket	$L_{\text{Jacket},4}$	= 138.5	[m]
	Height of the jacket	$H_{\text{Jacket},4}$	= 24	[m]
	Width of the jacket	$W_{\text{Jacket},4}$	= 30	[m]
	Centre of Gravity TLB	$x_{\text{CoG, Jacket},4}$	= 61.5	[m] (from bottom)
		$y_{\text{CoG, Jacket},4}$	= 25	[m]

Table 8: Parameters Reference Jacket

Assessment Reference Jacket Dimensions

Length of the jacket	$L_{\text{Jacket},1}$	= 130	[m]
Height of the jacket	$H_{\text{Jacket},1}$	= 15	[m]
Width of the jacket	$W_{\text{Jacket},1}$	= 40	[m]
Mass of the jacket	$M_{\text{Jacket},1}$	= 15 000	[mt]
Centre of Gravity TLB	$x_{\text{CoG, Jacket},1}$	= 50	[m] (from bottom)
	$y_{\text{CoG, Jacket},1}$	= 25	[m]

Table 9: Parameters Reference Jacket Assessment

General Parameters:

Location:			
Gravity	g	= 9.81	[m/s^2]
Water depth at the location	Z_{water}	= 120	[m]
Density seawater	ρ_{water}	= 1025	[kg/m^3]
Pioneering Spirit:			
Draft Pioneering Spirit	d	= 17	[m]
Displacement (at 17 m draft)	$M_{PioneeringSpirit}$	= 571 925	[mt]
Jacket Lift System:			
Length crane boom TLB (hinge to tip)	$L_{TLB,CraneBoom}$	= 112	[m]
Length Tail TLB (hinge to bottom)	$L_{TLB,Tail}$	= 32	[m]
Height of the TLB	H_{TLB}	= 10	[m]
Width of the TLB	W_{TLB}	= 10	[m]
Mass of the JLS (in total)	M_{JLS}	= 15 000	[mt]
Number of TLB's in the system	TLB_{numb}	= 2	[-]
Centre of Gravity TLB positioned from hinge	$x_{CoG,TLB}$	= 15	[m]
	$y_{CoG,TLB}$	= 5	[m]
Jacket (reference dimensions from Table 9)			
Mass of the jacket	M_{jacket}	= 15 000	[mt]
Centre of Gravity jacket (from hinge)	$x_{CoG,jacket}$	= 10	[m]
Centre of Gravity jacket (from hinge)	$y_{CoG,jacket}$	= 27	[m]
Length of the jacket	$L_{Jacket,1}$	= 130	[m]
Height of the jacket	$H_{Jacket,1}$	= 15	[m]
Width of the jacket	$W_{Jacket,1}$	= 40	[m]
Mass of the jacket	$M_{Jacket,1}$	= 15 000	[mt]
Centre of Gravity TLB	$x_{CoG, Jacket,1}$	= 40	[m] (from bottom)
	$y_{CoG, Jacket,1}$	= 20	[m]
Counterweight:			
Mass of the counterweight	M_{jacket}	= 10 000	[mt]
Centre of Gravity counterweight positioned	$x_{CoG,counterweight}$	= 24.5	[m] (from hinge)
from hinge	$y_{CoG,counterweight}$	= 5	[m]
Pushing System:			
Mass of the rigid construction	$M_{Upend,P}$	= 45 - 1 500	[mt]
Length of the rigid construction	$L_{Upend,P}$	= 2 – 68.5	[m]
Width of the rigid construction	$W_{Upend,P}$	= 10	[m]
Height of the rigid construction	H_{TLB}	= 2.5	[m]
Pushed System:			
Mass of the rigid construction	$M_{jacket,PP}$	= 2 000	[mt]
Length of the rigid construction	$L_{TLB,CraneBoom,PP}$	= 92.5	[m]
Width of the rigid construction	$W_{TLB,PP}$	= 10	[m]
Height of the rigid construction	$H_{TLB,PP}$	= 2.5	[m]

Table 10: General Parameters Static Equilibrium

5.5.3 Coordinate Reference System

A coordinate reference system is used in the static equilibrium analysis. The same coordinate reference system is used in the, later conducted, dynamic analysis. Because of the increasing or decreasing angle of the Jacket Lift System in reference to the x-axis, the positions of the points where a certain force is exerted to the system changes during the upend/tilt-over operation. The pivot point is taken as origin. The pivot point is a convenient point to take as origin as the system rotates around this point and therefore will not vary. The reference coordinate system is shown in Figure 51.

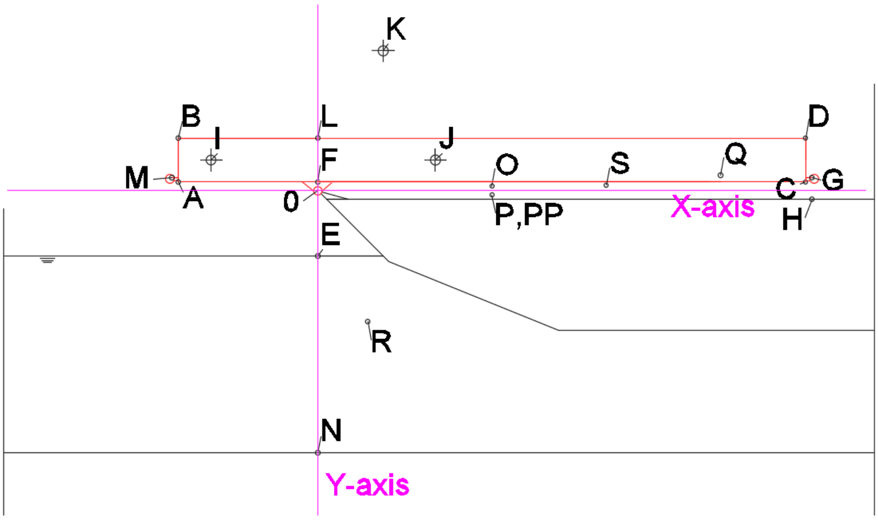


Figure 51: Reference Coordinate System

The most important points relevant for the calculation of the static equilibrium are given in Figure 51. The identification of the points and their coordinates in tilted position (transportation/initial position) are given in Table 11.

Name Point	Point	X Coordinate [m]	Y Coordinate [m]
Pivot Point	0	0	0
Corner TLB	A	-32	2
Corner TLB	B	-32	12
Corner TLB	C	112	2
Corner TLB	D	112	12
Water level	E	0	-15
Bottom TLB (in tilted position)	F	0	2
Attachment point Derrick Hoist System	G	115	3
Attachment point Base Derrick Hoist System	H	115	-1
Centre of Gravity Counterweight	I	-24.5	7
Centre of Gravity TLB	J	15	7
Centre of Gravity Jacket	K	10	32
Top TLB (in tilted position)	L	0	12
Attachment point TLB Pulling System	M	-33.5	3
Attachment point Suction Anchor	N	-1	-74
Attachment point TLB Pushing System	O	40	1
Attachment point Base Pushing System	P	40	-1
Attachment point Base Push/Pull System	PP	40	-1
Attachment point Push/Pull System	Q	92.5	3.5
Attachment point PS Pulling System	R	11.5	-32
Centre of Gravity Push/Pull System	S	26.25	2.25

Table 11: Coordinates Points in Tilted/Initial Position

5.5.4 Coordinates Points during Upending/Tilting-over

Most of the points, defined in Table 11, rotate together with the Tilting Lift Beams around the pivot point. (Points A, B, C, D, F, G, I, J, K, L, M and O). The length between a certain point and the pivot point (radius) remains the same during the entire upend/tilt-over operation. Exceptions are the points that represent the rigid construction in the Push/Pull system (points Q and S). Points Q and S do not rotate around the origin but revolve around point PP (see Figure 51).

Point Revolving around the Pivot Point (The Origin)

The following steps are carried-out to determine the position of the points during the upend/tilt-over operation. Determine:

1.	Angle in tilted/initial position	$\alpha_{n,0}$	[°]
2.	Length of origin to a point n (Radius)	$L_{n,0}$	[m]
3.	X coordinate (angle depend)	$x_n(\alpha_i)$	[m]
4.	Y coordinate (angle depend)	$y_n(\alpha_i)$	[m]

Where:

α_i = Angle in reference to the X-axis (i = 0…115) [°]
n = A, B, C, D, F, G, I, J, K, L, M and O.

The angle and length between a certain point and the pivot point (radius) in tilted position remains the same during the upend/tilt-over operation. If these values are known, the x- and y- coordinates can be calculated using geometry. An illustration is given in Figure 52. A detailed elaboration of the calculation of the coordinate points revolving around the pivot point is included in Appendix C.

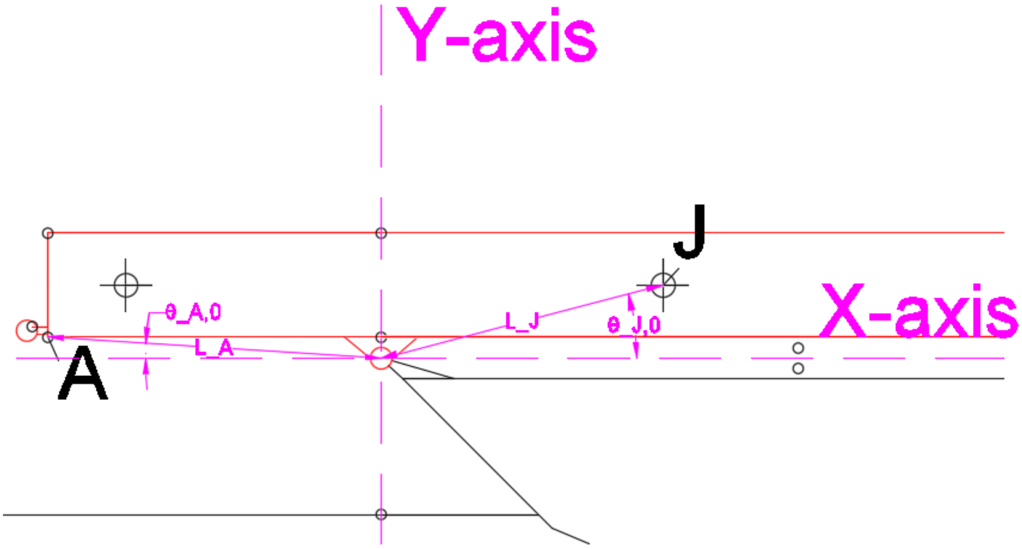


Figure 52: Coordinate example Point A and J

An overview of the coordinates of the points in an angle of 0 – 115 degrees is included in Appendix D.

Points Revolving around Point PP

As mentioned earlier, points Q and S do not rotate around the origin, but instead revolve around point PP. To determine the coordinates of points Q and S, during the upend/tilt-over operation, the intersection of a line through point Q at the same angle as the Tilting Lift Beams and a circle with a radius equal to length of the rigid construction and point PP as origin is calculated. See Figure 53.

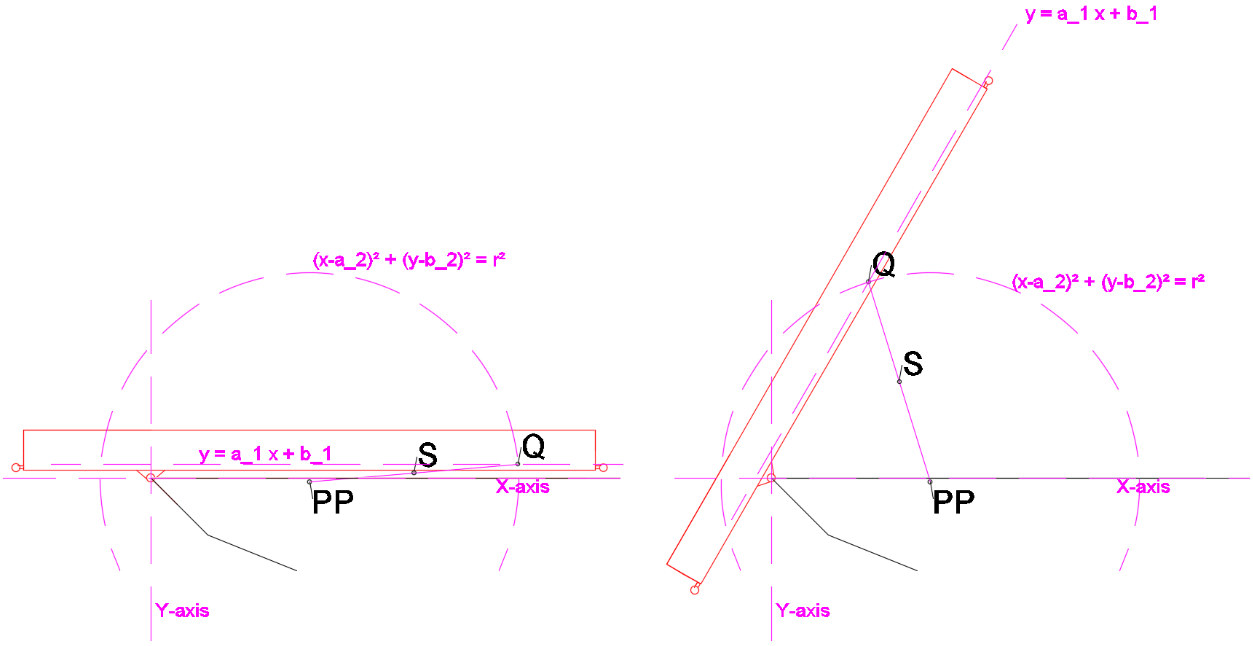


Figure 53: Coordinate Point Q and S

The X coordinate is calculated by calculating the intersection between:

Line: $y = a_1(\alpha_i) \cdot x + b_1(\alpha_i)$

And

Circle: $(x - a_2)^2 + (y - b_2)^2 = r^2$

Where:

a_1 = slope of the line (Angle depend)
b_1 = y(0) (Angle depend)
a_2 = $x_{Q,0}$
b_2 = $y_{Q,0}$
r = L_{PP-Q}

The same four steps as used for the points revolving around the origin are used.

1.	Angle in tilted position	$(\alpha_{Q,0})$	[°]
2.	Length rigid construction Push/Pull System (radius)	$(L_{Q,0})$	[m]
3.	X coordinate point	$(x_Q(\alpha i))$	[m]
4.	Y coordinate point	$(y_Q(\alpha i))$	[m]

3 phases are applicable during the upend/tilt-over operation:

$$\left.\begin{array}{ll} \textbf{1.} & \alpha_i < 90° \\ \textbf{2.} & \alpha_i = 90° \\ \textbf{3.} & \alpha_i > 90° \end{array}\right\} \text{for i = 0...115}$$

A full elaboration of this calculation method is included in Appendix C. A full overview of the coordinates of the points in an angle of 0 – 115 degrees is included in Appendix D.

5.5.5 Individual General Static Force Contributions

Gravitational Force

The gravitational forces of the components in the Jacket Lift System are calculated using the algebraic version of newton's second law, Force = mass x acceleration [39]. A schematisation of the forces is given in Figure 54. The gravitational moment is calculated by multiplying the gravitational force with the length between the point of application and rotation point.

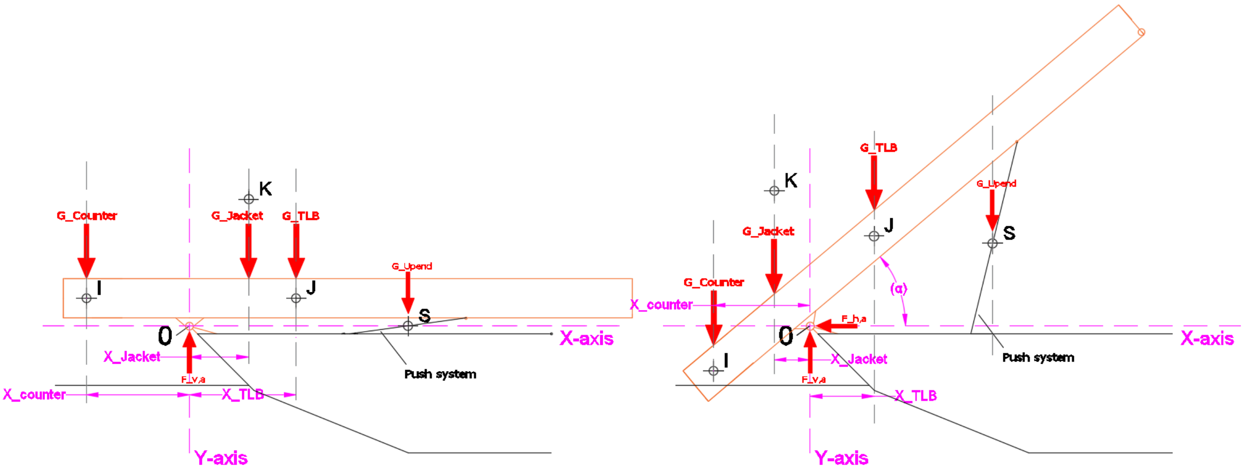


Figure 54: Overview Gravitational Forces

Components "n" considered:

- Tilting Lift Beams
- Rigid Upend/Tilt-over Mechanism in Pushing System Concept
- Rigid Upend/Tilt-over Mechanism in Push/Pull System Concept
- Jacket
- Counterweight

Gravitational forces:

$$G_n = m_n \cdot g \qquad [kN]$$

Where:

m_n = Mass of the component [mt]
g = Gravitational acceleration [m/s^2]
n = Component [-]

The mass of the rigid Upend/Tilt-over Mechanism in the Pushing System Concept is angle dependent. The length of the mechanism increases/decreases during the upend/tilt-over operation.

Gravitational Moments:

$$M_n(\alpha_i) = G_n \cdot x_n \qquad [kNm]$$

Where:

G_n = Gravitational force by component [mt]
$x_n(\alpha_i)$ = ΔX of rotation point and point of application of the force [m]
n = Component [-]
α_i = Angle of upend/tilt-over TLB's in reference to the X-axis [°]
i = 0…115 [-]

The ΔX of all component's "n" are angle dependent. The gravitational force in the rigid Upend/Tilt-over Mechanism of the Pushing System Concept is the only gravitational force that is dependent on an angle.

Remark on next page

Remark gravitational force in the Pushing and Push/Pull Concepts
The mass of the rigid Upend/Tilt-over Mechanism does not exert a force directly on the Tilting Lift Beam. First, the moment is calculated around the base point P or PP. Subsequently, the force at the connection point is calculation. This is further explained in the “concept specific upend/tilt-over mechanism” part of this paragraph.

Derrick Hoist System

The Derrick Hoist system is used to create a static equilibrium during the upend/tilt-over operation. The moment by the Derrick Hoist System is equal to the resulting moment in the system. In this static force analysis, the Derrick Hoist system exerts a force to the system when the resulting moment is positive. The positive or negative direction of the forces is given in Figure 50 (page 66). The moment by the Derrick Hoist System and the tension in the Derrick Hoist wires are calculated by:

$$M_{DerrickHoist}(\alpha_i) = -\sum(M_n(\alpha_i)) \qquad [\text{kNm}]$$

$$T_{DerrickHoist}(\alpha_i) = \frac{\frac{-\Sigma(M_{DerrickHoist}(\alpha_i))}{L_G}}{\mathrm{Cos}(\theta_{Derrick}(\alpha_i))} \qquad [\text{kN}]$$

Where

$\sum(M_n(\alpha_i))$ = Summation of moments applied to the system [kNm]
$L_G(\alpha_i)$ = ΔX of rotation point and point of application of the force [m]
α_i = Angle of upend/tilt-over TLB’s in reference to the X-axis [°]
i = 0…115 [-]

$$\theta_{Derrick}(\alpha_i) = 90 - \theta_{DerrickHoist}(\alpha_i) \qquad [°]$$

$$\theta_{DerrickHoist}(\alpha_i) = \tan\left(\frac{y_G(\alpha_i) - y_{H,0}}{x_{H,0} - x_G(\alpha_i)}\right) \qquad [°]$$

Where
$x_{H,0}$ and $y_{H,0}$ are the x and y coordinates in tilted/initial position (see Table 11 (page 70)). $x_G(\alpha_i)$ and $y_G(\alpha_i)$ are the angle dependent x and y coordinates of the location where the Derrick Hoist System exerts its force to the system (see Appendix D).

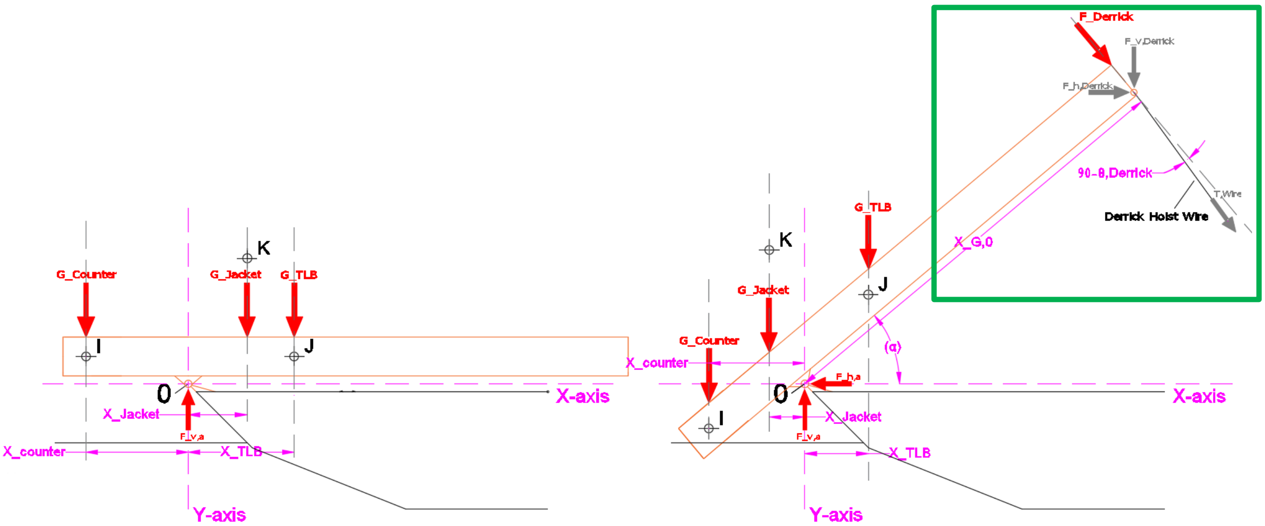


Figure 55: Gravitational Forces and Derrick Hoist System

The vertical and horizontal forces at the base of the Derrick Hoist System are:

$$F_{v,DerrickHoist} = -T_{DerrickHoist}(\alpha_i) \cdot \sin(\theta_{DerrickHoist}) \qquad [\text{kN}]$$

$$F_{h,DerrickHoist} = T_{DerrickHoist}(\alpha_i) \cdot \cos(\theta_{DerrickHoist}) \qquad [\text{kN}]$$

Buoyancy

The buoyancy is calculated using Archimedes' law. Archimedes' law states that a body immersed in a fluid experiences a vertical force equal to the weight of the fluid it displaces [40]. The Force is exerted in an upward direction at the centre of gravity of the displaced fluid [41]. The method is explained for the buoyancy regarding the Tilting Lift Beams. The same calculation method applies for the submersed parts of the jacket. A reference is made to the simplified jacket dimensions as described in paragraph 5.2. The moment caused by buoyancy is calculated by multiplying the buoyancy with the length between the point of application and rotation point.

Buoyancy:

$$\mathrm{F_{Buoyancy}}(\alpha_i) = \frac{1}{1000} \cdot \rho \cdot g \cdot \nabla_{\mathrm{TLB}}(\alpha_i) \qquad [\mathrm{kN}]$$

Where

$\nabla_{\mathrm{TLB}}(\alpha_i)$ = Displacement of the TLB's [m^2]
ρ = Density seawater [kg/m^3]
g = Gravitational acceleration [m/s^2]

$$\nabla_{\mathrm{TLB}}(\alpha_i) = \mathrm{A_{xy}}(\alpha_i) \cdot \mathrm{W_{TLB}} \cdot \mathrm{TLB_{Number}} \qquad [\mathrm{m^3}]$$

Where

$\mathrm{A_{xy}}(\alpha_i)$ = Submersed area (side view) (See also next page) [m^2]
$\mathrm{W_{TLB}}$ = Width TLB's [m]
$\mathrm{TLB_{Number}}$ = Number of TLB's [-]
α_i = Angle of upend/tilt-over TLB's in reference to the X-axis [°]
i = 0…115 [-]

Buoyancy Moment:

$$\mathrm{M_{Buoyancy}}(\alpha_i) = \mathrm{F_{Buoyancy}}(\alpha_i) \cdot \mathrm{x_{Buoyancy}}(\alpha_i) \qquad [\mathrm{kNm}]$$

Where:

$\mathrm{x_{Buoyancy}}(\alpha_i)$ = ΔX of rotation point and point of application of the force [m]
α_i = Angle of upend/tilt-over TLB's in reference to the X-axis [°]
i = 0…115 [-]

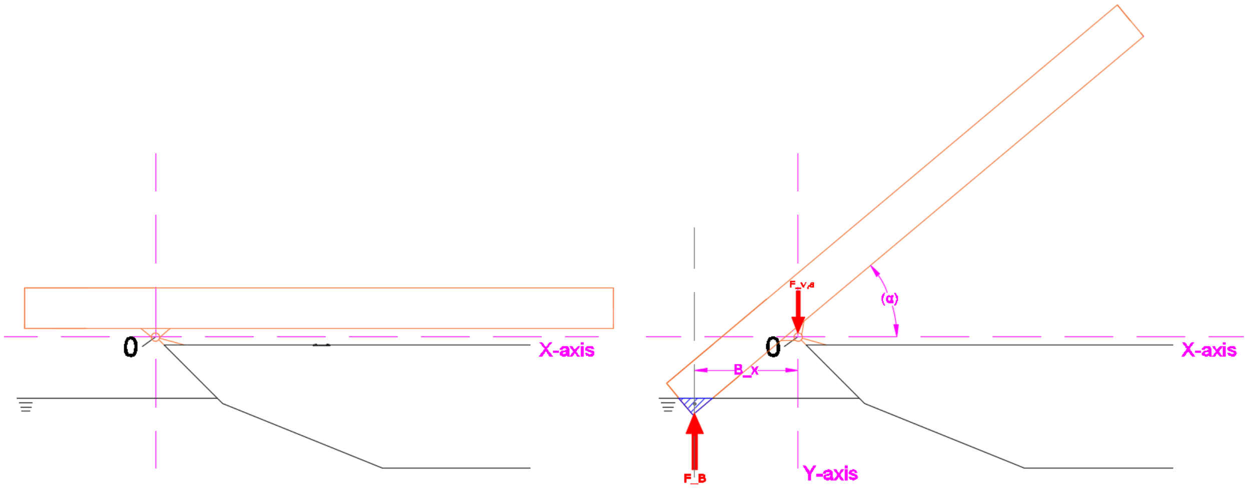


Figure 56: Graphical Representation of Buoyancy

The area (side view) of the submersed fluid depends on the angle in which the Jacket Lift System is positioned. A distinction is made between five stages during the upend/tilt-over operation:

$$\left.\begin{array}{ll} 1. & \alpha_{\mathrm{i}} < \alpha_{\mathrm{Point\ A}} \\ 2. & \alpha_{\mathrm{Point\ A}} < \alpha_{\mathrm{i}} < \alpha_{\mathrm{Point\ B}} \\ 3. & \alpha_{\mathrm{Point\ B}} < \alpha_{\mathrm{i}} < \alpha_{90^\circ} \\ 4. & \alpha_{\mathrm{i}} = \alpha_{90^\circ} \\ 5. & \alpha_{90^\circ} < \alpha_{\mathrm{i}} \end{array}\right\} \quad \text{for } 0 \leq \alpha_{\mathrm{i}} \leq 115$$

Where:

$\alpha_{\mathrm{Point\ A}}$ = Angle where Point A touches the water level [°]

$\alpha_{\mathrm{Point\ B}}$ = Angle where Point B touches the water level [°]

$\alpha_{\mathrm{Point\ n}} = \sin\left(\frac{|n_{y,0}|}{|L_n|}\right) + |\tan\left(\frac{n_{x,0}}{n_{y,0}}\right)|$ n = A, B [°]

A graphical representation of the five stages is given in Figure 57. The submerged area ($A_{xy}(\alpha_i)$) is indicated in blue. The area and the centre of application of the submersed fluid body is calculated using geometry. As indicated in Figure 57, the submerged area is calculated in two part, a rectangular and a triangular shape of the submerged part of the beam. The distance between the joint centre of gravity is calculated by:

$$x_{\mathrm{Buoyancy}} = \frac{(A_{\mathrm{Rectangle}} \cdot x_{\mathrm{Rectangle}} + A_{\mathrm{Triangle}} \cdot x_{\mathrm{Triangle}})}{(A_{\mathrm{Rectangle}} + A_{\mathrm{Triangle}})} \quad [\mathrm{m}]$$

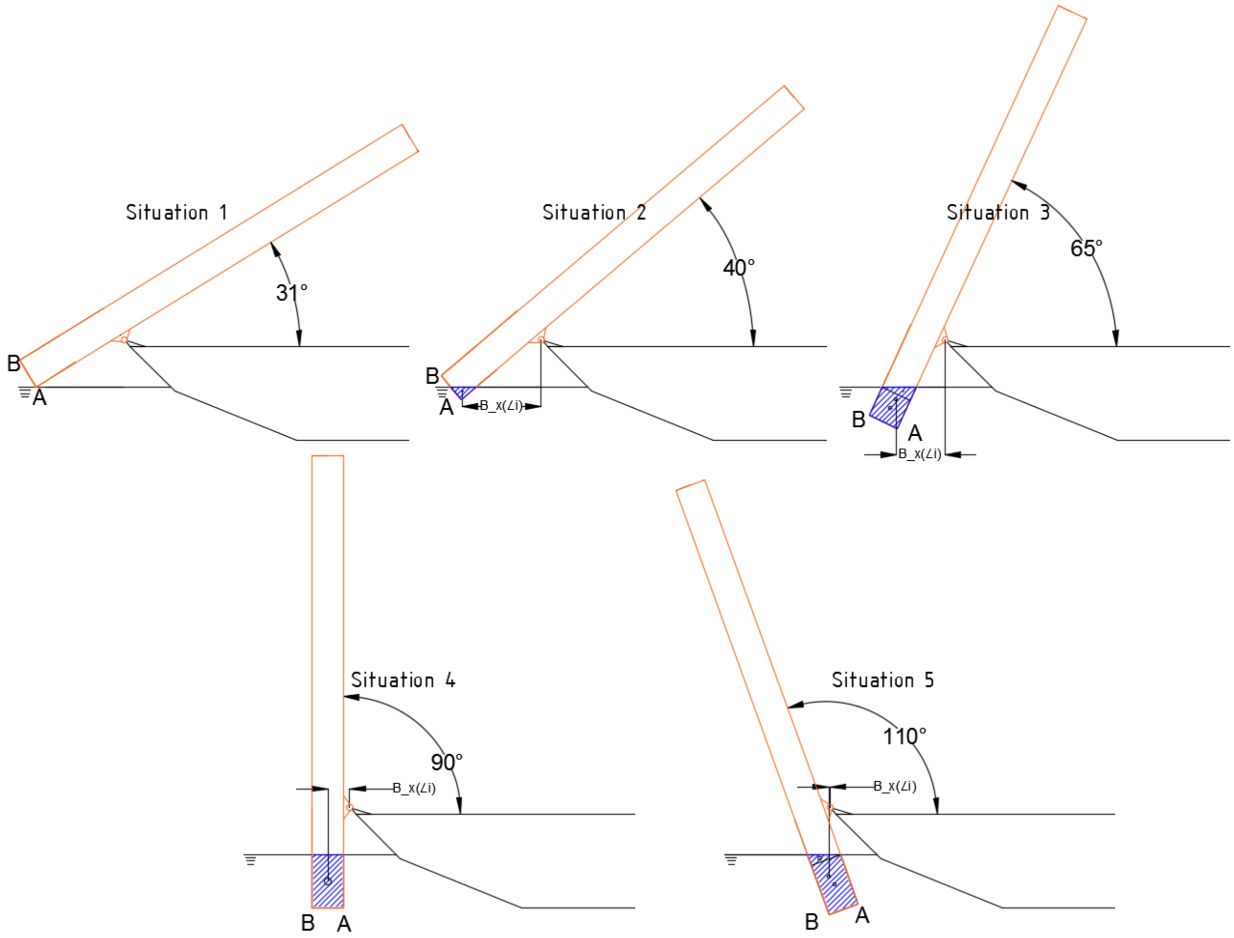


Figure 57: Five Stages During Upending/Tilting-over Buoyancy

5.5.6 Static Equilibrium per Concept

To calculate the moment exerted to the system by the upend/tilt-over mechanism, except the concepts based on gravitational force, a similar calculation as for the Derrick Hoist System is used. The moment exerted to the system by the Upend/Tilt-over Mechanism is equal to the resulting moment in the system. In this static force analysis, the Upend/Tilt-over Mechanism exerts a force to the system when the resulting moment is negative. The positive or negative direction of the forces is given in Figure 50 (page 66). The moment by means of the Upend/Tilt-over Mechanism is given by:

$$M_j(\alpha_i) = \sum\left(M_n(\alpha_i)\right) \qquad [\text{kNm}]$$

Where:

$\sum\left(M_n(\alpha_i)\right)$ = Summation of moment exerted to the system [kNm]
α_i = Angle of upend/tilt-over TLB's in reference to the X-axis [°]
i = 0…115 [-]
j = concepts (Suction Piled, Stern Winched, Push and Push/Pull) [-]

The force exerted by the Upend/Tilt-over Mechanism is concept dependent. The calculation methods are included in this paragraph together with the reaction forces in the support points.

Counterweight

An equilibrium state is achieved when the summation of the horizontal, vertical and rotational forces is (individually) zero. A representation is shown in Figure 58. The moment, to determine the tension in the Derrick Hoist Wires (See page 74), and the vertical and horizontal reaction forces in the hinge points are given below.

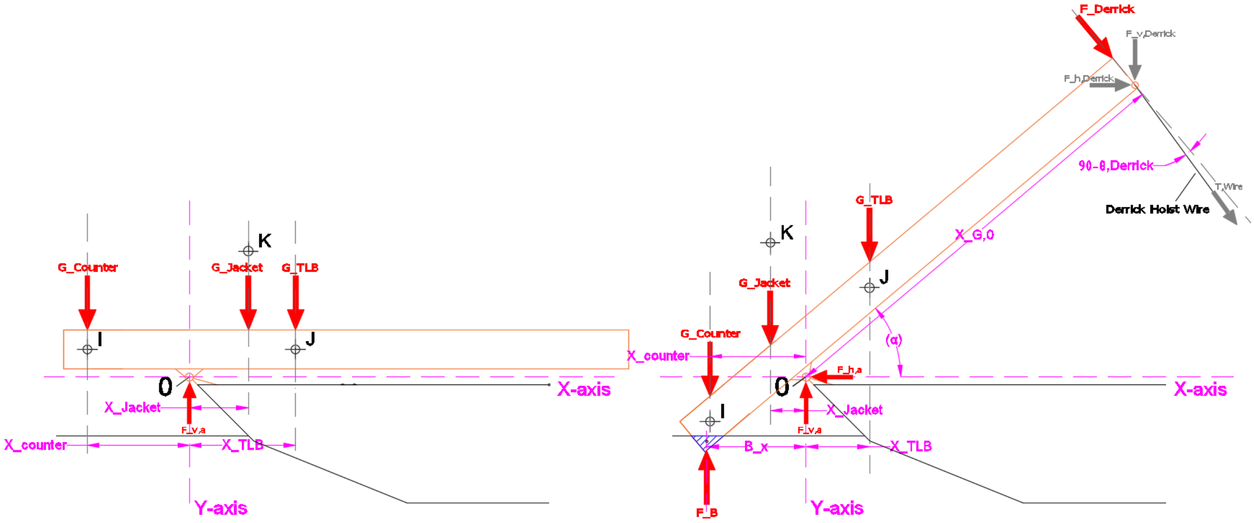


Figure 58: Static Equilibrium Gravitational Principle

$$\sum M = 0 \quad , M_{\text{Counterweight}} + M_{\text{TLB}} + M_{\text{Buoyancy}} + M_{\text{Jacket}} = M_{\text{Derrick Hoist}} \qquad [\text{kNm}]$$

$$\sum F_{v,j} = 0 \quad , G_{\text{Counterweight}} + G_{\text{TLB}} + G_{\text{Jacket}} + F_{\text{Buoyancy}} + F_{v,\text{Derrick}} = F_{v,a} \qquad [\text{kN}]$$

$$\sum F_{h,j} = 0 \quad , F_{h,\text{Derrick}} = F_{h,a} \qquad [\text{kN}]$$

Moving Frame

A representation is shown in Figure 58. The moment, to determine the tension in the Derrick Hoist Wires (See page 74), and the vertical and horizontal reaction forces in the hinge points are given below.

$$\sum M = 0 \quad , M_{\text{Counterweight}} + M_{\text{TLB}} + M_{\text{Buoyancy}} + M_{\text{Jacket}} = M_{\text{Derrick Hoist}} \qquad [\text{kNm}]$$

$$\sum F_{v,j} = 0 \quad , G_{\text{Counterweight}} + G_{\text{TLB}} + G_{\text{Jacket}} + F_{\text{Buoyancy}} + F_{v,\text{Derrick}} = F_{v,a} \qquad [\text{kN}]$$

$$\sum F_{h,j} = 0 \quad , F_{h,\text{Derrick}} = F_{h,a} \qquad [\text{kN}]$$

Suction Piled

A representation is shown in Figure 59. The moment, to determine the tension in the Derrick Hoist Wires (See page 74), and the vertical and horizontal reaction forces in the hinge points are given below.

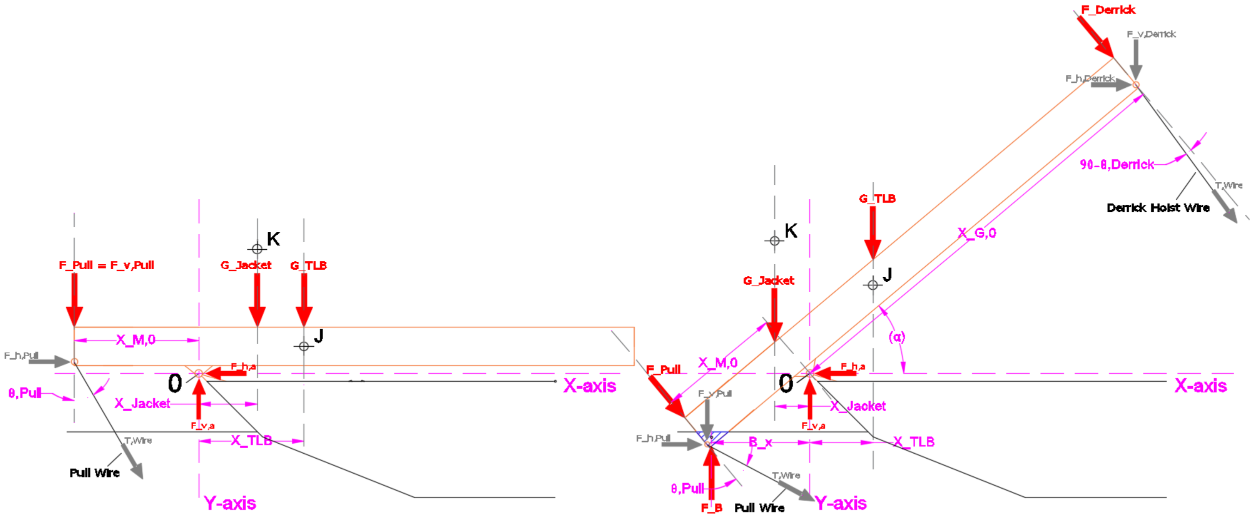


Figure 59: Static Equilibrium Pulled Principle

$$\sum M = 0 \qquad , M_{TLB} + M_{Buoyancy} + M_{Jacket} = M_{Derrick\ Hoist} \text{ or } M_{Suction\ Piled} \qquad \text{[kNm]}$$

$$\sum F_{v,j} = 0 \qquad , G_{TLB} + G_{Jacket} + F_{Buoyancy} + (F_{v,Derrick} \text{ or } F_{v,Pull}) = F_{v,a} \qquad \text{[kN]}$$

$$\sum F_{h,j} = 0 \qquad , (F_{h,Derrick} \text{ or } F_{h,Pull}) = F_{h,a} \qquad \text{[kN]}$$

Tension in wires upend/tilt-over mechanism:

$$F_{Suction\ piled}(\alpha_i) = \frac{\frac{\Sigma(M_{Suction\ Piled}(\alpha_i))}{|x_{M,0}|}}{Cos(\theta_{Pull,SF}(\alpha_i))} \qquad \text{[kN]}$$

Where:

$|y_{M,0}|$ = ΔX of rotation point and point of application of the force [m]

$$\theta_{Pull,SF}(\alpha_i) = -90 + |\theta_{Suction\ piled} + 90 - \alpha_i| \qquad [°]$$

$$\theta_{Suction\ piled} = \operatorname{atan}\left(\frac{x_M(\alpha_i) - x_{N,0}}{y_{N,0} - y_M(\alpha_i)}\right) \qquad [°]$$

α_i = Angle of upend/tilt-over TLB's in reference to the X-axis [°]

i = 0…115 [-]

Where:

$x_{N,0}$ and $y_{N,0}$ are the x and y coordinates in tilted/initial position (see Table 11 (page 70). $x_M(\alpha_i)$ and $y_M(\alpha_i)$ are the angle dependent x and y coordinates of the location where the Suction Piled System exerts its force to the system (see Appendix D).

The vertical and horizontal forces in the Suction Piled Upend/Tilt-over Mechanism are:

$$F_{v,Suction\ piled} = -F_{Suction\ piled}(\alpha_i) \cdot \cos(\theta_{Suction\ piled}) \qquad \text{[kN]}$$

$$F_{h,Suction\ piled} = F_{Suction\ piled}(\alpha_i) \cdot \sin(\theta_{Suction\ piled}) \qquad \text{[kN]}$$

Stern Winch

A representation is shown in Figure 59. The moment, to determine the tension in the Derrick Hoist Wires (See page 74), and the vertical and horizontal reaction forces in the hinge points are given below.

$$\sum \mathrm{M} = 0 \qquad , \mathrm{M_{TLB}} + \mathrm{M_{Buoyancy}} + \mathrm{M_{Jacket}} = \mathrm{M_{Derrick\ Hoist}}\ \mathrm{or}\ \mathrm{M_{Stern\ Winched}} \qquad [\mathrm{kNm}]$$

$$\sum \mathrm{F_{v,j}} = 0 \qquad , \mathrm{G_{TLB}} + \mathrm{G_{Jacket}} + \mathrm{F_{Buoyancy}} + (\mathrm{F_{v,Derrick}}\ \mathrm{or}\ \mathrm{F_{v,Pull}}) = \mathrm{F_{v,a}} \qquad [\mathrm{kN}]$$

$$\sum \mathrm{F_{h,j}} = 0 \qquad , (\mathrm{F_{h,Derrick}}\ \mathrm{or}\ \mathrm{F_{h,Pull}}) = \mathrm{F_{h,a}} \qquad [\mathrm{kN}]$$

Tension in wires upend/tilt-over mechanism:

$$\mathrm{F_{Stern\ Winched}}(\alpha_\mathrm{i}) = \frac{\frac{\Sigma\left(\mathrm{M_{Stern\ Winched}}(\alpha_\mathrm{i})\right)}{|\mathrm{x_{M,}}|}}{\mathrm{Cos}(\theta_\mathrm{Pull,V}(\alpha_\mathrm{i})\ )} \qquad [\mathrm{kN}]$$

Where

$|\mathrm{x_{M,0}}|$ = ΔX of rotation point and point of application of the force [m]

$\theta_\mathrm{Pull,V}(\alpha_\mathrm{i}) = -90 - \theta_\mathrm{Stern\ Winched}(\alpha_\mathrm{i}) + \alpha_\mathrm{i}$ [°]

$\alpha_\mathrm{Stern\ Winched}(\alpha_\mathrm{i}) = \tan\left(\frac{\mathrm{y_{R,0}} - \mathrm{y_m}(\alpha_\mathrm{i})}{\mathrm{x_{R,0}} - \mathrm{x_M}(\alpha_\mathrm{i})}\right)$ [°]

α_i = Angle of upend/tilt-over TLB's in reference to the X-axis [°]

i = 0…115 [-]

Where:

$\mathrm{x_{R,0}}$ and $\mathrm{y_{R,0}}$ are the x and y coordinates in tilted/initial position (see Table 11 (page 70). $\mathrm{x_M}(\alpha_\mathrm{i})$ and $\mathrm{y_M}(\alpha_\mathrm{i})$ are the angle dependent x and y coordinates of the location where the Stern Winched System exerts its force to the system (see Appendix D).

The vertical and horizontal forces in the Stern Winched Upend/Tilt-over Mechanism are:

$$\mathrm{F_{v,Stern\ Winched}} = \mathrm{F_{Stern\ Winched}}(\alpha_\mathrm{i}) \cdot \sin(\theta_\mathrm{Stern\ Winched}) \qquad [\mathrm{kN}]$$

$$\mathrm{F_{h,Stern\ Winched}} = \mathrm{F_{Stern\ Winched}}(\alpha_\mathrm{i}) \cdot \cos(\theta_\mathrm{Stern\ Winched}) \qquad [\mathrm{kN}]$$

Pushing System

A representation is shown in Figure 60. The moment, to determine the tension in the Derrick Hoist Wires (See page 74), and the vertical and horizontal reaction forces in the hinge points are given below.

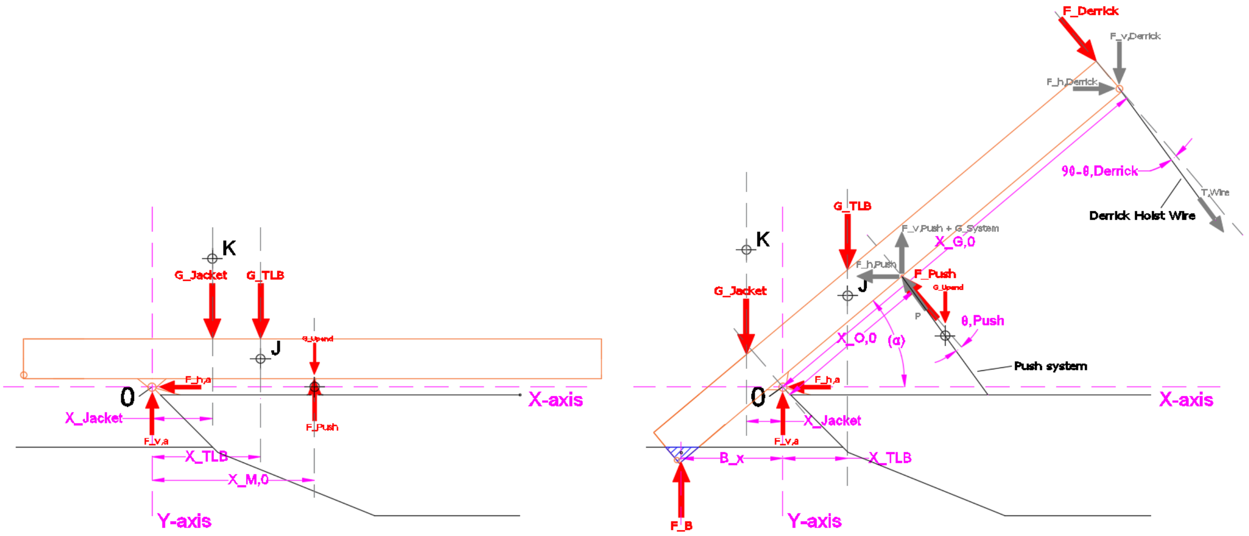


Figure 60: Static Equilibrium pushing Principle

$$\sum M = 0 \qquad , M_{TLB} + M_{Buoyancy} + M_{Jacket} + M_{Upend} + M_{massUpend} = M_{Derrick\ Hoist} \text{ or } M_{Push}$$

$$\sum F_{v,j} = 0 \qquad , G_{TLB} + G_{Jacket} + G_{Upend} + F_{Buoyancy} + \left(F_{v,Derrick} \text{ or } F_{v,Push}\right) = F_{v,a} + F_{v,b}$$

$$\sum F_{h,j} = 0 \qquad , \left(F_{h,Derrick} \text{ or } F_{h,Push}\right) = F_{h,a}(+F_{h,b})$$

Where:

$$M_{massUpend} = \frac{M_{Upend,Push}(\alpha_i)}{x_{Upend,Push}(\alpha_i)} \cdot \cos(\theta_{Pushsystem}(\alpha_i)) \qquad [kNm]$$

for $M_{Upend,Push}(\alpha_i)$ consult page 73.

Pressure in pushing system:

$$F_{Push}(\alpha_i) = \frac{\frac{\Sigma(M_{Push}(\alpha_i))}{|x_{O,0}|}}{\mathrm{Cos}(\theta_{Push}(\alpha_i))} \qquad [kN]$$

Where:

$|x_{O,0}|$ = ΔX of rotation point and point of application of the force [m]
$\theta_{Push}(\alpha_i) = 90 - \theta_{Pushsystem}(\alpha_i)$ [°]
$\theta_{Pushsystem}(\alpha_i) = \mathrm{atan}\left(\frac{y_O(\alpha_i) - y_{P,0}}{x_{P,0} - x_O(\alpha_i)}\right)$ [°]
α_i = Angle of upend/tilt-over TLB's in reference to the X-axis [°]
i = 0…115 [-]

Where:
$x_{P,0}$ and $y_{P,0}$ are the x and y coordinates in tilted/initial position (see Table 11 (page 70). $x_O(\alpha_i)$ and $y_O(\alpha_i)$ are the angle dependent x and y coordinates of the location where the Push System exerts its force to the system (see Appendix D).

The vertical and horizontal forces in the Pushing System Upend/Tilt-over Mechanism connection point:

$$F_{v,Push} = F_{Push}(\alpha_i) \cdot \sin(\theta_{Push}) + \frac{1}{2} \cdot G_{Upend} \qquad [kN]$$

$$F_{h,Push} = -F_{Push}(\alpha_i) \cdot \cos(\theta_{Push}) \qquad [kN]$$

Push/Pull System

A representation is shown in Figure 61. The moment, to determine the tension in the Derrick Hoist Wires (See page 74), and the vertical and horizontal reaction forces in the hinge points are given below. In the Push/Pull Concept, the force is induced by a winch system connected between the Tilting Lift Beams and the rigid construction between the aftdeck of Pioneering Spirit and the Tilting Lift Beams.

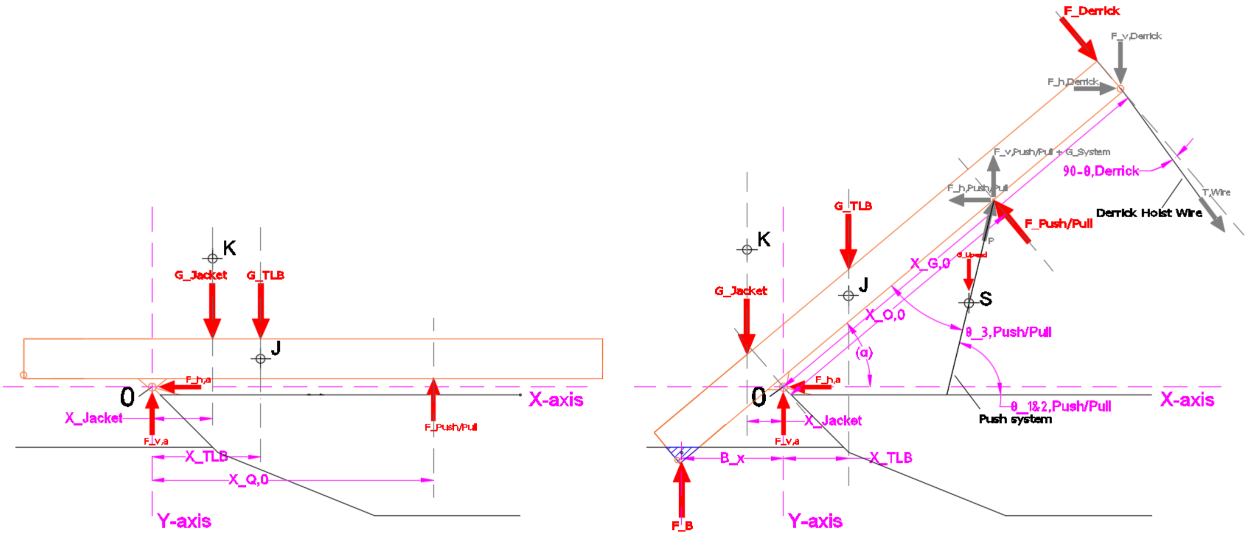


Figure 61: Static Equilibrium Push/Pull Principle

$$\sum M = 0 \quad, M_{TLB} + M_{Buoyancy} + M_{Jacket} + M_{Upend} + M_{massUpend} = M_{Derrick\ Hoist} \text{ or } M_{Push/Pull\ System}$$
$$\sum F_{v,j} = 0,\ G_{TLB} + G_{Jacket} + G_{Upend} + F_{Buoyancy} + \left(F_{v,Derrick} \text{ or } F_{v,Push/Pull}\right) = F_{v,a} + F_{v,b}$$
$$\sum F_{h,j} = 0,\ (F_{h,Derrick} \text{ or } F_{h,Push/Pull}) = F_{h,a}(+F_{h,b})$$

Where:

$$M_{massUpend} = \frac{M_{Upend,PushPull}(\alpha_i)}{x_{Upend,PushPull}(\alpha_i)} \cdot \cos(\theta_{PushPull,3}(\alpha_i)) \qquad [kNm]$$

for $M_{Upend,PushPull}(\alpha_i)$ consult page 73.

Tension in Push/Pull wires:

$$T_{PushPull\ wire} = F_{PushPull}(\alpha_i) \cdot \cos\left(\theta_{Push/Pull,3}\right) \qquad [kN]$$

Pressure in rigid Push/Pull system:

$$F_{PushPull}(\alpha_i) = \frac{\dfrac{\Sigma\left(M_{Push/Pull}(\alpha_i)\right)}{\left(\dfrac{y_Q(\alpha_i)}{\sin\left(\alpha_i+\alpha_{Q,0}\right)}\right)}}{\mathrm{Cos}\left(\theta_{PushPull,4}(\alpha_i)\right)} \qquad [kN]$$

Where:

$\frac{y_Q(\alpha_i)}{\sin(\alpha_i+\alpha_{Q,0})}$ = ΔX of rotation point and point of application of the force [m]

$\alpha_{Q,0}$ = Angle between rigid construction and x-axis in tilted position [°]

α_i = Angle of upend/tilt-over TLB's in reference to the X-axis [°]

i = 0…115 [-]

$$\theta_{PushPull,1}(\alpha_i) = \tan\left(\frac{y_Q(\alpha_i)-y_{PP,0}}{x_Q(\alpha_i)-x_{PP,0}}\right) \qquad [°]$$
$$\theta_{PushPull,2}(\alpha_i) = \theta_{PushPull,1}(\alpha_i) + 180 \quad \text{if} \quad \theta_{PushPull,1}(\alpha_i) \leq 0 \qquad [°]$$
$$\theta_{PushPull,2}(\alpha_i) = \theta_{PushPull,1}(\alpha_i) \quad \text{if} \quad \theta_{PushPull,1}(\alpha_i) > 0 \qquad [°]$$
$$\theta_{PushPull,3}(\alpha_i) = 180 - \left(180 - \theta_{PushPull,2}(\alpha_i) - (\alpha_i)\right) \qquad [°]$$
$$\theta_{PushPull,4}(\alpha_i) = 90 - \theta_{Push/Pull,3}(\alpha_i) \qquad [°]$$

Where:
$x_{PP,0}$ and $y_{PP,0}$ are the x and y coordinates in tilted/initial position (see Table 11 (page 70). $x_Q(\alpha_i)$ and $y_Q(\alpha_i)$ are the angle dependent x and y coordinates of the location where the Push/Pull System exerts its force to the system (see Appendix D).

The vertical and horizontal forces in the Push/Pull Upend/Tilt-over Mechanism connection point:

$$F_{v,Push/Pull} = F_{Push/Pull}(\alpha_i) \cdot \sin\left(\left|\theta_{Push/Pull,1}\right|\right) + \frac{1}{2} \cdot G_{Upend} \qquad [kN]$$

$$F_{h,Push/Pull} = -F_{Push/Pull}(\alpha_i) \cdot \cos\left(\left|\theta_{Push/Pull,1}\right|\right) \qquad [kN]$$

5.5.7 Feasibility Check Maximum Forces

As mentioned earlier, this preliminary design is a feasibility study. It is not meaningful the carry out a detailed risk and reliability analysis at this stage of the design. However, it is important to assess the maximum forces to obtain a static equilibrium during the upend/tilt-over operation. As provided in chapter 3, Pioneering Spirit has certain structural strength capabilities. It is important that the expectations are positive regarding the feasibility to install and operate the system.

A rough statement for feasibility is to check whether the resistance (structural strength), with safety factor, is greater than the load (maximum force) [42]. Regarding structures, this is often referred to as the Ultimate Limit State/Capacity (ULS/ULC) [43]. Regarding lifting equipment (for example a wire), this is often referred to as the Safe Working Load. This is the mass or force that the equipment must be able to lift without fear of breaking/failures. This value is often 1/4 or 1/5 of the Minimum Breaking Load/Strength (MBL/MBS) [44].

The maximum forces and Pioneering Spirit's structural capabilities are compared for the components in the enumeration below. Deck load capacities, as given in Table 5 (paragraph 3.2.4 (page 24)) are used.

Maximum force in:

- Tension Derrick Hoist Wires
- Pressure upend/tilt-over mechanism
- Tension wire upend/tilt-over mechanism
- Vertical reaction force hinge point
- Horizontal reaction force hinge point
- Vertical reaction force upend/tilt-over mechanism
- Horizontal reaction force upend/tilt-over mechanism

Reference wire [45]:

Type/class:	6xK36-IWRC	
Diameter:	110	[mm]
MBL:	974	[mt]
SWL:	195 (factor 1/5)	[mt]

5.6 Approach/Calculation Method Maximum Required Power

A rough estimation of the maximum required power to obtain a static equilibrium is part of the feasibility assessment. The purpose of the estimation is to investigate per concept whether the maximum installed power is exceeded and to examine the favourability of the location where the forces are applied. In the estimation, only the velocity of the component in the spatial direction of the force and the magnitude of the maximum force to obtain a static equilibrium are considered. The same assumptions, coordinates (and reference system) and general parameters are used as in the static forces analysis. This information can be consulted in the previous paragraphs of this chapter. Important to mention: the velocity is assumed constant. Subsequently, the maximum force to obtain a static equilibrium is used (see explanation in paragraph 5.5.5). The maximum force occurs when the system is carrying a jacket.

To recapitulate, the estimation is about the maximum power required, not about (for example) the power requirement of the total process. The forces in the upend/tilt-over components by means of the velocity of the upend/tilt-over operation are not considered.

The maximum power is defined by the maximum force multiplied by the velocity at that time moment [46].

Maximum Power:

$$W = \vec{F} \cdot \vec{v} \qquad [\text{kW}]$$

Where

$\vec{F}$ = Tension/Pressure in the component [kN]

$\vec{v}$ = Velocity in the direction of the force [m/s]

The (constant) velocity of the upend/tilt-over component is calculated by the length difference divided by the time interval [46].

$$v = \frac{\Delta x}{\Delta t} \qquad [\text{m/s}]$$

Where

Δx = Change in length [kN]

Δt = Time interval [m/s]

The time interval is 12 hours. The spatial mutation is calculated using the coordinates as calculated in paragraph 5.5.4.

$$\Delta x_n = L_{m,new} - L_{m,old} \qquad [\text{m}]$$

$$L_{m,new} = \sqrt{\Delta x_m^2(\alpha_i = 115) + \Delta y_m^2(\alpha_i = 115)} \qquad [\text{m}]$$

$$L_{m,old} = \sqrt{\Delta x_m^2(\alpha = 0) + \Delta y_m^2(\alpha = 0)} \qquad [\text{m}]$$

Where:

Δx = Horizontal distance between the two attachment points [m]

Δy = Vertical distance between the two attachment points [m]

α_i = Angle of upending in reference to the X-axis (i = 0…115) [°]

m = Component [-]

Important Assumption/Remark

It is extremely important to mention that this prediction is based on a single line arrangement. The lines in practise are bundled in sets of lines and lifting arrangements are used consisting of pulleys and suchlike. This results in a longer line(s) that needs to be taken-in or given-out. This affects the power requirement. The real maximum force per wire will be smaller. The real velocity of taking-in and taking-out wire will be larger. However, in the approach in this thesis project the changes are proportional to each other.

5.7 Results Static Equilibrium/Forces and Maximum Power Requirements

The static forces for each concept, calculated as explained in paragraph 5.5, are included in Appendix E. The maximum tension in the wires of the Derrick Hoist System, tension/pressure in the upend/tilt-over mechanisms and the reaction forces in the supports points are presented below in Table 12. These values are used in the preliminary feasibility check (integrated in the analysis in paragraph 5.8.1). The values given in Table 12 are with the reference jacket applied on the Tilting Lift Beams. The units are in metric tons (mt). The maximum forces without the reference jacket being applied on the Tilting Lift Beams are included in Table 15.

	Concepts					
Maximum Force **JACKET**	**Counter-weight**	**Moving frame**	**Suction piled**	**Stern Winch**	**Pushing System**	**Push/Pull System**
Tension Derrick Hoist Wires [mt]	4869	3824	5522	5522	5534	5532
Pressure in rigid Upend/Tilt-over Mechanism [mt]	-	-	-	-	9374	47562
Tension in wire(s) Upend/Tilt-over Mechanism [mt]	-	-	11504	18233	-	47388
Vertical reaction force at the hinge point [mt]	41764	32518	41194	41194	30029	31000
Horizontal reaction force at the hinge point [mt]	4117	3750	4669	14392	4679	51450
Vertical reaction force at the Upend/Tilt-over Mechanism [mt]	-	-	11194	11194	9404	11950
Horizontal reaction force at the Upend/Tilt-over Mechanism [mt]	-	-	2655	14392	700	94604

Table 12: Results Maximum Static Forces Concepts (Jacket)

	Concepts					
Spatial Mutation Components **JACKET**	**Counter-weight**	**Moving frame**	**Suction piled**	**Stern Winch**	**Pushing System**	**Push/Pull System**
Derrick Hoist Wires [m]	193	168	193	193	193	193
Upending Mechanism Wire [m]	-	-	57	38	67	75

Table 13: Results Spatial Mutation Components per Concept (Jacket)

	Concepts					
Maximum Required Power **JACKET**	**Counter-weight**	**Moving frame**	**Suction piled**	**Stern Winch**	**Pushing System**	**Push/Pull System**
Derrick Hoist Wires [kW]	213	145	242	242	242	242
Upending Mechanism [kW]	-	-	148	157	142	807

Table 14: Results Maximum Required Power (Jacket)

	Concepts					
Maximum Force **NO JACKET**	**Counter-weight**	**Moving frame**	**Suction piled**	**Stern Winch**	**Pushing System**	**Push/Pull System**
Tension Derrick Hoist Wires [mt]	2619	2507	3272	3272	3284	3283
Pressure in rigid Upend/Tilt-over Mechanism [mt]	-	-	-	-	5624	28587
Tension in wire(s) Upend/Tilt-over Mechanism [mt]	-	-	6902	10939	-	28483
Vertical reaction force at the hinge point [mt]	25828	15306	21716	21716	13237	16000
Horizontal reaction force at the hinge point [mt]	2215	2096	2767	8635	2777	30924
Vertical reaction force at the Upend/Tilt-over Mechanism [mt]	-	-	6716	6716	5654	8846
Horizontal reaction force at the Upend/Tilt-over Mechanism [mt]	-	-	1593	8635	1298	56862

Table 15: Results Maximum Static Forces Concepts (No Jacket)

5.8 Upend/Tilt-over Mechanism Analysis

As already indicated during the assessment criteria description, the analysis is divided in two parts. A quantitative assessment regarding static equilibrium/forces and maximum power requirements and a qualitative assessment regarding the complexity and new equipment.

5.8.1 Static Equilibrium

The analysis of the static equilibrium is further subdivided into a part with contributions that are the same for all concepts and a part where the concept specific components/contributions are analysed.

A. General Static Contributions

Results of the individually assessed static forces are included in Appendix E.1. To clarify the analysis description, a selection of figures is used in the following paragraph. For the complete set of figures, Appendix E.1 must be consulted.

Moment in general

In matter of courses, the magnitude of the moment depends on the distance between the point of application where the forces are exerted to the system and the pivot point (explanation in paragraph 5.5.5). The greater the distance, the greater the moment. Pertaining to gravitational moment and the moment by means of buoyancy, the forces working on the Tilting Lift Beams are exerted perpendicular to the earth surface (Figure 54 (page 73)). The distance between the point of application to the system and the pivot varies during the upend/tilt-down procedure. All other contributions work perpendicular to the Tilting Lift Beams, meaning that the distance between the point of application of the force to the system and the pivot points remains the same during the entire upend/tilt-over process (Figure 58 (page 77)).

What can be concluded, the position of the centre of gravity is decisive in reducing the moment in the system. By placing the joint centre of gravity in a more beneficial position (closer to the pivot point), the required moment (and therefore the force in the upend/tilt-over component) to upend/tilt-over the system can be reduced. This statement is investigated in chapter 6).

General/Gravitational forces due to mass

Pertaining to gravitational forces, the greatest moment is exerted to the system when the pivot point and the (joint) centre of gravity are placed in a horizontal line and the mutual distance is the largest. The force exerted to the system by means of gravitation remains the same during the entire upend/tilt-over operation as the mass of the object obviously does not change during the process. In Figure 62, the changing rotational direction of the moment can be observed. This is the moment in the upend/tilt-over operation when the concept specific Upend/Tilt-over Mechanism and the Derrick Hoist System switch from responsible mechanism to position and control the system.

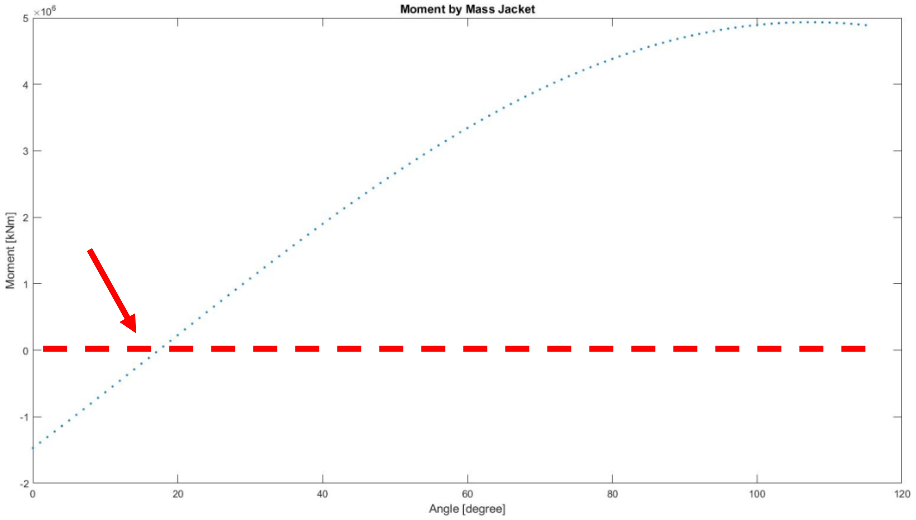


Figure 62: Moment due to the Mass of the Reference Jacket

Derrick Hoist System

Shown in Figure 63, the magnitude of the tension in the Derrick Hoist System increases until the maximum angle of 115 degrees is reached. This is due to the increasing moment in the system exerted by the different masses and the decreasing angle (angle starts at 90° in tilted position) of the Derrick Hoist wires in reference to the Tilting Lift Beams (Figure 139 (Page 179)).

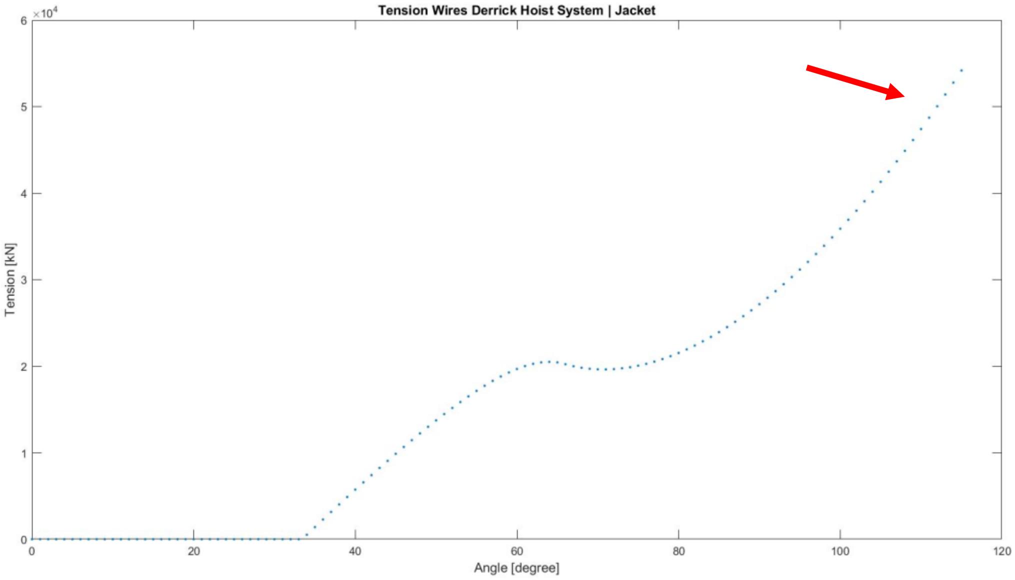


Figure 63: Moment by the Derrick Hoist System during Upending/Tilting-over

Buoyancy

In response to Figure 57 (page 76), no force by means of buoyancy is exerted to the Tilting Lift Beams in the first/last phase of the upend/tilt-over operation. During this phase, no fluid is displaced by the Tilting Lift Beams. Once the tip of the tail submerges, the buoyancy starts to work on the system. At the beginning of this process (situation 2 (Figure 57 (page 76)), the moment due to buoyancy increases the fastest. The distance between the point of application of the buoyancy and the pivot point is during this situation the largest. The same applies for the increasing displaced volume. What stands out from the figure, the moment is relatively small in upended position whereas the buoyancy is the largest of all upend/tilt-over positions. This is advantageously regarding the vertical force on the pivot points. In other words, the buoyancy by the submerged tail of the jacket Lift System has a positive effect on the system once the system is upended.

In the situation where no jacket is applied on the Jacket Lift System, the direction changes just before the maximum angle of upending is reached (Figure 65). This increases the tension in the Derrick Hoist System. As a result, it may be beneficial to upend the Tilting Lift Beams to a smaller angle when no Jacket is applied. As soon as the jacket is lifted, the angle can be increased to the largest angle possible, if this is required to gain sufficient clearance between the jacket and the Tilting Lift Beams. Also, for the situation where a jacket is placed on the Tilting lift Beams, it may be beneficial to upend the system to an angle of 100 degree instead of the maximum angle of 115 degrees.

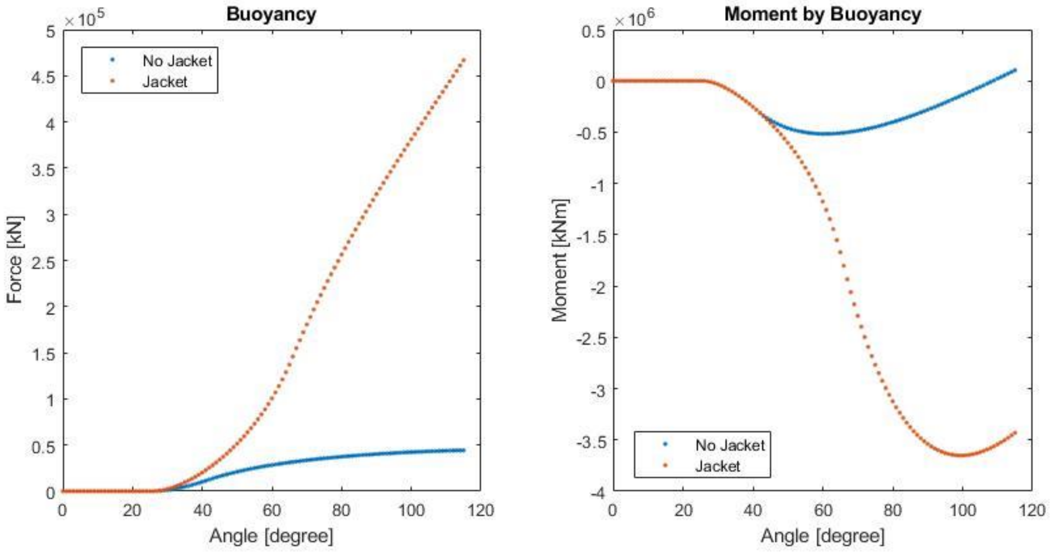


Figure 64: Moment/Force due to Buoyancy

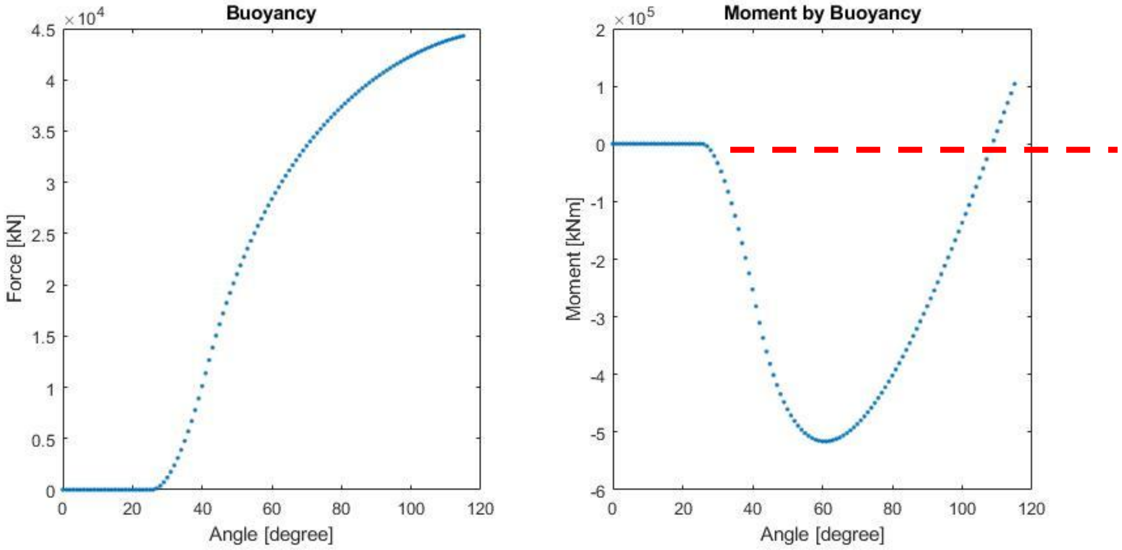


Figure 65: Moment/Force due to Buoyancy (No Jacket)

B. Concept Specific Static Contributions

The results per concepts on the assessed Static Forces without Jacket are included in Appendix E.2. The results per concepts with Jacket are included in Appendix E.3.

Counterweight

Shown in Figure 66, despite the unrealistically great mass of the counterweight (10 000 mt), the moment by means of the counterweight is not sufficient to obtain a static equilibrium. Consequently, the counterweight concept is non-feasible. The horizontal force on the hinge point is favourable. Because of the upend principle, the only component exerting horizontal force on the hinge point is the Derrick hoist System.

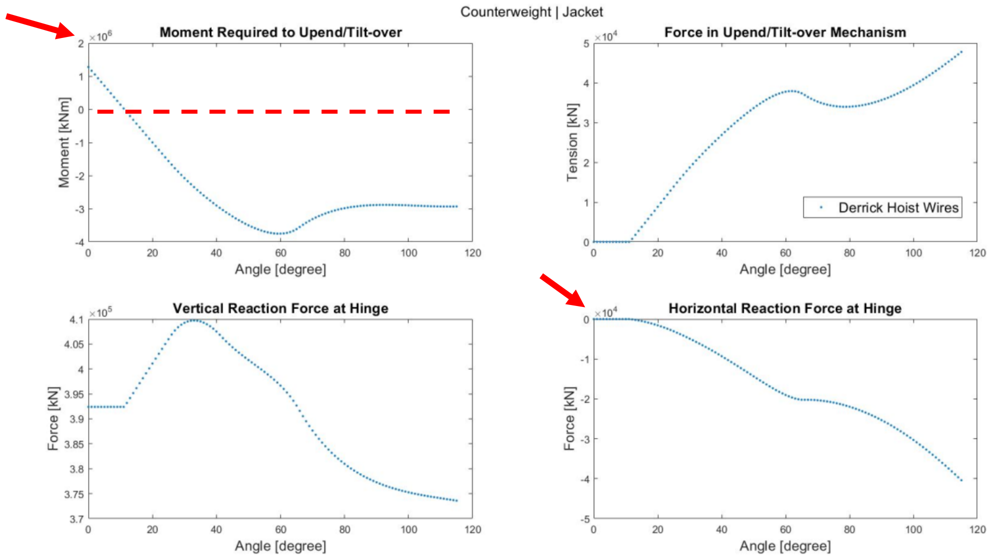


Figure 66: Moment/Force Counterweight Concept

Moving Frame

Figure 67. The figure shows that the moment by means of the mass, when no jacket is positioned on the Tilting Lift Beams, is smaller than the moment by means of buoyancy. Consequently, the system will not reach a static equilibrium and the concept is therefore considered non-feasible. One possibility to overcome this problem is to apply a system that has a much smaller fluid displacement. The same applies for the scenario where a jacket is applied. As with the Counterweight concept, the horizontal force applied to the pivot point is relatively low.

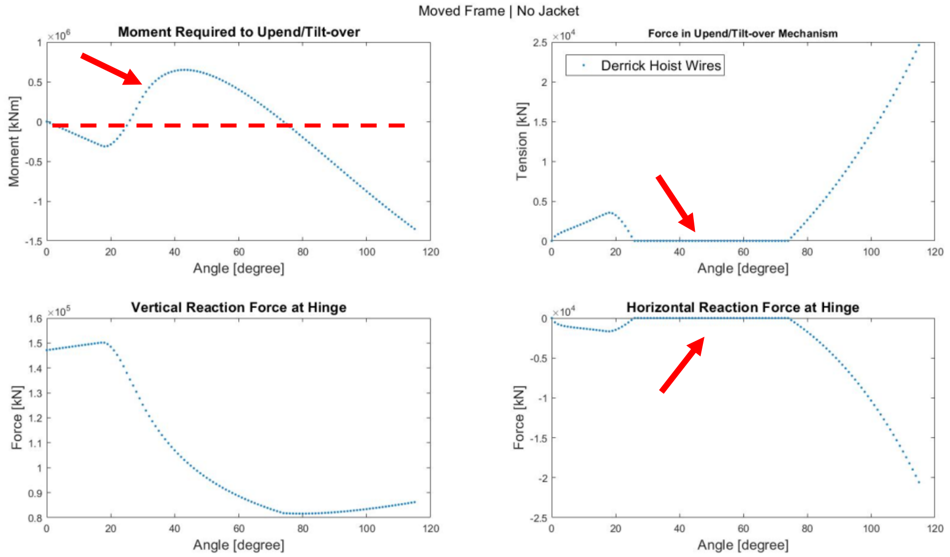


Figure 67: Moment/Force Moving Frame Concept

Suction Piled

Noteworthy to mention from the results, at a certain moment during the upend/tilt-over operation the sum of the moments becomes zero. This is the aforementioned moment during the upend/tilt-over operation where the mechanism, that is responsible for the positioning of the Tilting Lift Beams, switches from the mechanism to upend the Tilting Lift Beams to the Derrick Hoist System and vice versa. This applies for all pulling and pushing concepts.

The horizontal force on the hinge point is large. Because of the connection with the seabed, the horizontal force will exert a force to the vessel that pushes Pioneering Spirit out of her position. This horizontal force is much larger than the maximum capacity of Pioneering Spirit's thrusters. Consequently, Pioneering Spirit will not be able to stay in position. This concept is considered highly unfavourable. Anchors will be required to keep position.

In addition, due to the magnitude of the tension in the wires, an extensive system of suction piles has to be installed at the seabed. This will take a long time to install and remove and will cause difficulties due to the often congested seabed with other installed structures. Moreover, the capacity of the suction piles depends on many factors, which in some cases have great uncertainties. Examples are the geometry of the seabed, water depth and soil composition. The Suction Piled concept is considered non-feasible.

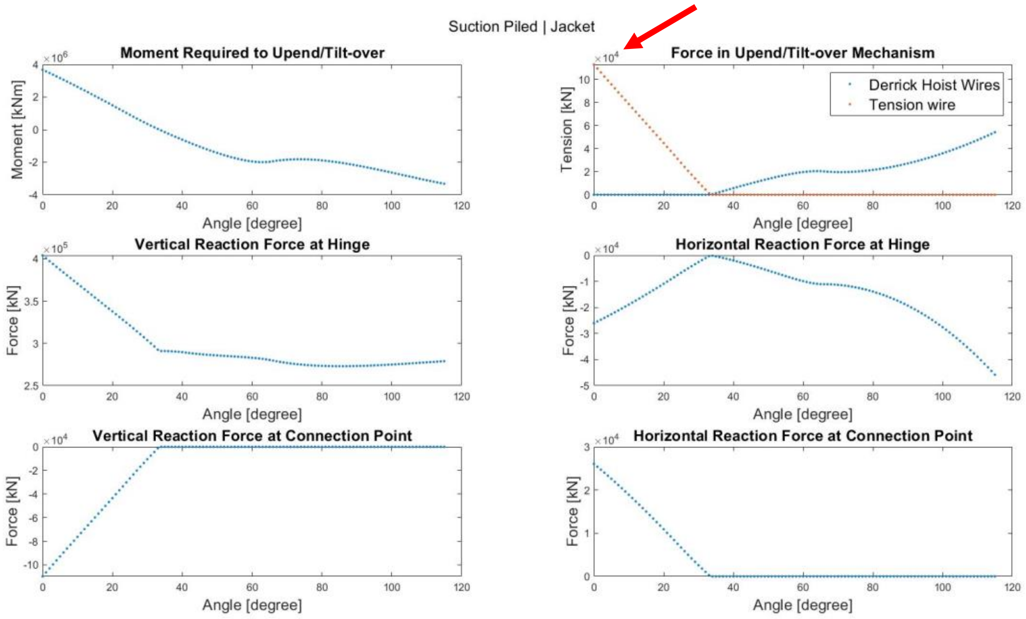


Figure 68: Moment/Force in the Suction Piled Concept

Stern Winch

In extend of the explanation of the Suction Piled concept, the static forces in the Stern Winch concept, in particular the upend/tilt-over mechanism, are much larger. This is mainly due to the disadvantageous angles in the system (Figure 141 (page 181)). The tension is of a magnitude that the feasibility is questionable. In contradiction to the Suction Piled concept, the forces of the Upend/Tilt-over Mechanism do not influence the dynamic position capability of Pioneering Spirit.

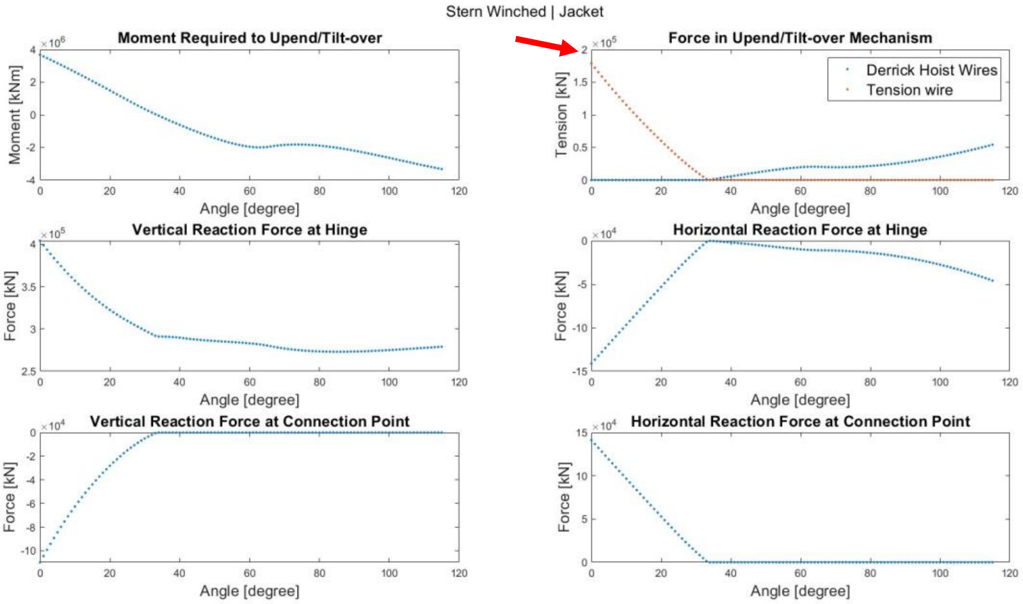


Figure 69: Moment/Force Stern Winch Concept

Pushing System

During the upend/tilt-over operation, the pushing system is subject to vertical and horizontal forces. The length of the pushing system will be large. The distance between the Tilting Lift Beams and the aftdeck of Pioneering Spirit in tilted position is small. Therefore, segments must be used during the elongation/shortening of the pushing system. The presence of horizontal forces during this process is highly unfavourable. The forces in the pushing system are compared to other concepts low. This comparison is elaborated in the next part of this paragraph.

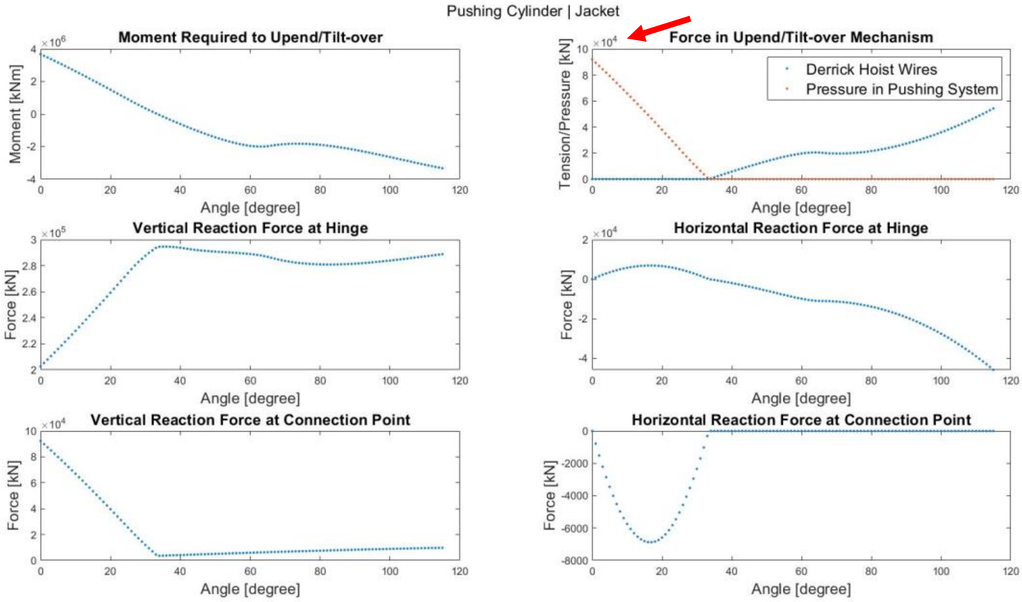


Figure 70: Moment/Force Pushing System Concept

The contribution of the mass of the pushing system is considered in the static equilibrium. The result is shown in Figure 71. The pushing system exerts the entire upend/tilt-over operation a positive moment. This results in a greater force in the Derrick Hoist System, especially for larger angles.

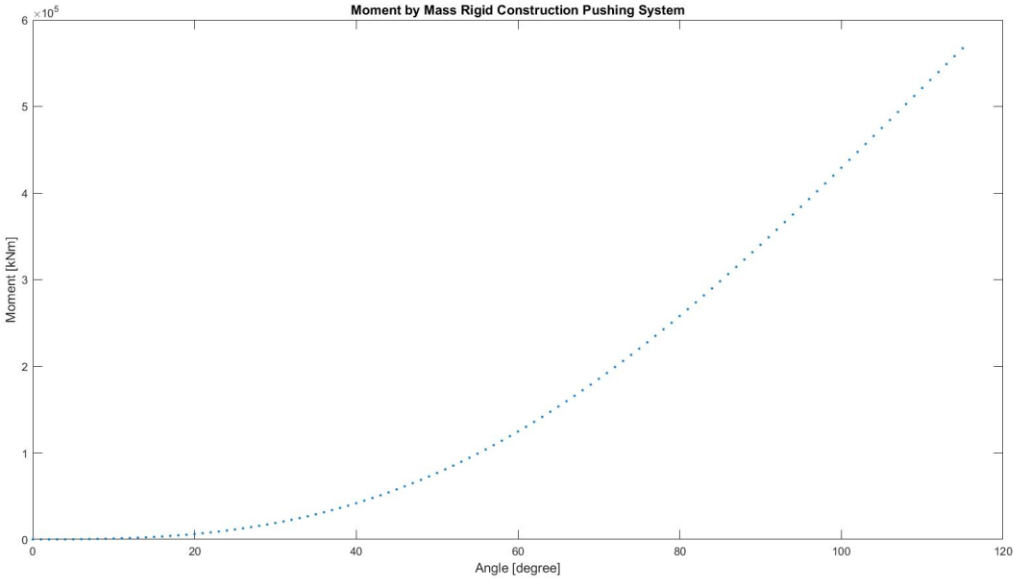


Figure 71: Moment, Mass Rigid Construction Pushing System

Push/Pull System

The angle between the Tilting Lift Beams and the upending construction in tilted/initial position is highly unfavourable (Figure 145 (Page 185)). Due to this small angle, the horizontal forces exerted to the system are exorbitantly large. This is despite the intended advantageous location of the point of application of the force to the Tilting Lift Beams. If the Tilting Lift Beams are sufficiently far upended, this concept is promising regarding the required static force in the upending component to obtain a static equilibrium. Because of the exorbitantly large forces in the system, in particular the pressure in the rigid construction and the horizontal forces exerted to the pivot point and support point, the Push/Pull System concept is considered non-feasible.

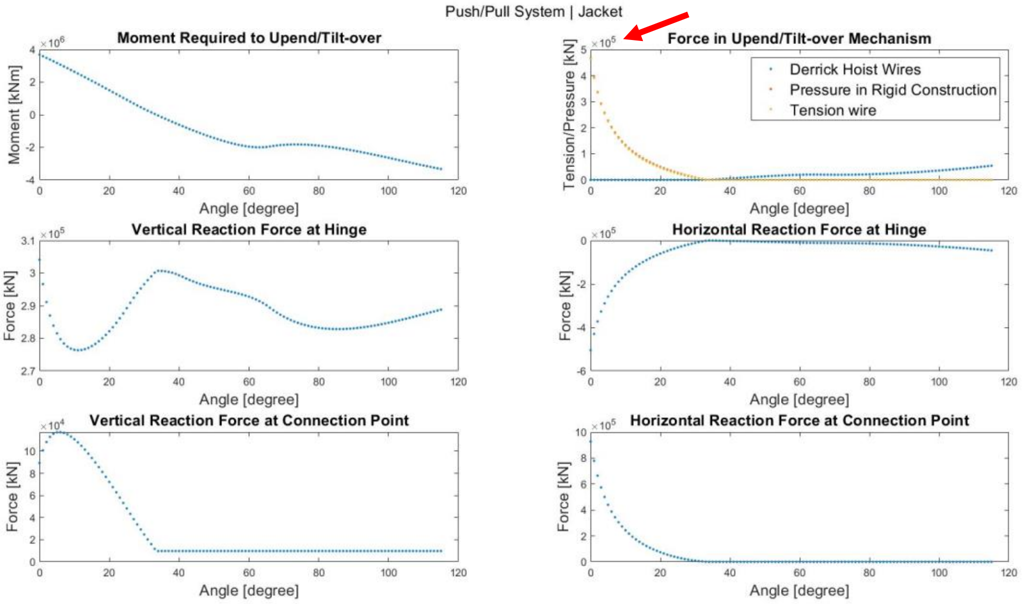


Figure 72: Forces Push/Pull System Concept

The contribution of the mass of the Push/Pull system is considered in the static equilibrium. The result is shown in Figure 73. The rigid construction exerts first a negative moment then a positive moment. The negative moment in the beginning/end of the upend/tilt-over operation is disadvantageously. This is an extra moment that must be compensated.

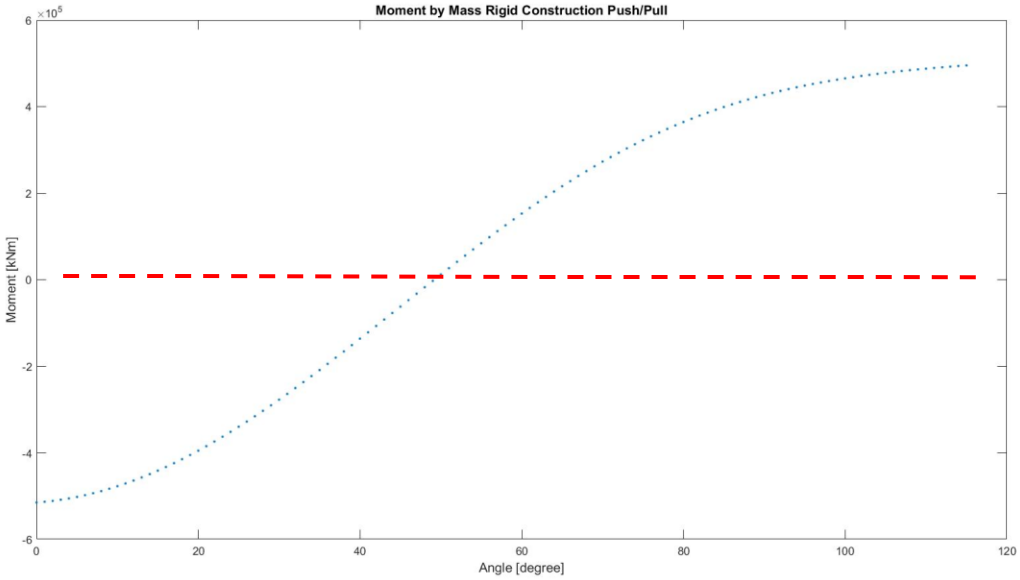


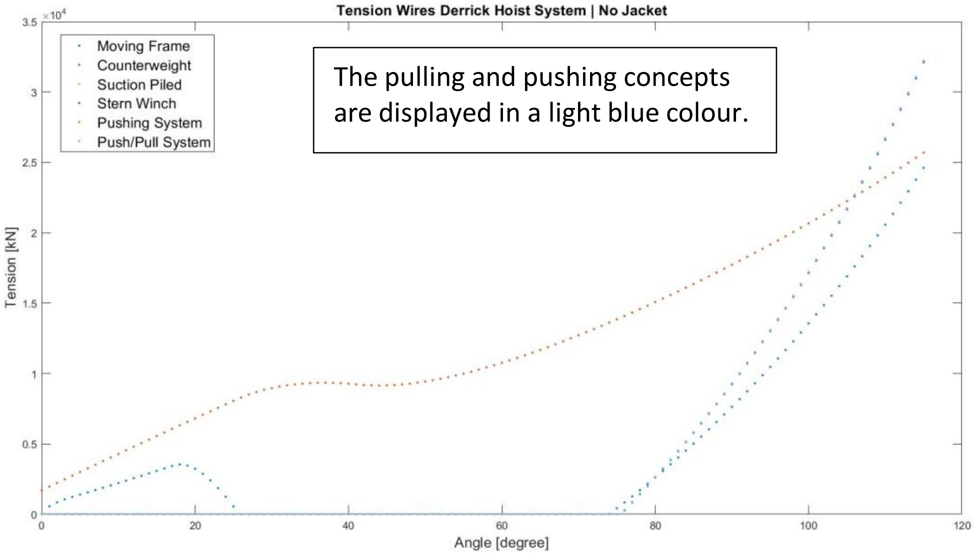
Figure 73: Moment, Mass Rigid Construction Push/Pull System

C. Concept Comparison, Maximum Force and Feasibility

Two situations apply when comparing the concepts. A situation where a jacket is placed on the Tilting Lift Beams and a situation where no jacket is placed on the Tilting Lift Beams (as elaborated in paragraph 3.3.2 (page 29). The forces are clearly (and obviously) greater when a jacket is placed on the Tilting Lift Beams. Variations in the forces, an example is buoyancy, are less prevalence when a jacket is placed on the Tilting Lift Beams. This is, for the buoyancy, shown in Figure 64. Because of this loss of details and the relatively greater influence of the individual influences, the situation where no jacket is placed on the Tilting Lift Beams has been used in the concept comparison. When assessing the maximum force, the maximum forces including a jacket are used. The results without jacket are shown in Appendix E.4. The results with jacket are shown in Appendix E.5. The figures used in this section are copies of the figures in the Appendix. The values of the maximum forces are shown in Table 12 (page 84).

Derrick Hoist System

Observed in Figure 74 and Table 12 (page 84), the maximum forces in the Derrick hoist System in all pushing and pulling concepts are about the same. The Moving frame and Counterweight concept have a smaller maximum tension. The difference between the pulling/pushing concepts and the moving frame and counterweight concepts is possibly accountable to the position of the joint centre of gravity. The joint centre of gravity is placed closer to the pivot point in these concepts. As aforementioned in this assessment, it seems favourable to position the centre of gravity of the total system closer to the pivot point. This is investigated in chapter 6. Another explanation of the smaller/larger tension in the Derrick Hoist System is de mass of the rigid component in the Pushing System and the Push/Pull System.



The pulling and pushing concepts are displayed in a light blue colour.

Figure 74: Concept Comparison Derrick Hoist System

Maximum Force:

The maximum tension in the Derrick Hoist wires is approximately 5530 mt. In the opinion of writer, a feasible maximum force. The used reference wire has a strength of 240 mt (SWL). The total force can be divided over sets of wires in a hoisting arrangement consisting of pulleys and suchlike.

Reference wire [45]:

Type/class:	6xK36-IWRC	
Diameter:	110	[mm]
MBL:	974	[mt]
SWL:	240 (factor 1/4)	[mt]

The Moving frame Concept has the lowest maximum tension in the Derrick Hoist Wires. This makes the Moving frame Concept favourable regarding the maximum tension in the Derrick Hoist System. An import remark is that the concept is not feasible because of the buoyancy.

Force Required to Upend/Tilt-over the System by Upend/Tilt-over Mechanism

The force required to upend/tilt-over the system by means of the Upend/Tilt-over Mechanism consists, concept dependent, of the force in the rigid construction and the tension in the wires.

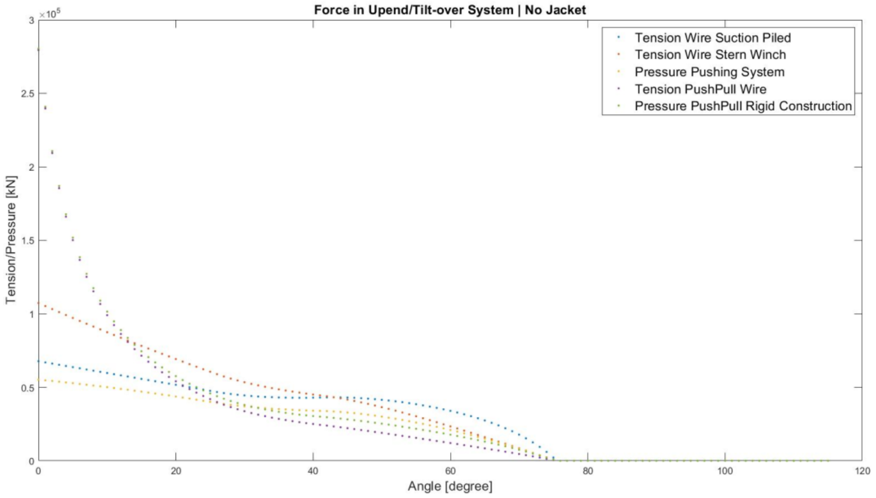


Figure 75: Concept Comparison Forces Required by the Upend/tilt-over Mechanism

The **gravitational based** concepts have no additional components. The forces to obtain a static equilibrium during the upend/tilt-over operation are only acting in the Derrick Hoist System. Noteworthy is the magnitude of the tension in the gravitational based concepts. The tension in the wires is smaller compared to the other concepts. The gravitational based concepts are by far favourable when looking at the maximum forces required by the Upend/Tilt-over Mechanism to obtain a static equilibrium during upend/tilt-over operation. The required forces are smaller and no additional equipment is needed.

The Upend/Tilt-over Mechanism in the **pulling based** concepts consist of a winch system. As earlier indicated, the required tension in the Stern Winch Concept is much larger compared to the Suction Piled concept because of the unfavourable angle of the winch connection with Pioneering Spirit. The maximum tension in the Stern Winch Concept is approximately 60% larger. In the opinion of the writer, the feasibility of both concepts is questionable in response to the magnitude of the tension in the wires. The tension in the wires is much larger compared to the tensions in the Derrick hoist System, 2 times for the Suction Piled concept and more than 3 times for the Stern Winch concept. The connection point with Pioneering Spirit for the Derrick Hoist System is already extensive. The pulling concepts requires an even more extensive system.

The **Pushing System** concept scores reasonably well regarding the maximum forces in the upend/tilt-over component compared to the other concepts (gravitational based concepts not included). The largest forces in the system work at the same moment as the other concepts. The time moment at which the maximum force occurs is favourable in the Pushing System. The largest force in the rigid upending component appears at the beginning of the upend process (or at the end of the tilt-over operation). This is when the pushing system has the smallest angle in reference to the y-axis. The maximum force in the pushing structure is approximately 9350 mt.

The **Push/Pull System** requires by far the largest maximum force to obtain a static equilibrium during the upend/tilt-over operation. The tension in the rigid construction of Push/Pull System is compared to the pushing concept almost five times larger. Pertaining to the wires in the upend/tilt-over mechanism, the tension in the wires of the Push/Pull System are in relation to the pulling concept also excessively large. The maximum tension in the wires is almost 10 times larger compared to the wires in the Derrick Hoist System. Moreover, due to the magnitude of the force, a heavily and large hoisting arrangement will be required. This enhances a lot of extra mass and takes a lot of space. The fact that the hoisting arrangement must be integrated in the Tilting Lift Beams, because of the detachability of the system, makes this concept extra unfavourable. The concept is considered non-feasible.

Vertical Reaction Force Hinge point

The smaller the maximum vertical reaction force, the better. The vertical reaction force at the hinge point is transferred to the hull of Pioneering Spirit. A large vertical reaction force at this point of the vessel causes unfavourable bending stresses in the structure of the vessel. As can be observed from Figure 76, the maximum vertical reaction force at the hinge point is the largest for the Counterweight concept. This is because of the additional mass applied in the tail of the Tilting Lift Beams. However, the maximum force is not considered as non-feasible.

The pulling concepts also have a large vertical reaction force compared to the Moved Frame concept and the Pushing System concept. This is because of the pulling force applied to the tail of the Tilting Lift Beams. This makes the principle of the pulling concepts regarding the vertical reaction force unfavourable.

In the result of the Push/Pull System concept, something remarkable can be observed. The force is of a magnitude that the reaction force is negative. This means that the pulling force is larger than the gravitational force of the mass of the Jacket Lift System. This is completely nonsense. Again, the force required to upend/tilt-over the system in the Push/Pull System concept is exorbitant large. The concept is non-feasible.

The Pushing System concept has a 10% smaller maximum reaction force compared to the Moving frame Concept. The Pushing System concept is favourable regarding the vertical reaction force at the hinge point.

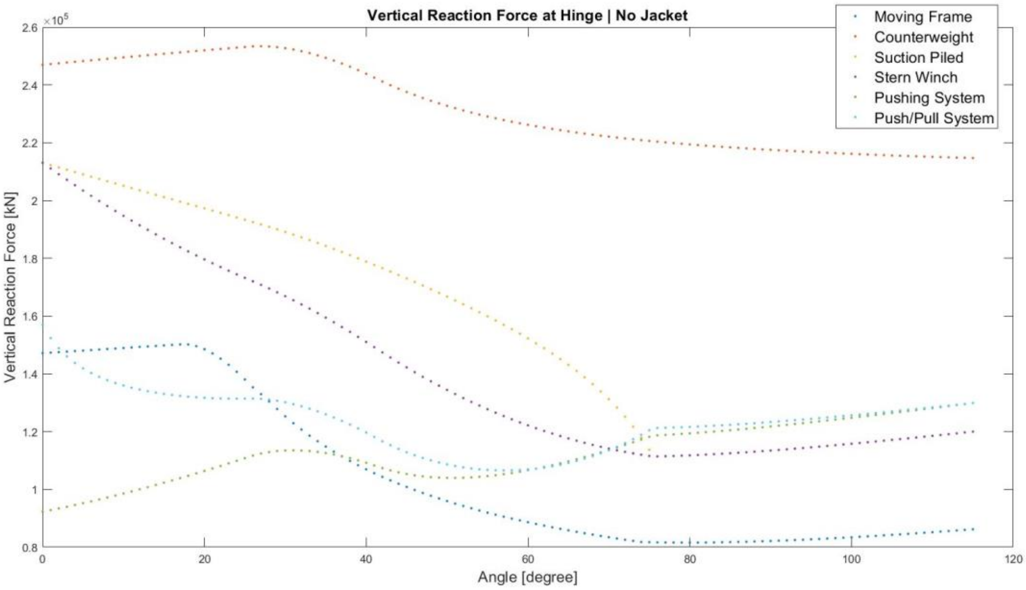


Figure 76: Concept Comparison Vertical Reaction Force Hinge

Horizontal Reaction Force Hinge point

The horizontal reaction force at the hinge point is approximately the same for all concepts, except for the Stern Winch concept. The maximum force in the Stern Winch concept is 4 times larger compared to the other concepts. The maximum horizontal force in the other concepts is reached in upended position and caused by the Derrick Hoist System. An exception is the Push/Pull System concept. The maximum horizontal reaction force in this concept is reached during the upend/tilt-over operation. The Moving Frame concept has the lowest horizontal reaction force at the hinge point. The Moved Frame concept is favourable regarding the horizontal reaction force at the hinge point. Again, it seems favourable to apply a movable frame.

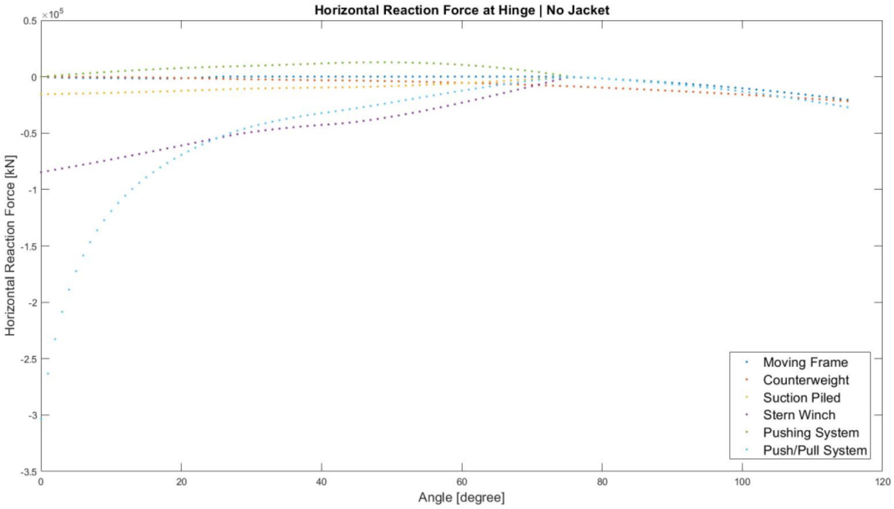


Figure 77: Concept Comparison Horizontal Reaction Force Hinge

Vertical Reaction Force Connection point

The pulling and pushing concepts have an additional connection to Pioneering Spirit. This connection must also be sufficient resistant to the loads. In the pulling concepts, the additional connection point is located at the stern of Pioneering Spirit. In the Pushing concepts, the already applied transverse frame at the aftdeck of Pioneering Spirit is used.

The vertical reaction forces in all concepts are large. The Pushing System concept is favourable regarding this vertical static force. The force is exerted to the already installed transverse frame. The maximum vertical reaction force is 9400 mt. This is compared to the hinge point a third of the load. From Table 5 (page 24)), the structural capability at this location is 300 mt/m compression and 450 mt/m tension. The feasibility without adjustments is questionable.

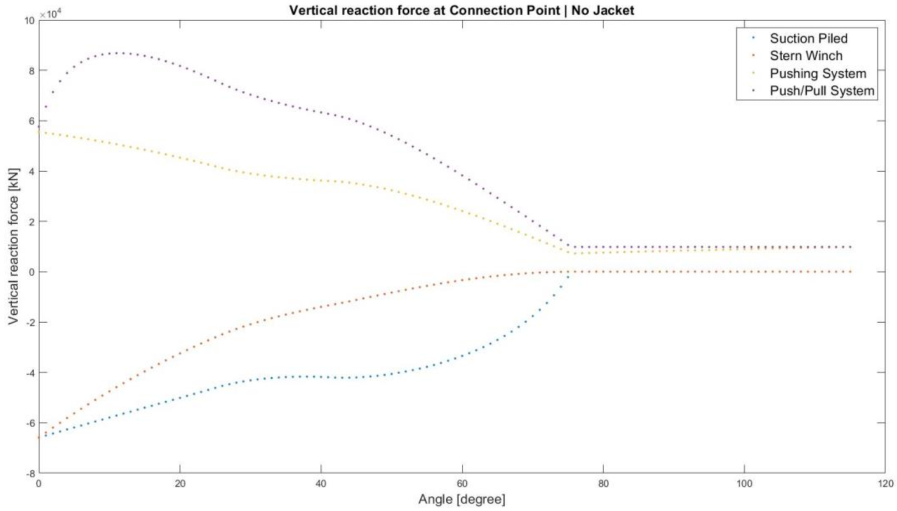


Figure 78: Static (Moment) Forces, Comparison Vertical Reaction Force Support (No Jacket)

Horizontal Reaction Force Connection point

Like the vertical reaction force, the pulling concepts are connected to the stern of Pioneering Spirit. The pushing concepts are connected to the transverse frame.

Shown in Figure 79, the horizontal reaction force at the connection point of the Push/Pull System concept is exorbitantly large during the first part of the upend/tilt-over operation. The force is of such a magnitude that the Push/Pull System concept is considered non-feasible. The horizontal reaction force of the Stern Winch concept is much smaller, but still many times larger than the Pushing System concept. The structural capacity of the crossing points of the bulkhead in the stern of Pioneering Spirit is 750 mt (Table 5 (page 24)). An extensive frame must be installed at the crossing points. The Derrick hoist System skids are already large, the skid system for the Stern Winch must be even larger. The Pushing System concept is by far the favourable concept in view of this static force.

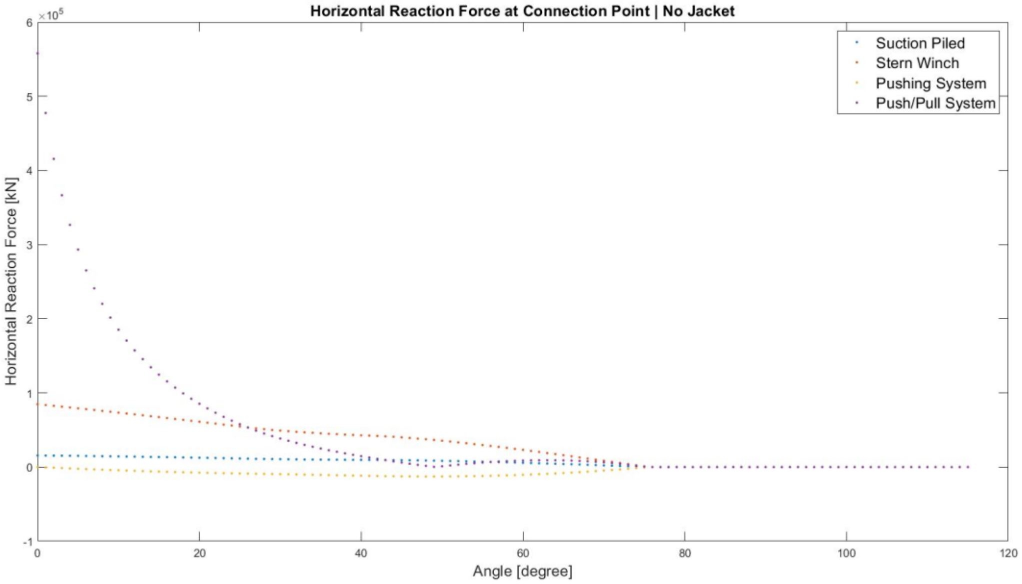


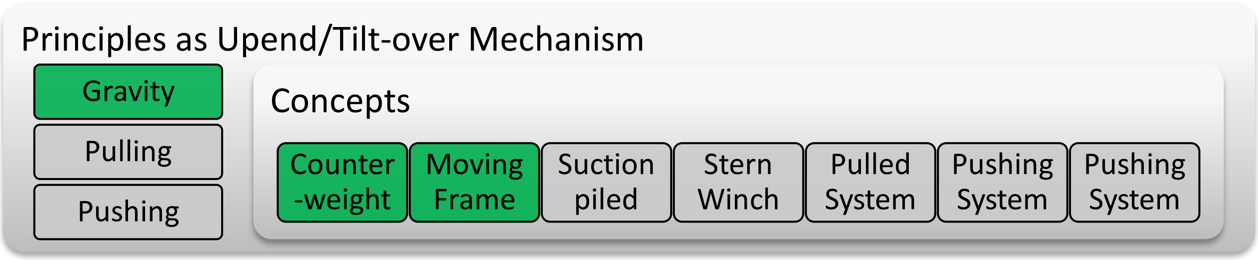
Figure 79: Static (Moment) Forces, Comparison Horizontal Reaction Force Support (No Jacket)

5.8.2 Maximum Power Requirement

As can been concluded from Table 14 in paragraph 5.7 (page 84), the maximum required power with regard to the derrick hoist system are approximately the same for all concepts. Regarding the upending mechanism, there are differences. The Pull/Push system concept requires by far the largest maximum power. The concepts in which mass is the driving force of the rotational movement obviously require no additional power. The other concepts require approximately the same maximum power compared to each other. What can be concluded, pertaining to the required maximum power to obtain a static equilibrium during the upend/tilt-over operation, the counterweight Concept and the Moving Frame concept are favourable. However, Pioneering Spirit has sufficient installed power to operate the system for all concepts.

5.8.3 Complexity and New Equipment

Gravity Principle (Counterweight and Moving frame)



Additional equipment and position equipment on the ship
The concepts based on the gravity principle do not require large additional equipment to upend or tilt-over. The gravity force on the system is such that the system rotates only by gravitational forces. In the case of the Moving Frame concept, a system must be installed to move the Tilting Lift Beams. This can be integrated in the Tilting Lift Beams. No major adjustments are needed to modify the aftdeck. Because of the lack of additional equipment, besides the jacket lift system itself, the installation and removal time between main activities is limited to a minimum. The lack of additional equipment is also beneficial regarding the available deck space and investment costs.

Pros and cons overview:

+ No additional equipment required
    + Relatively fast installable and removable
    + Less deck usage
    + Financially attractive

Position equipment on the vessel
All equipment is placed at the aftdeck. There are no important parts placed under the waterline during the upend/tilt-over operation, in upended position or in tilted position. This is favourable regarding the installation/removal of the system between different activities, the ability to visually monitor the most important components and the reduction of the degradation due to seawater of the components of the upend/tilt-over mechanism. The system is still subject to sea air though.

Pros and cons overview:

+ The equipment, except for the tail of the TLBs, is positioned above the waterline
    + Accurate visual monitoring of the equipment
    + Less degradation of the system due to seawater

Changing tensions in Derrick Hoist System
The Derrick hoist System is the only system in the Jacket Lift System responsible for the positioning of the Tilting Lift Beams during the upend/tilt-over operation. The tension in the Derrick Hoist System changes with the angle in which the system in positioned. An example is the aforementioned influence of buoyancy during the upend/tilt-over operation. Moreover, variations in the tension of the wires are expected due to vessel motions and other dynamic excitation forces. The ability to control these influences is limited in this principle. For example, it is not possible to apply pre-tension.

Pros and cons overview:

- Limited possibilities to control variations in the tension in the wires due to variable excitation forces.

Position of the central of gravity

The position of the joint centre of gravity of the jacket Lift System and the jacket is decisive in this principle. However, in particular regarding removal projects, there are uncertainties about the exact location of this point. An example of a factor that increases the uncertainty is marine growth. A Jacket that has been installed in seawater for a long time is subject to the growth of plants and insects that affects the mass of the jacket and the location of the centre of gravity. In situations where the joint centre of gravity is placed close to the pivot point, the controllability of the upend/tilt-over operation may be lost. The Tilting Lift Beams, with or without jacket, may fall to the aftdeck of Pioneering Spirit with disastrous consequences. The joint centre of gravity for jackets in installation projects can be reasonably determined.

Pros and cons overview:

- The exact location of the joint centre of gravity is uncertain
    - This accounts in particular for removal projects, an example is marine growth
    - The controllability of the upend/tilt-over process may be lost

Counterweight specific

The centre of gravity of the jacket is of great importance in the counterweight concept. In most cases, there are possibilities to position the jacket in a way that the centre of gravity is located close to the pivot point. This reduces the required mass of the counterweight in the tail. However, the system must be able to upend/tilt-over when no jacket is placed on the system. An unrealistically large counterweight is required to upend the system. As already mentioned, a larger mass increases the vertical force in the pivot point. This makes the design of the pivot point complicated and is disadvantageous regarding the load on the construction of Pioneering Spirit.

Pros and cons overview:

- An unrealistically large counterweight is required
- The increase in the total mass of the system also increases the forces in the pivot point and the construction of the Pioneering Spirit

Moving Frame specific

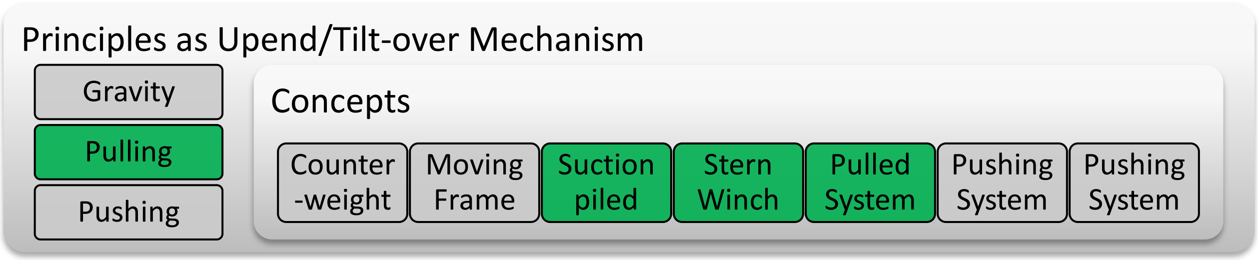
By moving the Tilting Lift Beams in the direction of the pivot point, the magnitude of the moment, initiated by gravitational force, and the time moment at which the system starts to upend can be influences. This increases the controllability of the process and reduces the magnitude of the forces. However, the maximum lift height decreases approximately with the length by which the system is moved in the direction of the stern of Pioneering Spirit.

Pros and cons overview:

+ The magnitude of the moment and the timing can be influenced, this increases the controllability.

- The maximum lift height decreases approximately with the length by which the system is moved to the stern of Pioneering Spirit.

Pulling Principle (Suction Piled and Stern Winched)



Additional equipment and position equipment on the ship
In the pulling principle, the Tilting Lift beams are upended by pulling to the system by means of a winch system. The force required to upend the system is large, consequently a large pulling system is required. The winch system will require a lot of space and finding a suitable location to install the system will be a challenge. A reason is the location of the connection of the winch system between the tail of the Tilting Lift Beams and the suction pile(s) or stern of Pioneering Spirit. The system will be, for the biggest part, submerged in the seawater. This is a major disadvantage. The various components in the system cannot be visually monitored before and during the upend/tilt-over operation, are much more affected by degradation by seawater and it is much more complex to install and remove.

Pros and cons overview:

- − A large system consisting of winches must by installed on the vessel, to find a suitable location will be a challenge
- − Parts of the winch system will be located below the waterline
    - − The various components in the system cannot be visually monitored before and during the upend/tilt-over operation
    - − The level of degradation by seawater is much higher
    - − Complex to install and remove between main activities

Changing tensions in Derrick Hoist System and Position of the Central of Gravity
The controllability of the upend/tilt-over operation within the pulling principle is expected to be good. Together with the Derrick Hoist System, the Tilting Lift Beams can be pulled in two rotational directions. This makes it possible to apply pre-tension in the wires. In this manner, variating tensions in the wires can be compensated. Possible uncertainty about the joint centre of gravity can also be controlled this way.

Pros and cons overview:

- + The controllability of the upend/tilt-over operation is expected to be high due to the possibility of pulling in two rotational directions
- + Possibilities to add pre-tension
- + Less sensitive to uncertainties about the location of the joint centre of gravity

Suction piled specific
To upend the system, it is necessary to install suction pile(s) at the seabed. The suction pile(s) are installed close to the jacket to be installed or removed. This involves extra risk and extra work. Moreover, the connection between the suction piles and Pioneering Spirit will cause an external horizontal force to the vessel. The Dynamic Positioning System of Pioneering Spirit must compensate this external horizontal force. The analysis of the static forces, the previous assessment point, shows that the horizontal force during the upend/tilt-over operation is larger than the capacity of the thrusters and the Dynamic Positioning System.

Pros and cons overview:

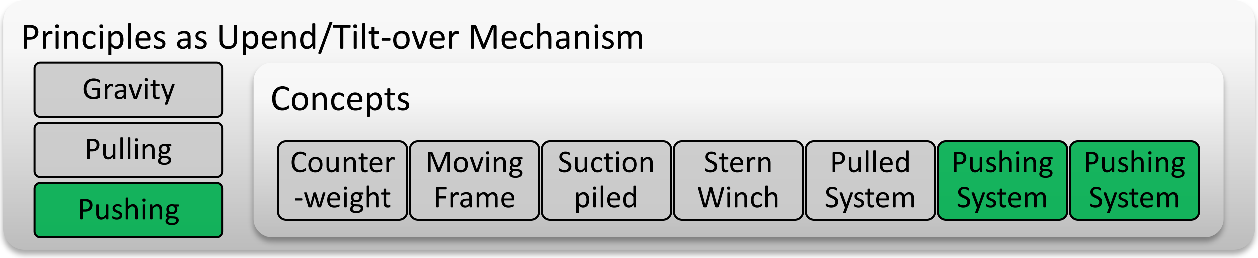
- Additional preparatory work due to the installation and removal of suction pile(s)
- Suction piles must be placed relatively close to the jacket to be installed or removed, this involves risks and difficulties
- The horizontal force on the vessel by the pulling system is larger than the capacity of the Dynamic Positioning System of Pioneering Spirit.

Stern Winch specific
A connection is made between the reinforced stern of Pioneering Spirit and the tail of the Tilting Lift Beams. However, the angle of the wires in tilted position is highly unfavourable and great forces are exerted to the hull of the vessel. The same accounts for the tension in the pulling system.

Pros and cons overview:

- Large forces in the pulling wires are expected and large forces are exerted to the hull of Pioneering Spirit

Pushing Principle (Pushing System and Push/Pull Construction)



Principles as Upend/Tilt-over Mechanism

Gravity

Pulling

🟩 Pushing

Concepts

Counter-weight

Moving Frame

Suction piled

Stern Winch

Pulled System

🟩 Pushing System

🟩 Pushing System

Additional equipment and position equipment on the ship

The concepts within the pushing principle are equipped with a pushing system installed at the aftdeck of Pioneering on the already applied reinforced transverse strip. Although the limited space between the Tilting Lift Beams and the aftdeck, the pushing system will have to be relatively large. Reasons are the length of the system and the pressure/tension that will be exerted on the pushing system. The system must be connected to the Tilting Lift Beams during the entire upend/tilt-over process. The total mass of the system is divided between the pivot point and the pushing system during some parts of the upend/tilt-over process. Due to the angle between the pushing system and the Tilting Lift Beams, lateral forces are exerted in the pushing system. Moreover, the direction of the resulting moment changes during the upend/tilt-over Operation. It is possible that this will change the pressure in the pushing system into a tension. This depends on the tension in the Derrick Hoist System.

Pros and cons overview:

- − A large and robust pushing system is required
- − Little space is available between the Tilting Lift Beams and the aftdeck. This results in a complex and expensive system

Changing tensions in Derrick Hoist System and Position of the Central of Gravity

The controllability of the upend/tilt-over operation in the concepts within the push principle is expected to be large. Because of the system can be pushed/pulled in two rotational directions by the pushing system and the derrick hoist system, it is possible to apply pre-tension. In this way, fluctuations in the tension in the wires and possible uncertainty about the joint centre of gravity can be compensated.

Pros and cons overview:

- + The controllability of the upend/tilt-over process is expected to be high due to the ability to move the system in two directions of rotation.
- + Possibilities to add pre-tension
- + Less sensitive to the position of centre of gravity

Position of the Central of Gravity

The push system is entirely installed on the aftdeck. This is favourable regarding the installation and removal of the system between main activities. The system can also be installed and removed with Pioneering Spirits own equipment. For example, the 5000 mt special purpose crane can be used. Moreover, the system is located above the aftdeck during the entire upend/tilt-over process. It is therefore easy to visually monitor the components in the system and the system will be less subject to degradation by seawater.

Pros and cons overview:

- + The position of the push system is located above the aftdeck during the entire upend/tilt-over operation
- + The system can be visually monitored during the entire upend/tilt-over operation
- + The system is easy to install and remove with Pioneering Spirit’s own equipment
- + The system is less subject to degradation by seawater

Pushing System specific

The pushing system will be complex. The system is subject to lateral forces during the upend/tilt-over operation and the length between the base of the pushing system and the attachment point to the Tilting Lift Beams is great. Therefore, a robust system consisting of segments is required. Due to the presence of lateral forces in the system a segmented pushing system is non-feasible.

Pros and cons overview:

- Lateral forces in the pushing system makes it non-feasible to use a segmented system

Push/Pull construction specific

The difference between the pushing system concept and the push/pull construction concept is that the pushing part of the system consists of a rigid construction with a fixed length. This will exclude the need to apply a segmented pushing system or enormous multi stage cylinders. However, the dimensions of the rigid construction must be large because of the large pressure and lateral forces in the system.

Pros and cons overview:

+ No segmented pushing system or multi stage cylinders necessary

- Robust rigid construction required to be able to resists the large pressure and lateral forces in the system

5.9 Evaluation Upend/Tilt-over Mechanism and Conclusion

5.9.1 Static Equilibrium

In view of the static equilibrium and maximum required forces, most concepts are immediately excluded. The **Counterweight** concept is considered non-feasible due to the exorbitant heavy counterweight required to achieve a static equilibrium. The heavy counterweight has many disadvantages. An example is the large vertical reaction force at the hinge point. The **Moving Frame** concept is considered non-feasible due to the magnitude of the buoyancy. The Tilting Lift Beams are expected to remain floating during the upend/tilt-over operation when no jacket is being applied on the Tilting Lift Beams. The **Push/Pull** concept is considered non-feasible due to the immense horizontal force in the system during the first/last part of the upend/tilt-over operation. This is mainly due to the unfavourable angles in the system during those stages of the operation. The **Suction Piled** concept is non-feasible due to the large horizontal force exerted to the vessel by the tension in the pulling system. The horizontal force exerted to the vessel exceeds Pioneering Spirit's dynamic positioning capability, which means that Pioneering Spirit will not remain in position during the operation. Furthermore, the seabed is often congested by other constructions. The installation of suction piles may cause these structures to be damaged.

This leaves the **Stern Winch** concept and the **Pushing System** concept the only two concepts to be feasible as a standalone concept, with the disadvantageous aspects of the concepts in mind. Of those two concepts, the **Pushing System** concept is favourable regarding the maximum static forces in the system. The forces are divided over the hinge point and the pushing system, which lowers to maximum forces at those points. In addition, the required force to obtain a static equilibrium by the Upend/Tilt-over Mechanism is significantly smaller.

5.9.2 Maximum Required power

Regarding the required maximum power, the concepts in which gravitational force induces the rotational movement require the lowest amount of maximum power. This is mainly because of the smaller required moment to upend/tilt-over the system. However, the installed power on Pioneering Spirit is of a magnitude that the differences between the concepts is not significant. The static equilibrium, the complexity of the system and the new to add equipment are more decisive. Of course, a smaller power requirement and usage is still beneficial.

5.9.3 Complexity and New Equipment

A system that uses as little equipment as possible is favourable. The equipment to upend/tilt-over the system must be integrated in the Tilting Lift Beams as much as possible. This is an assumption given that the increase of the mass of the Jacket Lift System is limited and the additional equipment is placed in a favourable location in the system. The **Moving Frame** concept is favourable regarding this assessment point nonetheless considered non-feasible regarding the static equilibrium. Regarding the New Equipment assessment point, the **Stern Winch** concept is the favourable concept of the two remaining concept from the static equilibrium analysis. However, the system is located beneath the water level during the upend/tilt-over operation and the forces exerted to the hull are large. The equipment is hard to monitor and the installation/removal of the equipment after completion of the total operation is difficult. In view of this, the **Pushing System** concept includes more equipment but is by far the favourable concept. So, the **Pushing System** concept is considered favourable regarding Complexity and New equipment.

In the **pulling** and **pushing** concepts it is possible to apply pre-tension. This is favourable regarding the controllability of the system. Uncertainties about the exact location of the joint centre of gravity are less decisive since small deviations can be compensated using the pre-tension.

5.9.4 Noteworthy Concept Specific Findings

Even though the **Counterweight** and the **Moving Frame** concepts are considered non-feasible or highly unfavourable, the concepts have potentially positive aspects. The equipment in both concepts is located above the waterline or is integrated in the Tilting Lift Beams during the upend/tilt-over operation. Both concepts require little additional equipment and both concepts have in view of the static equilibrium in the Derrick Hoist System and the Upend/Tilt-over Mechanism positive values. It seems favourable to combine the **pulling** and **pushing** concepts with the **Counterweight** and **Moving Frame** concepts. This is investigated in the next subpart (chapter 6) of the concept development.

The **Push/Pull System** concept is unfavourable regarding the maximum static forces when the system is positioned in a small angle in reference to the aftdeck of Pioneering Spirit. However, if the angle of the system with the aftdeck of Pioneering Spirit is sufficiently large, the static forces to obtain a static equilibrium are similar to the other concepts. The **Push/Pull System concept** is mainly conceived with the controllability of the system in mind. By not connecting the Tilting Lift Beams and the Upend/Tilt-over mechanism, the dynamic forces are not applied to the connecting point but to the wires of the upend/tilt-over mechanism. It is much easier and more favourable to compensate dynamic forces this way. This type of systems may possibly prevent lateral static forces in the pushing component as both parts of the system can be independently positioned. In this way, it is possible to keep the pushing system in a perfectly vertical position during the elongation/shortening of the rigid component.

5.9.5 Conclusion Evaluation and Concept Choice

Based on the static equilibrium the concepts, **Counterweight, Moving Frame, Suction Piled and Push/Pull system** are excluded. The **Stern Winch** and the **Pushing System** are the only concepts considered feasible as a standalone concept. Between these two concepts, the **Pushing System** concept is favourable regarding the maximum static forces in the system, maximum required power, complexity of the system and the required New Equipment. The main reasons for this are the smaller maximum forces in the **Pushing System** concept and the equipment that is located above the water level on the aftdeck. The equipment can be monitored during the upend/tilt-over operation and is easier to install/remove before/after completion of an operation. The biggest disadvantage of the **Pushing System** concept is the lateral force in the rigid construction during the extension/shortening of the pushing system. The pushing component must consist of segments as a result of the length of the pushing component. This type of systems cannot withstand large lateral forces. Ideally, there would be no lateral force at all during the extension/shorting operation of the system. This main disadvantage may be prevented by combining the **Pushing System** with the **Push/Pull System**. Furthermore, the maximum required force to obtain a static equilibrium during the upend/tilt-over operation is possibly reduced by combining this combination with the **Moving frame** concept and/or the **Counterweight** concept.

Concept Choice

The **Pushing System** concept combined with the **Push/Pull System** concept is chosen as the base concept for further development. This combination will be further combined with the **Moving frame** concept, **Counterweight** concept and a **combination** of the **Moving Frame** and **Counterweight** concepts to investigate possible optimisations.

6 Concept Choice and Optimisation

6.1 Introduction Concept Optimisation

The findings of the previous subparts are in this third and final subpart of the concept development used to development a favourable design solution. The most favourable concept, until now, is optimised by combining the concept with positive assessed aspects of the other concepts. This includes the combination of the Pushing System concept with the Push/Pull System concept. This new Push/Pull Variant System concept is then combined with the Moving Frame concept, Counterweight concept and a combination of the Moving Frame concept and Counterweight concept. The new concept must eliminate the greatest disadvantages of the Pushing System concept, use the idea behind the controllability of the Push/Pull System concept and answer the question whether or not it is beneficial to bring the joint centre of gravity closer to the pivot point and in which way. Information is included in appendices B, C and F.

6.2 Assessment Criteria Concept Optimisation

The main objective of this optimisation subpart is to achieve a smaller maximum for all static forces previously assessed. Moreover, the lateral force during the elongation/shortening of the rigid pushing system must be eliminated. Enumeration of the previously assessed Static forces:

- Tension Derrick Hoist Wires
- Pressure in rigid upend/tilt-over mechanism
- Tension in wire(s) upend/tilt-over mechanism
- Vertical reaction force at the hinge point
- Horizontal reaction force at the hinge point
- Vertical reaction force at the upend/tilt-over mechanism
- Horizontal reaction force at the upend/tilt-over mechanism

Push/Pull Variant Concept Assessment

One of the assessment criteria is that no lateral static forces on the rigid upend component are permitted during the elongation/shortening of the rigid component. This is during the first phase of the upend operation or the last phase of the tilt-over operation. The rigid upend/tilt-over component can be positioned independently of the Tilting Lift Beams. The rigid construction is held in a vertical position by a winch system. To check whether the lateral forces are excluded and the static forces for obtaining a static equilibrium are smaller, the Pushing System, the Push/Pull System in the new Push/Pull Variant system concepts are compared. A table with maximum static forces is provided. Graphical results for the situation without jacket are given in Appendix F.1. Graphical results for the situation with jacket are given in Appendix F.2. An analysis of the results is given in the next paragraph.

Moved Centre of Gravity Assessment

One of the research questions is, if the hinged system principle proved to be favourable to upend/tilt-over a jacket, whether it is beneficial to bring the centre of gravity of the hinged construction with or without a jacket closer to the hinge construction before or during upending/tilting-over. This question is investigated in this paragraph by comparing the results of the individual, assessed, static forces for a situation where the Tilting Lift Beams have not been moved, moved 5 meters in the direction of the pivot point and moved 10 meters to the pivot point. The results are included in Appendix F.3. An analysis of the results is given in the next paragraph.

Push/Pull Variant Concept Optimisation Assessment

If the analysis of the new concept proves to fulfil the objective of the new concept, smaller maximum static forces and no lateral forces during elongation/shortening of the rigid construction, an answer is sought to determine whether it is beneficial to move the centre of gravity of the total system closer to the pivot point. This is described on the previous page. If this also yields a positive result, the favourable way to bring the centre of gravity closer to the pivot point is examined. Three variations have been chosen to be investigated.

Three variations:

1. Push/Pull Variant System concept combined with the Moving Frame Concept
2. Push/Pull Variant System concept combined with the Counterweight Concept
3. Push/Pull Variant System concept combined with the Moving Frame and Counterweight Concept

1. Concept Optimisation Variation Moving Frame

In variation 1, the Tilting Lift Beams are moved 10 meters to the pivot point. The starting point is that the distance of 10 meters is not sufficient to upend the system on gravitational force alone. The aim is to reduce the required moment and to investigate the effect on the other, assessed, static forces.

2. Concept Optimisation Variation Counterweight

In variation 2, a counterweight of a mass of 2500 mt is applied to the tail of the Tilting Lift beams. Again, the starting point is that the mass of the counterweight is not sufficient to upend the system on gravitational force alone. The reduction of the required moment and the influence on the other, assessed, static forces are investigated with the help of this combination.

3. Concept Optimisation Variation Moving Frame + Counterweight

In this third and last variation, a counterweight of a mass of 2500 mt is applied and the Tilting Lift beams are moved 5 meters towards the pivot point. The objective of this combination is to investigate the possibility to combine a pre-applied counterweight with a moved frame. Possibly, an optimum can be found using this combination.

The results of the three optimisation variations and the initial new concept are compared per static force with use of figures. The evaluation is included in next paragraph. The graphical results for the situation without jacket are given in Appendix F.4. The graphical results for the situation with jacket are given in Appendix F.5.

6.3 Push/Pull Variant System Concept Description

As mentioned earlier, the Pushing System and the Push/Pull System are combined in a new concept, the Push/Pull Variant System concept. The Pushing System concept is explained in paragraph 5.4.1 (page 60), the Push/Pull System concept is explained in paragraph 5.4.3 (page 63).

Push/Pull Variant System:

The system is upended by means of a rigid system that pushes against the Tilting Lift Beams. The rigid pushing system consists of hydraulic segmented cylinders and is installed on the aftdeck of Pioneering Spirit on the already applied transverse reinforced frames. The rigid pushing system is held perfectly vertically during the elongation/shortening of the system. This is done by means of a winch system that is connected to the rigid construction and the Tilting Lift Beams. The rigid construction and the Tilting Lift Beams are not fixed to each other and can therefore be positioned independently of each other. As soon as the maximum length of the rigid pushing system is reached (49 meters), the rigid construction is pulled against the Tilting Lift Beams by means of the winch system. In this way, it is possible to exert force during the entire operation in both rotational directions. Similar to the other concepts, the positioning of the beams is taken over by the Derrick Hoist system as soon as the joint centre of gravity is beyond the pivot point in reference to the stern of Pioneering Spirit. This process is shown in Figure 80 (and Appendix B).

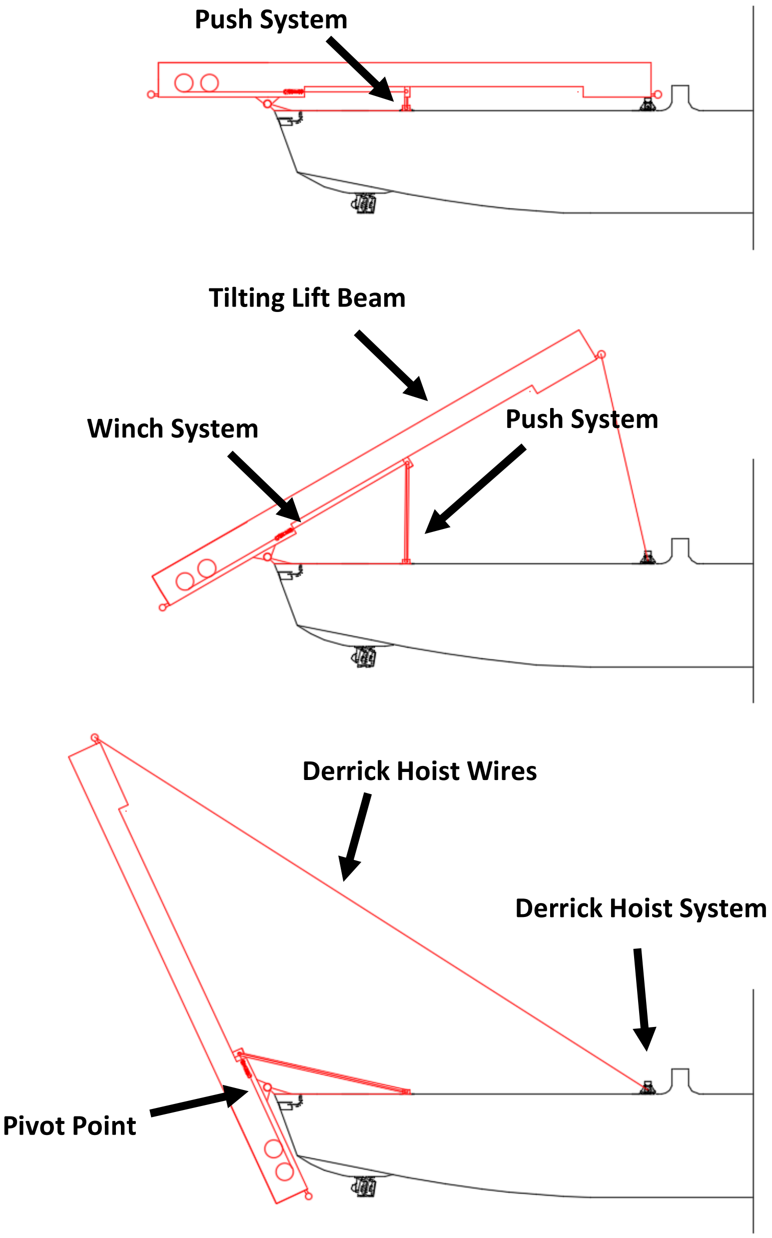


Figure 80: Upend/Tilt-over Stages in Concept "Push/Pull Variant System"

6.4 Approach/ Calculation Method Static Equilibrium/Forces

6.4.1 General Parameters, Assumptions and Simplifications

The same general parameters (paragraph 5.5.2 (Page 66)), assumptions and simplifications (paragraph 5.5.2 (page 66)) are used as in the static equilibrium calculations, described in chapter 5. The differences and additions are described in this paragraph. The general parameters used are repeated below.

General Parameters

Location:			
Gravity	g	= 9.81	[m/s^{2}]
Water depth at the location	Z_{water}	= 120	[m]
Density seawater	ρ_{water}	= 1025	[kg/m^{3}]
Pioneering Spirit:			
Draft Pioneering Spirit	d	= 17	[m]
Displacement (at 17 m draft)	$M_{PioneeringSpirit}$	= 571 925	[mt]
Jacket Lift System:			
Length crane boom TLB (hinge to tip)	$L_{TLB,CraneBoom}$	= 112	[m]
Length Tail TLB (hinge to bottom)	$L_{TLB,Tail}$	= 32	[m]
Height of the TLB	H_{TLB}	= 10	[m]
Width of the TLB	W_{TLB}	= 10	[m]
Mass of the JLS (in total)	M_{JLS}	= 15 000	[mt]
Number of TLB's in the system	TLB_{numb}	= 2	[-]
Centre of Gravity TLB positioned from hinge	$x_{CoG,TLB}$	= 15	[m]
	$y_{CoG,TLB}$	= 5	[m]
Jacket (reference dimensions from Table 9)			
Mass of the jacket	M_{jacket}	= 15 000	[mt]
Centre of Gravity jacket (from hinge)	$x_{CoG,jacket}$	= 10	[m]
Centre of Gravity jacket (from hinge)	$y_{CoG,jacket}$	= 27	[m]
Length of the jacket	$L_{Jacket,1}$	= 130	[m]
Height of the jacket	$H_{Jacket,1}$	= 15	[m]
Width of the jacket	$W_{Jacket,1}$	= 40	[m]
Mass of the jacket	$M_{Jacket,1}$	= 15 000	[mt]
Centre of Gravity jacket	$x_{CoG, Jacket,1}$	= 40	[m] (from bottom)
	$y_{CoG, Jacket,1}$	= 20	[m]
Rigid System:			
Mass of the rigid construction	$M_{Upend,P}$	= 185 – 2000	[mt]
Length of the rigid construction	$L_{Upend,P}$	= 4.5 – 49	[m]
Width of the rigid construction	$W_{Upend,P}$	= 10	[m]
Height of the rigid construction	H_{TLB}	= 2.5	[m]

Table 16: General Parameters Concept choice and Optimisation

6.4.2 Coordinate Reference System and Points in Tilted/Initial Position

The same reference coordinate system is used as used in the previous concept development subpart, described in paragraph 5.5.3 (page 70)). The differences and additions are described in this paragraph. The coordinate points PP, Q and S are replaced by PV, QV and SV. The coordinates in tilted/initial position are given in Table 17. An overview is given in Figure 81.

Name Point	Point	X Coordinate [m]	Y Coordinate [m]
Pivot Point	0	0	0
Corner TLB	A	-32	2
Corner TLB	B	-32	12
Corner TLB	C	112	2
Corner TLB	D	112	12
Water level	E	0	-15
Bottom TLB (in tilted position)	F	0	2
Attachment point Derrick Hoist System	G	115	3
Attachment point Base Derrick Hoist System	H	115	-1
Centre of Gravity Counterweight	I	-24.5	7
Centre of Gravity TLB	J	15	7
Centre of Gravity Jacket	K	10	32
Top TLB (in tilted position)	L	0	12
Attachment point TLB Pulling System	M	-33.5	3
Attachment point Suction Anchor	N	-1	-74
Attachment point TLB Pushing System	O	40	1
Attachment point PS Pulling System	R	11.5	-32
Attachment point Base Pushed/Pulled Variant System	PV	40	-1
Attachment point Pushed/Pulled Variant System	QV	40	3.5
Centre of Gravity Pushed/Pulled Variant System	SV	40	1.25

Table 17: Coordinates Important Points in Tilted/Initial Position of the Combination Concept

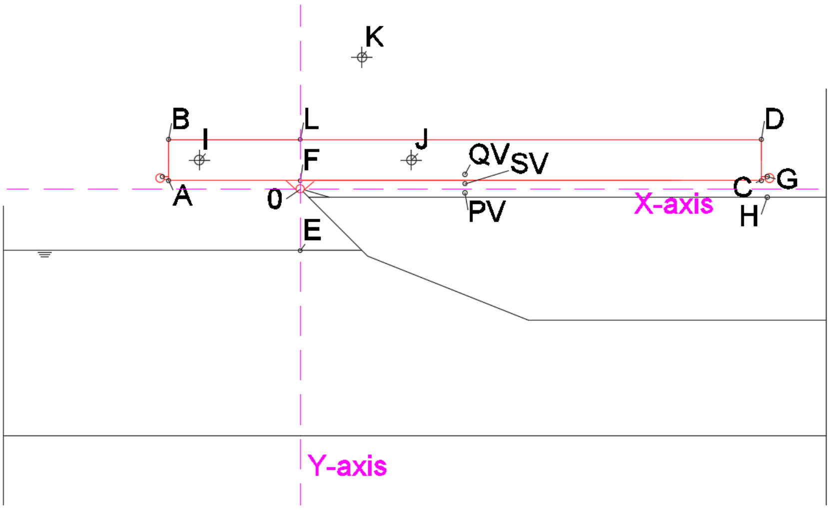


Figure 81: Coordinates Points

6.4.3 Coordinates Points during Upending/Tilting-over

To calculate the coordinate points of QV and SV during the upend/tilt-over operation, the same calculation method is used as in the calculation of points Q and S (paragraph 5.5.4 (see page 72)). However, small differences apply. During the upend/tilt-over operation of the Push/Pull Variant System concept (QV and SV), a distinction is made between four stages instead of three. The stages are:

1. $\alpha_i < \alpha_{L_{rigid,max}}$ [°]
2. $\alpha_{L_{rigid,max}} \leq \alpha_i < 90$ [°]
3. $\alpha_i = 90$ [°]
4. $\alpha_i > 90$ [°]

The full elaboration is attached in Appendix C

6.4.4 Upend/Tilt-over process

The phases shown above, describe the upend/tilt-over operation. A visualisation of the path of the coordinates has been added in Appendix D. The first stage describes the phase of the upend/tilt-over operation in which the maximum length of the rigid construction has not yet been reached. The rigid construction is elongated/shortened during this phase. The position is held vertically by the winch system to eliminate horizontal forces in the rigid construction. The second stage is the phase between when the rigid construction has reached its maximum length and the moment just before the Tilting Lift Beams are positioned in a vertical position. The third stage comprises the phase in which the Tilting Lift Beams are positioned in a vertical position. The final stage is the phase in which the Tilting Lift Beams are rotated the remaining part to the maximum angle. The results of the coordinates from 0 degree to 115 degrees in reference to the aftdeck of Pioneering Spirit is given in Appendix D.

6.4.5 Static Equilibrium

Again, the same method is used as in the previous concept development subpart, chapter 5. The calculation method described in paragraph 5.5.6 (page 80) is used with the differences mentioned in this section. The concept specific overview of the static forces acting on the system is shown in Figure 82. For further details, a reference is made to page 81.

The results of the maximum force per assessed static force are included in the next paragraph, paragraph 6.5 Optimisation Results and Analysis.

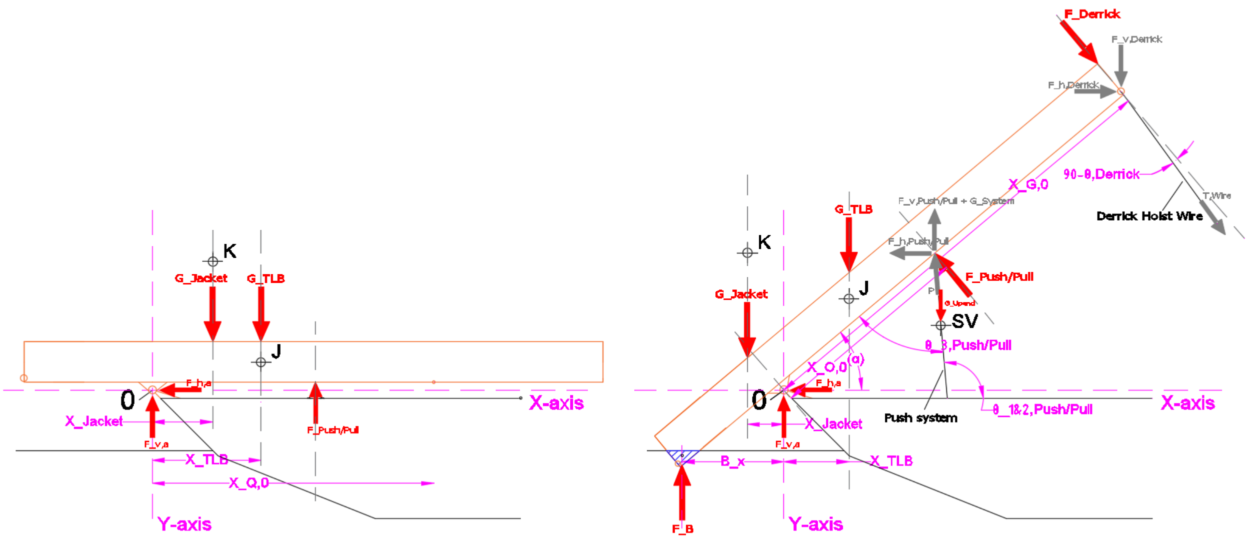


Figure 82: Static Equilibrium Push/Pull Variant Principle

6.5 Optimisation Results and Analysis

6.5.1 Push/Pull Variant Concept Assessment

The Push/Pull Variant System concept has been compared with the Pushing System concept and the Push/Pull System concept. First, an overview is given of the maximum force per assessed static force. Secondly, the behaviour of the static forces during the upend/tilt-over operation is compared. The comparison includes graphs that contain the static forces required to obtain a static equilibrium during the upend/tilt-over operation. The focus in the analysis is on deviating behaviour of the forces. Examples are rapidly changing forces or a short peak load during the operation.

Maximum Forces

	Concepts		
Maximum Force: **JACKET**	**Pushing System**	**Push/Pull System**	**Push/Pull Variant System**
Tension Derrick Hoist Wires [mt]	5533	5532	5533
Pressure in rigid Upend/Tilt-over Mechanism [mt]	9374	47562	9339
Tension in wire(s) Upend/Tilt-over Mechanism [mt]	-	47388	9339
Vertical reaction force at the hinge point [mt]	30029	31000	30328
Horizontal reaction force at the hinge point [mt]	4679	51450	4679
Vertical reaction force at the Upend/Tilt-over Mechanism [mt]	9404	11950	18770
Horizontal reaction force at the Upend/Tilt-over Mechanism [mt]	700	94604	0

Table 18: Results Maximum Static Forces Concept Comparison (Jacket)

As can be seen in Table 18, the magnitude of most assessed static forces is comparable to the best result of the other two concepts. The horizontal force has indeed been eliminated, a crucial requirement. What is striking, however, is the result of the vertical reaction force at the connection point of the rigid construction. The reaction force is much larger compared to the other two concepts. The main reason for this is the additional force of the winch system to keep the rigid pushing mechanism in a vertical position. This is disadvantageous and must be investigated further, this result can possibly be optimised.

To provide the full set of results, the maximum forces without a jacket applied on the Jacket Lift System is included in Table 19.

	Concepts		
Maximum Force: **NO JACKET**	**Pushing System**	**Push/Pull System**	**Push/Pull Variant System**
Tension Derrick Hoist Wires [mt]	3284	3283	3283
Pressure in rigid Upend/Tilt-over Mechanism [mt]	5624	28587	5603
Tension in wire(s) Upend/Tilt-over Mechanism [mt]	-	28483	5603
Vertical reaction force at the hinge point [mt]	13237	16000	13237
Horizontal reaction force at the hinge point [mt]	2777	30924	3209
Vertical reaction force at the Upend/Tilt-over Mechanism [mt]	5654	8846	11299
Horizontal reaction force at the Upend/Tilt-over Mechanism [mt]	1298	56862	1336

Table 19: Results Maximum Static Forces Concept Comparison (No Jacket)

Remark:
In Table 19 a maximum horizontal reaction force at the support point of the Upend/Tilt-over Mechanism can be perceived. This horizontal force acts up when the rigid construction of the Upend/Tilt-over Mechanism has reached its maximum length.

Analysis per Assessment Static Force

Derrick Hoist System

As can be seen in Figure 83, the static force in the Derrick Hoist system is the same for all three concepts. The same applies as described on page 94 regarding feasibility and maximum force. Furthermore, no striking phenomena have been observed.

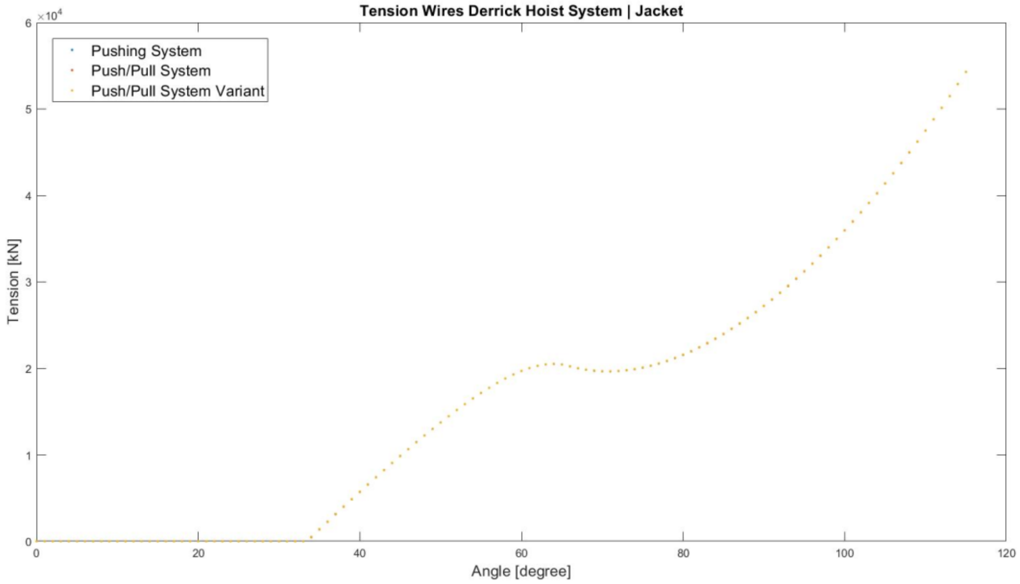


Figure 83: Comparison Derrick Hoist System

Pressure in rigid Upend/Tilt-over Mechanism and Tension in wire(s) upend/tilt-over mechanism

Shown in Figure 84, the tension in the wires and the pressure in the rigid construction in the Push/Pull Variant System concept are almost 5 times smaller compared to the Push/Pull System concept. The pressure in the system is comparable to the pressure in the pushing system in the Pushing System concept. Regarding the pressure/tension in the upend/tilt-over mechanism, the Push/Pull Variant System concept meets the purpose of the concept. Furthermore, no deviating results were observed.

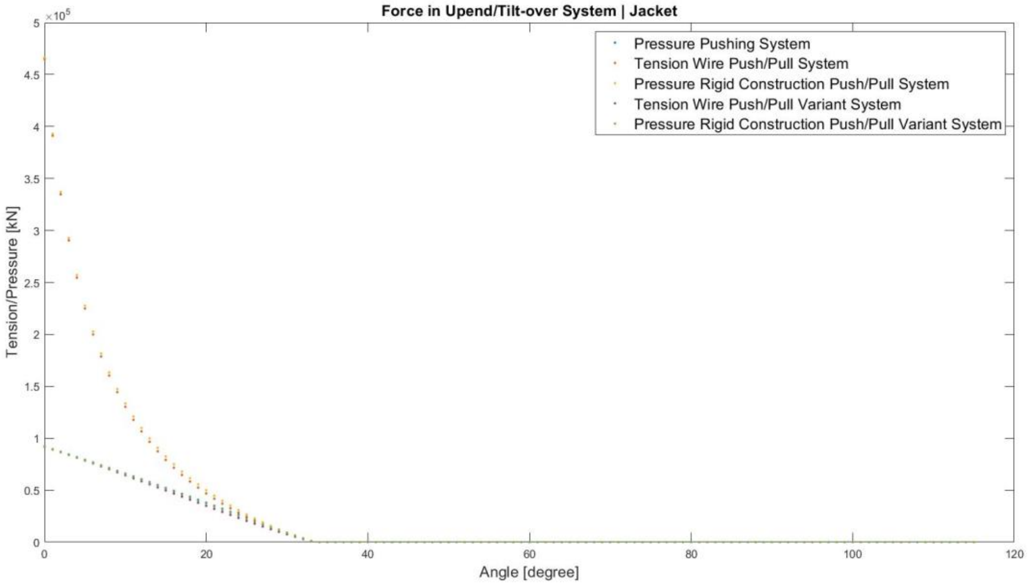


Figure 84: Comparison Tension/Pressure Upend/Tilt-over Mechanism

Vertical reaction force at the hinge point

Shown in Figure 85, the vertical reaction force at the pivot point for the Push/Pull Variant System concept is much smaller. An explanation for this is the pulling force by means of the winch system to keep the rigid construction in a vertical position. This effect is also an explanation why the vertical reaction force at the pivot point of the upend component is much larger. A smaller vertical reaction force is desirable. However, as can be observed in Table 18 and Figure 85, the maximum reaction force is for all three concepts about the same.

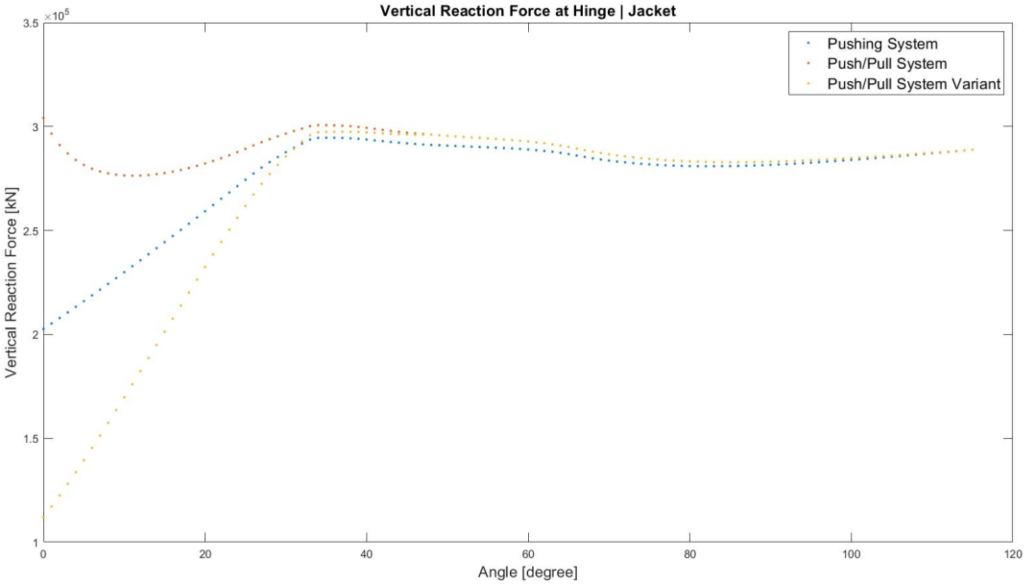


Figure 85: Comparison Vertical Reaction Force at Hinge

Horizontal reaction force at the hinge point

As mentioned earlier, the goal is to exclude the large horizontal forces in the system during the upend/tilt-over operation. As can be seen in Figure 86, the large horizontal reaction forces are indeed excluded in the Push/Pull Variant System concept. The reaction force is comparable with the Pushing System concept. In the Push/Pull Variant System concept, only negative (pressure) forces apply.

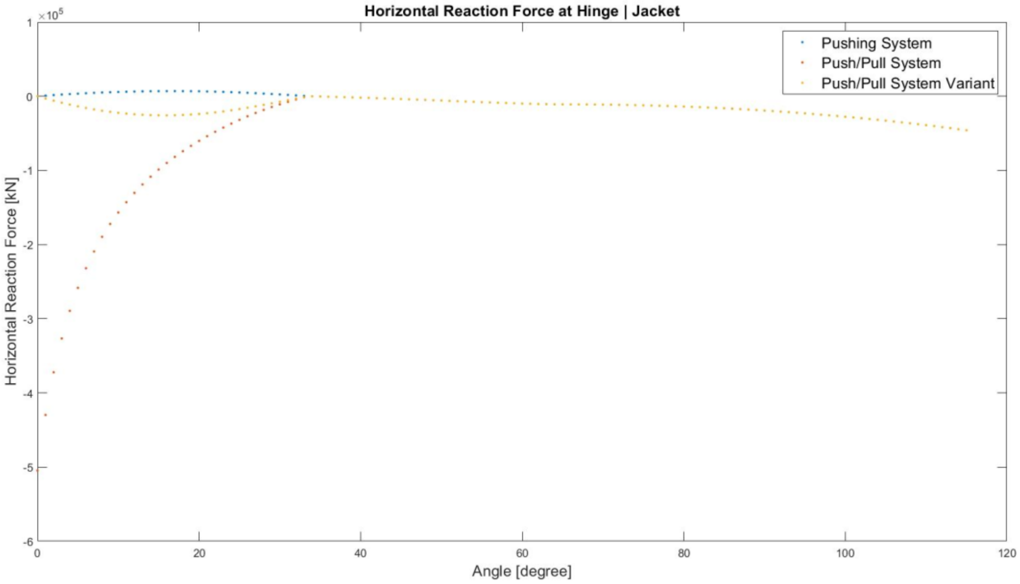


Figure 86: Comparison Horizontal Reaction Force at Hinge

Vertical reaction force at the upend/tilt-over mechanism

The maximum vertical reaction force in the, new, Push/Pull Variant System concept is much larger compared to the original two concepts. A reason for this is the additional force exerted to the rigid construction by the winch system to keep the rigid construction into a vertical position. Another explanation for the larger vertical reaction force compared to the Push/Pull System concept is the different angle in tilted/initial position. The initial angle in the Push/Pull System concept is in the beginning small. This results in large horizontal forces and smaller vertical forces. In the Push/Pull Variant concept, the upend operation starts in an angle of 90 degrees. The force is completely transferred vertically to the reinforced transverse frame that is applied on the aftdeck of Pioneering Spirit. This is much more favourable regarding the structural capability of Pioneering Spirit. The horizontal pressure/tension in the surrounding aftdeck and the bending forces in the hull will be smaller. Pioneering Spirit has at this place of the vessel a larger water displacement. The capacity of the transverse frame is 450 mt/m tension and 300 mt/m pressure (see paragraph 3.2.4 (page 24)). The transverse frame and construction of Pioneering Spirit must be strengthened to accommodate the maximum forces.

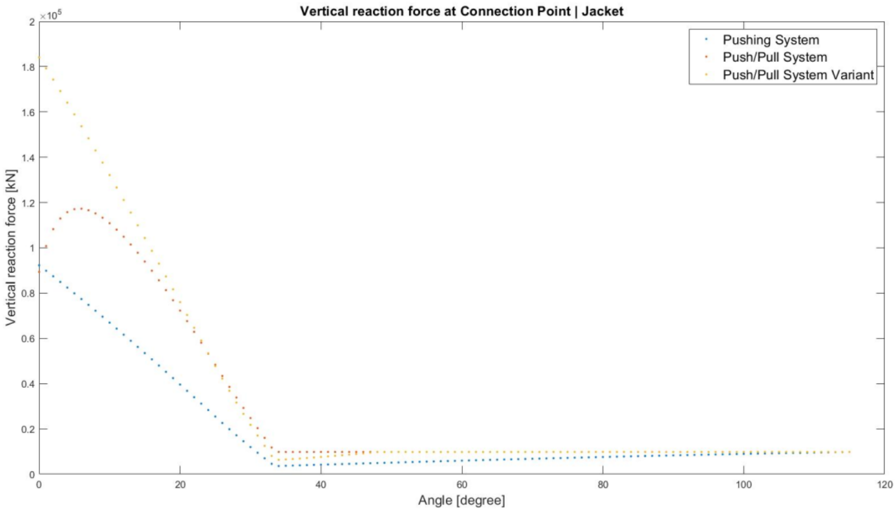


Figure 87: Comparison Vertical Reaction Force at Connection Point

Horizontal reaction force at the upend/tilt-over mechanism

The horizontal reaction force at the pivot point of the rigid construction is comparable with the Pushing System concept. This is in accordance with the purpose of the (new) Push/Pull Variant System concept. Furthermore, no deviating observation are visible. See Figure 88.

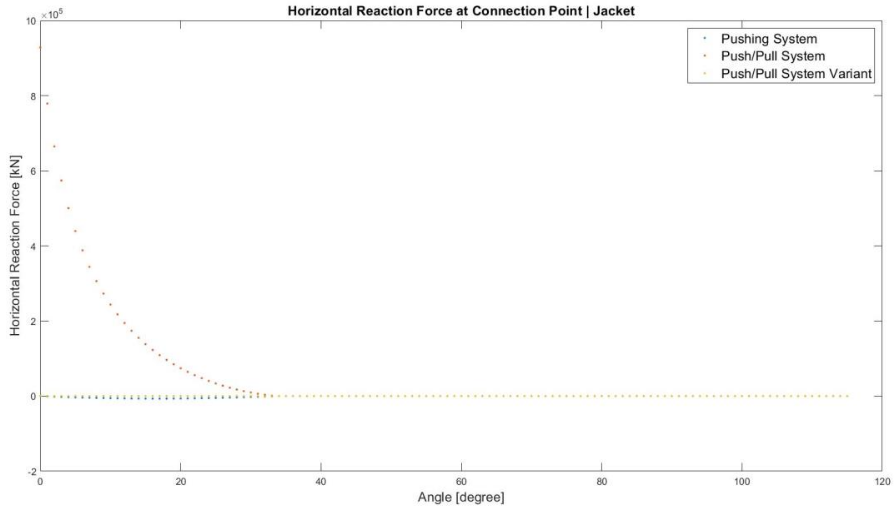


Figure 88: Comparison Horizontal Reaction Force at Connection Point

6.5.2 Moved Centre of Gravity Assessment

Regarding the question whether or not it is favourable to bring the joint centre of gravity of the system with and without jacket closer to the pivot point is clear and uniform. For all assessed static forces, except the buoyancy, it is advantageous to move the joint centre of gravity closer to the pivot point. This can be observed in the figures per static force included in Appendix F.3. As an example, the moment required by the Upend/Tilt-over Mechanism to obtain a static equilibrium is shown in Figure 89.

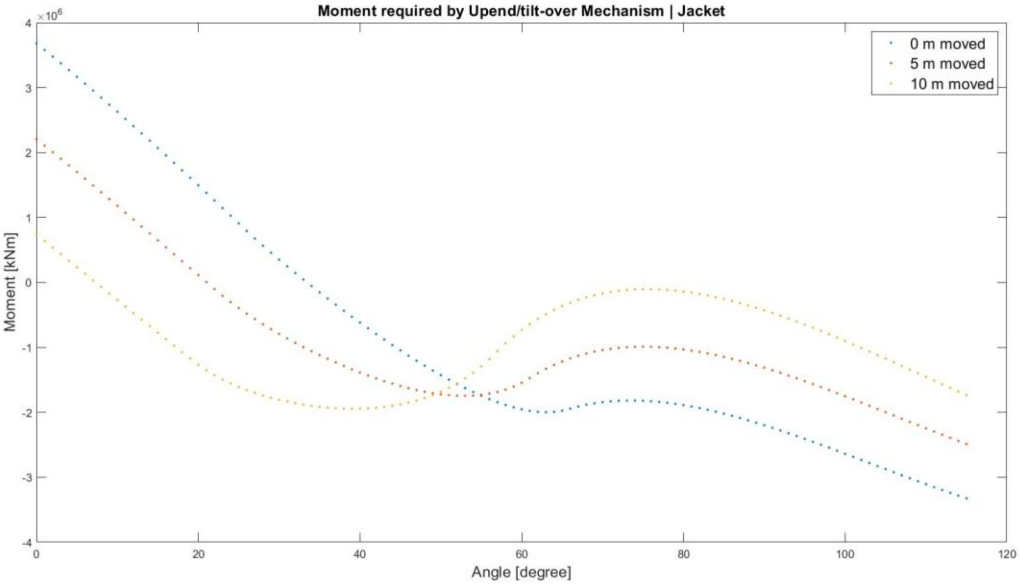


Figure 89: Moment Required by Upend/Tilt-over Mechanism

All static forces show the same pattern for the different angles during the upend/tilt-over process as shown in Figure 89, except for the forces by means of the counterweight. The maximum force decreases each step closer to the pivot point. The maximum forces generally occur at the beginning and end of the upend/tilt-over process. In the example given in Figure 89 the centre of gravity of the jacket is placed on top of the pivot point. The centre of gravity of the system is placed 5 meters to the inner direction of the vessel. This position appears to be favourable in this example. Repositioning of the centre of gravity past the pivot point in reference to the aft of Pioneering causes unfavourable effect as described in paragraph 5.8.1.

Regarding the moment by means of the **counterweight**, the moment is greater in the situation where the centre of gravity is shifted towards the pivot point. This is, off course, perfectly logical. The mutual distance between the centre of gravity of the counterweight and the pivot point becomes greater. Due to the greater contribution of the **counterweight**, the remaining required moment to the Upend/Tilt-over Mechanism is smaller, this is beneficial.

The pattern of the **buoyancy** during the different angles in the upend/tilt-over process is shown in Figure 90. The more the system is shifter towards the pivot point, the larger the buoyancy contribution. This is, once again, perfectly logical. The submerged part of the system increases with the positioning of the centre of gravity of the system closer to the pivot point. An increasing buoyancy has, as described earlier in this thesis report, some beneficial effects. An example is the maximum vertical reaction force at the hinge of the Tilting Lift Beams in upended position. However, the buoyancy can also cause that the Tilting Lift Beams to remain floating. Extra force must be delivered by the Upend/Tilt-over Mechanism to compensate this.

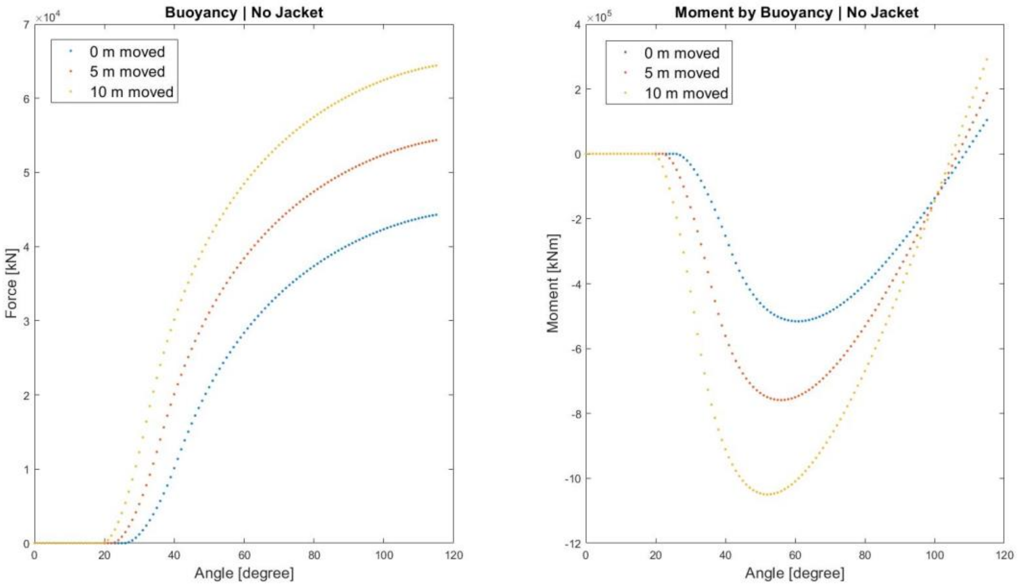


Figure 90: Static (Moment) Force, Buoyancy (Moved)

Optimisation possibilities

A clear conclusion can be drawn regarding moving the centre of gravity closer to the pivot point. In general, it is beneficial to move the centre of gravity closer to the pivot point. The most important influencers are the masses of the components in the system and the buoyancy. It is possible to find an optimum so that the lowest force to upend/tilt-over the system is required and the controllability of the process is the greatest. An example of this is the tension in the Derrick Hoist System wires shown in Figure 91. The tension starts to act up earlier by moving the centre of gravity closer to the pivot point. However, the moment by means of the buoyancy also starts to act up earlier and is greater. This reduces the maximum tension in the Derrick Hoist system. The system is positioned in such a way that the wires are tensioned throughout the process as soon as tension occurs. The most beneficial manner to reposition the centre of gravity is investigated in the next paragraph.

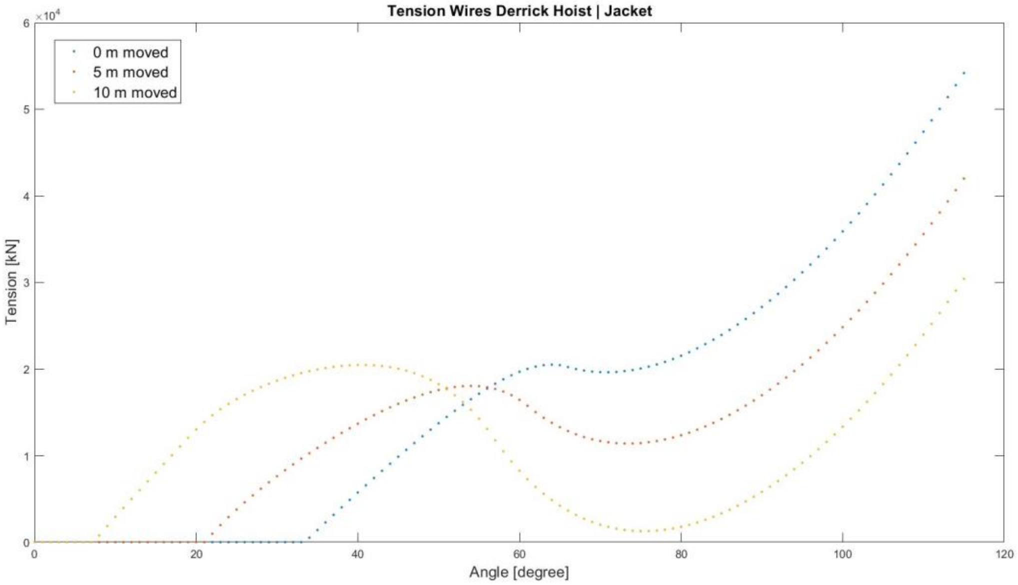


Figure 91: Static (Moment) Force, Derrick Hoist System (jacket) (Moved)

6.5.3 Push/Pull Variant Concept Optimisation Assessment

Three variants were assessed by comparing the results per static force to each other. In the comparison, the results of the situation with and without jacket are considered. In the analysis below, the situation with jacket is used. The main difference of the situation with and without jacket is the total mass of the system and the increased buoyancy. The results without jacket are included in Appendix F.4. The results with jacket are included in Appendix F.5.

Maximum Forces

	Concepts			
Maximum Force: **NO JACKET**	**Push/Pull Variant System**	**Push/Pull Variant System + Moved Frame**	**Push/Pull Variant System + Counterweight**	**Push/Pull Variant System + Moved Frame and Counterweight**
Tension Derrick Hoist Wires [mt]	3283	2754	3120	2840
Pressure in rigid Upend/Tilt-over Mechanism [mt]	5603	2069	4078	2210
Tension in wire(s) Upend/Tilt-over Mechanism [mt]	5603	1867	4078	2210
Vertical reaction force at the hinge point [mt]	13237	13883	15650	16589
Horizontal reaction force at the hinge point [mt]	3209	2311	2639	2393
Vertical reaction force at Upend/Tilt-over Mechanism [mt]	11299	4434	10748	7012
Horizontal reaction force at Upend/Tilt-over Mechanism [mt]	1336	880	507	297

Table 20: Results Maximum Static Forces Concepts Optimisation (No Jacket)

	Concepts			
Maximum Force: **JACKET**	**Push/Pull Variant System**	**Push/Pull Variant System + Moved Frame**	**Push/Pull Variant System + Counterweight**	**Push/Pull Variant System + Moved Frame and Counterweight**
Tension Derrick Hoist Wires [mt]	5533	3110	5369	4121
Pressure in rigid Upend/Tilt-over Mechanism [mt]	9339	1867	7813	4078
Tension in wire(s) Upend/Tilt-over Mechanism [mt]	9339	1867	7813	4078
Vertical reaction force at the hinge point [mt]	30328	31704	33345	33869
Horizontal reaction force at the hinge point [mt]	4679	2610	4541	3473
Vertical reaction force at Upend/Tilt-over Mechanism [mt]	18770	3827	18219	10748
Horizontal reaction force at Upend/Tilt-over Mechanism [mt]	0	0	0	0

Table 21: Results Maximum Static Forces Concepts Optimisation (Jacket)

Analysis per Assessment Static Force

Derrick Hoist System

Clearly perceptible in Figure 92, the variant with the moved Frame concept is the most effective concept regarding the tension in the Derrick Hoist System. The maximum force in the system is about 20% smaller compared to the second smallest value. A reduction of almost 50% is obtained compared to the initial Push/Pull Variant System concept. In the variant with the Moved Frame concept, less power is required, and less heavy-duty equipment must be installed. A point of attention in the variant with the Moved Frame concept is the situation where the system is moved past the pivot point. In this situation, the tension in the Derrick Hoist System is lost and the dominant mechanism to position the Tilting Lift Beams switches. This is as previously explained unfavourable and should be avoided.

In the situation without a jacket, the wave pattern, as perceptible in Figure 92, does not occur during the upend/tilt-over operation. In this case, the tension starts to build up when the system is in an angle of 63 – 75 degrees, depending on the variant. The tension in the system is built up until the maximum angle is reached. (see Figure 214). The wave pattern in the figure can be assigned to the influence of the buoyancy.

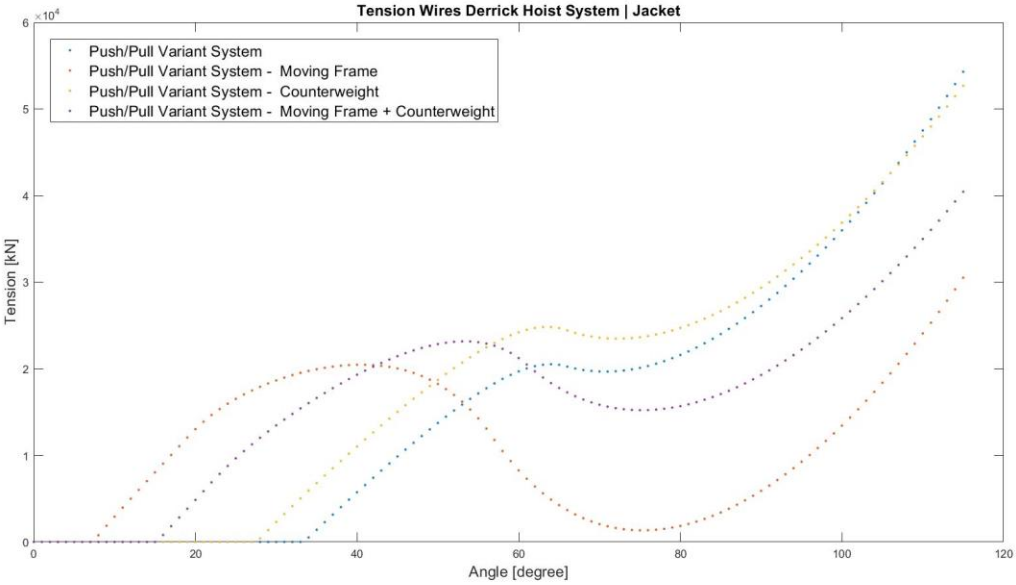


Figure 92: Static (Moment) Forces Optimisation, Comparison Tension in Derrick Hoist System (Jacket)

Pressure in rigid Upend/Tilt-over Mechanism and Tension in wire(s) upend/tilt-over mechanism
A huge improvement is achieved by the variation with the Moved Frame concept. The pressure in the rigid component and the tension in the wires is almost 5 times smaller compared to the initial Push/Pull Variant System concept. The second favourable variation is the combination with the Moved Frame and Counterweight concept. However, the maximum force in this concept is twice as large.

The wave pattern due to buoyancy during the upend/tilt-over process, like the Derrick Hoist System, occurs in the situation without jacket (see Figure 92 and Figure 216). The maximum force in the system in the variations with the Moved Frame concept and the Moved Frame and Counterweight concept is almost the same. However, the combination with the Moved Frame and Counterweight concept requires less power with regard to the entire process. This difference can be attributed to the contribution of the counterweight. This contribution is much more effective without a jacket applied on the Jacket Lift System.

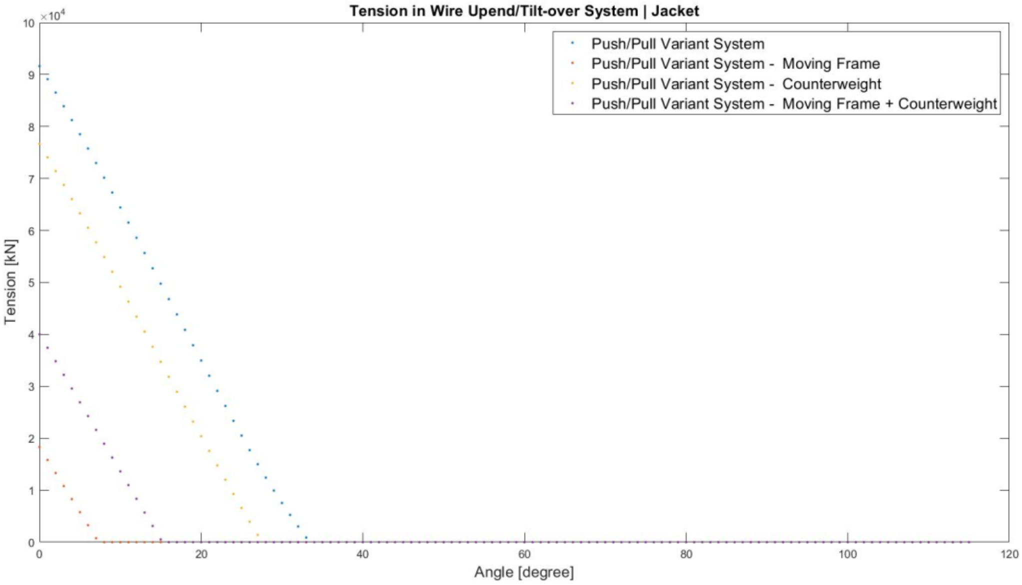


Figure 93: Static (Moment) Forces Optimisation, Comparison Tension in Upend/Tilt-over Component (Jacket)

Vertical reaction force at the hinge point

The maximum vertical reaction force at the pivot point is approximately the same for all variants. The difference is about 10%. The increase of the vertical reaction force can be assigned to the joint centre of gravity placed closer the pivot point. The pivot point supports a larger part of the system by doing this. This is in particularly evident in the first part of the upend process or last part of the tilt-over operation. An advantage of this effect is that forces at the pivot point of the Upend/Tilt-over Mechanism are smaller. This is further analysed on the next pages.

Just as with the pressure and tension in the upend/Tilt-over mechanism, a wave pattern occurs during the upend/tilt-over operation in a situation without a jacket applied on the jacket lift System. The variant with the Push/Pull Variant System concept combined with the Moved Frame concept proves the be beneficial for both situations.

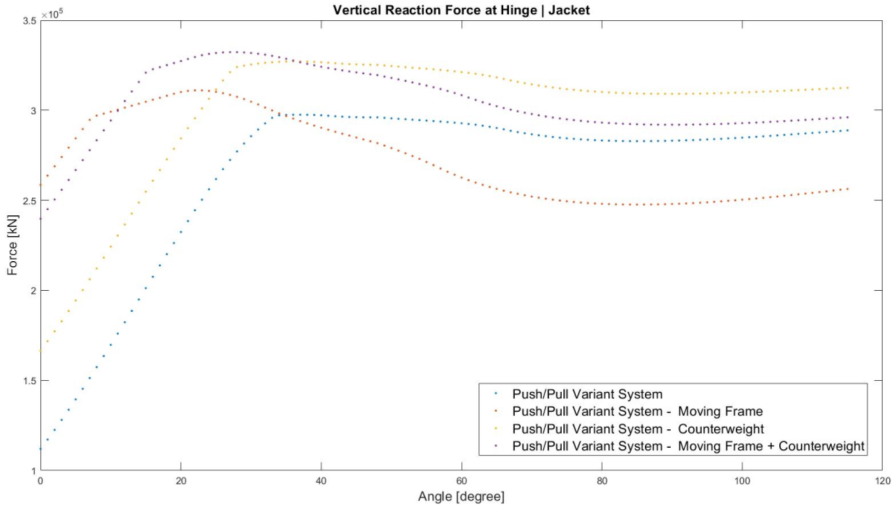


Figure 94: Static (Moment) Forces Optimisation, Comparison Vertical Reaction Force Hinge (Jacket)

Horizontal reaction force at the hinge point

Regarding the horizontal reaction force at het hinge, no remarkable phenomena occur. The variant with the Moved Frame concept has by far the lowest maximum horizontal reaction force at the hinge. Also, the pattern of the force during the upend/tilt-over operation is more constant. Compared to the original Push/Pull Variant System concept, a reduction of 50% of the maximum reaction force is achieved. This reduction is even greater during the upend/tilt-over operation. The same applies to the situation without a jacket applied on the jacket Lift System.

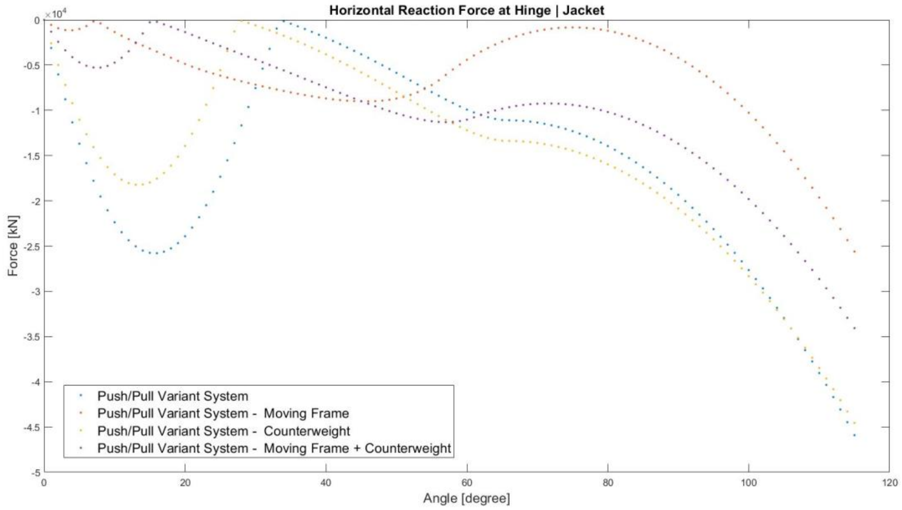


Figure 95: Static (Moment) Forces Optimisation, Comparison Horizontal Reaction Force Hinge (Jacket)

Vertical reaction force at the upend/tilt-over mechanism

From the previous analysis in this thesis project, the maximum vertical reaction force at the pivot point of the Upend/Tilt-over Mechanism proved to be a huge disadvantage. An extreme reduction of the maximum vertical reaction force is achieved by applying the variant with the Moved Frame concept. This is even more clear without a jacket applied on the Tilting lift Beams (see Figure 218). The vertical reaction force is reduced to 25% of the vertical reaction force of the initial Push/Pull Variant System concept. The biggest disadvantage of the Push/Pull Variant System concept can be resolved by applying the variation with the moved Frame concept.

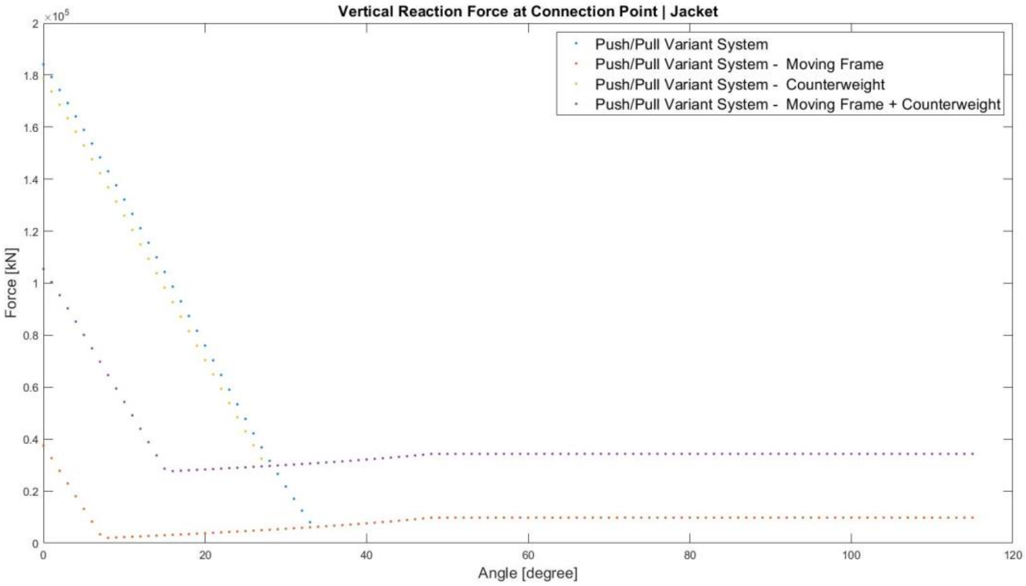


Figure 96: Static (Moment) Forces Optimisation, Comparison Vertical Reaction Force Support (Jacket)

Horizontal reaction force at the upend/tilt-over mechanism

As can be seen in the figure below, there is no horizontal reaction force at the hinge point of the Upend/Tilt-over Mechanism during the upend/tilt-over operation. This is mainly because the Derrick Hoist System becomes the dominant system to position the Tilting Lift Beams before the maximum length of the rigid construction of the Upend/Tilt-over Mechanism is reached. This also applies for the situation without a jacket applied on the Tilting Lift Beams, depending on the position of the centre of gravity of the system.

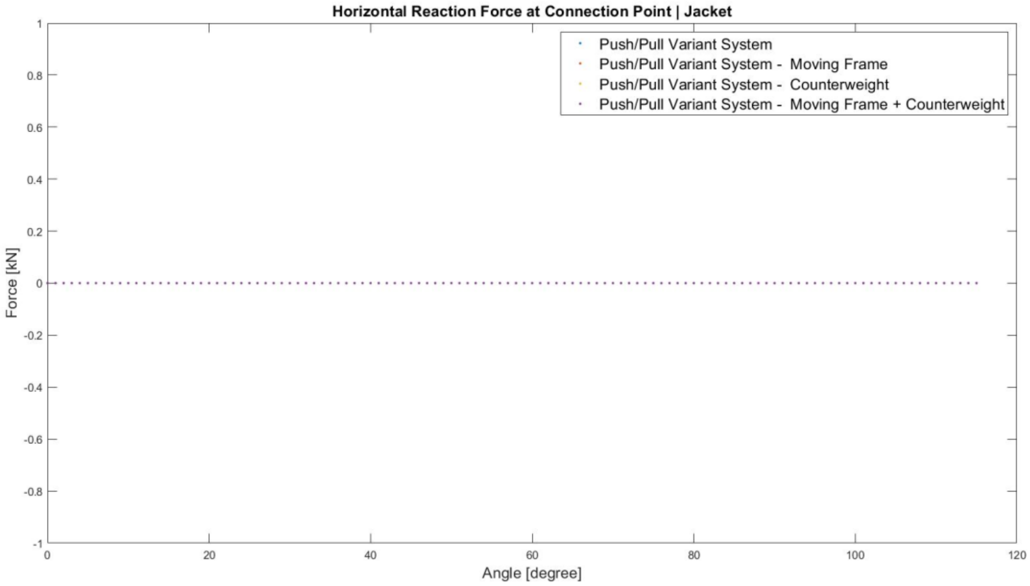


Figure 97: Static (Moment) Forces Optimisation, Comparison Horizontal Reaction Force Support (Jacket)

6.6 Optimisation Evaluation and Conclusion

In this chapter, three variants of the Push/Pull Variant System concept were investigated. The goal was to optimise the concept and to answer whether or not it would be beneficial to move the joint centre of gravity closer to the pivot point of the jacket lift System and in which manner.

To do this, the Push/Pull Variant System concept was first examined. An answer was sought whether or not the new concept uses the strong aspect of the Pushing System concept and the Push/Pull System concept and whether or not the lateral force in the Upend/Tilt-over Mechanism has been eliminated during the elongation/shorting of the system. The results are positive. The lateral force in the Upend/Tilt-over Mechanism has indeed been eliminated and the assessed static forces are all smaller except the vertical reaction force of the upend/tilt-over mechanism. How to reduce this negative result, has been investigated later in this optimisation subpart.

Secondly, the effect of moving the centre of gravity closer to the pivot point was investigated. This was also favourable for all assessed static forces. The contribution of the masses of the components and the buoyancy are dominant, as expected. To conclude, the centre of gravity must be positioned as close as possible to the pivot point. However, it is important not to go past the pivot point in reference to the stern of Pioneering Spirit.

Finally, the method of moving the joint centre of gravity towards the pivot point was investigated. The variant of combining the Push/Pull Variant System concept with the Moved Frame concept proved to be the most favourable combination. Regarding the static equilibrium, the required force by the Upend/Tilt-over Mechanism is 20% compared to the required force in the original Push/Pull Variant System concept. The same applies to the vertical reaction force at the pivot point of the upend/tilt-over mechanism. This was the biggest disadvantage that had to be solved. In some situations, the variant of the combination with the Moved Frame and the Counterweight concept seemed favourable. This applies in particular to the situation without a jacket applied on the Jacket Lift System. However, the reduction of the static forces, with and without a jacket applied on the Tilting Lift Beams is in the variation with the Moved Frame much larger. This is more decisive as this will be responsible for the required dimensions and feasibility of the system.

It can be concluded that the Push/Pull Variant System concept meets the desired requirements and that the centre of the gravity of the system must be movable. The repositioning of the system must be done by moving the jacket Lift System towards the hinge of the Tilting Lift Beams before upending and after tilting-over. In this manner, the controllability of the exact position of the centre of gravity is the greatest without adding mass to the total system (counterweight). Extra mass results in a greater reaction force at the hinged support point and proved to be less effective.

7 Dynamics and Feasibility

7.1 Dynamics and Feasibility Introduction

In this third part, Dynamics and Feasibility, the design solution that was obtained in part 2 (chapter 6) of this thesis report (see paragraph 1.4 for the report structure) is further elaborated. The dynamic stability of the system is checked and the dynamic behaviour of the system, caused by vessel motions, is analysed. This results in an answer on whether or not the concept is dynamically stable, an estimation of the response amplitude of the system and a probable maximum tension/force in the controlling wires, rigid construction and support points. With this information and the information obtained in the previous parts, an answer is given on whether or not the chosen system is likely to be feasible. Information is included into appendices G, H, I and J.

To recapitulate, the objective in this chapter is to find or obtain information about:

- The natural frequency of the system and its operation window
- The dynamic stability of the system
- The dynamic responses and forces during the upend/tilt-over operation in vessel motions
- Total forces/tensions in the system
- Overall assessment on feasibility based on the static and dynamic contributions

7.2 Dynamics and Feasibility Assessment Strategy

As described above, the focus in this chapter is first on the feasibility of the system based on the natural frequency, stability and maximum response amplitude in vessel motions. This information is subsequently used as input, along with information from previous parts, to check whether the concept is presumably feasible and whether or not the controllability of the upend/tilt-over operation is secured. The assessment is divided into three main topics.

1. Natural frequency and the operation window (Paragraph 7.5)
2. Dynamic stability (Paragraph 7.6)
3. Response amplitude (Paragraph 7.7)
    a. Most probable maximum in regular waves
    b. Maximum amplitude in irregular waves
    c. Maximum Forces

The topics described above are used to create and asses a most favourable configuration for the Upend/Tilt-Over mechanism. The configuration complements the design solution as conceived in this thesis project. The results of these assessment topics for the favourable configuration are described in section 7.8. The results are supplemented with an overview of the total forces on the assessed components and the ratio between dynamic and total forces. This is to provide an overview about how critical the dynamic forces are. Finally yet importantly, a total assessment about the feasibility of the design solution is given. This is intended as a definite conclusion about the favourability and feasibility of the system (paragraph 7.8).

7.3 Calculation Model Dynamic Behaviour of the System

7.3.1 Schematisation Jacket Lift System Dynamic Analysis

In the dynamic analysis, the schematisation shown in Figure 98 is used. The system is based on a mass-spring system. The Tilting Lift Beams and the rigid construction of the Upend/Tilt-over Mechanism are represented by a mass. Other components in the system are assumed to be massless. The centre of gravity of the masses of the Tilting Lift Beams and the rigid construction of the Upend/Tilt-over Component are indicated by points J and SV. The Tilting Lift Beams are shown as a beam in magenta and are supported by point 0. Point 0 is a pivot point allowing the Tilting Lift Beams to rotate freely. The rigid construction of the Upend/Tilt-over Mechanism is also displayed as a beam in magenta standing on point PV. Point PV is also a hinge point. The rigid construction of the Upend/Tilt-over Component can thus also rotate freely. The Tilting Lift Beams and the rigid construction of the Upend/Tilt-over Mechanism can be regarded as two rigid inverted pendulums. The two components are connected to each other by means of a roller/slide support. The two components may roll/slide against each other (frictionless) but cannot be separated from each other.

The Derrick Hoist System and the winch system of the Upend/Tilt-over Mechanism are each represented by a spring. The Derrick Hoist system is shown in red as K_Derrick. The winch system of the Upend/Tilt-over Component is shown in red as K_Upend. The springs are restricted by only exerting a force on the system when the springs are stretched. This is in accordance with the principle of a winch system. The springs must ensure dynamic stability and are responsible for the positioning of the system.

In the case of a jacket that is applied on the Jacket Lift System, an addition mass is added to the schematisation. The centre of gravity of this mass is represented by point K. The jacket is assumed to be connected to the Tilting Lift Beams and therefore it is assumed that it functions as one with the Jacket Lift System. The moment of inertia of the jacket is added to the moment of inertia of the Tilting Lift Beams. The moment of inertia of the jacket depends on the positioning of the jacket on the Jacket Lift System. This is included in the dynamic analysis.

The motions of the vessel in the 6 degrees of freedom (Surge, Sway, heave, pitch, roll and yaw motions) of the vessel are translated into a horizontal and vertical motion in a two-dimensional plane. The accelerations are shown in orange in the schematisation below, by u_dd1, u_dd2, u_dd3, v_dd1, v_dd2 and v_dd3.

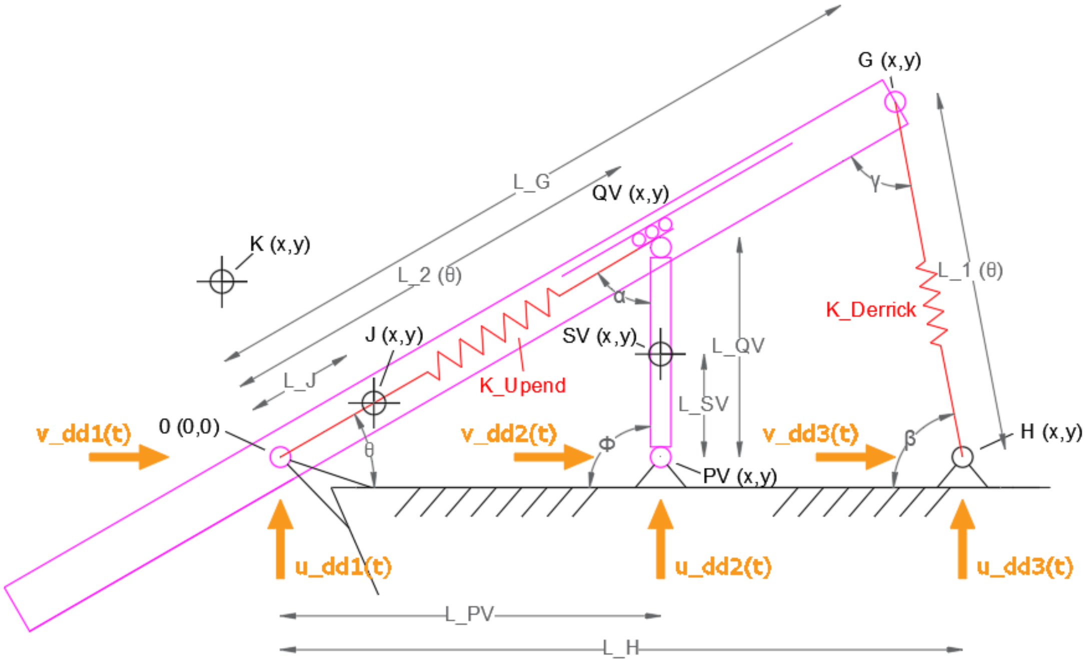


Figure 98: Schematisation of the System Regarding Dynamics in Vessel Motions

7.3.2 Assumptions and Simplification

The dynamic model should be as simple as possible to be fast and effective but also accurate enough to provide representative results [47]. The following assumptions and simplification are applied, in addition to the assumptions and simplification that have already been mentioned in the schematisation shown in paragraph 7.3.1.

1) Stiff vessel construction

Every construction is subject to internal forces, bending responses and vibrations. These effects are particularly important in the structural analysis of a particular component in the system. Nevertheless, the focus in this analysis is on the response and controllability of the total system with the objective to give an expectation of the feasibility. The vessel is therefore considered to be a stiff structure and therefore vibrations and internal forces are not considered. As a result, the mutual distance between the support points of the system with the vessel is kept the same throughout the analysis.

2) Stiff Tilting Lift Beams and Rigid upend/tilt-over construction

The Tilting Lift Beams and the rigid construction of the Upend/Tilt-over Component are also assumed to be a stiff structure. The same explanation applies as for the vessel construction. The focus in this thesis is on the response of the total system with the objective to give an expectation about the feasibility of the system. Thus, the influences of internal forces and vibrations are not considered. Superfluous to mention, after the conclusion of this thesis project these effects should be included in the further analysis.

3) No damping in the system

In nature, every system is subject to damping [48]. An example is viscous damping by movements in air or friction in the pivot points. In this analysis, the response due to vessel motions and the dynamic stability is investigated. The damping depends on detailed shapes and other system specifications. This type of information is not available in this stage of the design and not the point of interest. In general, damping takes energy out of the system. By considering no damping, conservative results are obtained. However, it is important to keep in mind that damping can also cause instability due to, for instance, negative damping [49]. Damping must be incorporated into the dynamic analysis together with other contributions such as drag forces in the further assessment in extent of this thesis project.

4) Static equilibrium as starting point – discreet operation process

The dynamic analysis is conducted with the static equilibrium as initial position. The dynamic analysis is conducted for the 115 degrees for theta (an angle of 0 degrees is not considered) in which the system can be positioned during upend/tilt-over operation. The same assumptions/simplification as in the static analysis are applied in the dynamic analysis (paragraph 5.5.2 (page 66)). The upend/tilt-over operation is approached as a discreet process. This assumption is based om the low angular velocity of the upend/tilt-over procedure.

5) Linear spring behaviour – discreet operation process

It is assumed that the springs behave linearly. This means that the stiffness of the springs is assumed to be constant during stretching/compression. The displacement and the force are assumed to be proportional to each other. This approach/assumption is also known as Hooke's law ($\mathrm{f_k = k \cdot x}$) [36]. Hooke's Law applies for wires stretched over the elastic range [50]. The cable regains its original shape after the tensioning has been released. Normally, the stiffness of the springs changes in a continue process throughout the upend/tilt-over operation. The stiffness depends on the initial length without stretching/shortening. The operation is approached as a discreet process. The stiffness is determined for the 115 degrees for theta in which the system can be positioned. The assumption of the discrete operation process is the same as in assumption 4.

6) Wires described by massless springs

Again, the focus in this analysis is on the movements of the system in vessel motions. In addition to the movement of the total system, the wires will also response separately. These responses can damp the system but can also enhance the response of the total system [47]. These and other reasons can lead to instability of the system. At this stage of the design solution development, the wires are considered massless.

7) The mass of the Jacket Lift System with or without jacket does not influence the response of Pioneering Spirit in certain wave motions

Usually, two dynamic bodies affect each other's response in dynamic conditions. The vessel is one mass and the Jacket Lift System the other mass in this statement. In a situation where one body has a considerably larger mass than the other body, the dynamic model can be simplified to a body that behaves in response of the other body. In the dynamic model used in this thesis, the mass of the Jacket Lift System with Jacket is only 4% of the mass of Pioneering Spirit. The situation has been simplified to a model where the response of the Jacket Lift System including a jacket does not affect the response of Pioneering spirit in environmental waves. The motions of the Jacket Lift System analysed in this dynamic analysis are the relative motions with respect to Pioneering Spirit. An elaboration on this assumption is included in Appendix I. Especially the pitch motion of Pioneering Spirit in waves should be affected by the additional mass of the Jacket Lift System and Jacket. As can be concluded from the elaboration, the differences are negligibly small.

8) A two-dimensional analysis

A two-dimensional analysis is conducted. With regard to the maximum tensions in the wires, the rotational response over the pivot points is decisive. Responses in the 3D plane are counteracted by the construction of the hinge and the construction of the Tilting Lift Beams. This is not considered in this analysis. Important to mention, the 6 degrees of motions of the vessel are included in the analysis. The motions are translated by means of the Transfer Function of the Response Amplitude Operators into a motion in the 2D plane (see paragraph 7.4.1).

7.3.3 General Parameters Dynamic Analysis

The same general parameters used in the static analysis are used in the dynamic analysis. An actualised table is included below for convenience.

Location:			
Gravity	g	= 9.81	$[m/s^2]$
Water depth at the location	Z_{water}	= 120	[m]
Density seawater	ρ_{water}	= 1025	$[kg/m^3]$
Pioneering Spirit:			
Draft Pioneering Spirit	d	= 17	[m]
Displacement (at 17 m draft)	$M_{PioneeringSpirit}$	= 571 925	[mt]
Waterplane Area	A_{wl}	= 38 180	$[m^2]$
Moment of Inertia Longitudinal	I_L	= 369 717 664	$[m^4]$
Jacket Lift System:			
Length crane boom TLB (hinge to tip)	$L_{TLB,CraneBoom}$	= 112	[m]
Length Tail TLB (hinge to bottom)	$L_{TLB,Tail}$	= 32	[m]
Height of the TLB	H_{TLB}	= 10	[m]
Width of the TLB	W_{TLB}	= 10	[m]
Mass of the JLS (in total)	M_{JLS}	= 15 000	[mt]
Number of TLB's in the system	TLB_{numb}	= 2	[-]
Centre of Gravity TLB positioned from hinge	$x_{CoG,TLB}$	= 5	[m]
Jacket (reference dimensions from Table 9)			
Mass of the jacket	M_{jacket}	= 15 000	[mt]
Centre of Gravity jacket (from hinge)	$x_{CoG,jacket}$	= 0	[m]
Centre of Gravity jacket (from hinge)	$y_{CoG,jacket}$	= 27	[m]
Rigid construction of the Upend/Tilt-over Mechanism:			
Mass of the rigid construction	$M_{Upend,P}$	= 185 – 2000	[mt]
Length of the rigid construction	$L_{Upend,P}$	= 4.5 – 49	[m]
Width of the rigid construction	$W_{Upend,P}$	= 10	[m]
Height of the rigid construction	H_{TLB}	= 2.5	[m]

Table 22: General Parameters Dynamic Analysis

7.3.4 Equation of Motion

Definition Equation of Motion

The dynamic behaviour of a system can be described mathematically. This is done by formulating the Equation of motion(s). The equation of motion is a mathematically description in terms of dynamic variables for the masses and degrees of freedom in the system [50]. The dynamic variables in the equation of motion can consist of different types of variables. In mechanics, the dynamic variable mostly consists of a spatial coordinate as a function of time (movements of the mass in a certain degree of freedom). The dynamic variable in this thesis project is of this type of dynamic variable.

Two methods are mostly used to formulate the equation of motion. The first method is the displacement method. The displacement method is based on Newton's second law. Newton's second law is based on the forces on the system (masses and accelerations). The second method is the Lagrangian method. The Lagrangian method is based on the potential and kinetic energy in the system.

The displacement method is commonly used for systems where the bodies/masses in the system can move independently in the directions of the cartesian reference system [47]. The Lagrangian method is commonly used for problems with rigid constraints [47]. The system of the Jacket Lift System in this thesis has a rigid constraint, nevertheless, the movements of the system are described mathematically with the displacement method. The most important reasons for this are the geometrically constraint of the movements of the system and, in view of the Autor, a better overview of the contribution of the different components in the system. For example, the contribution of a Jacket applied on the Jacket Lift System or the springs working on the system.

Equation of Motion

The system, shown in paragraph 7.3.1, comprises two masses and therefore two components. Each component has one degree of freedom, a rational movement around its pivot point. As mentioned earlier, the two components may slide against each other but can never be separated from each other. This restriction is met by including geometry in the equation of motion. Because of this constraint, the two components are dependent on each other's movement. If one of the components rotates in a positive direction, the other component must follow this rotation. Although, with respect to its own restrictions. This dependence on each other results in a system with one degree of freedom. The equation of motion will therefore be expressed with a spatial dynamic variable in the form of the time dependent angle of one of the two components. The time dependent angle of the other component is then expressed in terms of this chosen angle. In this thesis project, the angle of the Tilting Lift Beams with respect to the aftdeck of Pioneering Spirit is used as dynamic variable. This angle is expressed as "theta".

In formulating the equation of motion, elaborated on the next page, the two components are first described separately. The dependency of each other is described by $\mathrm{M}_{\mathrm{Connection}}$. $\mathrm{M}_{\mathrm{Connection}}$ consists of a force vector ($\mathrm{F}_{\mathrm{Connection}}$) and a point of application to the system. After both components have been described, the rigid component is solved in terms of the force vector dependent on theta ($\mathrm{F}_{\mathrm{Connection}}$). This force is substituted in the equation of the Tilting Lift Beams. This results in is a single equation with a time-dependent variable, external forces excluded.

In formulating the equation of motion, the positive orientations shown in Figure 99 are used. The same positive orientations are used in the static analysis.

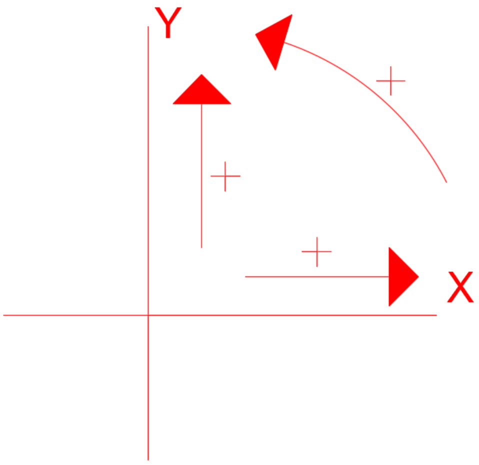


Figure 99: Positive Orientation Forces/Moment

The equation of motion per mass(component) is compiled by:

$$I_n \cdot \ddot{\theta} = \sum M$$

$$\sum M = M_{Mass} + M_k + M_{k,0} + M_u + M_v + M_{Connection} + M_{Jacket}$$

Where de contribution of "…" is described by:

- mass is described by M_{Mass}
- springs are described by M_k (for each spring an own term)
- the vertical external force on the system due to vessel motions is described by M_u
- the horizontal external force on the system due to vessel motions is described by M_v
- the interaction between the two components is described by $M_{Connection}$
- the jacket is described by M_{Jacket}

The moment of inertia is described by I_n. The moment of inertia of the jacket, when applied to the system, is added to the moment of inertia of the Tilting Lift Beams. The asymmetric position of the jacket is taken into account by applying the parallel axis theorem (or Huygens-Steiner Theorem [36]).

Static Equilibrium:
As mentioned earlier, the system starts (t = 0) in the static equilibrium for a certain initial angle of theta. This is achieved by adding $M_{kn,0}$ to the equation of motion. $M_{kn,0}$ compensates gravitational contributions on the system in the initial position at t = 0. If this term is not added, the system rotates until one of the springs is sufficiently stretched to exert a force on the system that compensates for the gravitational affects. This results in an undamped oscillation. Which spring accounts for this effect depends on the initial angle of the system (theta). In other words, $M_{kn,0}$ is added to ensure that the system starts in the static equilibrium. A large stiffness is chosen as a value for the stiffness of the imaginary spring. The value of $M_{kn,0}$ is a constant and will therefore not vary in time. $M_{k1,0}$ and $M_{k2,0}$ are defined by (terms such as β_0 are explained on the next pages):

$$M_{k1,0} = -k_{1,0} \cdot dL_{k1,0} \cdot L_G \cdot \sin(\frac{\pi}{2} - \beta_0)$$

$$M_{k2,0} = k_{2,0} \cdot dL_{k2,0} \cdot L_{QV} \cdot \sin(\alpha_0)$$

$dL_{1,0}$ and $dL_{2,0}$ are calculated with the relation (equilibrium):

$$M_{Mass1,0} + M_{k1,0} + M_{Connection1} + M_{Jacket,0} = M_{Mass2,0} + M_{k2,0} + M_{Connection2}$$

As with the equation of motion, $M_{Connection}$ is used to substitute the two (mass) components in a single equation.

Pretension:
The possibility to add pretension is desirable in the further elaboration, with regard to the controllability of the system. The possibility to add pretension is included by adding the terms $dL_{1,0}$ and $dL_{2,0}$ in the description of the springs. The springs are described by:

$$M_{k1} = -F_{k1} \cdot L_G \cdot \sin(\frac{\pi}{2} - \beta) \qquad \text{with:} \qquad F_{k1} = k_1 \cdot (L_1 - L_{1,0} + dL_{1,0})$$

$$M_{k2} = F_{k2} \cdot L_{QV} \cdot \sin(\alpha) \qquad \text{with:} \qquad F_{k2} = k_2 \cdot (L_2 - L_{2,0} + dL_{2,0})$$

The pretension should not cause the system to shift to a new equilibrium with respect to the static equilibrium. This shifting is prevented by adding pretension to both wires in such a way that the pretension in the wires exert an equal moment in opposite rotational direction on the system. This is done by determining the relationship between the two wires. The dependency is mathematically described by:

$$M_{Mass1} + M_{k1} + M_{k1,0} + M_{Connection1} + M_{Jacket} = M_{Mass2} + M_{k2} + M_{k2,0} + M_{Connection2}$$

As with the equation of motion, $M_{Connection}$ is used to substitute the two (mass) components in a single equation.

Equation of motion of the rigid construction of the Upend/Tilt-over Component:

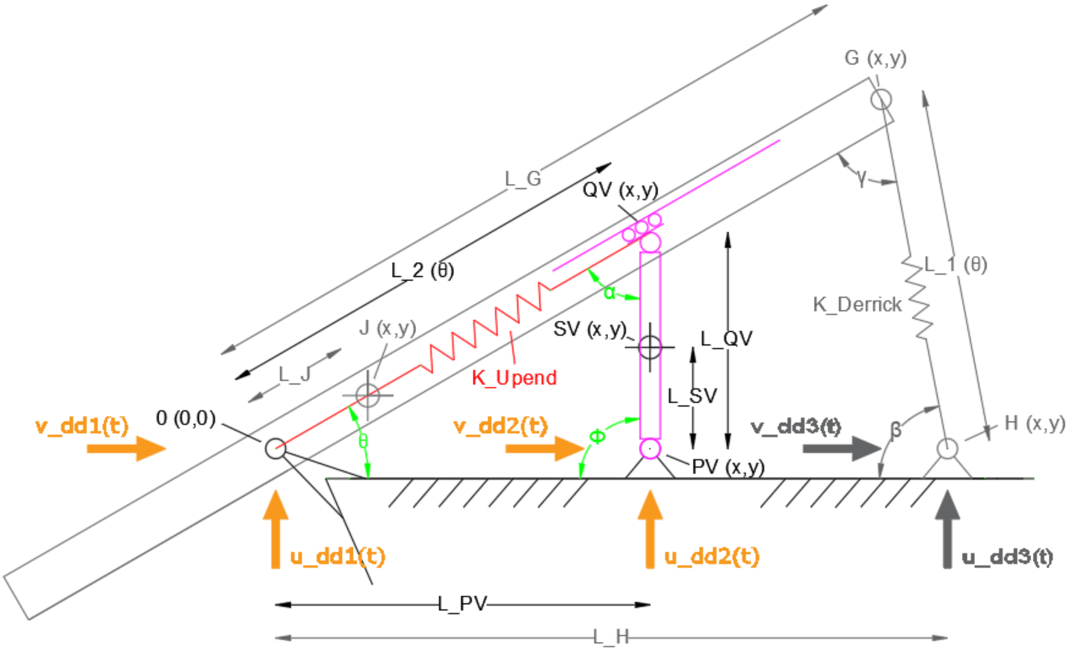


Figure 100: Schematisation of the Rigid Construction of the Upend/Tilt-over Component

The individually equation of motion of the rigid construction in the Upend/Tilt-over Mechanism is given by:

$$I_2 \cdot \ddot{\phi} = \sum M$$

$$\sum M = M_{Mass2} + M_{k2} + M_{k2,0} + M_{u2} + M_{v2} + M_{Connection2}$$

Where:

$$M_{Mass2} = m_{Upend} \cdot g \cdot L_{QV} \cdot \cos(\phi)$$

$$M_{k2} = F_{k2} \cdot L_{QV} \cdot \sin(\alpha)$$

$$F_{k2} = k_2 \cdot (L_2 - L_{2,0} + dL_{2,0})$$

$$M_{k2,0} = k_{2,0} \cdot dL_{k2,0} \cdot L_{QV} \cdot \sin(\alpha_0)$$

$$M_{u2} = m_{Upend} \cdot \ddot{u}_2 \cdot L_{SV} \cdot \cos(\phi)$$

$$M_{v2} = m_{Upend} \cdot \ddot{v}_2 \cdot L_{SV} \cdot \sin(\phi)$$

$$M_{Connection,2} = -F_{Connection} \cdot L_{QV} \cdot \sin\left(\frac{\pi}{2} - \alpha\right)$$

The constraints of the roller/slide connection are given by:

$$L_2 = \sqrt{L_{PV}^2 \cdot L_{QV}^2 - 2 \cdot L_{PV} \cdot L_{QV} \cdot \cos(\phi)} \qquad \text{(Law of Cosines)}$$

$$\alpha = \sin^1(\frac{L_{PV} \cdot \sin(\theta(t))}{L_{QV}}) \qquad \text{(Relation: } \frac{\sin(\theta)}{L_{QV}} = \frac{\sin(\alpha)}{L_{PV}} \text{)}$$

$$\phi = \pi - \alpha - \theta(t)$$

Furthermore:

$$\dot{\phi} = \frac{d}{dt}\phi = \frac{d}{dt}(\pi - \alpha - \theta) = \frac{d}{dt}(\pi - \sin^1\left(\frac{L_{PV} \cdot \sin(\theta)}{L_{QV}}\right) - \theta)$$

$$\ddot{\phi} = \frac{d^2}{dt^2}\phi = \frac{d^2}{dt^2}(\pi - \alpha - \theta) = \frac{d^2}{dt^2}(\pi - \sin^1\left(\frac{L_{PV} \cdot \sin(\theta)}{L_{QV}}\right) - \theta)$$

Equation of motion Tilting Lift Beams:

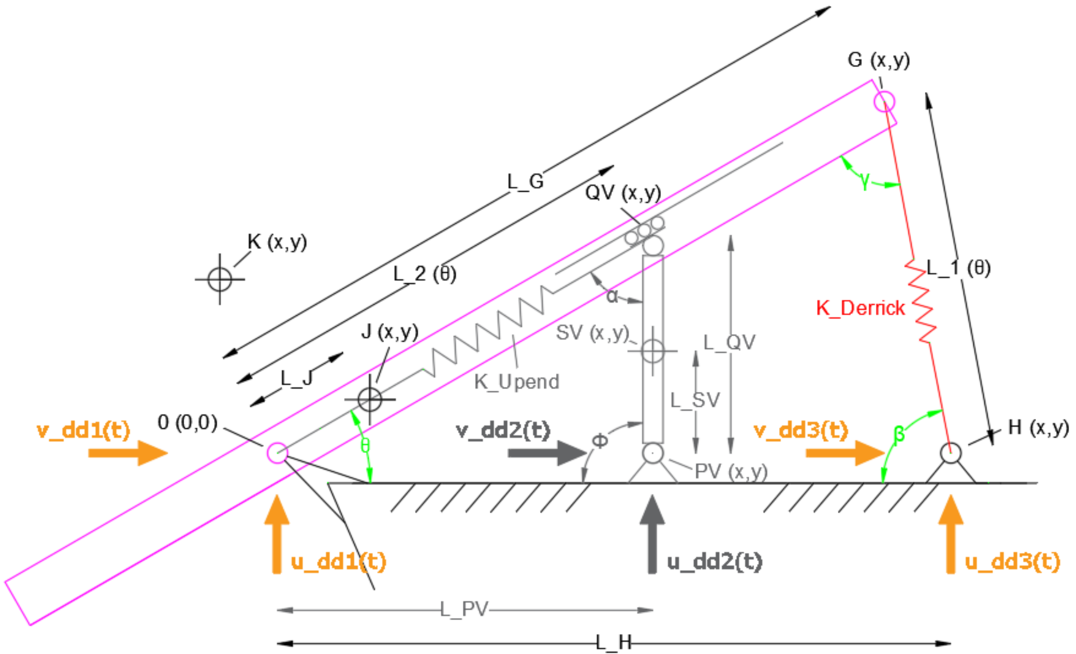


Figure 101: Schematisation of the Tilting Lift Beams

The individually equation of motion of the Tilting Lift Beams is given by:

$$(I_1 + I_3) \cdot \ddot{\theta} = \sum M$$

$$\sum M = M_{Mass1} + M_{k1} + M_{k1,0} + M_{u1} + M_{v1} + M_{Connection1} + M_{Jacket}$$

Where:

$$M_{Mass1} = -m_{TLB} \cdot g \cdot L_J \cdot \cos(\theta)$$

$$M_{k1} = -F_{k1} \cdot L_G \cdot \sin(\frac{\pi}{2} - \beta)$$

$$F_{k1} = k_1 \cdot (L_1 - L_{1,0} + dL_{1,0})$$

$$M_{k1,0} = -k_{1,0} \cdot dL_{k1,0} \cdot L_G \cdot \sin(\frac{\pi}{2} - \beta_0)$$

$$M_{u1} = -m_{TLB} \cdot \ddot{u}_1 \cdot L_{SV} \cdot \cos(\theta)$$

$$M_{v1} = -m_{TLB} \cdot \ddot{v}_1 \cdot L_{SV} \cdot \sin(\theta)$$

$$M_{Connection,\theta} = F_{Connection} \cdot L_2$$

$$M_{Jacket} = -m_{Jacket} \cdot g \cdot L_K \cdot \cos(\theta + \theta_{K,0})$$

The constraints of the roller/slide connection are given by (see also Figure 101):

$$L_2 = \sqrt{L_{PV}^2 \cdot L_{QV}^2 - 2 \cdot L_{PV} \cdot L_{QV} \cdot \cos(\phi)}$$ (Law of Cosines)

$$L_1 = \sqrt{L_G^2 \cdot L_H^2 - 2 \cdot L_G \cdot L_H \cdot \cos(\theta)}$$ (Law of Cosines)

$$\beta = \sin^1(\frac{L_H \cdot \sin(\theta_1)}{L_1})$$ (Relation: $\frac{\sin(\theta)}{L_{QV}} = \frac{\sin(\alpha)}{L_{PV}}$)

$$\gamma = \pi - \beta - \theta$$

MATLAB Numerical Ordinary Differential Equation (ODE) Solver

After compiling the equation of motion, the solutions for the angular speed and position for each angle of theta in each scenario are sought. This is done by using the built-in ODE45 solver in MATLAB. The ODE solver in MATLAB solves the equation of motion in variable time steps based on the explicit Runge-Kutta formula [51]. The ode45 solver can be used to solve ordinary differential equations of the non-stiff type with medium accuracy. The ordinary differential equation in this project consists of a second order. Before entering this equation in the solver, this order must be reduced by one order.

7.3.5 Validation model

A common method for validating a calculation model is to perform a model test or to run similar experimental computational models to verify the results [52]. However, these resources are not available in this thesis project. What is possible, is to use calculation methods that have been thoroughly researched and tested and therefore plausible to give representative results. Subsequently, the calculation model can be tested on predictable behaviour of the system.

The dynamic calculation model in this thesis project is tested by means of looking at:

- Whether or not the simulation starts in its static equilibrium
- The stability of the system by applying a pulse at a given moment
- Geometric properties

The tests are conducted for the scenario’s in which the Jacket Lift System has to operate (described in paragraph 3.3.2 (page 28)) supplemented with optimisation parameters. The tests are conducted for:

- No Jacket applied on the Tilting Lift Beams
- A jacket applied on the Tilting Lift Beams
- Tilting Lift Beams placed in original position
- Tilting Lift Beams placed in a moved position
- A system without pretension
- A system with pretension

Static equilibrium:

To prove that the calculation model is likely to provide representative results, the model is first checked to see whether the system starts and remains in the static equilibrium. No dynamic external forces are exerted to the system and therefore no oscillations are allowed as a result. This is done for the 115 degrees in which the system can be positioned and the scenario’s and optimisation parameters described above. An example of the results is shown in Figure 102. A negligible oscillation is noticeable in the figure. This small perturbation of the static equilibrium is caused by a numerical error by the ODE solver in the MATLAB program.

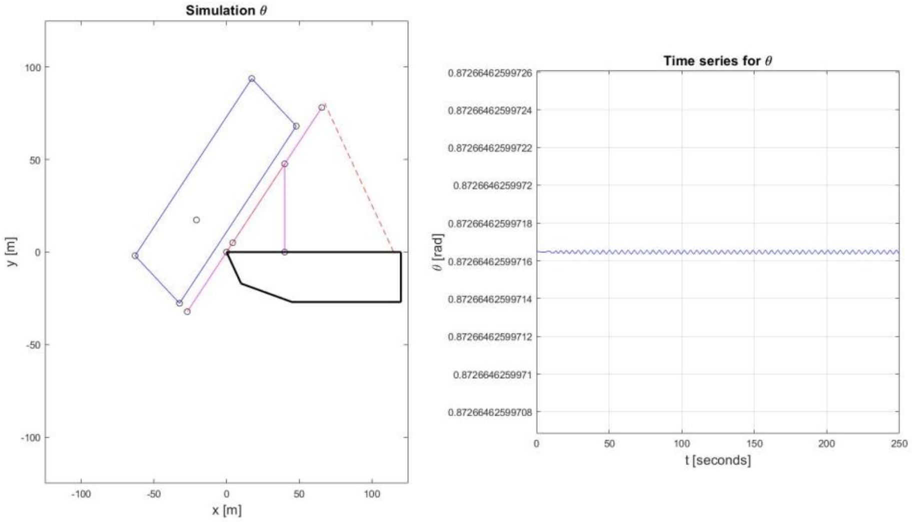


Figure 102: Check Static Equilibrium Dynamic Calculation Model

Single pulse:

No damping is added to the system. The system is therefore expected to oscillate at a constant amplitude and constant period after a pulse has been applied to the system (this also proves whether the system is stable (elaborated in the next paragraph)). This check was conducted for 115 degrees for theta, different scenarios as described earlier and for different pulse magnitudes. An example of a result is shown in Figure 103. Clearly noticeable, the system has a constant amplitude and period after a pulse has been applied to the system. The pulse is applied to the system after 10 seconds.

The results in Figure 103 are for a scenario with jacket, moved frame and pretension. The results of the tensions in the Derrick Hoist wires and the upend/tilt-over wires are shown in Figure 104 and Figure 105. Noticeable in Figure 104, first the tensions in the wires are equal to the pretension (40 mt and +/- 60 mt) and the system does not oscillate. Then a pulse is applied to the system. The system starts to oscillates in a constant amplitude and period. This is the same for the tension in the wires (springs). In other words, this proves that the pretension does not pull the system in a different equilibrium with respect to the static equilibrium. In Figure 105 noticeable, the springs do only exert a force to the system when the wires are stretched. The pretension is removed in Figure 105.

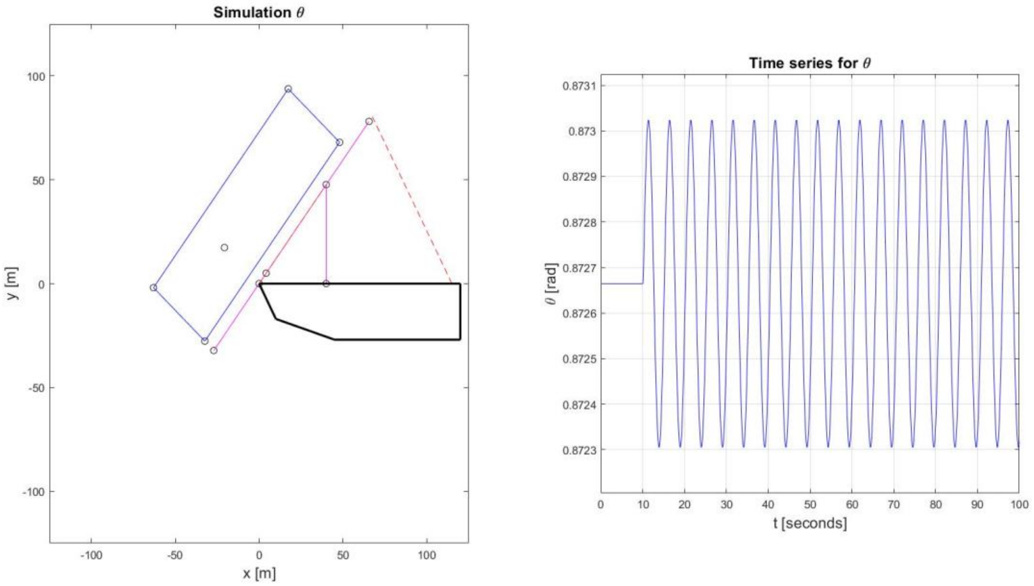


Figure 103: Check Single Pulse Dynamic Calculation Model

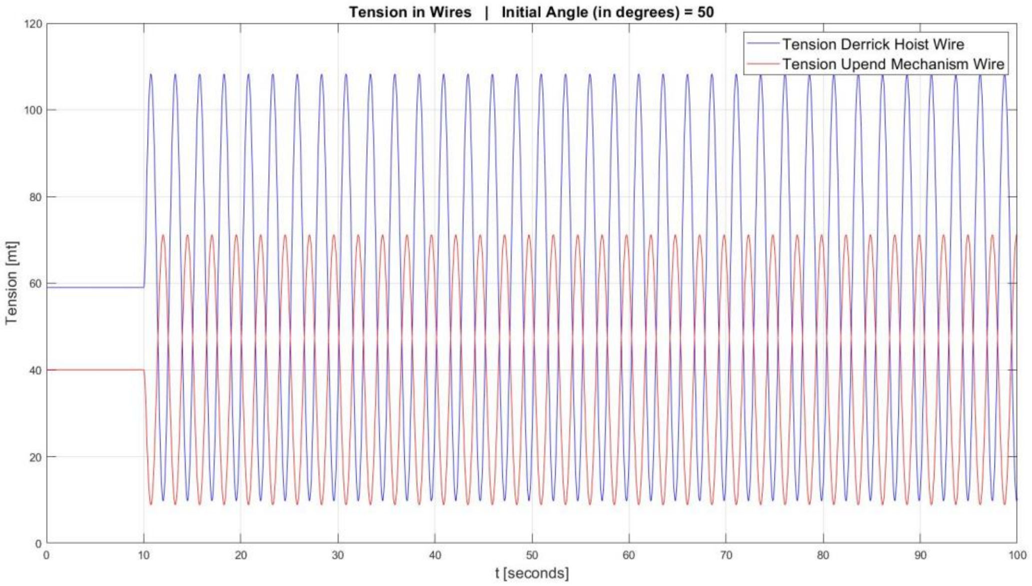


Figure 104: Pretension Check

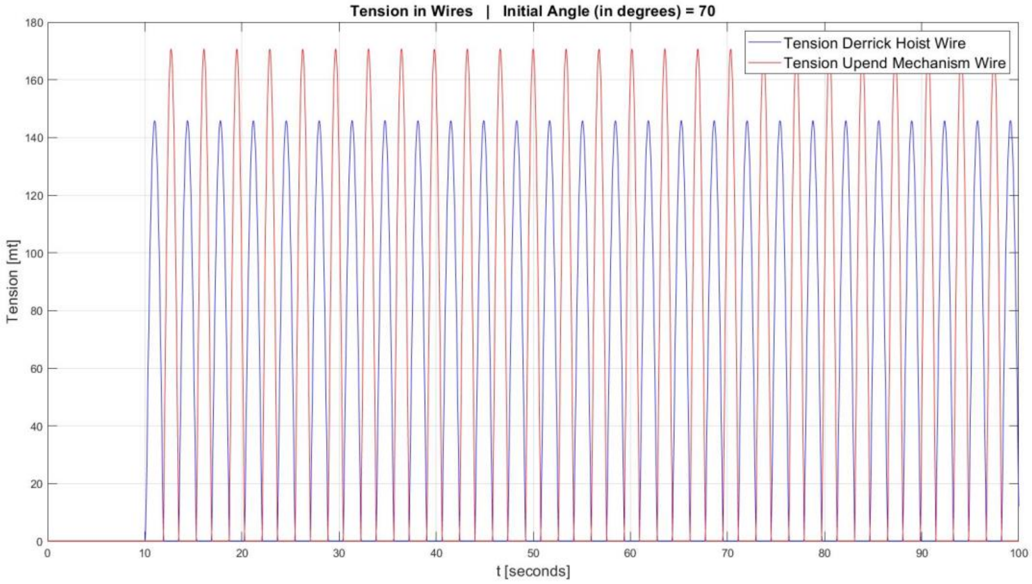


Figure 105: Springs Working Under Tension check

Geometric Properties:

The two (mass)components in the system may slide/roll against each other but must always be connected to each other. This is checked by inspecting the summation of the angles in the system. The summation must be 180 degrees. In addition, an animation is used. As with the other testing methods, this check was conducted for all 115 degrees for theta in which the system can be positioned and for all optimisation parameters. An example of the summation of the angles is given in Figure 106.

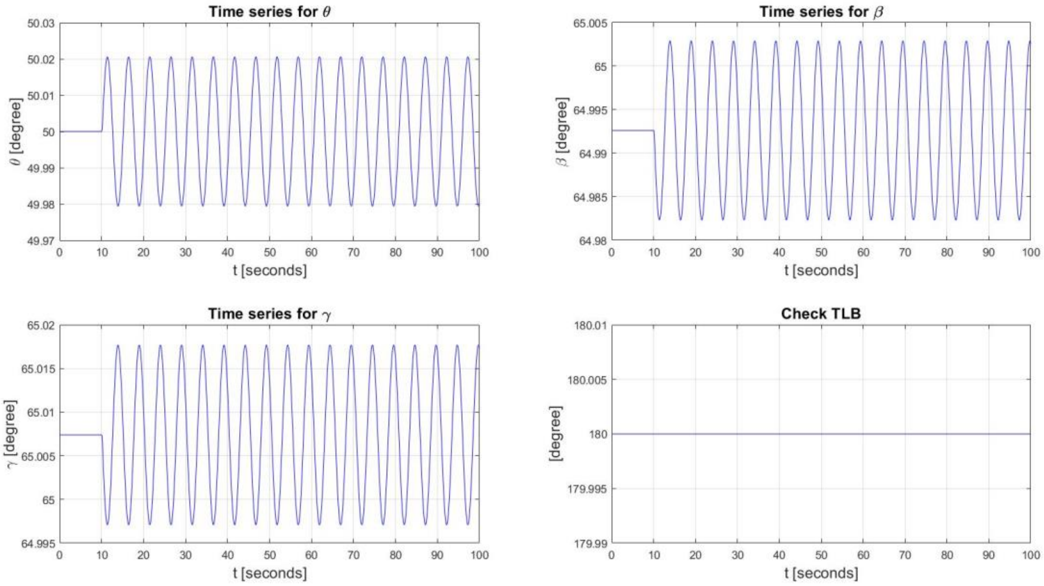


Figure 106: Check Geometry Dynamic Calculation Model

Conclusion

The system behaves as expected. It is likely that the calculation model for the dynamic behaviour of the system produces representative results.

7.4 Environmental Input

In the equation of motions, which mathematically describes the movements of the system with respect to the vessel, the vessel motions in waves are represented by the terms u_dd1, u_dd2, u_dd3, v_dd1, v_dd2 and v_dd3. These terms represent the horizontal and vertical acceleration at the support point of the rigid construction of the Upend/Tilt-over Mechanism (point PV), the support point of the Tilting Lift Beams (point 0) and the connection point of the Derrick Hoist System (point H). The positions (for verifying purposes) and accelerations are calculated using the response spectrum (paragraph 7.4.1).

The Response Spectra at the support points for the positions and accelerations are calculated for 13 different headings. The headings are in a range from 0 degree to 180 degrees in steps of 15 degrees. The orientation of the headings in reference to Pioneering Spirit is given in Table 23 and Figure 107.

Heading 1	0	Heading 6	75	Heading 11	150
Heading 2	15	Heading 7	90	Heading 12	165
Heading 3	30	Heading 8	105	Heading 13	180
Heading 4	45	Heading 9	120		
Heading 5	60	Heading 10	135		

Table 23: Overview Heading Directions Incoming Waves

With regard to the environmental input, the commonly used reference system in the maritime sector is applied. This reference system is shown in Figure 107. This figure includes the orientation of the headings, the origin of the reference system, the centre of gravity of Pioneering Spirit and the definition of the vessel motions in 6 degrees of freedom.

Environmental Reference System, Positions Origin and Centre of Gravity and Definition Vessel Motions:

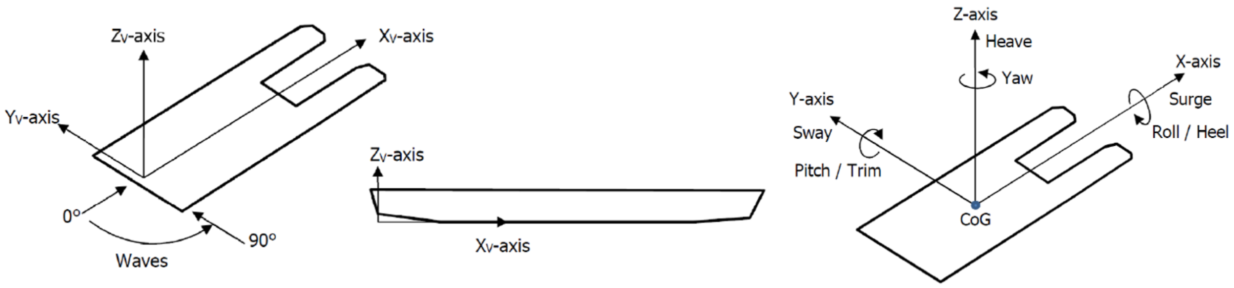


Figure 107: Environmental Reference System, Origin, Position Centre of Gravity and Definition Vessel Motions

The coordinates of the Centre of Gravity of Pioneering Spirit in the maritime reference system:

Name Point	Point	X Coordinate [m]	Y Coordinate [m]	Z Coordinate [m]
Centre of Gravity	CoG	170	0	14

Table 24: Coordinates Centre of Gravity of Pioneering Spirit in the Environmental Reference System

The coordinates of Points H, 0 and PV, which are the connection points of the Derrick Hoist System and the support points of the Tilting Lift Beams and rigid structure of the Upend/Tilt-over Mechanism (See also Figure 98 (page 126)) are given below in Table 25.

Name Point	Point	X Coordinate [m]	Y Coordinate [m]	Z Coordinate [m]
Support point Tilting Lift Beams	0	-5	40	18
Support Point rigid construction	PV	35	40	18
Connection point Derrick Hoist System	H	105	40	18

Table 25: Coordinates Support points 0, PV and H in the Environmental Reference System

7.4.1 Response Spectrum

The response spectrum ($E_X(\omega)$) at the support points of the system for position or acceleration, in horizontal or vertical direction and in a certain heading is calculated by multiplying the wave spectrum ($S_\zeta(\omega)$) with the squared absolute value of the transfer function of the Response Amplitude Operator (RAO) ($\widehat{R}_X(\omega)$) at that particular support point, for position or acceleration, in horizontal or vertical direction and in a certain heading [53].

$$E_X(\omega) = S_\zeta(\omega) \cdot \left|\widehat{R}_X(\omega)\right|^2 \qquad [m^2s] \text{ or } [m^2/s^3]$$

Where:
X represents position/acceleration, horizontal/vertical direction and the chosen heading.

Wave Spectrum [$S_\zeta(\omega)$]

As mentioned in the Introduction, Allseas has designated the North Sea Region as the target area for installing and removing Jackets using Pioneering Spirit. The wave conditions in which Pioneering Spirit, and the Jacket Lift System, has to operate is given in Table 6 (page 31). To recapitulate: The maximum significant wave height is set to 2.5 meters, the mean centroid wave period to 6 seconds and the wave statistics are described by the Modified (Two-Parameter) Pierson-Moskowitz Wave Spectrum, also known as the ITTC Wave Spectrum [38]. The Modified Two-Parameter Pierson-Moskowitz Wave Spectrum is especially suitable for open sea areas with fully developed waves [53] and is given by [38]:

$$S_\zeta(\omega) = \frac{173 \cdot H_{\frac{1}{3}}^2}{T_1^2} \cdot \omega^{-5} \cdot \exp\left(-\frac{692}{T_1^4} \cdot \omega^{-4}\right) \qquad [m^2s]$$

The spectrum depends on the Significant wave height (H_s), the mean centroid wave period (T_1) and is displayed per frequency (ω). The wave spectrum of the designated sea state is shown in Figure 108.

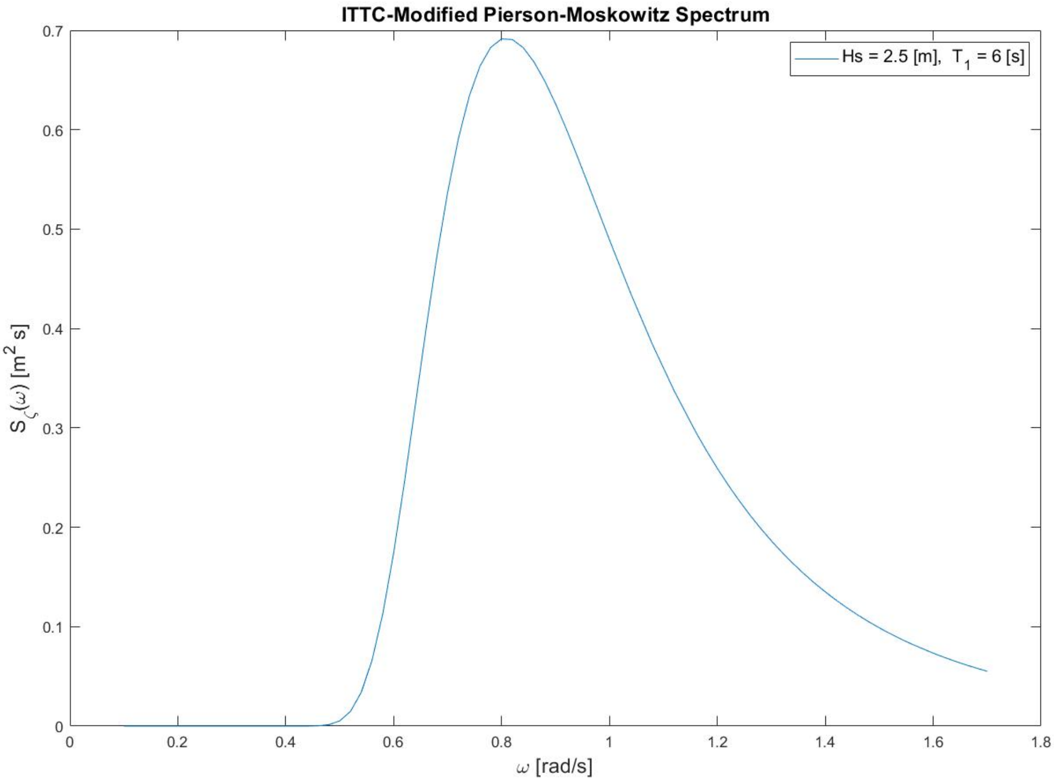


Figure 108: ITTC-Pierson-Moskowitz Spectrum

Transfer Function of the Response Amplitude Operator (RAO) $[\widehat{\mathrm{R}}(\omega)]$

The displacement, velocity and acceleration in horizontal or vertical direction at a particular location in the vessel can be calculated using the transfer function of the Response Amplitude Operators (RAO's) in the Centre of Gravity (CoG) of the vessel. The RAO('s) represent the motions of the vessel in the different frequencies and headings. The RAO's are usually obtained by studying the behaviour of scale models in a test basin and/or by using specialised Computational Fluid Dynamics (CFD) computer models [54].

The absolute motion for an arbitrary point in the vessel in x, y and z direction is calculated by [38]:

$$\begin{aligned} x_p &= x - y_n \cdot \psi + z_n \cdot \theta && [\mathrm{m}] \\ y_p &= y + x_n \cdot \psi - z_n \cdot \phi && [\mathrm{m}] \quad \{1\} \\ z_p &= z - x_b \cdot \theta + y_b \cdot \phi && [\mathrm{m}] \end{aligned}$$

Where:

x_n, y_n and z_n are the coordinates of the point of interest in reference of the CoG of the vessel

x, y, z, ϕ, θ and ψ are the vessel motions about the CoG.

The angles are calculated in radians, the motions are linearized ($\sin(\theta) \approx \theta$ and $\cos(\theta) \approx 1$ [38]

The amplitude (p_a) and the phase shift ($\epsilon_{h\zeta}$) for x_p, y_p and z_p are calculated by [38]:

$$p_a = \sqrt{\left(h_a \cdot \sin(\epsilon_{h\zeta})\right)^2 + \left(h_a \cdot \cos(\epsilon_{h\zeta})\right)^2} \qquad [\mathrm{m/m}]$$

$$\epsilon_{p\zeta} = \arctan\left(\frac{h_a \cdot \sin(\epsilon_{h\zeta})}{h_a \cdot \cos(\epsilon_{h\zeta})}\right) \qquad \text{with } 0 \leq \epsilon_{h\zeta} \leq 2 \cdot \pi \qquad [\mathrm{rad}]$$

Where:

$$\begin{aligned} h_a \cdot \cos(\epsilon_{h\zeta}) &= z_a \cdot \cos(\epsilon_{h\zeta}) - x_b \cdot \theta_a \cdot \cos(\epsilon_{h\zeta}) + y_b \cdot \phi_a \cdot \cos(\epsilon_{h\zeta}) \\ h_a \cdot \sin(\epsilon_{h\zeta}) &= z_a \cdot \sin(\epsilon_{h\zeta}) - x_b \cdot \theta_a \cdot \sin(\epsilon_{h\zeta}) + y_b \cdot \phi_a \cdot \sin(\epsilon_{h\zeta}) \end{aligned}$$

The acceleration is calculated by taking the second derivative of the displacement with respect to time [38]:

$$\ddot{p}_a = -\omega^2 \cdot p_a \cdot \cos(\omega_e \cdot t + \epsilon_{p\zeta}) \qquad [\mathrm{m/ms^2}]$$

$$\text{or} \qquad \ddot{p}_a = \omega^2 \cdot p_a \cdot \cos(\omega_e \cdot t + \epsilon_{p\zeta} - \pi) \qquad [\mathrm{m/ms^2}]$$

The elaboration above applies to any point in the vessel for a vertical motion(z_p) and acceleration ($\ddot{z}_p$). The other directions are calculated according to the same method, taking into account the right signs ("+" and "–") (see {1} above). In this thesis project, the vertical (z) and horizontal (x) motions are considered.

Response Spectrum Support Points

So, the response spectrum ($E_X(\omega)$) at an arbitrary point in the vessel for position or acceleration, in horizontal or vertical direction and in a certain heading is calculated by multiplying the wave spectrum ($S_\zeta(\omega)$) with the squared absolute value of the transfer function of the Response Amplitude Operator (RAO) ($\widehat{R}_X(\omega)$). An example of this multiplication is given in Figure 109.

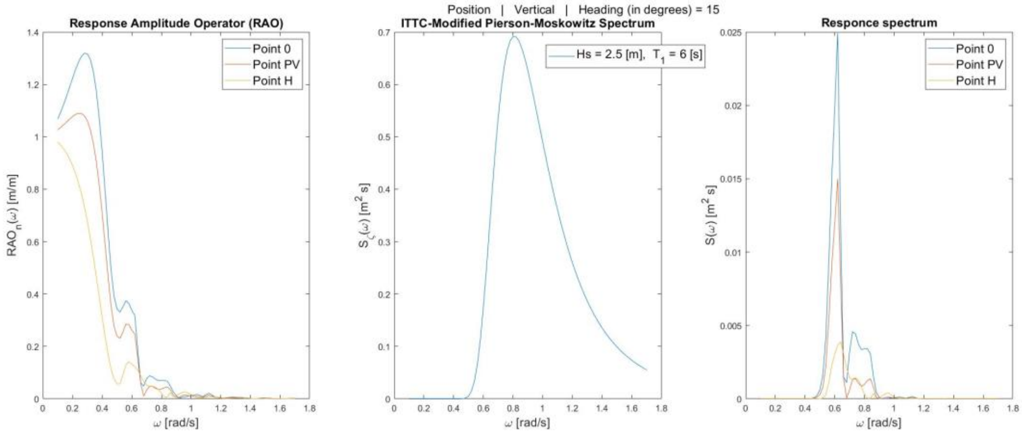


Figure 109: Response Spectrum for Acceleration in Vertical Direction in a Heading of 15 degrees

The response spectra per heading of the position and acceleration at the support point is included in Appendix G. This comprises 13 figures.

Frequency Range

With regard to the natural frequency of the system, one is interested in the highest frequency in the response spectra. The type of system in this thesis project is known for the high possibility of having a natural frequency in the range of the response spectra. If the natural frequency of the system is in this range, the system must be stiffened until it has a higher frequency than the highest frequency in the response spectra. The highest frequency in the response spectra per support point in all headings is shown in Figure 110. These figures are later used in the natural frequency analysis.

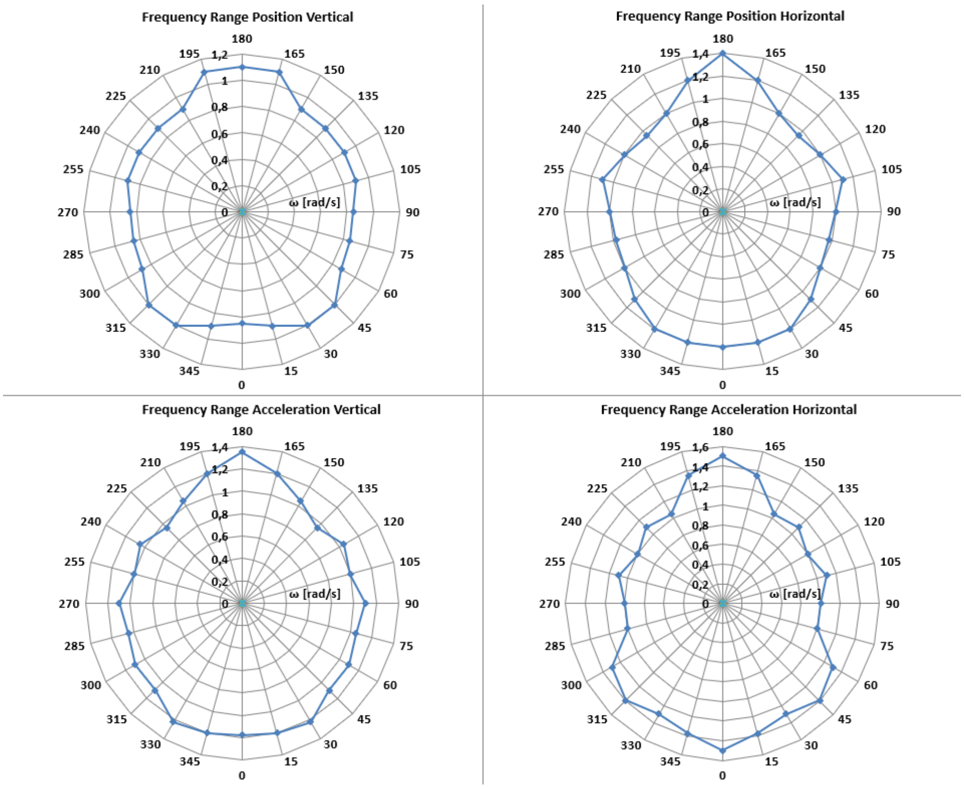


Figure 110: Overview Highest Frequencies at the Support Points for all Headings, Position/Acceleration in Vertical/Horizontal Direction

7.5 Natural Frequency and Operation Window

Resonance:

The phenomena resonance can be described as a sharp increase of the response amplitude for a certain combination of parameters (or: an infinite small response can lead to an infinite large response) [47]. Resonance can occur when the frequency of the excitation is close to the natural frequency of the system [49]. A system in resonance does not require input energy for an increasing response. Resonance is (in general) checked by the ratio between the frequency of the excitation and the natural frequency (Magnification Factor). If this ratio is close to 1, resonance may occur. (Source Figure 111 [48]).

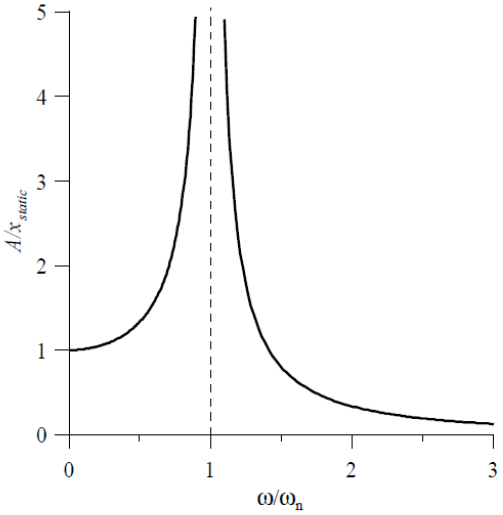


Figure 111: Visualisation of the Magnification Factor, Excitation Frequency and Natural Frequency

To check whether or not the natural frequency of the system is close to the excitation frequency due to vessel motions, a (partial) free vibration analysis is carried out. Free vibrations mean that no external forces are applied to the system.

Natural Frequency Calculation Experimentally

The natural frequency of a system can be determined mathematically and experimentally. In the experimental method, a pulse is applied to the system. As a result, the undamped system will oscillate at its natural frequency. This must be done for all scenario's (see paragraph 7.3.5 (page 134)), all optimisation parameters and all possible angles for theta (1 – 115). The resulting oscillation is the homogeneous solution and must be synchronic [50]. Synchronic means that the system oscillates in the same frequency regardless of the magnitude, position and orientation of the pulse. This has also been checked during the validation of the system (paragraph 7.3.5 (page 134)).

Natural Frequency Calculation Mathematically

A more accurate method to check the natural frequency and the operation window is to calculate the natural frequency mathematically. The system in this thesis project is linear and time- invariant. This means that the mass (m) and stiffness (k) of the system do no change in time. This only applies for an analysis per angle of theta (the static equilibrium. For linear systems, the natural frequency can be found by solving the generalised eigenvalue problem [49]. However, due to the formulation of the equation of the motion and the constraints of the system, the natural frequency is only determined by the experimentally method. An elaboration of this choice is given in Appendix H.

Operation Window and Stiffness

The natural frequency depends on the moment of inertia and the stiffness of the system. In other words, a system with a jacket applied on the Jacket Lift System has a different natural frequency compared to a situation without a jacket applied on the Jacket Lift System and a system with pretension is stiffer than a system without pretension. These effects are examined and resulted in the final configuration described in paragraph 7.8.

A valuable tool in finding the most favourable configuration is a plot of the natural frequency expressed as a function of theta, the angle of the Tilting Lift Beams with respect to the aftdeck of Pioneering Spirit. With this plot, the critical angle can be easily found. An example for a random configuration is shown in Figure 112.

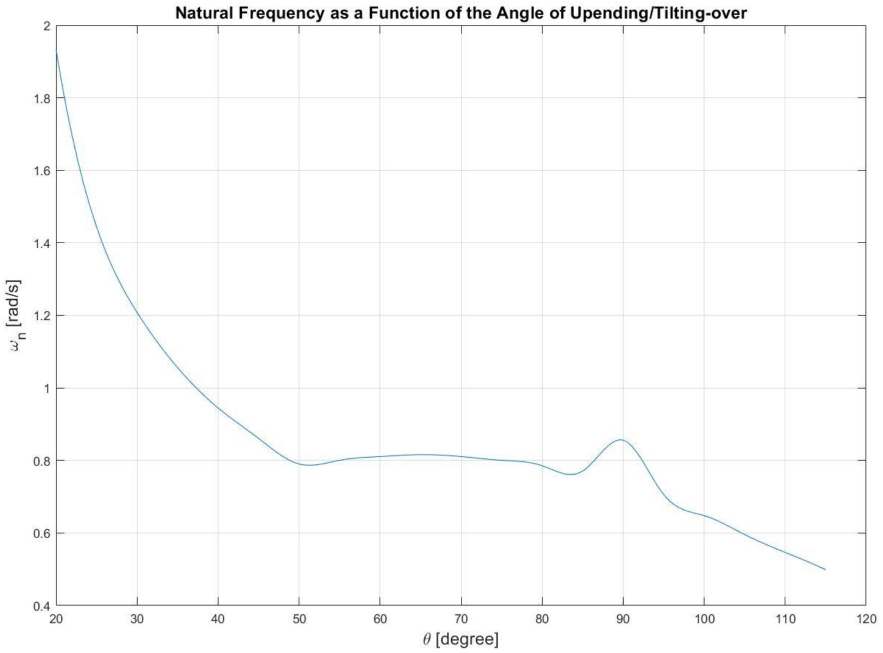


Figure 112: Natural Frequency Expressed as a Function of the Angle of Upending/Tilting-over

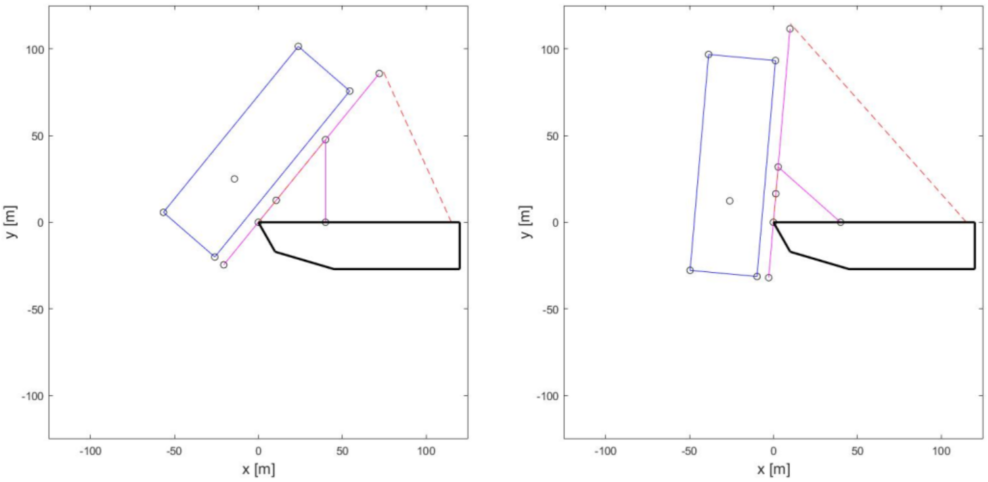


Figure 113: Position System theta = 50 and theta = 85

Observed from Figure 112, the natural frequency is the lowest for an upended position of 115 degree. An angle of 115 degrees for the lowest natural frequency is no surprise as the length of the wires of the Derrick Hoist System is the largest in this position. With a constant Young's modulus, the axial stiffness of the cables reduces with initial length.

The axial stiffness is given by:

$$k = \frac{AE}{L} \qquad [N/m]$$

where:

A = cross section area [m^2]
E = Young's Modulus [N/m^2]
L = Length of the wire [m]

7.6 Dynamic Stability

The static equilibrium of the system for different angles of theta was investigated in chapter 5 and 6. To recapitulate, a system is in its static equilibrium if the sum of the horizontal, vertical and rotational static forces is individually zero [38]. In addition, the system must be dynamically stable as well. The system in this thesis project comprises two inverted pendulums. A pendulum is by definition unstable except in a downward position. Nevertheless, the system includes two linear springs (wires) especially included to provide stability and include controllability of the position of the system. The system in this thesis project is, as mentioned earlier, a linear and time- invariant system given that the process is assumed to be discreet. (An analysis per angle of theta (the static equilibrium).

Dynamic Stability

In the definition of dynamic stability, a distinction can be made between asymptotically stable and marginally stable [55]. A system is defined asymptotically stable when its free vibration response approaches zero as time approaches infinity. A system is defined marginally stable if the response of the free vibration remains constant (as time approaches infinity) [55]. The system in this thesis project is undamped and should be marginally stable. The definition of instability is given by a free vibration response that grows without bound as time approaches infinity [55]. The growth of the amplitude of the response of an unstable system is commonly non-linear [49]. The source causing instability does not have to contain a vibrating component [47]. For instance, a single pulse or viscous damping can cause instability as well.

Stability Check Approach

The stability of a system can be determined mathematically and experimentally. The system is experimentally checked by exciting the system by means of a pulse. The resulting free vibration response of the system should be marginally constant, as explained above. This check is also conducted during the "validation" of the dynamic model elaborated on page 134. However, for a more thorough and accurate stability test the system should be checked mathematically. The same calculation method as described for the natural frequency is used. The stability of a system depends and is fully described by the character of the roots of the characteristic polynomial [47]. The dynamic stability is checked by looking whether one of the eigenvalues has a positive real part [47]. If this is true, the system is unstable. A reference is made to Appendix H for an elaboration about mathematically solving the stability.

Displacement Ratio Angles Tilting Lift Beams and Rigid Construction

The angle of the rigid construction in reference to the Tilting Lift Beams is an important subject to take into consideration. This angle is defined as α (see Figure 114). The angle α must be smaller than 90 degrees during the entire upend/tilt-over process. If this angle is larger than 90 degrees, the connection between the rigid construction and the Tilting Lift Beams is lost and the system is instable. The length of the rigid construction is chosen such that this situation will not occur in the designated sea state. However, at the beginning of the upend process and the end of the tilt-over process, α is close to an angle of 90 degrees. This is because α in initial position is 90 degrees. In addition to the angle α limited by a maximum angle of 90 degree, the ratio of the movement is also important to mention. At the beginning of the upend operation and at the end of the tilt-over operation the length of the rigid construction of the Upend/Tilt-over Mechanism is relatively small. This causes the rigid construction of the Upend/Tilt-over Mechanism to rotate over a large angle (ϕ) with respect to a small angle for the Tilting Lift Beams (θ). This ratio is shown for 4 initial angles of theta in Appendix J. Also shown in the figures is the magnitude of the displacement of the slider/roll connection between the Tilting Lift Beams and the rigid construction of the Upend/Tilt-over Mechanism. Observable in the figures, when angle theta is small, less than 30 degrees, the movement of the slider/roller is non-linear (see Figure 235). As mentioned, the ratio between θ and ϕ is large for a small angle of θ. The system is stiff as a result of the movement and the ratio of displacement between the two components for this small angle of θ.

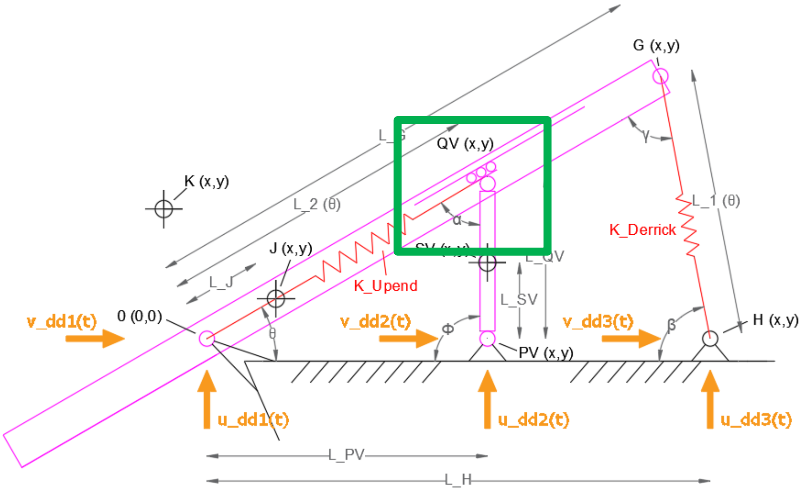


Figure 114: Schematisation of the System regarding Dynamics in Vessel Motions

A measure that has been taken is to hold the structure for the first/last 30 degrees for theta with the help of an auxiliary structure. This means that the rigid construction of the Upend/Tilt-over Mechanism cannot rotate during the first/last 30 degrees of the upend/tilt-over operation. The tension in the upend/tilt-over wire is now applicable to the auxiliary structure. At an angle of 30 degrees for theta, this fixation is released/applied. The length of the rigid construction of the Upend/Tilt-over Mechanism is 23.1 m at this moment. In addition, it is also important to hold the system during the first/last 30 degrees for theta of the upend/tilt-over operation due to the ratio of the pretension of the Derrick Hoist System and the Upend wires. To achieve a static equilibrium during this phase, a large pre-tension is required.

7.7 Response in Vessel Motions and Corresponding Forces

The focus in this thesis project is on the controllability and the feasibility of the design solution. Part of the feasibility study is the maximum forces in and to the system. The same topics as considered in the static analysis are considered in the dynamic analysis. The topics are repeated in the enumeration given below.

Forces considered:
- Tension Derrick Hoist Wires
- Pressure in rigid upend/tilt-over mechanism
- Tension in wire(s) upend/tilt-over mechanism
- Vertical reaction force at the hinge point
- Horizontal reaction force at the hinge point
- Vertical reaction force at the upend/tilt-over mechanism
- Horizontal reaction force at the upend/tilt-over mechanism

In this thesis project, the dynamic behaviour consists of the response of the system due to vessel motions in waves. The vessel motions in waves are represented by the accelerations on the support points of the system. The response of the system, as described earlier, is expressed in terms of theta, the angle of the system in reference to the aftdeck of Pioneering Spirit. The maximum forces in the system occur when the perturbation from the initial position, the static equilibrium, is the largest. This maximum perturbation from the static equilibrium may occurs when the system is excited by the maximum acceleration at the support points. The maximum acceleration at the support points can be obtained statistically based on the most probable maximum accelerations at the support points. Another method to determine the biggest perturbation from the static equilibrium is based on a simulation of the response of the system in irregular vessel motions. At this point, it is unclear which method will show the largest perturbation from the static equilibrium.

The most probable maximum acceleration at the support point of the system and the corresponding response in the frequency domain is described in paragraph 7.7.1. The maximum perturbation from static the equilibrium based on irregular vessel motions is described in paragraph 7.7.2.

7.7.1 Most Probable Maximum Acceleration at Support Points (Frequency Domain)

As mentioned above, one method to determine the maximum response amplitude is by calculating the maximum accelerations at the support points. The maximum accelerations are applied in the equation of motions for a single pulse or/and regular wave resulting in the corresponding response amplitude. A method for calculating the maximum acceleration at the support points is the statistic most probable maximum amplitude (of the acceleration oscillations) in the frequency domain. The Rayleigh Amplitude Distribution is used for this. The Rayleigh Amplitude distribution is an ocean wave specific version of the Probability Density Function [42]. The Rayleigh Amplitude distribution may be used with the assumption that the range of frequencies in a wave field is not to large and that the surface elevation follows a gaussian distribution [38]. The Rayleigh Amplitude distribution is given by:

$$\mathrm{f(x)} = \frac{\mathrm{x}}{\sigma^2} \cdot \exp\left\{-\left(\frac{\mathrm{x}}{\sigma\cdot\sqrt{2}}\right)^2\right\}$$

Where:

x = variable being studied (the acceleration (a [m/s^2]))
σ = standard deviation (the area under the spectral curve (see Figure 109)

The standard deviation is calculated by the square root of the moment of area under the response spectrum ($\mathrm{E_X}(\omega)$) at $\omega = 0$ [38]:

$$\sigma = \sqrt{\mathrm{m_{0,X}}}$$ (X represents orientation and location of support point)

The moment of area under the response spectrum at $\omega = 0$ is calculated by [38]:

$$\mathrm{m_{0,X}} = \int_0^\infty \omega^0 \cdot \mathrm{E_X}(\omega)\, d\omega$$

The maximum acceleration amplitude is calculated by determining the maximum amplitude with a certain probability of exceedance. This is a thorough tested statistically-based guess [38]. The probability of exceedance used in this thesis project for the frequency domain is derived from the time domain analysis. The probability of exceedance is set to 1/1000. This probability is based on a storm with a duration of 3 hours. It is assumed that it takes no longer than 3 hours in a storm before the maximum value has occurred. Important to mention, the sea state in this analysis is of course not a sea state of a storm.

The probability of exceedance is given by [42]:

$$P(X > x) = F_x(x) = \frac{1}{1000} \qquad \frac{\text{Numer of wave tops with (X>x) in duration D}}{\text{Total number of wave tops in duration D}} = \frac{\overline{f_x}}{\overline{f_0}}$$

Where/resulting in:

$$F_x(x) = \int_a^\infty f(x)\,dx = \frac{1}{m_{0,X}} \int_a^\infty x \cdot \exp\left\{-\frac{x^2}{2 \cdot m_{0,X}}\right\} dx = \exp\left\{-\frac{a_X^2}{2 \cdot m_{0,X}}\right\}$$

This results in a maximum acceleration of:

$$a_x = \sqrt{2 \cdot m_{0,X} \cdot -\ln\left(\frac{1}{1000}\right)} \qquad \text{(X represents orientation and position)} \qquad [m/s^2]$$

The results are shown in Figure 115. The most severe situation occurs in beam waves (90 or 270 degrees).

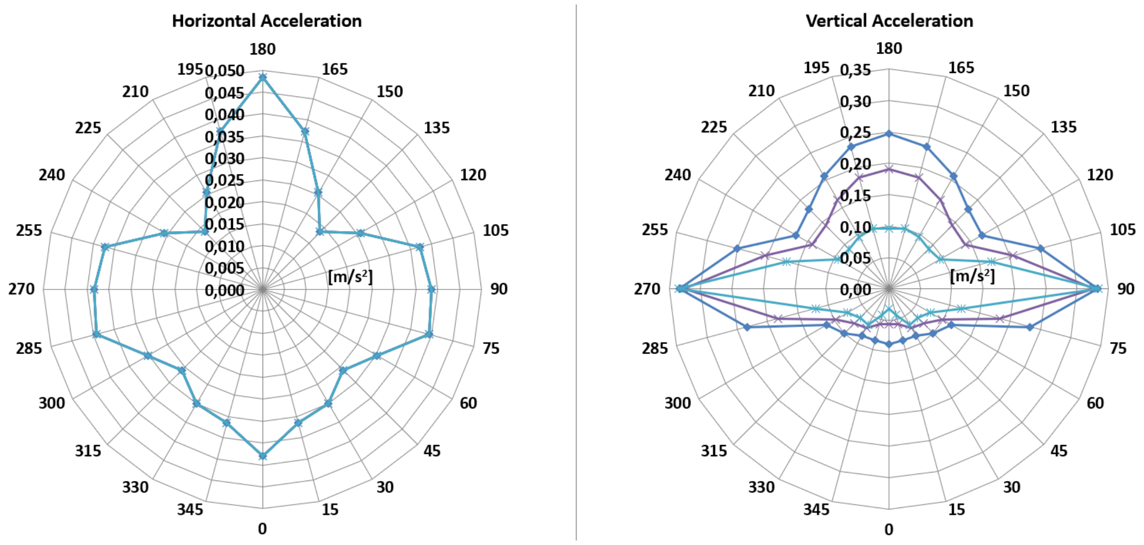


Figure 115: Maximum Acceleration in Different Headings with Corresponding Response Amplitude for the Most Unfavourable Initial Angle (Frequency Domain)

The accelerations shown in Figure 115 are used to find the maximum response amplitude for theta for different configuration parameters. The results of the proposed configuration are included in paragraph 7.8. The maximum response amplitude of the system ($\Delta\theta$) is calculated by subtracting the initial angle (θ_0) from the maximum/minimum angle (θ_{max} and θ_{min}):

$$\Delta\theta = |(\theta_{max} \text{ or } \theta_{min}) - \theta_0| \qquad [rad]$$

7.7.2 Most Probable Maximum in Irregular Waves

The second method to determine the maximum response amplitude of the system is to perform a Time Series Simulation in irregular vessel motions. A strong point of this method is that the behaviour of the system is also included. The maximum acceleration, at a support point in the system, does not have to occur when the system is in its static equilibrium position. This can also occur when the system has already been perturbated from the static equilibrium. This can result in a greater response amplitude.

A time-series simulation for the accelerations at the support point in horizontal and vertical orientation can be obtained from the response spectrum of the support points. This is done by performing an Inverse Fourier Transformation. The following equation is used [38]:

$$\zeta_X (t) = \sum_{i=1}^{I} \zeta_{a,i} \cos(k_i \cdot x - \omega_i \cdot t + \epsilon_i) \qquad \text{[m] or [m/s}^2\text{]}$$

The amplitude ($\zeta_{a,i}$) is determined by calculating the area under the associated segment of the response spectrum ($E_X(\omega)$) [38]:

$$\zeta_{a,i} = \sqrt{2 \cdot E_X(\omega) \cdot \Delta\omega} \qquad \text{[m] or [m/s}^2\text{]}$$

The wave number (k_i) is determined by the dispersion relationship [53]:

$$\omega^2 = g \cdot k \cdot \tanh(k \cdot d)$$

Where:

d	= Water depth	[m]
k	= Wave Number	[m^{-1}]
g	= Gravitational acceleration	[m/s^2]
ω	= Radial frequency	[rad/s]

An example of a time record of an irregular wave and the irregular wave motions for position and acceleration at the support points in a heading of 45 degrees is given in Figure 116, Figure 117 and Figure 118.

The maximum response amplitude of the system ($\Delta\theta$) is calculated by subtracting the initial angle (θ_0) from the maximum/minimum angle (θ_{max} and θ_{min}):

$$\Delta\theta = |(\theta_{max} \text{ or } \theta_{min}) - \theta_0| \qquad \text{[rad]}$$

The results for the proposed configuration for the wires in the design solution are shown in paragraph 7.8 using a polar plot for the maximum response amplitude of theta.

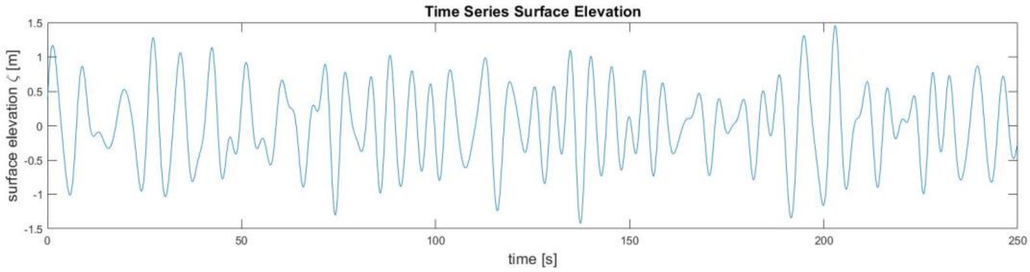


Figure 116: Time Record Irregular wave Surface Elevation

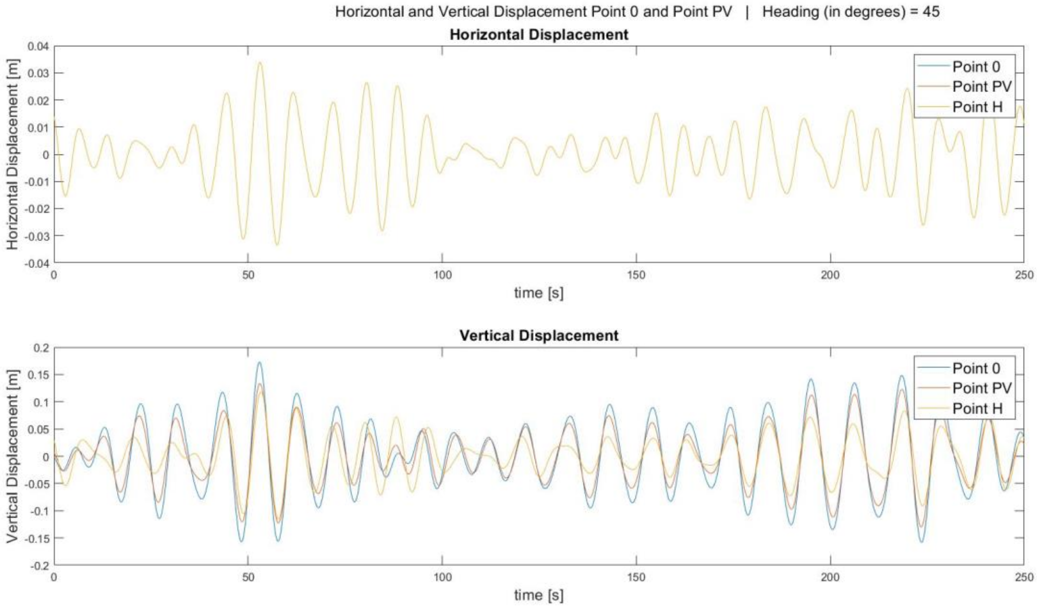


Figure 117: Time Record Irregular Wave of the Support Points Position

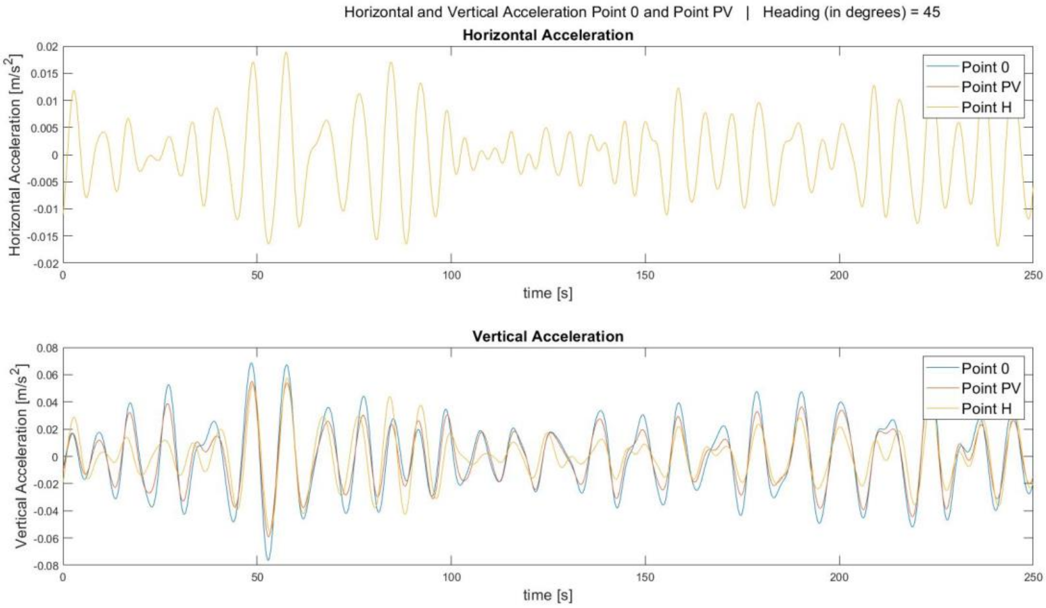


Figure 118: Time Record Irregular Wave of the Support Points Acceleration

7.7.3 Dynamical Forces

Small angles are assumed for the maximum response of the system in vessel motions. The motions are therefore linearized ($\sin(\theta(t)) \approx \theta$ and $\cos(\theta(t)) \approx 1$). The schematisation of this dynamic analysis is for convenience repeated in Figure 119. The dynamic forces assessed in this thesis project are calculated by:

Dynamic tension in Derrick Hoist Wires (F_{k1} or $F_{k,Derrick}$) and Upend/Tilt-over Mechanism wires (F_{k2} or $F_{k,Upend}$):

$$F_{k1} = k_1 \cdot \frac{L_1 - L_{1,0} + dL_{1,0}}{g \cdot 1000} \qquad [mt]$$

$$F_{k2} = k_2 \cdot \frac{L_2 - L_{2,0} + dL_{2,0}}{g \cdot 1000} \qquad [mt]$$

Dynamic pressure in rigid upend/tilt-over mechanism:

$$F_{BAR} = F_{k2} \cdot \cos(\alpha_0) \qquad [mt]$$

Dynamic pressure in Tilting Lift Beams:

$$F_{TLB} = F_{k1} \cdot \cos(\gamma_0) \qquad [mt]$$

Dynamic vertical and horizontal reaction force at the hinge support point

$$F_{v,0} = F_{TLB} \cdot \sin(\beta_0) \text{ or } -F_{k2} \cdot \sin(\theta_0) \qquad [mt]$$

and

$$F_{h,0} = -F_{TLB} \cdot \cos(\beta_0) \text{ or } -F_{k2} \cdot \cos(\theta_0) \qquad [mt]$$

Dynamic vertical and horizontal reaction force at the Upend/Tilt-over Mechanism support point

$$F_{v,PV} = F_{Rigid\ Construction} \cdot \sin(\phi_0) \qquad [mt]$$

and

$$F_{h,PV} = F_{Rigid\ Construction} \cdot \cos(\phi_0) \qquad [mt]$$

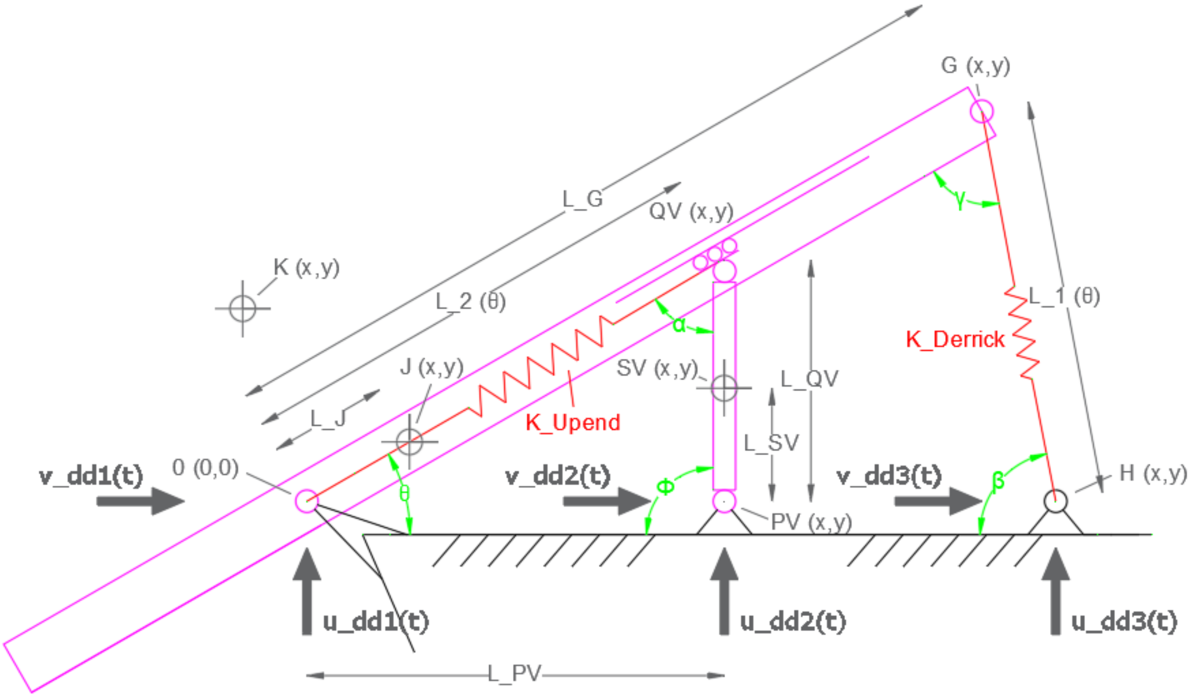


Figure 119: Overview Angles

7.8 Dynamic Evaluation Configuration Design Solution

This paragraph contains the results of the proposed configuration of the Jacket Lift System. The methods for calculating the dynamic forces are explained in the previous paragraphs. For each topic, a reference to the relevant paragraph has been included in the results.

Examining the most favourable and feasible configuration for the wires of the Derrick Hoist System and the Upend/Tilt-over Mechanism has resulted in the following configuration:

Reference wire [45]:

Type/class:	6xK36-IWRC		
MBL:	974		[mt]
SWL:	240 (factor 1/4)		[mt]
Diameter:	110		[mm]
Young's Modulus:	125000		[N/mm^2]
Number of wires and reeving:			
Derrick Hoist System	10 wires	1 reeving	[-]
Upend/Tilt-over Mechanism	8 wires	1 reeving	[-]
Pretension:			
Derrick Hoist System	20 - 205		[mt]
Upend/Tilt-over Mechanism	25 - 350		[mt]

Pre-tension		
Angle θ	Derrick Hoist Wires	Upend/Tilt-over Mechanism Wires
30	187,3	25
35	118,3	30
40	90,66	35
45	75,69	40
50	66,38	45
55	65,77	50
60	65,97	55
65	65,45	60
70	64	65
75	61,47	70
80	115,7	150
85	166,4	250
90	204,3	350
95	117,3	250
100	57,74	150
105	31,25	100
110	25,22	100
115	20,3	100

Table 26: Pre-tension Derrick Hoist Wires and Upend/Tilt-over Mechanism Wires

This configuration is tested regarding the natural frequency and operation window, the stability and the maximum response amplitude. The tests are conducted for the scenario's in which the Jacket Lift System has to operate (described in paragraph 3.3.2 (page 28)) supplemented with optimisation parameters. This comprises:

- No Jacket applied on the Tilting Lift Beams
- Jacket applied on the Tilting Lift Beams

7.8.1 Natural Frequency and Stability Check

Natural Frequency

The natural frequency for the different angles in which the system can be positioned for a situation with and without jacket is given in Figure 120. The natural frequencies are determined as described in paragraph 7.5. The most critical value in reference to the most critical value of the vessel's response is shown in Figure 121. The most critical natural frequency without the reference jacket applied on the Jacket Lift System is shown in purple. The most critical natural frequency with the reference jacket applied on the Jacket Lift System is shown in red. It is clear that the natural frequency of the proposed system configuration is not in the frequency range of the vessel motions. Therefore, it is unlikely that resonance will occur in the assessed sea state. The system positioned in the most far upended position, theta is 115, is for both scenario's the most critical angle regarding the natural frequency.

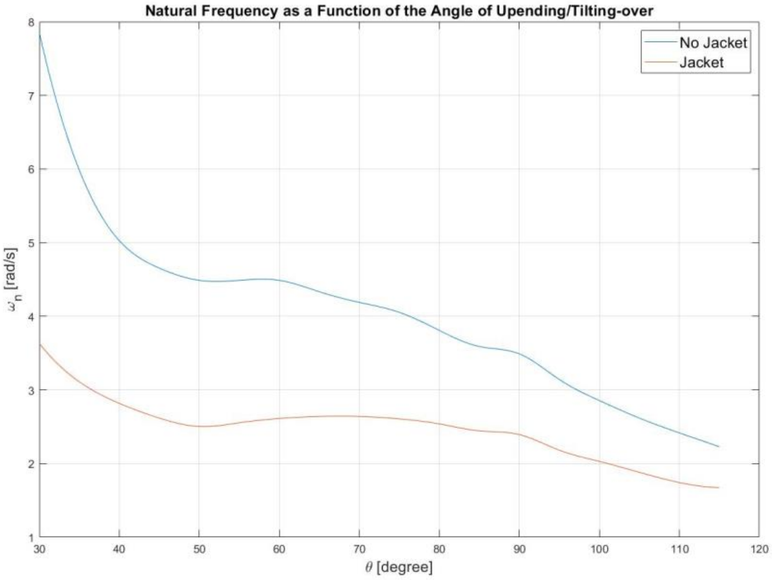


Figure 120: Natural Frequency with and without Jacket for the Angles of Theta

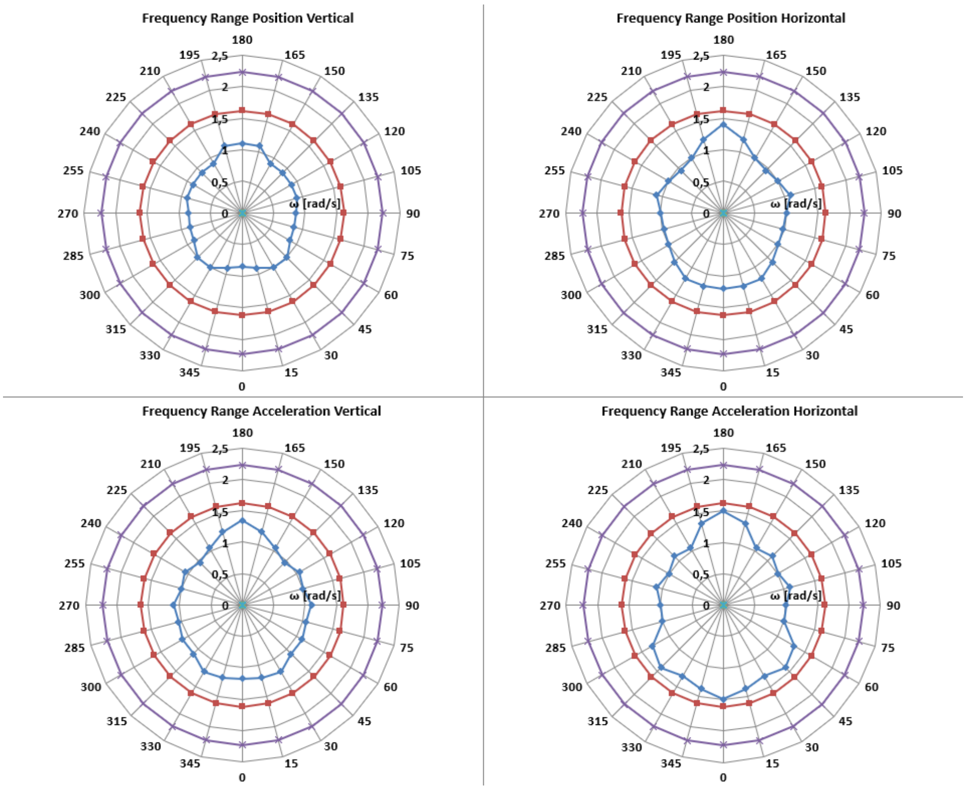


Figure 121: The Most Critical Natural Frequency in Reference to the Upper Bound in Terms of the Frequency in the Response Spectra

Stability

The experimental stability check for the configuration was conducted for all angles of theta in which the system van be positioned for all 13 headings. The system is marginally stable for all these situations. The method applied is explained in paragraph 7.6.

7.8.2 Maximum Response Amplitude and Maximum Forces

Maximum Response Amplitude

The maximum response amplitude is calculated as described in paragraph 7.7 using the frequency domain and a time series simulation. The maximum response amplitude based on the frequency domain in shown in Table 27. The maximum responses are presented for every 5 degrees for theta in which the system can be positioned. The largest values are marked in red. The results of the time series simulation are presented in Figure 122 for 6 different angles of theta in all headings. The **largest amplitude is 0,0027 radians**. The maximum responses are included in the results for the maximum dynamic forces and the maximum total forces, static plus dynamic.

Based on the maximum response in the frequency domain and time series, the most unfavourable position for the Jacket Lift System appeared to be in an angle for theta of 90 degrees. The most unfavourable heading is in the direction of beam waves, 90/270 degrees in reference to the vessel. The response amplitude in a time series simulation is greater compared to a frequency domain. The main reason is that in a time series the waves are calculated using a random phase. It is possible that the system is excited again while it has not yet returned to the static equilibrium position. The maximum values for the maximum forces in the system are therefore originate from the time series. A safety factor must be applied in the final dimensioning.

The maximum responses based on the frequency domain are displayed below.

Frequency Domain		
Angle θ	**Maximum Response [rad]**	
	No Jacket	**No Jacket**
30	2,49E-05	9,80E-06
35	1,76E-05	9,06E-06
40	1,49E-05	8,13E-06
45	1,26E-05	6,90E-06
50	1,00E-05	5,28E-06
55	3,47E-06	1,30E-06
60	7,15E-06	4,23E-06
65	1,56E-05	9,62E-06
70	2,53E-05	1,60E-05
75	3,75E-05	2,44E-05
80	5,66E-05	3,83E-05
85	1,07E-04	7,47E-05
90	5,04E-04	**3,14E-04**
95	**9,67E-04**	6,91E-05
100	5,12E-05	3,63E-05
105	3,72E-05	2,66E-05
110	3,18E-05	2,29E-05
115	3,00E-05	2,16E-05

Table 27: Maximum Response Amplitude for the Proposed Configuration, frequency based

The maximum responses based on the time series are displayed on the next page.

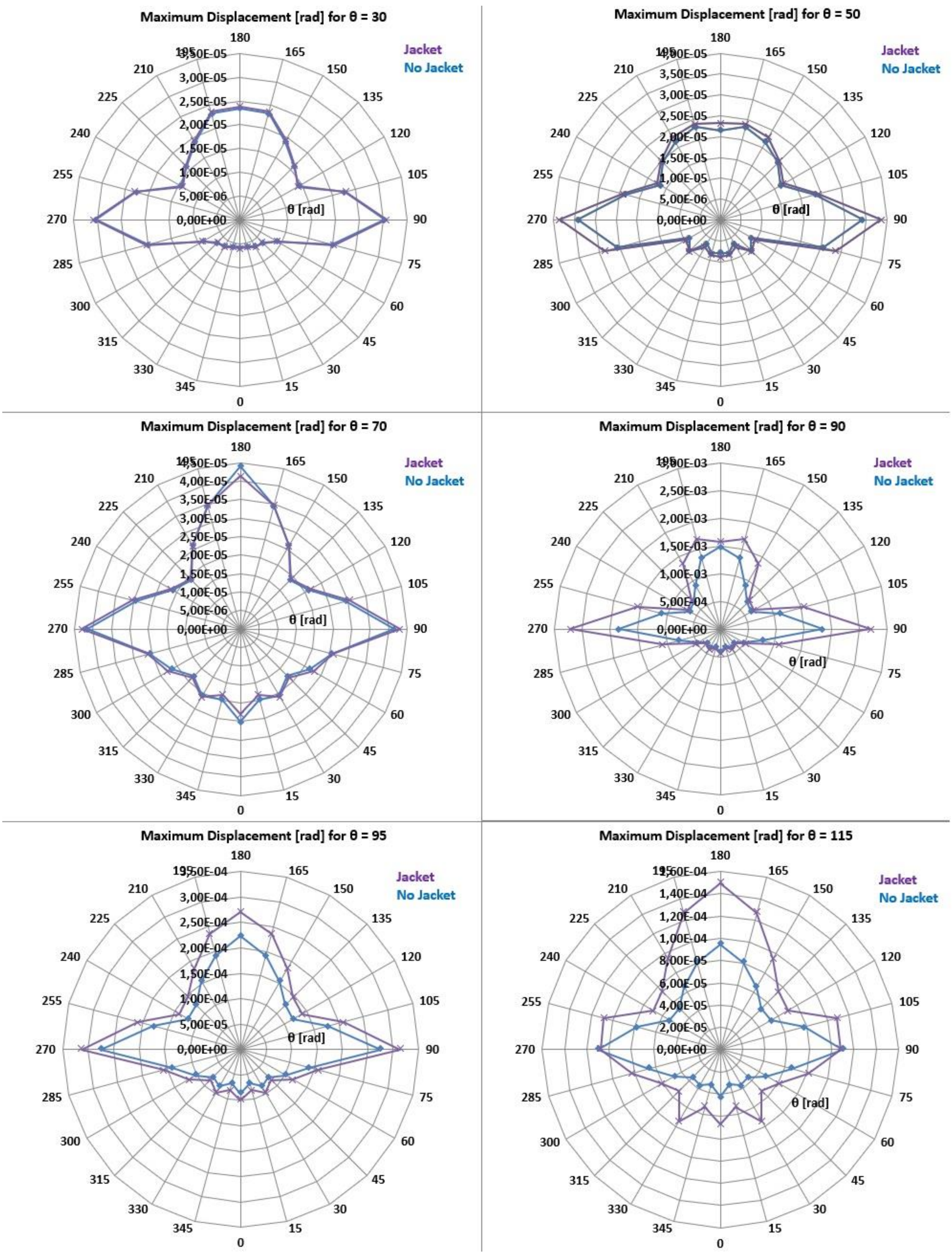


Figure 122: Maximum Response Amplitude for the Proposed Configuration, Time Series Based

Maximum Dynamic Forces

The maximum dynamic forces obtained according to the method explained in paragraph 7.7.3 are shown in Table 28.

	Theta θ [degrees]	**Maximum Dynamic Force [mt]**
Tension Derrick Hoist Wires	90	1035
Pressure in rigid Upend/Tilt-over Mechanism	90	1107
Tension in wire(s) Upend/Tilt-over Mechanism	90	1917
Vertical reaction force at the hinge point	90	1917
Horizontal reaction force at the hinge point	90	536
Vertical reaction force at Upend/Tilt-over Mechanism	90	655
Horizontal reaction force at Upend/Tilt-over Mechanism	90	892

Table 28: Maximum Dynamic Forces for the Proposed Configuration

The dynamic forces in the system are extremely large due to the required pre-tension to prevent wires hanging slack. The dynamic forces are much lower for angles for theta smaller than 90 degrees and larger than 90 degrees.

Maximum Total Forces and Ratio Dynamic/Total Forces

The maximum forces of both the static and the dynamic analysis are shown in Table 29. These total forces have been determined by summing-up the dynamic forces to the static forces. It was important to look at when the maximum forces occur for both the static forces and dynamic forces. The total forces in the system are extremely large.

Component	**Theta θ [degrees]**	**Static Force [mt]**	**Dynamic Force [mt]**	**Total Force [mt]**	**Dynamic/ Total Force**
Tension Derrick Hoist Wires	115	3110	1035	4145	25%
Pressure in rigid Upend/Tilt-over Mechanism	1	2069	25	2094	1.2%
Tension in wire(s) Upend/Tilt-over Mechanism	90	0	1917	1917	0%
Vertical reaction force at the hinge point	23	31704	85	31789	0.3%
Horizontal reaction force at the hinge point	115	2610	75	2685	2.8%
Vertical reaction force at Upend/Tilt-over Mechanism	90	4434	655	5089	12.9%
Horizontal reaction force at Upend/Tilt-over Mechanism	90	880	892	1772	50.3%

Table 29: Maximum Forces and Ratio

7.9 Overall Evaluation/Conclusion on Feasibility

This evaluation includes the final conclusion on the feasibility and favourability of the design solution for the Upend/Tilt-over Mechanism for Pioneering Spirit's Jacket Lift System developed in this thesis project. This final conclusion comprises an evaluation of the maximum forces and an overall assessment based on the qualitative subjects of earlier concept development parts.

Dynamic Forces and the Ratio with the Total Forces

The dynamic forces in the system caused by vessel motions in waves are generally small in reference to the total forces. Less than 5%. An exception is the range close to a vertical position of the system. In this position, the wires are in terms of the controllability the least effective. A large pre-tension is required to prevent the wires from slacking. This also results in a maximum response amplitude in this position. The largest ratio of the dynamic force in the derrick hoist wires in reference to the total force is 0.5. Furthermore, it is striking that the maximum tension in the derrick hoist wires occurs when the system is completely upended. The main reason is the fast-increasing static force during the last part of the upend process. In this position, the contribution of the dynamic forces due to vessel motions in waves is 25%.

The ratio between the dynamic and total forces in general depends on the angle in which the system is positioned (theta). An important influence is the distribution of the static forces at a certain angle of theta. In other words, it depends on which mechanism is responsible for acquiring the static equilibrium. The responsible mechanism switches during the upend/tilt-over operation. With this phenomenon, the ratio between the dynamic force and total force also changes considerably. For example, at an angle of 50 degrees for theta the tension in the derrick hoist wires, along with the pretension, is 100% induced by the dynamic behaviour of the system in vessel motions. In a fully upended position this is, as aforesaid, 25%.

Magnitude of the Maximum forces and feasibility

The total forces in the system are excessively large. The static forces deliver in general the largest contribution to the total forces. At a certain moment in the tilting procedure, the entire mass of the Jacket Lift System (15 000 mt) and Jacket (15 000 mt) is applied to the pivot points at the stern of Pioneering Spirit. As already elaborated in the analysis of the static forces, the foundation of the hinge points can and must be strengthened. This can be done by applying large arrangements to the base of the support points. Other activities on lower decks may not be affected. The maximum tension in the derrick hoist wires is 4125 mt. The maximum tension in the upend/tilt-over wires 1917 mt. The proposed configuration for the wires of the Derrick Hoist System and the Upend/Tilt-over Mechanism have a SWL of 4800 mt and 3840 mt. This is sufficient to resists the loads in the systems. To draw conclusions on the feasibility of the total forces, based on the dynamic forces induced by vessel motions in waves and the static forces to acquire a static equilibrium, it is in the author's opinion possible to design and construct equipment that can resist the exorbitant large forces. The uncertainly, however, remains large because of the lack of experience with this kind of systems.

Stiffness, Natural Frequency and Stability

The required stiffness of the system is similar to the total forces also exorbitantly large. To prevent the system from having a natural frequency in the same frequency range as the response of the vessel in ocean waves, an extremely rigid wire arrangement must be applied. To obtain a sufficient rigid system, many winches are required. With regard to the Derrick Hoist System, 10 winch system are required, all of which must be placed in an effective position. 8 winch systems are required for the Upend/Tilt-over Mechanism. An evaluation on the placement of the winch systems is elaborated below. Due to the extremely rigid system configuration, the response amplitude of the system in vessel motions is small. The proposed configuration for the wires is marginally stable in all scenarios and situations.

Compatibility in the Current Appearance of Pioneering Spirit
The compatibility of the winch systems is a concern, however considered feasible. The Derrick Hoist system will consist of 10 winches. The 10 winches can be placed in a line integrated in the derrick hoist skids attached to the reinforced transverse frame on the aftdeck of Pioneering Spirit. The reinforced transverse frame must be strengthened to resist the largest forces. The Upend/Tilt-over Mechanism will consist of 8 winches. The installation of these winches is more complicated with regard to the limited deck space and the detachability of the system. A solution was found by integrating those winches in the tilting lift beams. The configuration is shown in chapter: Preliminary Design.

Workability of the System
The response of Pioneering Spirit in the designated wave conditions is such that it causes small movements and accelerations at the support points. In the designated sea state, the static forces to obtain a static equilibrium are the largest contribution to the maximum forces. However, when examining the effects of the wave conditions, it appears that when the significant wave height and in particular the mean period increases, the dynamic response of Pioneering Spirit increases rapidly. A sufficient margin has been included to resist a small exceedance of the designated sea-state, taking into account the assessed contributions. Though, it is important to assess the weather forecast before and during every upend/tilt-over operation. The upend/tilt-over operation lasts a maximum of 12 hours, during this period the sea-state can change rapidly. The workability is considered feasible.

New Equipment Required
Many new extra equipment is required. Additional winches must be added and an auxiliary structure must be applied during the first and last 30 degrees of the upend/tilt-over operation. Fortunately, these extra devises can be installed in the tail of the Tilting Lift Beams and close to the already reinforced transverse frame at the aftdeck of Pioneering Spirit. During the development of the concept design solution, extra equipment was added to the design step by step. This is disadvantageously with regard to the new equipment. However, the positive assessment on new equipment and the installation position of the equipment still applies. Although a lot of additional equipment is required with regard to the other concepts, the equipment can be installed at favourable locations on the vessel and the advantages with regard to the maximum forces are still decisive. The configuration is shown in chapter: Preliminary Design.

Complexity of the Operation
The complexity of the procedure has also become increasingly complex during concept development. For example, during the first and last 30 degrees of the upend/tilt-over process, the system must be held in a vertical position by means of an auxiliary structure to prevent instability of the system and to keep the response of the system manageable. According to the author, however, these additions do not have to cause problems. The upend/tilt-over operation is a slow process. During this process, the additional work can be carried out without significantly delaying the total operation.

Investment Costs
The extra equipment must be heavy constructed. This results in high investment costs and leaves only few suppliers who have the capacity and are skilled enough to produce and deliver the equipment. All in all, the expectation is that this Jacket Lift System involves high investment costs. However, in view of the other assessment points and the fact that the additional equipment mostly can be constructed at a separate construction site, the investment costs is considered to be the most favourable.

Conclusion

The conclusion of this thesis project is, similar to the entire elaboration of the thesis project, divided into 4 main parts. Parts 2 and 3 are the most important parts in this conclusion. Parts 2 and 3 are the parts where the design solution for the mechanism to upend/tilt-over a jacket was investigated and developed.

Conclusion part 1, Design Information

The first part of the concept development was to perform a coarse background study of the main subjects in this thesis project. The central question in this part was "What are the most critical and important system requirements and aspects regarding the upend and/or tilt-over component of the Jacket Lift System?" This central research question was answered by answering:

- What are the (technical) specifications and dimensions of normative jackets at this moment and in the future?
- What are the operational conditions and (technical) specifications of Pioneering Spirit?
- What is the general procedure of a jacket installation/removal and what must the system be able to do?

The information collected in this part is not required to be included in this conclusion. The dimensions of the noramtive jacket and designated operation conditions are given below.

The normative jacket used in this thesis project is a single lumped beam and described by:

Length of the jacket	$L_{Jacket,1}$	= 130	[m]
Height of the jacket	$H_{Jacket,1}$	= 15	[m]
Width of the jacket	$W_{Jacket,1}$	= 40	[m]
Mass of the jacket	$M_{Jacket,1}$	= 15 000	[mt]
Centre of Gravity TLB	$x_{CoG, Jacket,1}$	= 40	[m] (from bottom)
	$y_{CoG, Jacket,1}$	= 20	[m]

The conditions in which Pioneering Spirit must be able the upend/tilt-over the normative jacket is:

Significant wave height	2.5	[m]	
Wave period (centroid mean)	6	[s]	Spectrum type: Pierson-Moskowitz
Wind Speed	12	[m/s]	1-hour average, 19 m above sea level
Current	0.5	[m/s]	

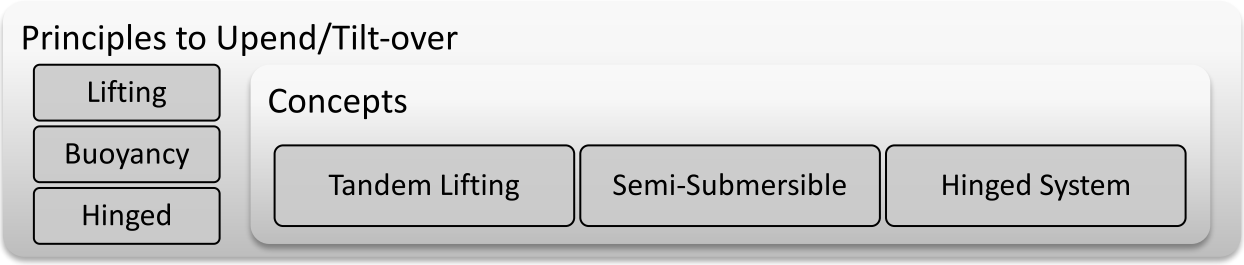
Conclusion part 2, Concept Development

In the second part, Concept Development, a design solution was developed. The central question "What is the favourable (drive) mechanism to upend/tilt-over the system keeping the feasibility, compatibility, controllability, efficiency and the finances in mind?" was used. In order to develop a design solution in a coherent and accurate manner, the development was subdivided into three subparts with the following sub questions:

- Principe to Upend/Tilt-over
  - Which principles are possible, wide-ranging, to upend/tilt-over a jacket?
  - What components in the principles are most favourable?
- Upend/Tilt-over Mechanism
  - Based on the favourable principle, which concepts as (drive) mechanism to upend/tilt-over are possible?
  - What are the static forces on the system during the upend/tilt-over operation to obtain a static equilibrium?
  - What are (the most) important parameters/influences in the composed concepts?
- Concept Choice and Optimisation
  - What optimisation and combination are possible and what is favourable?

Principe to Upend/Tilt-over:

An enormous amount of principles to upend/tilt-over the system was possible in this first concept development subpart. The number of principles was narrowed down to 3 basic principles, each with an as general as possible concept. The principles were summarised by the principles to upend/tilt-over the system based on its own **buoyancy (1)**, a **lift operation (2)** and a **hinged support frame (3)**.



The three principles were qualitatively assessed based on the following assessment criteria:

- Compatibility in Pioneering Spirit's current appearance
- Workability of the system in offshore conditions
- New Equipment required
- Complexity of the upend/tilt-over procedure
- Investments costs

This has led to the following conclusion:

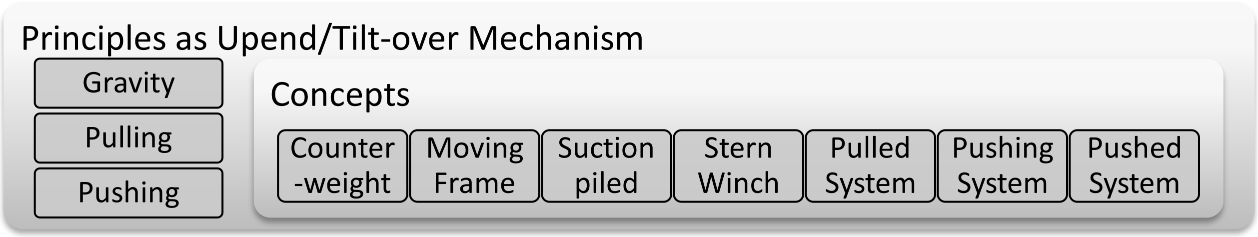
The principle **Buoyancy** with the semi-submersible concept is considered non-feasible. Too many modifications are required to integrate this principle and concept in Pioneering Spirit's current appearance. The investment costs will be exorbitant and the vessel must be completely redesigned and rebuilt.

The offshore sector has experience with **Lifting** type of operations. The specifications of Pioneering Spirit are such that a large gain in capacity can be achieved in comparison with competing vessels in the Offshore market. The ability to transport a jacket on Pioneering Spirit's own deck complements the concept of installing and removing a jacket using a tandem lift principle with Pioneering Spirit. However, the process of manoeuvring a jacket from the stern of the vessel to the aftdeck and vice versa will be complex. The crane tips must operate independently. This causes negative influences with regard to the loads on the jacket and the position keeping of the jacket. Moreover, the fact that existing cranes must be replaced, the construction of Pioneering Spirit must be strengthened at the base of the cranes and the investment of the already installed cranes is lost is a decisive disadvantage.

The principle based on a **Hinged Support Frame** has been used in the design of Pioneering Spirit. Facilities for this type of system have already been applied. If the design is adapted to these facilities, a system based on this principle can be easily implemented in the current appearance of Pioneering Spirit. No major adjustments and hindrances to other activities are expected. The workability of this principle is considered favourable. The jacket is connected to the support frame during the upend/tilt-over operation. This results in a total system that is less sensitive to environmental effects and easier to control. The biggest disadvantage of this concept is that similar systems do not exist. This means that the degree of uncertainty about the feasibility is high. However, the hinged system principle appeared to be the most favourable principle to apply on Pioneering Spirit, based on the assessment criteria used. The thorough and detailed vessel design of Pioneering Spirit leaves no other principles and concepts than the principle of the reference design that was developed in the past.

Upend/Tilt-over Mechanism:

The focus in the second concept development subpart was on acquiring information about the static forces required to obtain a static equilibrium during the upend/tilt-over operation, to understand what is mechanically desirable and what the most important influencers are during the operation. The main topic in this concept development subpart was the mechanism to initiate the motion to upend/tilt-over the system. 7 main concepts were elaborated based on a gravitational, pushing and pulling principle.



The seven concepts were assessed qualitatively and quantitively on the following assessment criteria:

- Quantitively: static forces/equilibrium
    - Static forces required to obtain a static equilibrium during the upend/tilt-over procedure
    - Maximum power use during the upend/tilt-over procedure
- Qualitatively: complexity and new equipment
    - Complexity of the mechanism’s upend/tilt-over procedure
    - New Equipment required

This has led to the following conclusion:

Based on the static equilibrium, the concepts **Counterweight, Moving Frame, Suction Piled and Push/Pull system** are excluded. The **Stern Winch** and the **Pushing System** are the only concepts that are considered feasible as a standalone concept. Between these two concepts, the **Pushing System** concept is favourable in terms of the maximum static forces on the system, maximum required power, complexity of the system and the required new equipment. The main reasons for this are the smaller maximum forces for all assessed static forces in the **Pushing System** concept and the positioning of the equipment. The equipment is located above the water level and on the aftdeck. The equipment can be monitored during the entire upend/tilt-over operation and is easier to install/remove before/after completion of an operation.

The biggest disadvantage of the **Pushing System** concept is the lateral force in the rigid construction during the extension/shortening of the pushing system. The pushing component must consist of segments as a result of the length of the pushing component. This type of system cannot withstand large lateral forces. Ideally, there would be no lateral force during the extension/shorting operation of the system. This biggest disadvantage may be resolved by combining the **Pushing System** with the **Push/Pull System**.

The **Push/Pull System** concept is unfavourable regarding the maximum static forces/equilibrium when the system is positioned at a small angle in reference to the aftdeck of Pioneering Spirit. However, if the angle of the system with the aftdeck of Pioneering Spirit is sufficiently large, the static forces to obtain a static equilibrium are comparable with the other concepts. The **Push/Pull System** concept is mainly conceived with the controllability of the system in mind. By not connecting the Tilting Lift Beams and the Upend/Tilt-over mechanism, the dynamic forces are not exerted on the connecting point but on the wires of the upend/tilt-over mechanism. It is easier and favourable to compensate dynamic contributions this way. This type of system may prevent lateral static forces in the pushing component as both parts of the system can be positioned independently of each other. In this way, it is possible to keep the pushing system in a vertical position during the elongation/shortening of the rigid component. Horizontal forces are compensated by the wires.

Furthermore, the maximum required force and power use to obtain a static equilibrium during the upend/tilt-over operation may be reduced by combining the new concept with the **Moving Frame** concept and/or the **Counterweight** concept. Although the **Counterweight** and the **Moving Frame** concepts are considered non-feasible or highly unfavourable, the concepts have potentially positive aspects. The equipment in both concepts is located above the waterline on the aftdeck or is integrated in the Tilting Lift Beams. Both concepts require little additional equipment and both concepts have in view of the static equilibrium in the Derrick Hoist System and the Upend/Tilt-over Mechanism positive values. The **Pushing System** concept combined with the **Push/Pull System** concept was chosen as the basic concept for further development.

Concept Choice and Optimisation:

In the last subpart of the concept development, the previously described favourable parts of the concepts were combined to find a most favourable design solution. The Pushing System concept was combined with the Push/Pull System concept. This new Push/Pull Variant System concept was subsequently combined with the Moving Frame concept, Counterweight concept and a combination of the Moving Frame concept and Counterweight concept. The Push/Pull Variant System concept was assessed on whether the combination eliminates the biggest disadvantages of the Pushing System concept, requires smaller maximum static forces to obtain a static equilibrium, uses the idea behind the controllability of the Push/Pull System concept and answers if it is beneficial to bring the joint centre of gravity closer to the pivot point and in which way. This examination resulted in the following findings:

The lateral force in the Upend/Tilt-over Mechanism is indeed eliminated by combining the Pushing System concept with the Push/Pull System Concept. Also, the assessed static forces are all smaller except the vertical reaction force of the upend/tilt-over mechanism. This is a result of the more favourable distribution of the masses of the system and the reference jacket between the support points.

Moving the centre of gravity closer to the pivot point was also favourable for all assessed static forces. The contribution of the masses of the components and the buoyancy are dominant, as expected. The masses and the point of application of the buoyancy are placed more favourable by moving the system closer to the hinge point.

Finally, the variant of combining the Push/Pull Variant System concept with the Moved Frame concept proved to be the most favourable combination to bring the centre of gravity closer to the pivot point. With regard to the static equilibrium, the required force by the Upend/Tilt-over Mechanism is reduced to 20% of the force required in the original Push/Pull Variant System concept. The same applies to the vertical reaction force at the pivot point of the upend/tilt-over mechanism. This was the biggest disadvantage that had to be solved. In some situations, the variant of the combination with the Moved Frame and the Counterweight concept appeared favourable. This applies in particular to the situation without a jacket applied on the Jacket Lift System. However, the reduction of the static forces, with and without a jacket applied on the Tilting Lift Beams in the variation with the Moved Frame is the largest. This is more decisive as this results in the required dimensions and whether or not the system is feasible.

Overall Conclusion on the Concept Development

It can be concluded that the Push/Pull Variant System concept meets the desired requirements and that the centre of the gravity of the system must be movable. The repositioning of the system must be carried out by moving the jacket Lift System closer to/away from the hinge of the Tilting Lift Beams prior to upending or after tilting-over. In this way, the maximum static forces are the lowest and the controllability the greatest.

Conclusion part 3, Dynamics in Vessel Motions and Feasibility

In the third part, Dynamics and Feasibility, the design solution, obtained in part 2, was further elaborated. Time dependent (Dynamic) contributions (vessel motions) were added to the feasibility analysis and the stability of the system was checked. This resulted in an answer whether the system is stable, an estimation of the total loads on the system and the controllability. Eventually, this resulted in the answer whether or not the chosen system is feasible.

Dynamic Forces and the Ratio with the Total Forces

The dynamic forces in the system caused by vessel motions in waves are generally small in reference to the total forces. Less than 5%. An exception is the range close to a vertical position of the system. In this position, the wires are in terms of the controllability the least effective. A large pre-tension is required to prevent the wires from slacking. This also results in a maximum response amplitude in this position. The largest ratio of the dynamic force in the derrick hoist wires in reference to the total force is 0.5. Furthermore, it is striking that the maximum tension in the derrick hoist wires occurs when the system is completely upended. The main reason is the fast-increasing static force during the last part of the upend process. In this position, the contribution of the dynamic forces due to vessel motions in waves is 25%.

The ratio between the dynamic and total forces in general depends on the angle in which the system is positioned (theta). An important influence is the distribution of the static forces at a certain angle of theta. In other words, it depends on which mechanism is responsible for acquiring the static equilibrium. The responsible mechanism switches during the upend/tilt-over operation. With this phenomenon, the ratio between the dynamic force and total force also changes considerably. For example, at an angle of 50 degrees for theta the tension in the derrick hoist wires, along with the pretension, is 100% induced by the dynamic behaviour of the system in vessel motions. In a fully upended position this is, as aforesaid, 25%.

Magnitude of the Maximum forces and feasibility

The total forces in the system are excessively large. The static forces deliver in general the largest contribution to the total forces. At a certain moment in the tilting procedure, the entire mass of the Jacket Lift System (15 000 mt) and Jacket (15 000 mt) is applied to the pivot points at the stern of Pioneering Spirit. As already elaborated in the analysis of the static forces, the foundation of the hinge points can and must be strengthened. This can be done by applying large arrangements to the base of the support points. Other activities on lower decks may not be affected. The maximum tension in the derrick hoist wires is 4125 mt. The maximum tension in the upend/tilt-over wires 1917 mt. The proposed configuration for the wires of the Derrick Hoist System and the Upend/Tilt-over Mechanism have a SWL of 4800 mt and 3840 mt. This is sufficient to resists the loads in the systems. To draw conclusions on the feasibility of the total forces, based on the dynamic forces induced by vessel motions in waves and the static forces to acquire a static equilibrium, it is in the author’s opinion possible to design and construct equipment that can resist the exorbitant large forces. The uncertainly, however, remains large because of the lack of experience with this kind of systems.

Stiffness, Natural Frequency and Stability

The required stiffness of the system is similar to the total forces also exorbitantly large. To prevent the system from having a natural frequency in the same frequency range as the response of the vessel in ocean waves, an extremely rigid wire arrangement must be applied. To obtain a sufficient rigid system, many winches are required. With regard to the Derrick Hoist System, 10 winch system are required, all of which must be placed in an effective position. 8 winch systems are required for the Upend/Tilt-over Mechanism. An evaluation on the placement of the winch systems is elaborated below. Due to the extremely rigid system configuration, the response amplitude of the system in vessel motions is small. The proposed configuration for the wires is marginally stable in all scenarios and situations.

Compatibility in the Current Appearance of Pioneering Spirit
The compatibility of the winch systems is a concern, however considered feasible. The Derrick Hoist system will consist of 10 winches. The 10 winches can be placed in a line integrated in the derrick hoist skids attached to the reinforced transverse frame on the aftdeck of Pioneering Spirit. The reinforced transverse frame must be strengthened to resist the largest forces. The Upend/Tilt-over Mechanism will consist of 8 winches. The installation of these winches is more complicated with regard to the limited deck space and the detachability of the system. A solution was found by integrating those winches in the tilting lift beams. The configuration is shown in chapter: Preliminary Design.

Workability of the System
The response of Pioneering Spirit in the designated wave conditions is such that it causes small movements and accelerations at the support points. In the designated sea state, the static forces to obtain a static equilibrium are the largest contribution to the maximum forces. However, when examining the effects of the wave conditions, it appears that when the significant wave height and in particular the mean period increases, the dynamic response of Pioneering Spirit increases rapidly. A sufficient margin has been included to resist a small exceedance of the designated sea-state, taking into account the assessed contributions. Though, it is important to assess the weather forecast before and during every upend/tilt-over operation. The upend/tilt-over operation lasts a maximum of 12 hours, during this period the sea-state can change rapidly. The workability is considered feasible.

New Equipment Required
Many new extra equipment is required. Additional winches must be added and an auxiliary structure must be applied during the first and last 30 degrees of the upend/tilt-over operation. Fortunately, these extra devises can be installed in the tail of the Tilting Lift Beams and close to the already reinforced transverse frame at the aftdeck of Pioneering Spirit. During the development of the concept design solution, extra equipment was added to the design step by step. This is disadvantageously with regard to the new equipment. However, the positive assessment on new equipment and the installation position of the equipment still applies. Although a lot of additional equipment is required with regard to the other concepts, the equipment can be installed at favourable locations on the vessel and the advantages with regard to the maximum forces are still decisive. The configuration is shown in chapter: Preliminary Design.

Complexity of the Operation
The complexity of the procedure has also become increasingly complex during concept development. For example, during the first and last 30 degrees of the upend/tilt-over process, the system must be held in a vertical position by means of an auxiliary structure to prevent instability of the system and to keep the response of the system manageable. According to the author, however, these additions do not have to cause problems. The upend/tilt-over operation is a slow process. During this process, the additional work can be carried out without significantly delaying the total operation.

Investment Costs
The extra equipment must be heavy constructed. This results in high investment costs and leaves only few suppliers who have the capacity and are skilled enough to produce and deliver the equipment. All in all, the expectation is that this Jacket Lift System involves high investment costs. However, in view of the other assessment points and the fact that the additional equipment mostly can be constructed at a separate construction site, the investment costs is considered to be the most favourable.

Conclusion part 4, Preliminary Design

This final concept development part comprises a list with adjustments to the current appearance of Pioneering Spirit, new to install components and a description of the upend/tilt-over operation. An inventor sketch is added to clarify the design solution. Thus, this part includes the presentation of the design solution pertaining to the upend/tilt-over component of Pioneering Spirit's Jacket Lift System. The information gathered in this part is not suitable and required to include in this conclusion. A reference is made to page 167.

Final Conclusion

During this graduation project, it became clear again that upending/tilting-over of the designated jackets using Pioneering Spirit is complicated and that the maximum loads on the system are excessively large. Pioneering Spirit is designed and built to perform three main activities from which two activities are already put into operation. The processes of these activities may not be significantly modified or impeded. This leaves a limited amount of options and space for the Jacket Lift System, besides the design that was considered in the past and integrated in the construction of Pioneering Spirit. This makes it difficult to develop a system to install/remove a jacket for Pioneering Spirit. If a system is designed for another vessel or construction, perhaps a more effective system is conceivable. The systems must be heavily built and the investment costs and uncertainty about the feasibility are high. Furthermore, many specific aspects need to be further investigated. Examples are additional dynamic aspects and the forces in certain components on a detailed level. However, the concept design solution for the Upend/Tilt-over Component of Pioneering Spirit's Jacket Lift System is considered feasible and favourable, based on the assessment criteria and contributions that have been considered in the elaboration. An important remark is the foundation of the system (vessel construction of Pioneering Spirit). The design solution as conceived in this graduation project is described by a system that consists of a tilting support system that rotates over the stern of Pioneering Spirit, is driven by a pushing system installed on the reinforced transverse frames on the aftdeck and is movable to relocate the centre of gravity prior to upending or after tilting-over of the system. The system is controlled by two winch systems, one attached to the tip of the tilting lift beams (Derrick Hoist system, consisting of 10 winches) and the other to the upper pivot point of the pushing system (Upend/Tilt-over Mechanism, consisting of 8 winches). The system can be controlled in both rotational directions with the two winch systems. The tilting lift beams and pushing system are connected by means of a roller/slider connection.

Recommendations

In extend of this thesis project the analysis of the system should be expanded by investigating on the assumptions that have been taken, the points of concern found in the elaboration of the graduation project and analysing the detailed components. This includes, for example, the concerns about the strength of the construction of Pioneering Spirit and conducting a more advanced dynamic analysis.

Many assumptions and simplifications have been included in the elaboration of this thesis project. The assumptions with the biggest consequences are the assumption of representing the normative jacket as a lumped beam with uniform dimensions and the assumption that the components in the system are rigid. In the further elaboration a more detailed jackets should be used and more dynamic contributions should be included in the analysis of the loads, stability and controllability. This comprises jackets consisting of different heights, masses, beam diameters and brace patterns. Dynamic contributions (and/or quasi-static) that should be included in the further elaboration are:

- Environmental loads
    - Waves (pressure differences)
    - Wind
    - Current
    - Wave slamming

- Vessel motions due to positioning of the vessel

- Miscellaneous
    - Wake flow by the thrusters

In the assumptions, the system is assumed to be rigid. This simplification was made with regard to the objective to look at the total response amplitude of the system and the feasibility of the resulting maximum loads. In the further elaboration, the vibration and deformations in/of the system should be taken into consideration. This is part of the analysis of the local stresses in the components and the fatigue in the system.

No damping is considered in the coarse dynamic assessment in this graduation project. Usually, damping extracts energy from the system. This results in a smaller response amplitude of the system, but can also cause instability of the system, for instance, due to negative damping. With the more detailed jacket dimensions and additional dynamic contribution, damping can be included in the analysis. Also damping such as shearforces in the hinge points should be included.

The behaviour of the wires should also be included in the dynamic analysis. The required dimenions of the wires are large. Therefore, the mass of the wires will also be large. A large mass for the wires will defenetely affect the response of the system. Similar to the damping, the wire motions can damp the system, but can also cause resonance and instability.

Finally, the loads on Pioneering Spirit should be compared to the resistance of the construction of Pioneering Spirit. It is espected that strengtening measures must be taken at the support points of the Jacket Lift System. Which measures are required should be investigated. Furthermore, other stresses in Pioneering Spirit as a result of the system installed on the vessel should also be taken into consideration. An example is the bending stress in the hull. At a certain moment during the upend/tilt-over operation the entire mass of the Jacket Lift System and jacket is exerted to the stern of Pioneering Spirit.

Preliminary Design

In this final part of the thesis project, the design solution is presented. This includes a description of the upend/tilt-over operation and the components of the upend/tilt-over component of Pioneering Spirit's Jacket Lift System. An inventor sketch is added to clarify the description. A preview of the preliminary Design is shown in Figure 123. Dimensions and other structural subjects are not taken into account in the inventor sketch. The wires are not included in the sketch.

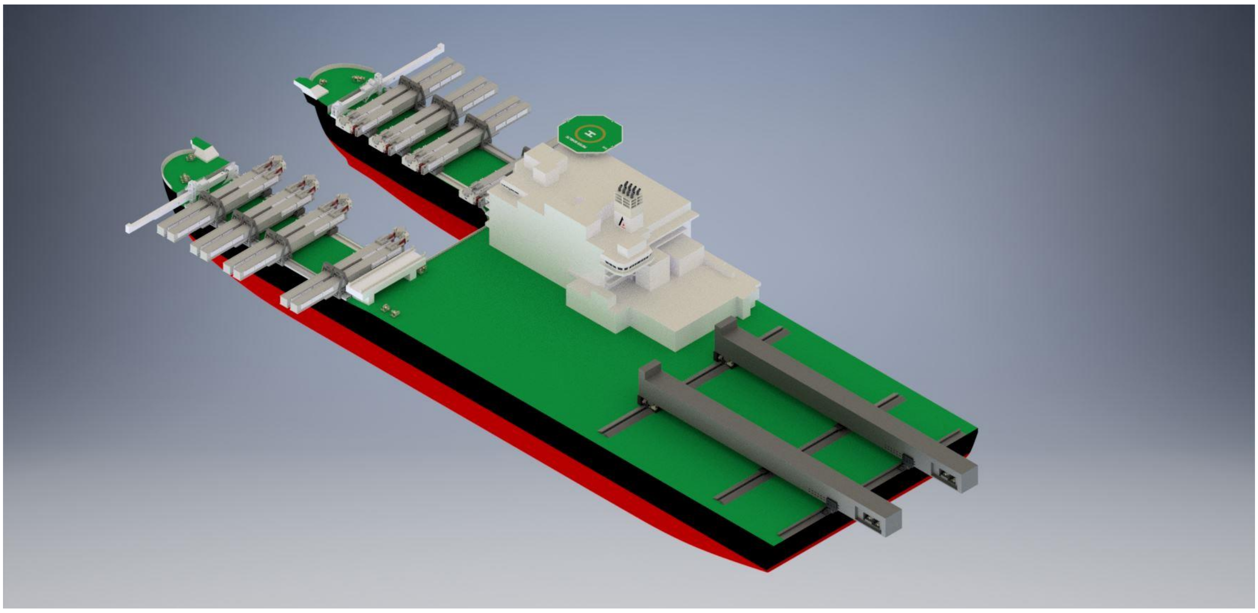


Figure 123: Overview Preliminary Design Jacket Lift System

General Description of the Jacket Lift System

The Jacket Lift System as conceived in this graduation project consists of 2 identical Tilting Lift Beams (Figure 130). The Jacket Lift System further consists of the Upend/Tilt-over System (Figure 134) and the Derrick Hoist System (Figure 129). The Upend/Tilt-over System consists of a pushing/supporting construction and a winch system, which, together with the Derrick Hoist System, is responsible for the positioning and the stability of the system. The winch system of the Upend/Tilt-over System is installed in the tail of the Tilting Lift Beams (Figure 131) and attached to the hinged connection between the construction of the upend/tilt-over System and the Tilting Lift Beams (Figure 134). Each Tilting Lift Beam is equipped with an Upend/Tilt-over System and a Derrick Hoist System. In short, the Jacket Lift System consists of 2 identical parts. Each Tilting Lift Beam is connected in 3 places with the aftdeck of Pioneering Spirit. The connection points are: a hinged support point with regard to the Tilting Lift Beams, a hinged support point with regard to the construction of the Upend/Tilt-over Mechanism and the Derrick Hoist System (Figure 128). All 3 connection points can be moved transversely so that the system can adapt to the dimensions of the jacket that is installed or removed. This is achieved by incorporating wheels to the base of the components, similar to the Topside Lift System. The system is locked by means of pinhole connections. The Derrick Hoist System is equipped with winch systems (Figure 129). The winches must be able to move with the Tilting Lift Beams during upending/tilting-over of the system.

Upend/Tilt-over Operation Description

The system is initially positioned in a horizontal position. The system is supported by the hinged connection of the Tilting Lift Beams and the construction of the Upend/Tilt-over System. In this horizontal position, the Tilting Lift Beams are moved in the direction of the stern of Pioneering Spirit. The Tilting Lift Beams can be moved because of the wheels incorporated in the Tilting Lift Beams and the hinged construction of the Tilting Lift Beams. This principle is similar to the Topside Lift System (Lift capacity of 48 000 mt, own mass not included). Once the system is positioned in the right place, the system is locked by means of pinhole connections (Figure 131). The pinholes are hydraulically controlled. The upend/tilt-over constructions remain in place during the relocation of the Tilting Lift Beams (Figure 132). The connection between the Tilting Lift Beams and upend/tilt-over construction is a roller connection. The upend/tilt-over construction is held in a vertical position by an auxiliary structure based on bracings.

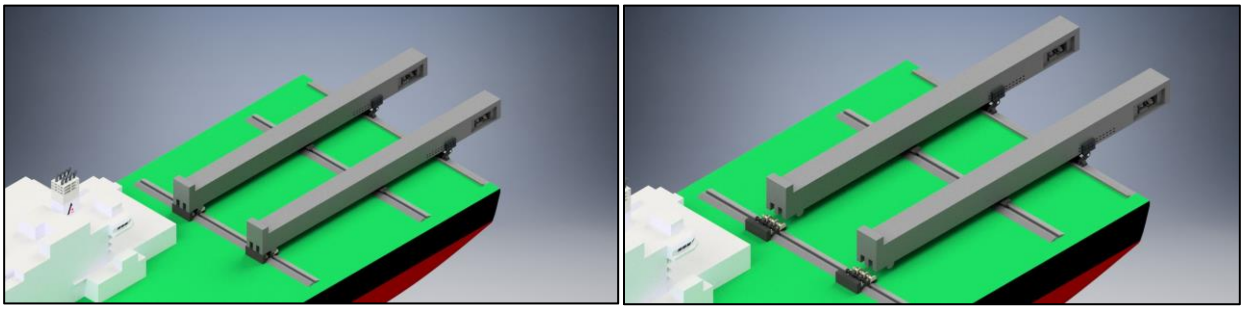


Figure 124: Repositioning Jacket Lift System

After the system is moved and locked again, the actual upend operation begins. The upend/tilt-over construction consists of segments installed on a platform that is part of the hinged support. The system is upended in the first phase by adding segments to the upend/tilt-over construction. A hydraulic system is installed on the platform to add or subtract segments (Figure 133). The system remains in a vertical position during this process to minimize horizontal forces in the system. During the first 30 degrees of the upend operation, the vertically position is secured by means of an auxiliary construction. This is the same construction that locks the upend/tilt-over construction during the relocation operation of the Tilting Lift Beams. This is a construction based on bracings between the segments in the upend/tilt-over construction and the aftdeck of Pioneering Spirit. After the system is upended 30 degrees, the auxiliary structure is removed and the winch system of the Upend/Tilt-over System takes over the positioning of the upend/tilt-over construction. The previously mentioned roller connection between the Upend/Tilt-over System and the Tilting Lift Beams is hinged, this allows the Tilting Lift Beams and the Upend/tilt-over construction to move freely along each other.

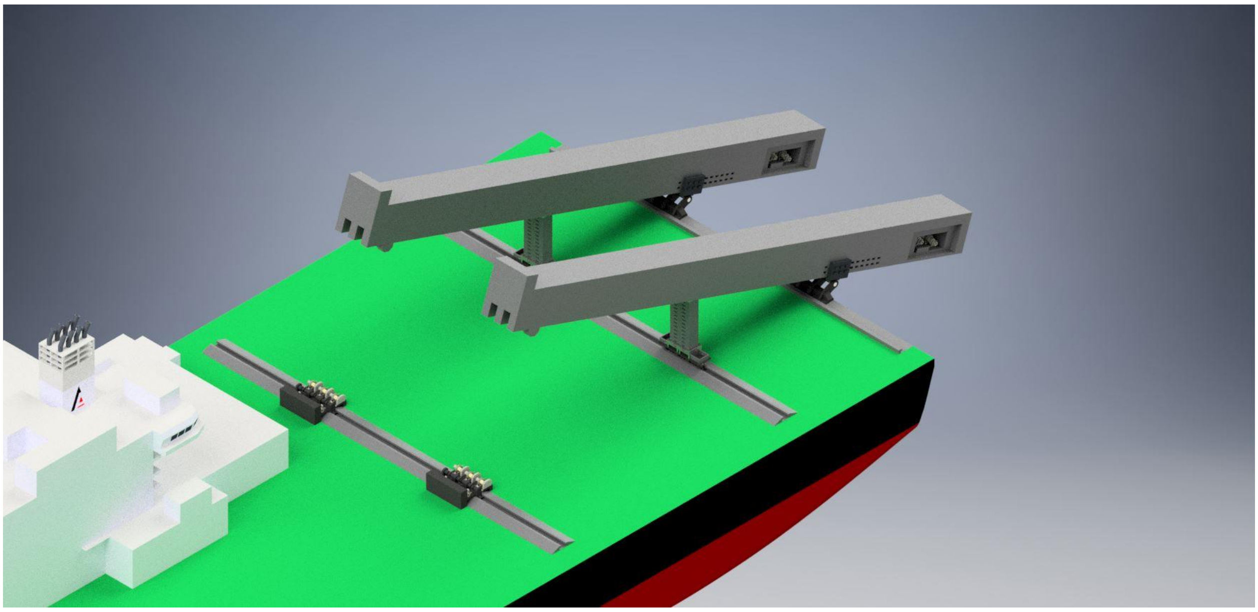


Figure 125: Elongating/Shortening of the Upend/Tilt-over Construction of the Upend/Tilt-over System

The maximum length of the upend/tilt-over construction of the Upend/Tilt-over System is 49 meters. As soon as this maximum length is reached, the upend/tilt-over construction follows the Tilting Lift Beams. In other words, the system does not have to remain in a vertically position anymore. The winch system of the Upend/Tilt-over System ensures a pressure in the upend/tilt-over construction throughout the upend/tilt-over procedure. This secures that the Upend/Tilt-over System and the Tilting Lift Beams are connecting all times.

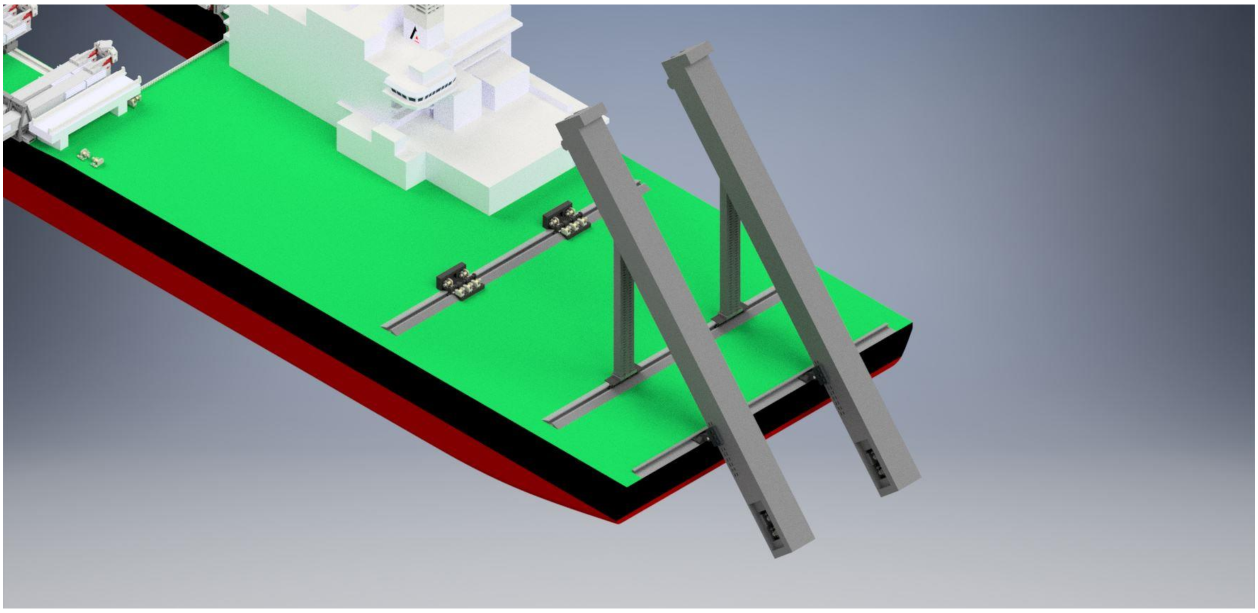


Figure 126: Maximum Length Upend/Tilt-over Construction of the Upend/Tilt-over System

As soon as the system is tilted to the maximum angle or to the desired angle, the lifting operation can begin.

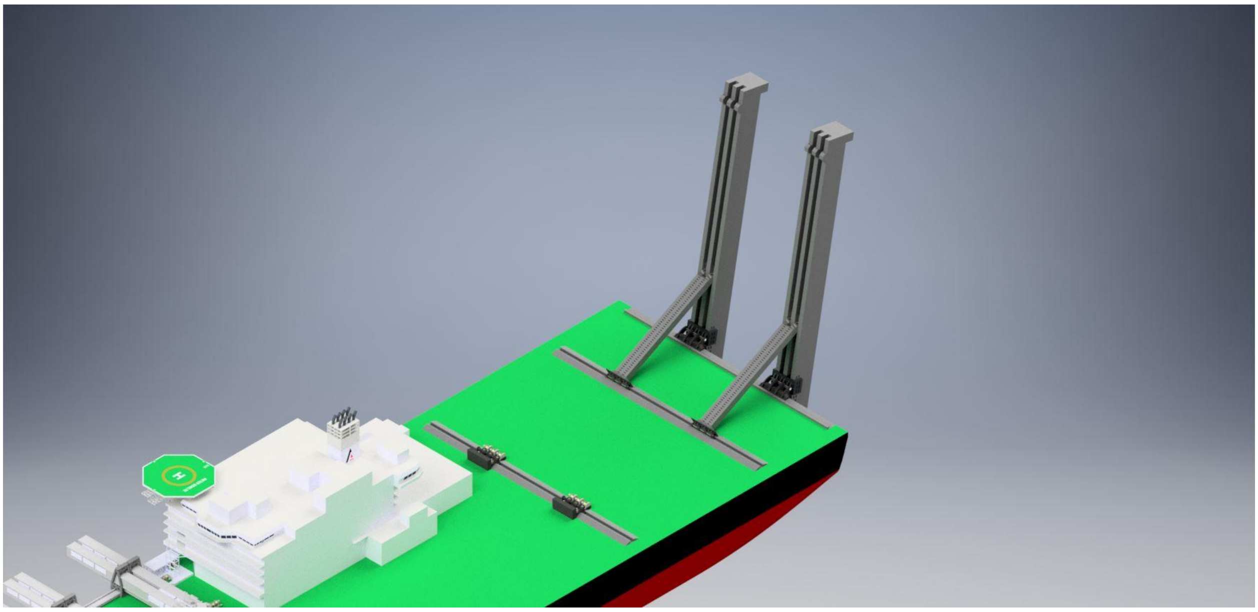


Figure 127: Jacket Lift System in Upended Position

Adjustments Vessel

The biggest required adjustments to Pioneering Spirit are the reinforcement of the support points. As stated in the recommendations, research must be carried out into the strength of the construction of Pioneering Spirit at the location of the transverse frames and the bulkheads. It is likely that the structure at these locations must be strengthened. Furthermore, only minor adjustments are required. The equipment is positioned, where possible, in the system itself and the height of the Tilting Lift Beams in reference to the aftdeck is such that the current activities are not hindered. Examples of a minor adjustments to Pioneering Spirit are the connection of the power supply and including the control system.

Components Upend/Tilt-over Mechanism Jacket Lift System

Components Decomposition

The Upend/Tilt-over Mechanism of Pioneering Spirits Jacket Lift System consists of the following main components, the components are explained in the previous text:

- Transverse Reinforced Frames and Base (hinge) Construction	Figure 128
○ Tilting Lift Beams	Figure 128
○ Upend/Tilt-over Mechanism	Figure 128
○ Derrick Hoist System	Figure 129
- Tilting Lift Beams	Figure 130
○ Tilting Lift Beams	Figure 130
○ Hinge Point Tilting Lift Beams	Figure 131
○ Winch System	Figure 131
- Upend/Tilt-over construction Upend/Tilt-over Mechanism	Figure 132
○ Hinge Point Upend/Tilt-over Construction	Figure 132
○ Segmented Upend/Tilt-over Construction	Figure 133
○ Hydraulic System	Figure 133
○ Connection Tilting Lift Beams and Upend/Tilt-over Mechanism	Figure 134

Photo Collage Components

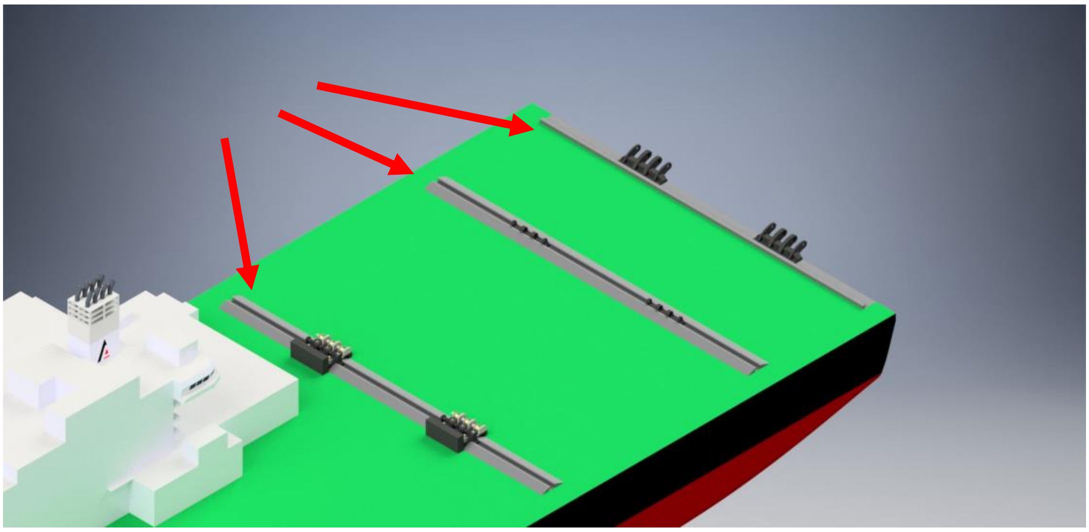


Figure 128: Transverse Reinforced Frames and Base (hinge) Construction

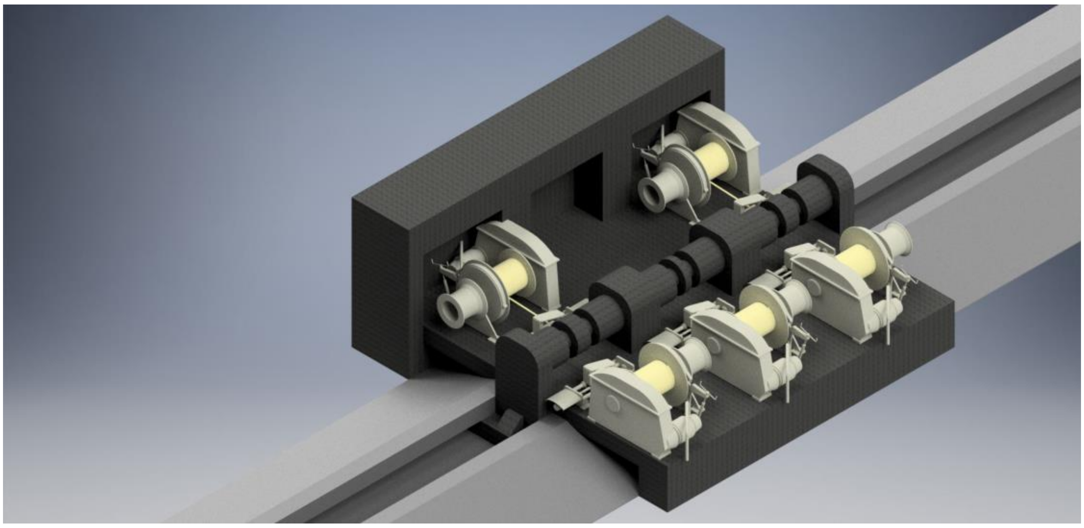


Figure 129: Derrick Hoist System

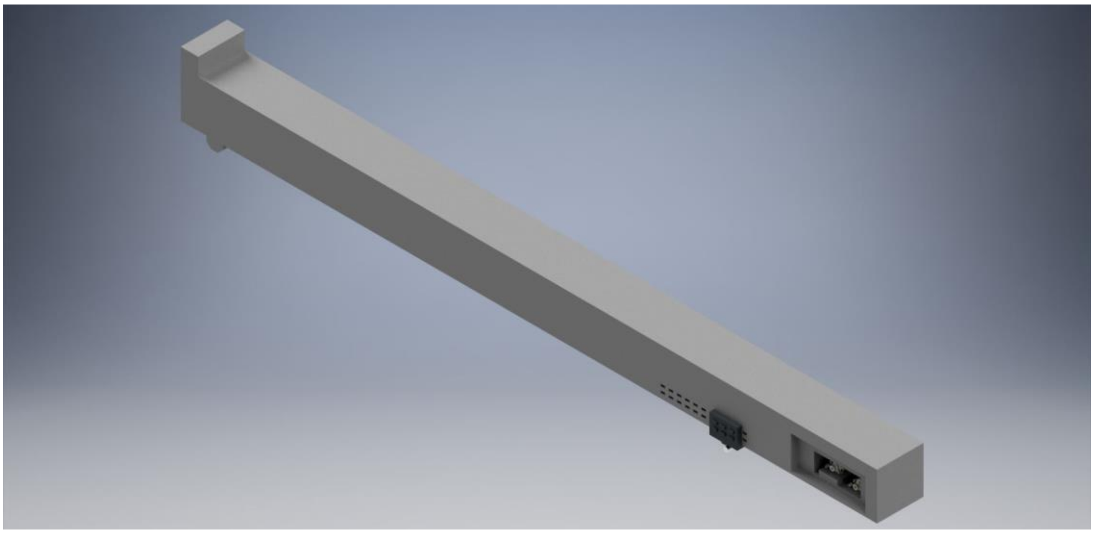


Figure 130: Tilting Lift Beam

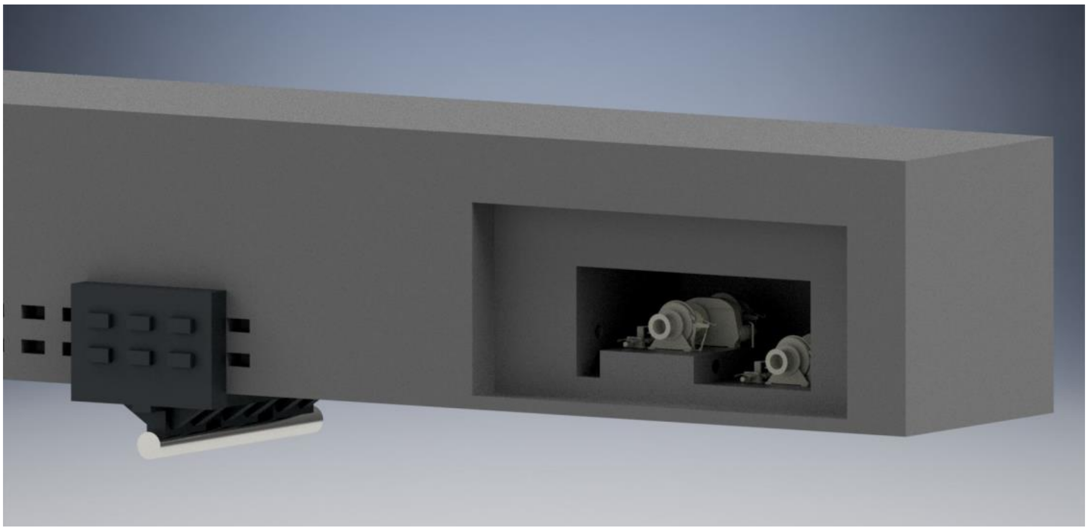


Figure 131: Winch System Upend/Tilt-over System and Pivot Construction TLB

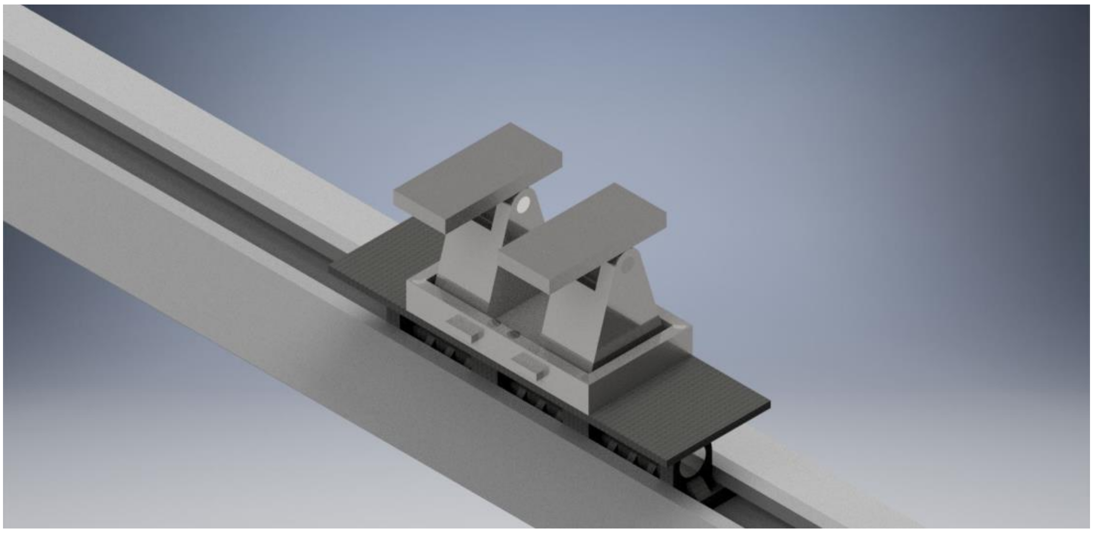


Figure 132: Upend/Tilt-over System Initial Position

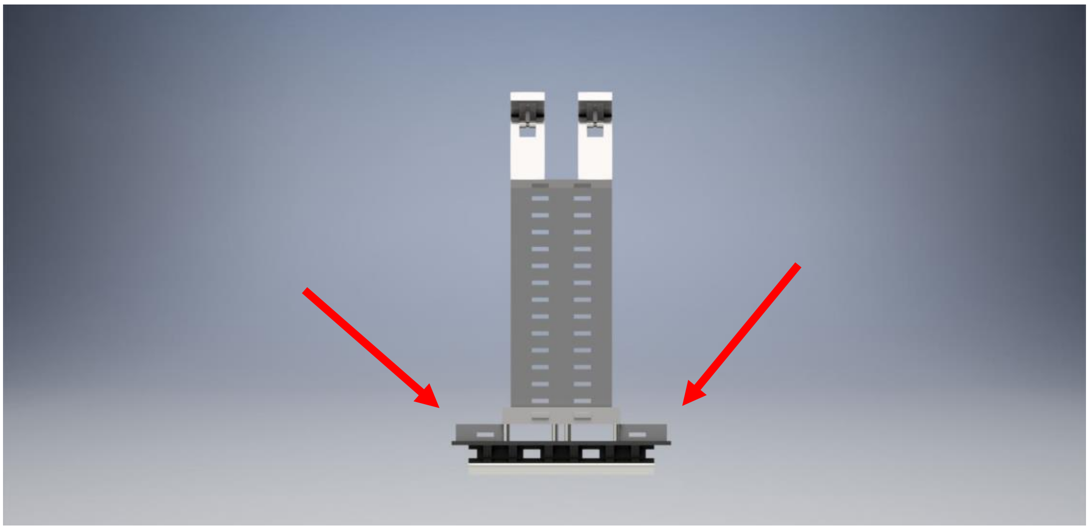


Figure 133: Segmented System Upend/Tilt-over System

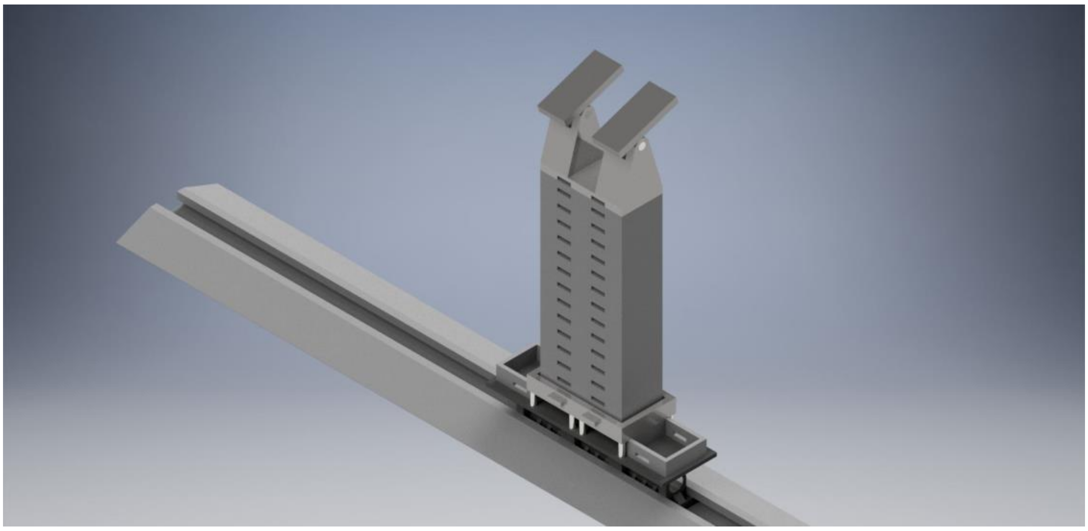


Figure 134: Construction Upend/Tilt-over System

Appendices

A. Reference Jackets

A1. Brent Alpha (1)

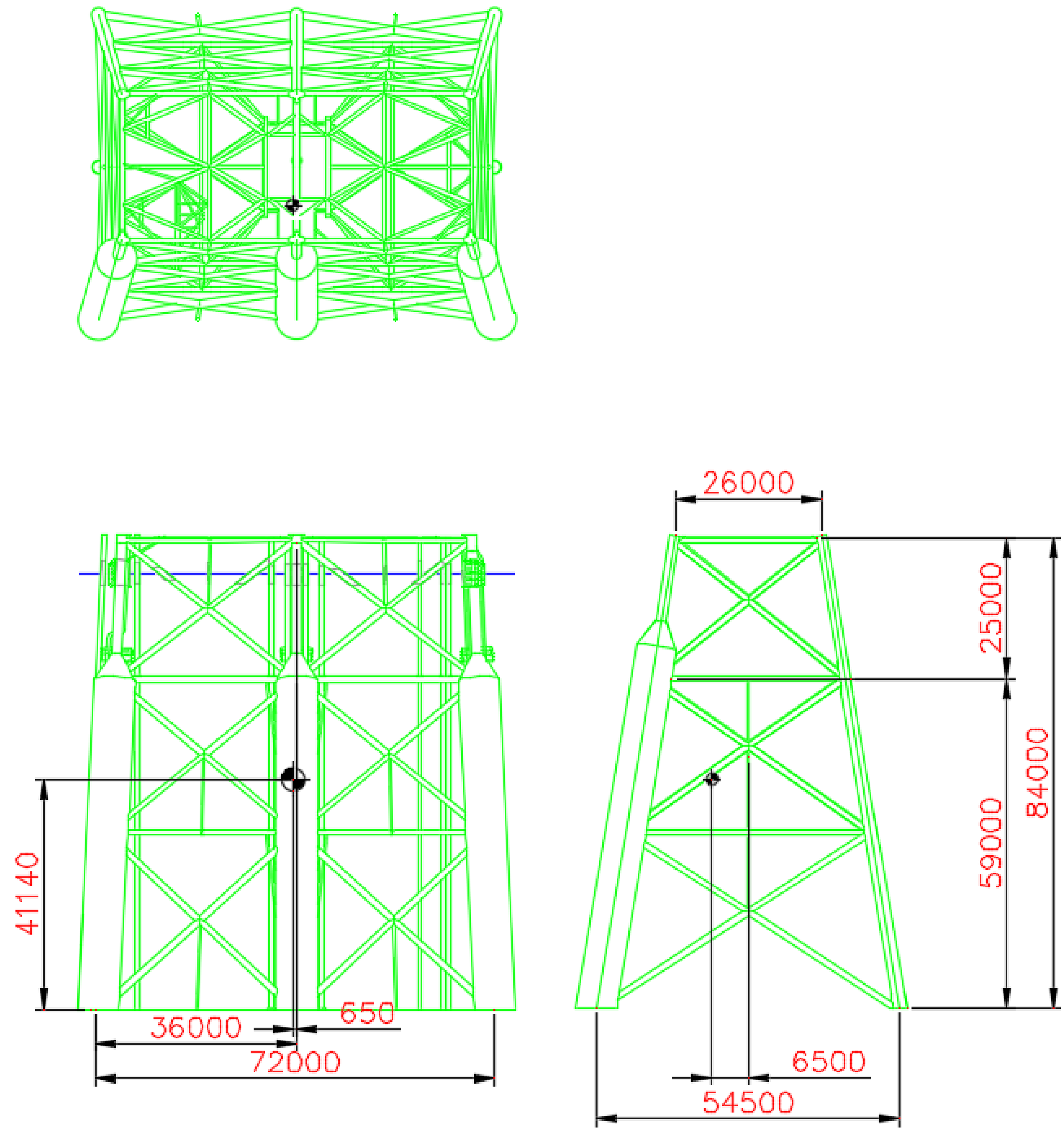


Figure 135: Brent Alpha

A2. Murchison (2)

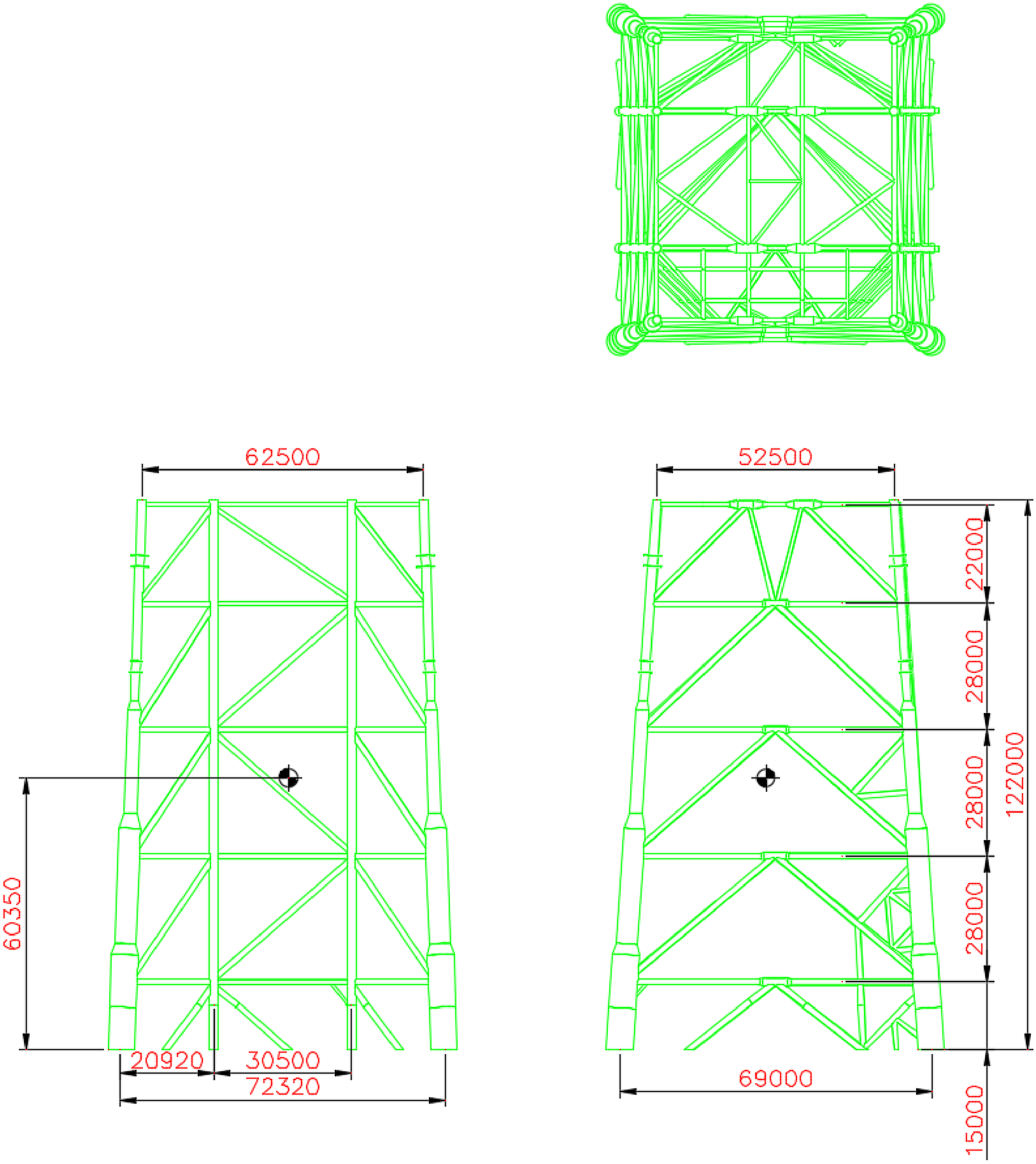


Figure 136: Murchison

A3. Kvitebjørn (3)

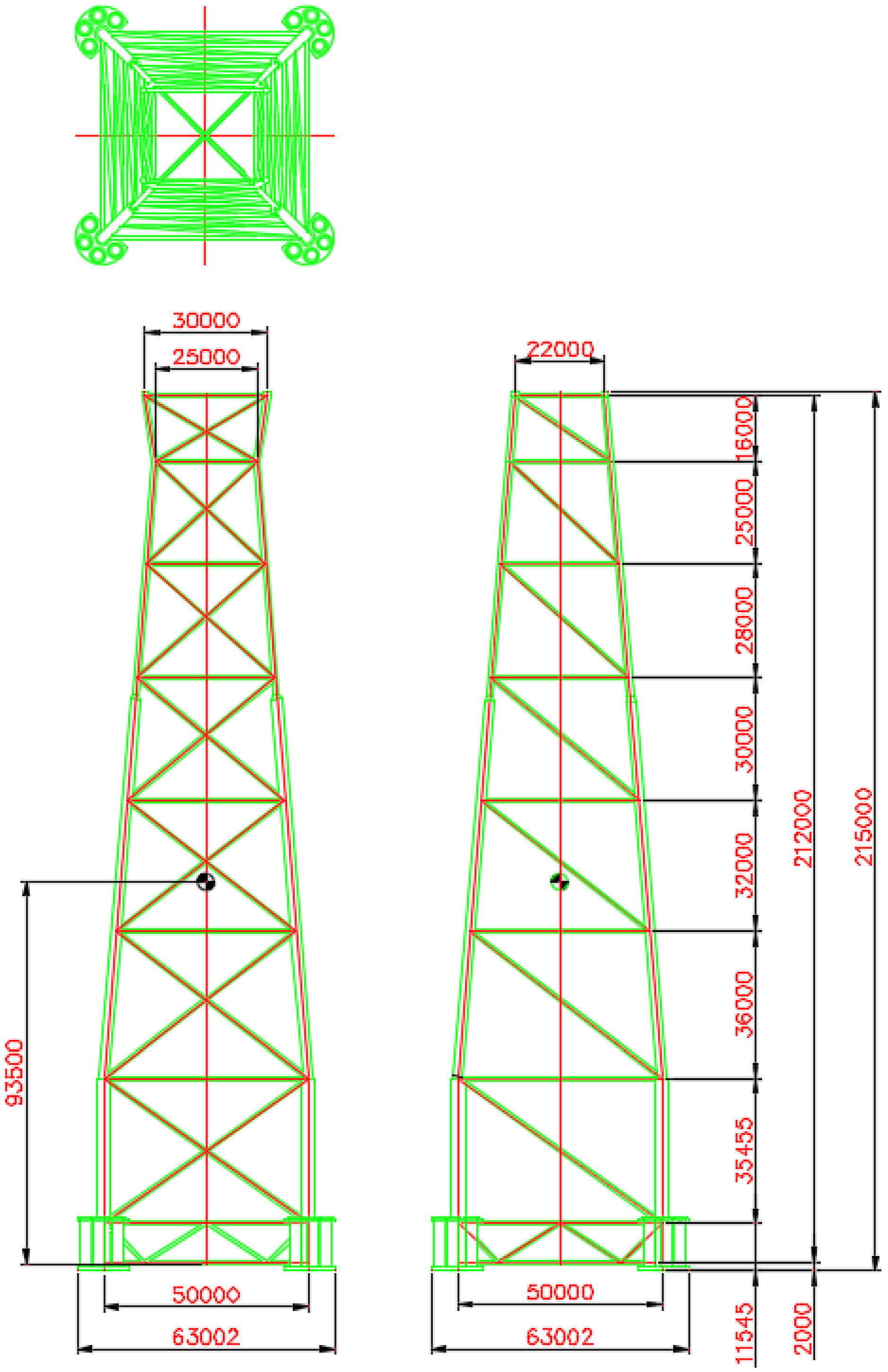


Figure 137: Kvitebjørn

A4. Sverdrup P1 (4)

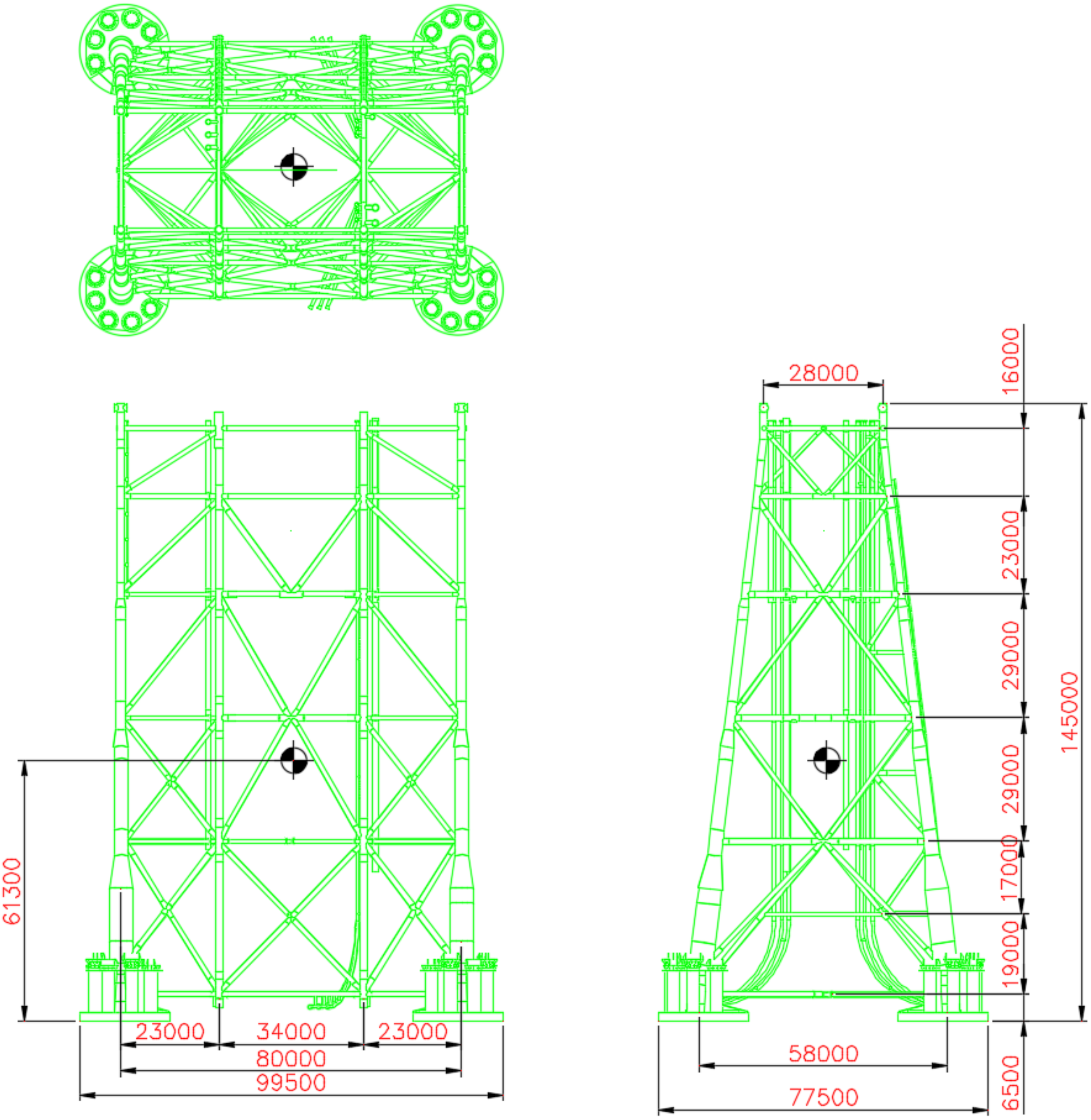


Figure 138: Sverdrup P1

B. Upend/Tilt-over Mechanism Concepts

B1. Counterweight

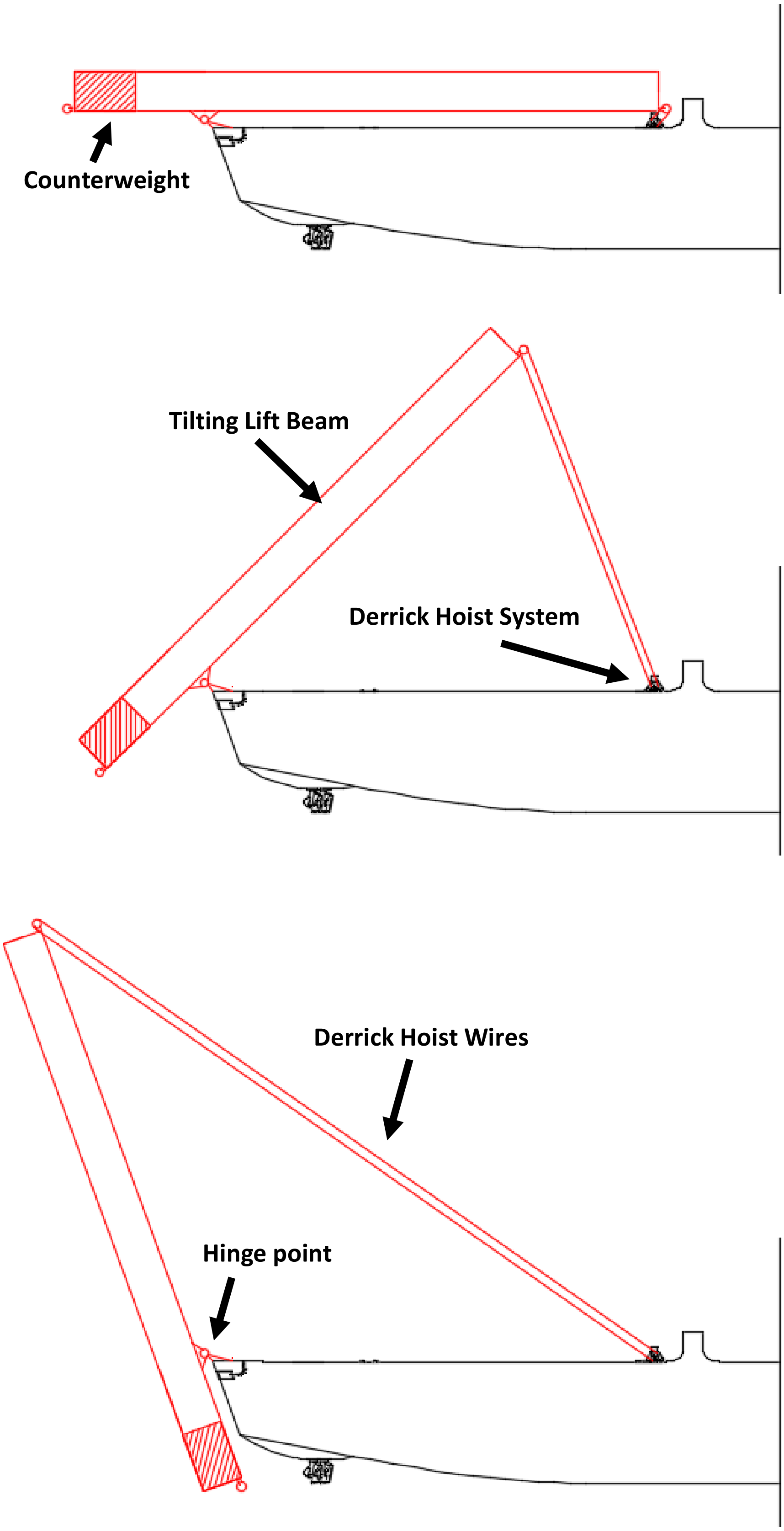


Figure 139: Upend/Tilt-over Stages in Concept "Counterweight"

B2. Suction Piled

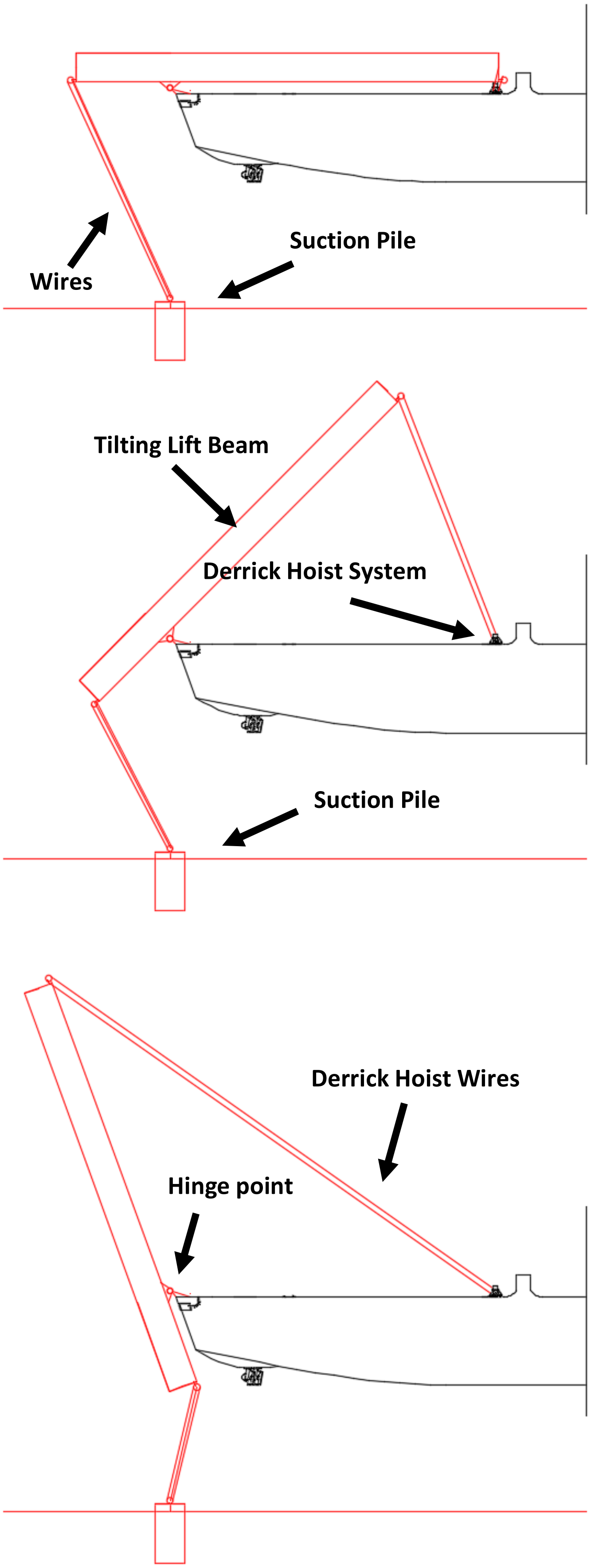


Figure 140: Upend/Tilt-over Stages in Concept “Suction piled”

B3. Stern Winch

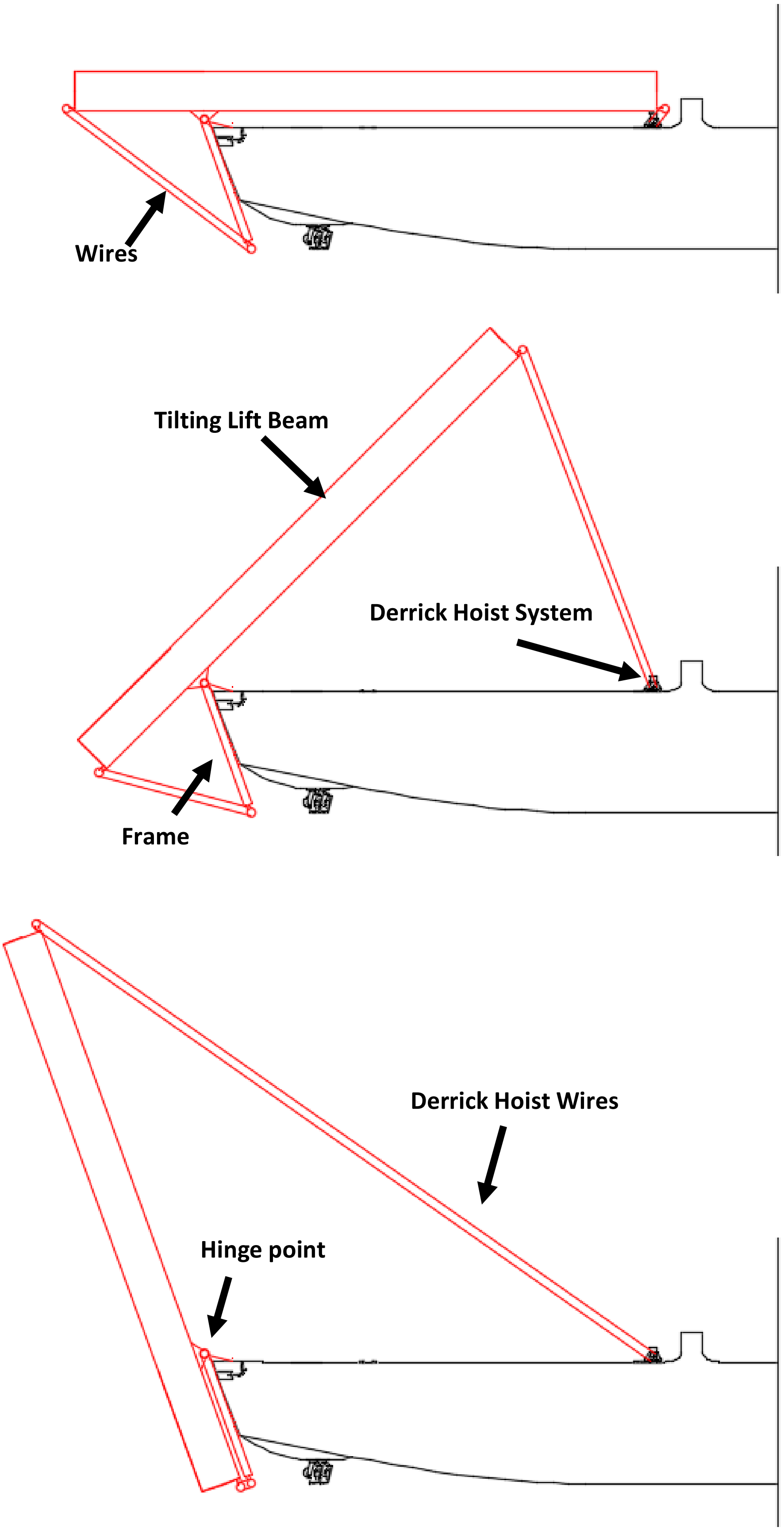


Figure 141: Upend/Tilt-over Stages in Concept “Stern Winch”

B4. Pulled System (Push/Pull System)

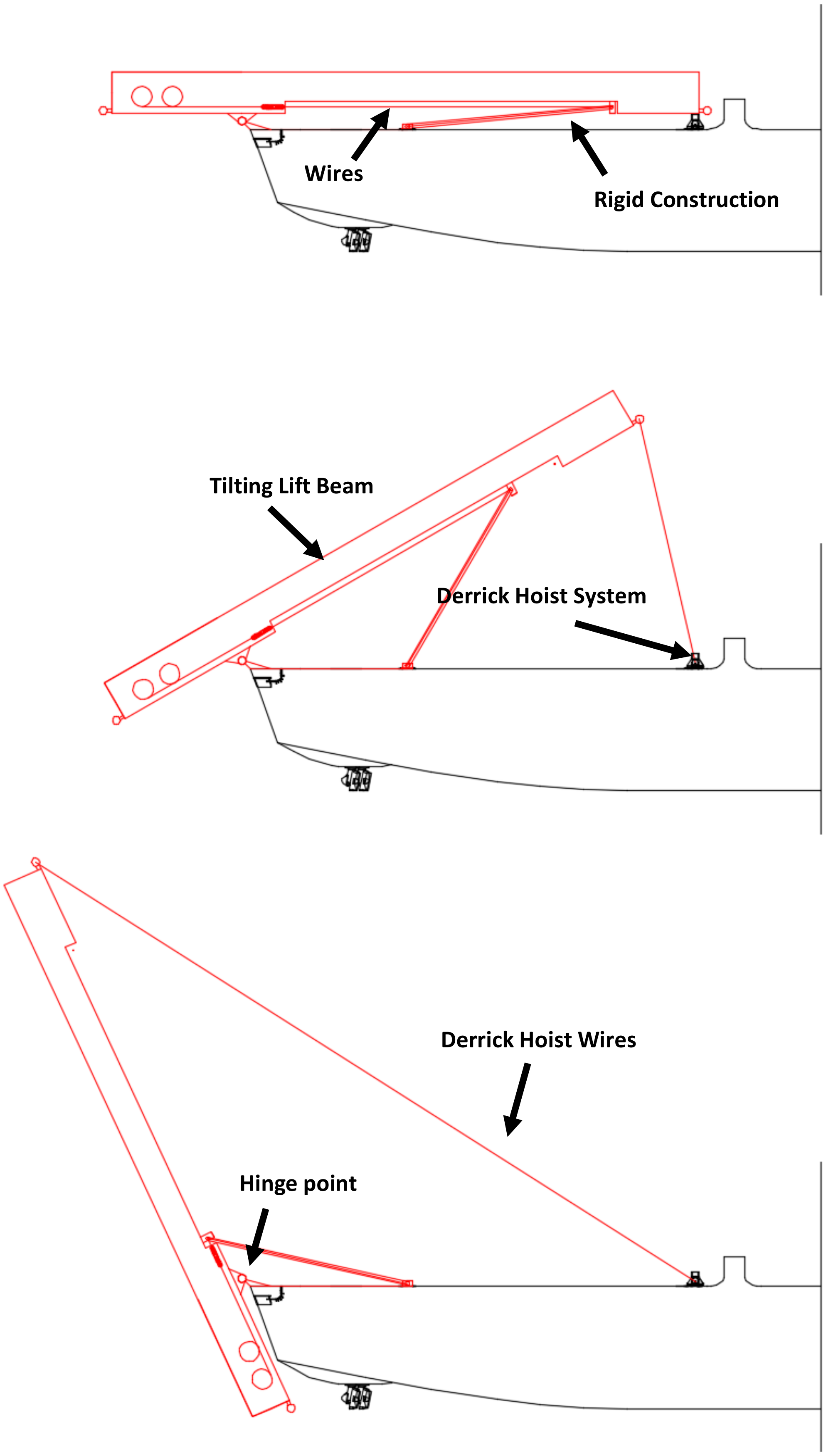


Figure 142: Upend/Tilt-over Stages in Concept “Pulled System”

B5. Pushing System

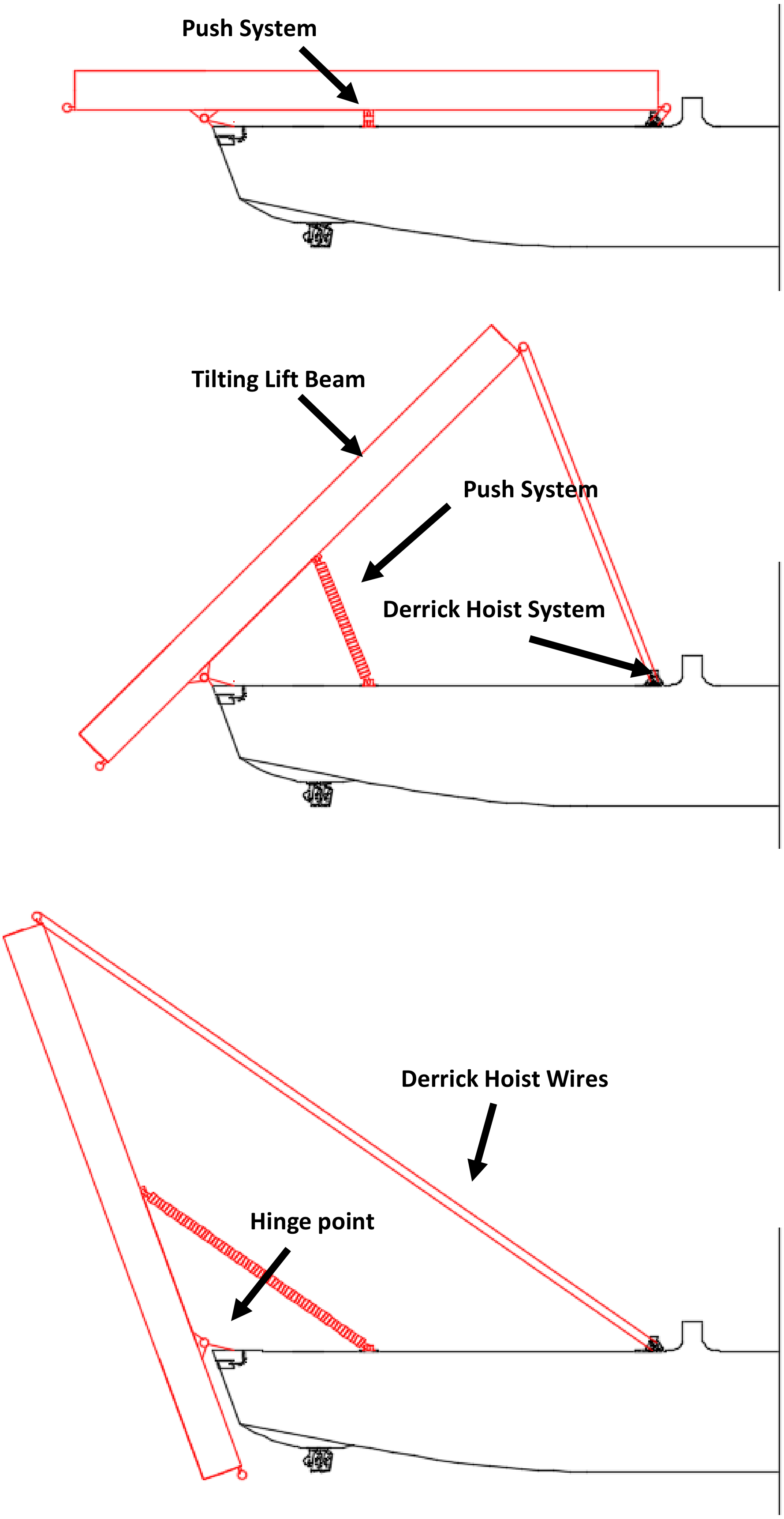


Figure 143: Upend/Tilt-over Stages in Concept “Pushing Cylinder”

B6. Pushed System

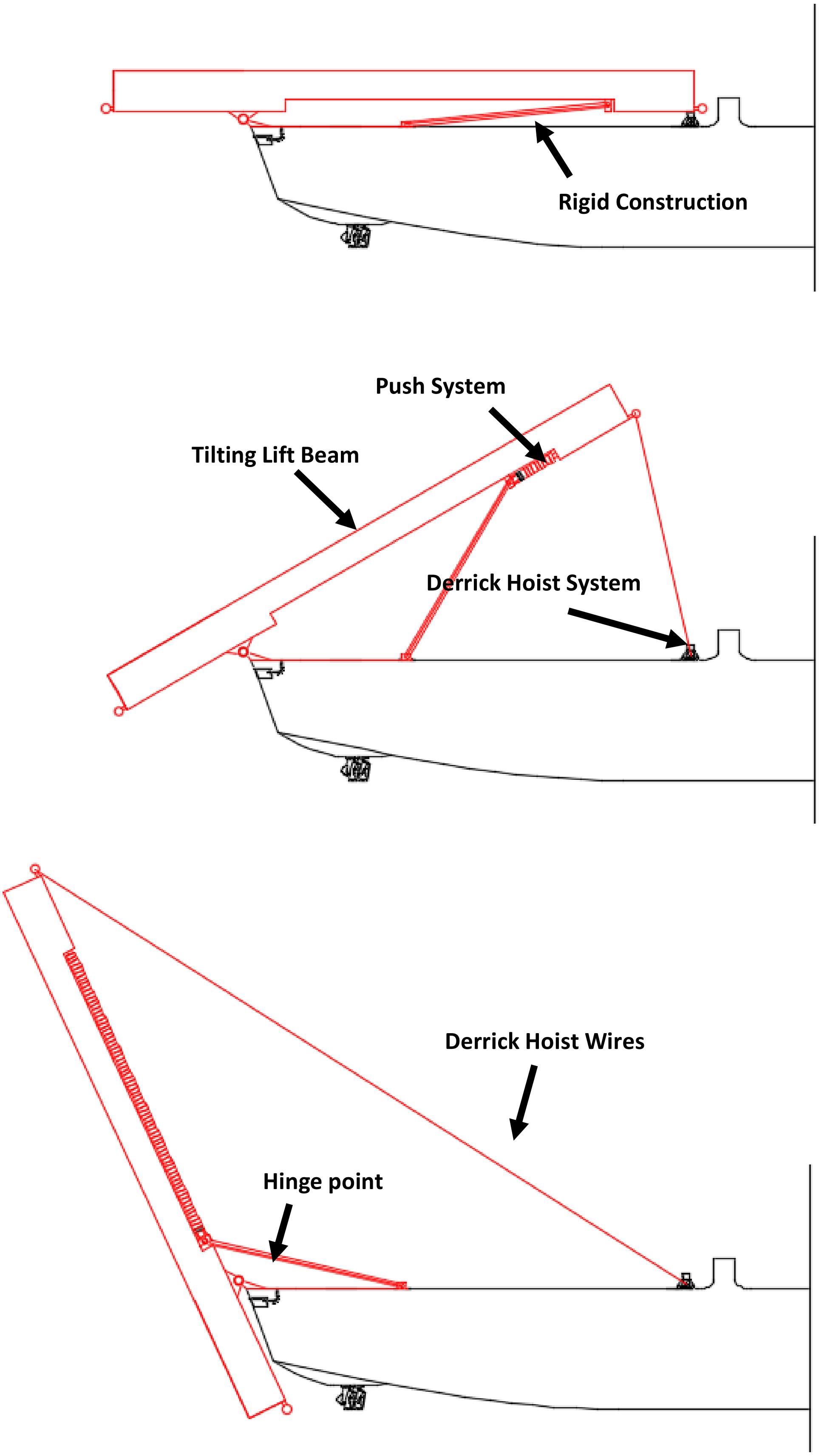


Figure 144: Upend/Tilt-over Stages in Concept “Pushed System”

B7. Push/Pull Variant System

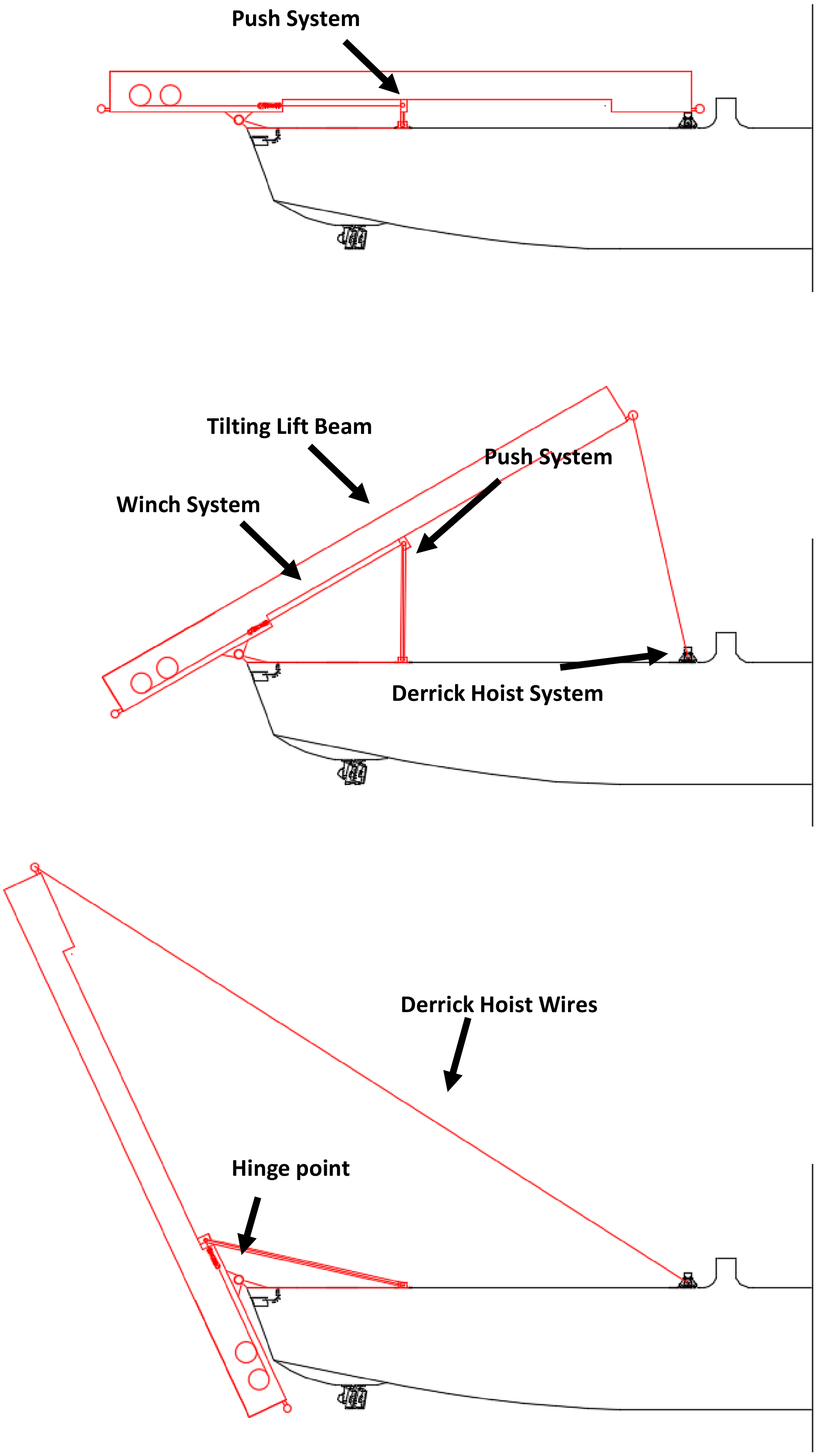


Figure 145: Upend/Tilt-over Stages in Concept “Push/Pull Variant System”

C. Elaboration Coordinates

C.1 Point Revolving around Pivot Point

1. Angle in tilted/initial position

$$\alpha_{n,0} = \arctan\left(\frac{y_{n,0}}{x_{n,0}}\right) \qquad [°]$$

Where:

$x_{n,0}$ and $y_{n,0}$ are the x and y coordinates in tilted/initial position. The coordinates are given in Table 11 (page 70).

n = A, B, C, D, F, G, I, J, K, L, M and O

2. Length of origin to a point n (radius)

$$L_n = \frac{x_{n,0}}{\cos(\alpha_{n,0})} \qquad [m]$$

Figure 146 is added to clarify the meaning of the length of the origin to a certain point (radius). Points A and Point J are used as an example.

3. X coordinate

$$x_n(\alpha_i) = L_n \cdot \cos(\alpha_i + \alpha_{n,0})$$

4. Y coordinate

$$y_n(\alpha_i) = L_n \cdot \sin(\alpha_i + \alpha_{n,0})$$

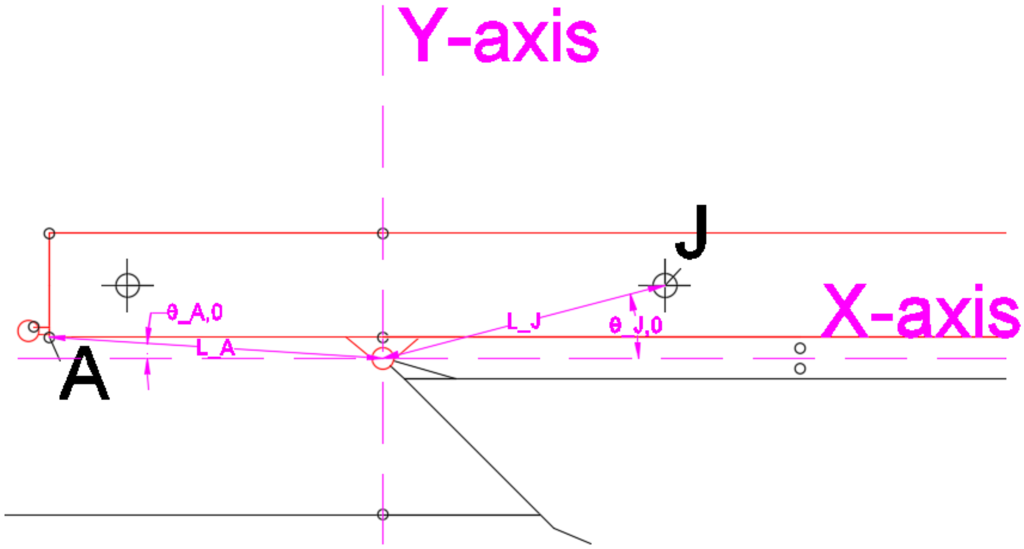


Figure 146: Coordinate example Point A and J

C.1 Point Q and S

1. Angle in tilted position ($\alpha_{n,0}$):

$$\alpha_{Q,0} = \arctan\left(\frac{y_{Q,0} - y_{PP,0}}{x_{Q,0} - x_{PP,0}}\right) \qquad [°]$$

Where:

$x_{Q,0}$,$y_{Q,0}$, $y_{PP,0}$and $x_{PP,0}$ are the x and y coordinates in tilted position. The positions are given in Table 11 (page 70).

2. Length rigid construction Push/Pull System ($L_{n,0}$):

$$L_{PP-Q} = \frac{x_{Q,0} - x_{PP,0}}{\cos(\alpha_{Q,0})} \qquad [m]$$

3. X coordinate point ($x_Q(\alpha_i)$):

The X coordinate is calculated by calculating the intersection between:

Line: $y = a_1(\alpha_i) \cdot x + b_1(\alpha_i)$

And

Circle: $(x - a_2)^2 + (y - b_2)^2 = r^2$

Where:

a_1 = slope of the line (Angle depend)
b_1 = y(0) (Angle depend)
a_2 = $x_{Q,0}$
b_2 = $y_{Q,0}$
r = L_{PP-Q}

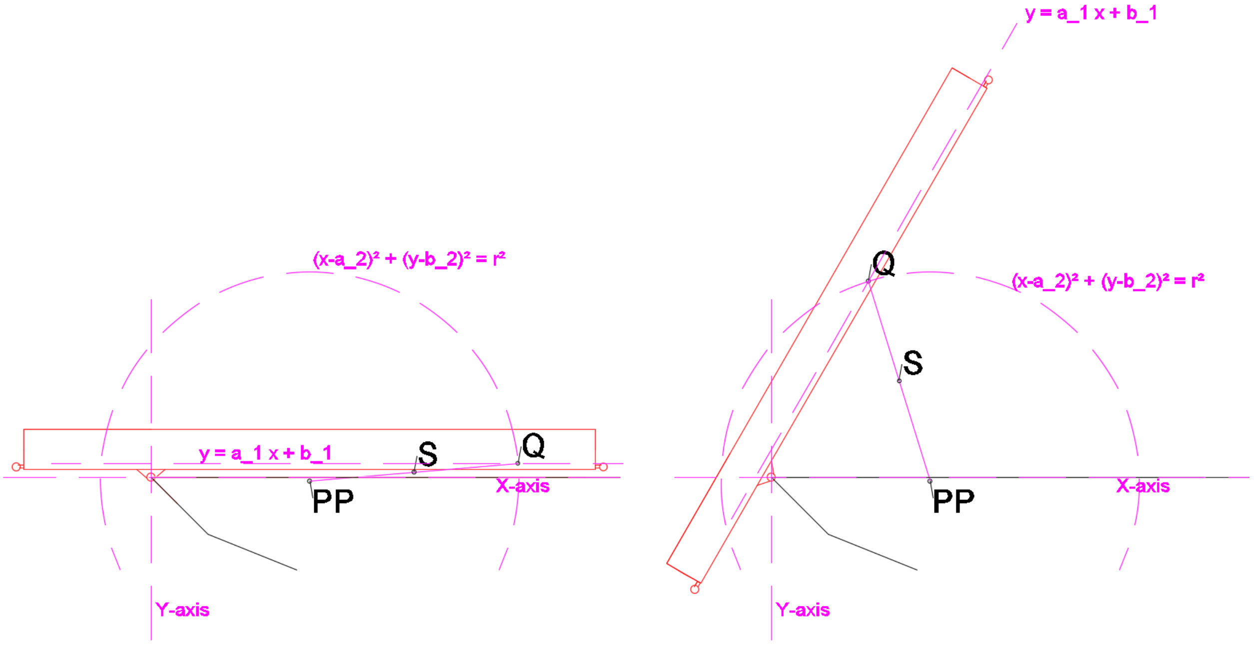


Figure 147: Coordinate Point Q and S

Intersection point:

Line = Circle $\quad (y = a_1(\alpha_i) \cdot x + b_1(\alpha_i)$ substituted in circle formula)

$(x - a_2)^2 + (y - b_2)^2 = r^2$

$$(x - a_2)^2 = x^2 + {a_2}^2 - 2a_2x$$
$$(y - b_2)^2 = y^2 + {b_2}^2 - 2b_2y$$

$$x^2 + {a_2}^2 - 2a_2x + y^2 + {b_2}^2 - 2b_2y = r^2$$

$$x^2 + {a_2}^2 - 2a_2x + a_1^2x^2 + b_1^2 + 2a_1b_1x + {b_2}^2 - 2a_1b_2x - 2b_1b_2 - r^2 = 0$$

ABC Formula:

$Ax^2 + Bx + C = 0$

$x = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$

$Ax^2 + Bx + C = 0$:

$(1 + a_1^2) \cdot x^2 + (2a_1b_1 - 2a_2 - 2a_1b_2) \cdot x + (b_1^2 + {b_2}^2 + {a_2}^2 - 2b_1b_2 - r^2) = 0$

$$A = 1 + a_1^2$$
$$B = 2a_1b_1 - 2a_2 - 2a_1b_2$$
$$C = b_1^2 + {b_2}^2 + {a_2}^2 - 2b_1b_2 - r^2$$

3 phases are applicable during the upend/tilt-over process:

1. $\alpha_i < 90°$
2. $\alpha_i = 90°$
3. $\alpha_i > 90°$

$\alpha_i < 90°$ and $\alpha_i > 90°$:

$$a_1(\alpha_i) = \tan(\alpha_i)$$
$$b_1(\alpha_i) = \frac{y_{Q,0}}{\cos(\alpha_i)}$$

$$a_2 = x_{PP,0}$$
$$b_2 = y_{PP,0}$$
$$r = L_{PP-Q}$$

$\alpha_i = 90°$:

$$a_1(\alpha_i) = 0$$
$$b_1(\alpha_i) = 0$$

$$a_2 = x_{PP,0}$$
$$b_2 = y_{PP,0}$$
$$r = L_{PP-Q}$$

$$x = y_{Q,0}$$

Where:

$x_{PP,0}$, $y_{PP,0}$, and $y_{Q,0}$, are the x and y coordinates in tilted position. The positions are given in Table 11. (Paragraph 5.5.3).

4. Y coordinate point ($y_Q(\alpha_i)$):

The basic formula $y = a_1 \cdot x + b_1$ is used to determine the y coordinate.

$$y_Q(\alpha_i) = a_1 \cdot x_Q(\alpha_i) + b_1$$

Where

$a_1 = \tan(\alpha_i)$

$b_1 = \frac{Q_{y,0}}{\cos(\alpha_i)}$

$x_Q(\alpha_i) = \text{see previous step (3.)}$

Point S:

$$x_S(\alpha_i) = \frac{1}{2} \cdot \left(x_Q(\alpha_i) - x_{PP,0}\right) + x_{PP,0}$$

$$y_S(\alpha_i) = \frac{1}{2} \cdot \left(y_Q(\alpha_i) - y_{PP,0}\right) + y_{PP,0}$$

Where:

$x_{PP,0}$, $y_{PP,0}$, and $y_{Q,0}$, are the x and y coordinates in tilted position. The positions are given in Table 11. (Paragraph 5.5.3).

The x and y coordinates of the points during the upend/tilt-over process are included in Appendix D.

D. Coordinates During Upending/Tilting-over

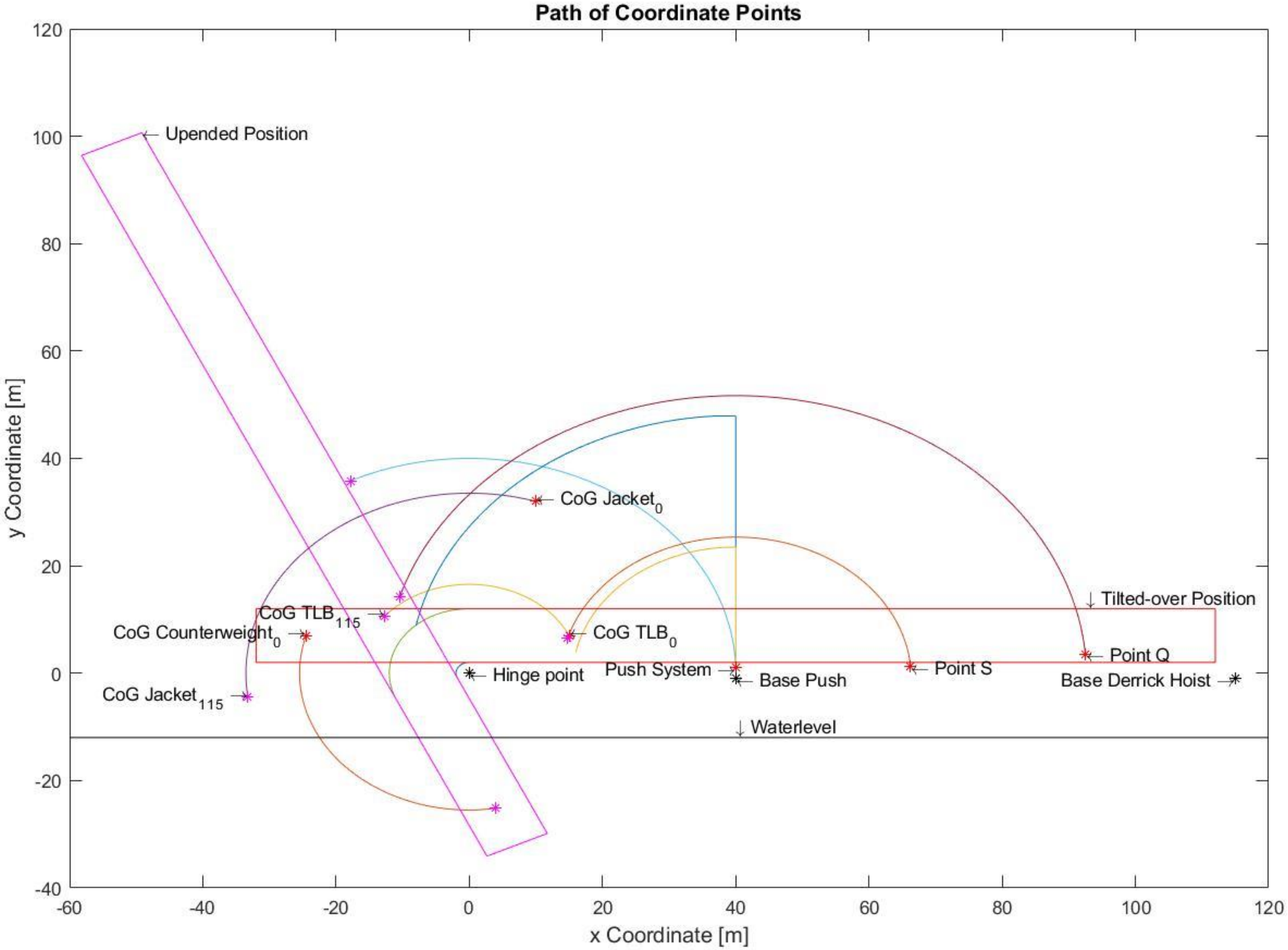


Figure 148: Path of Coordinate (example) Points during Upending/Tilting-over

E. Results Static Forces (Chapter 5)

E.1 Individually Forces

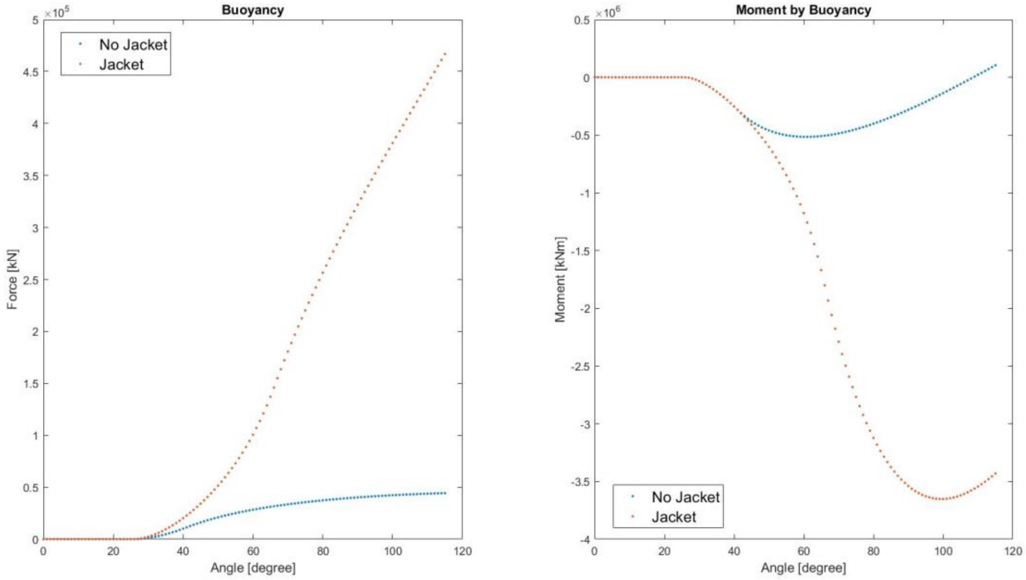


Figure 149: Static (Moment) Force, Buoyancy

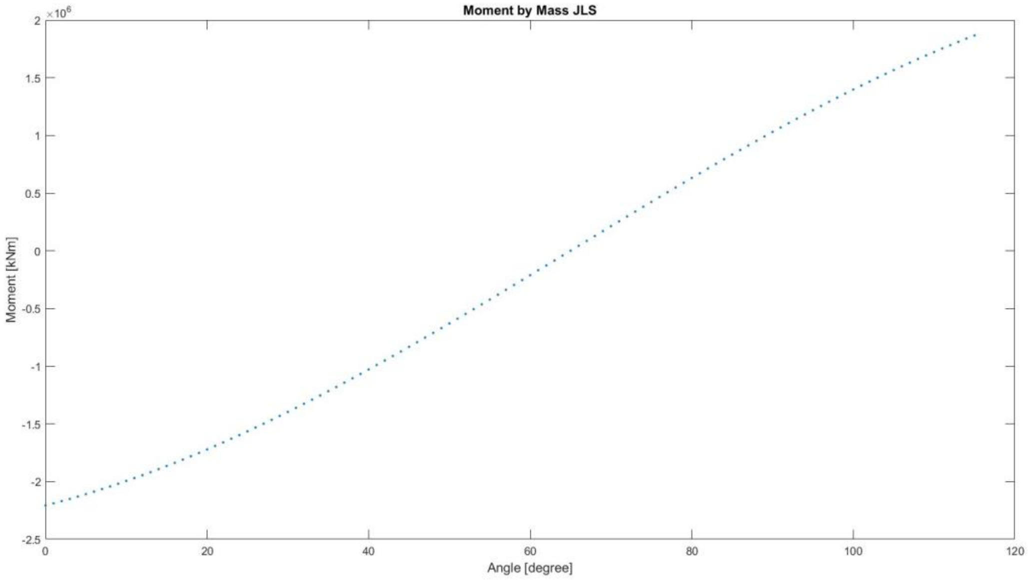


Figure 150: Static (Moment) Force, Mass JLS

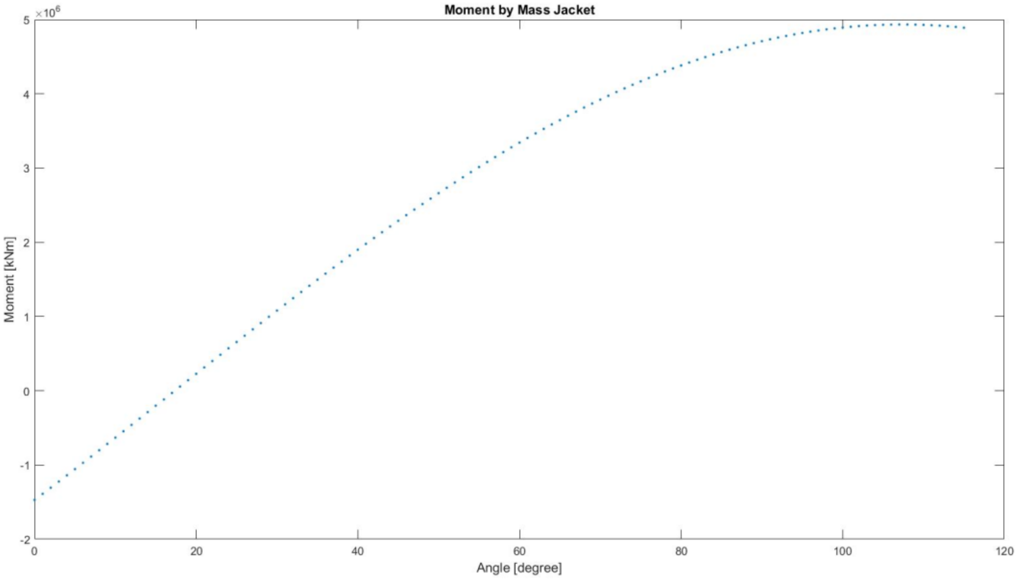


Figure 151: Static (Moment) Force, Mass Jacket

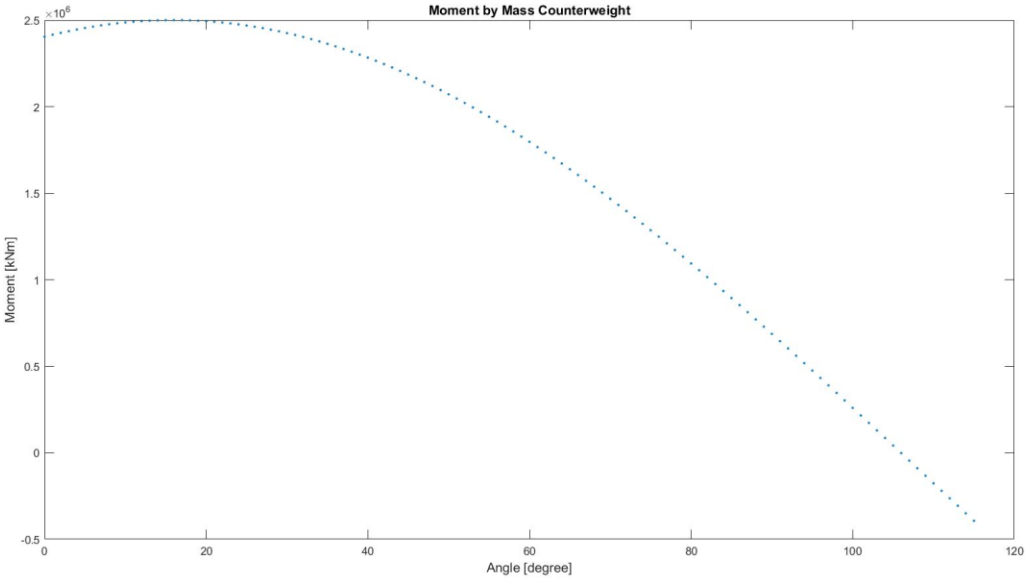


Figure 152: Static (Moment) Force, Mass Counterweight

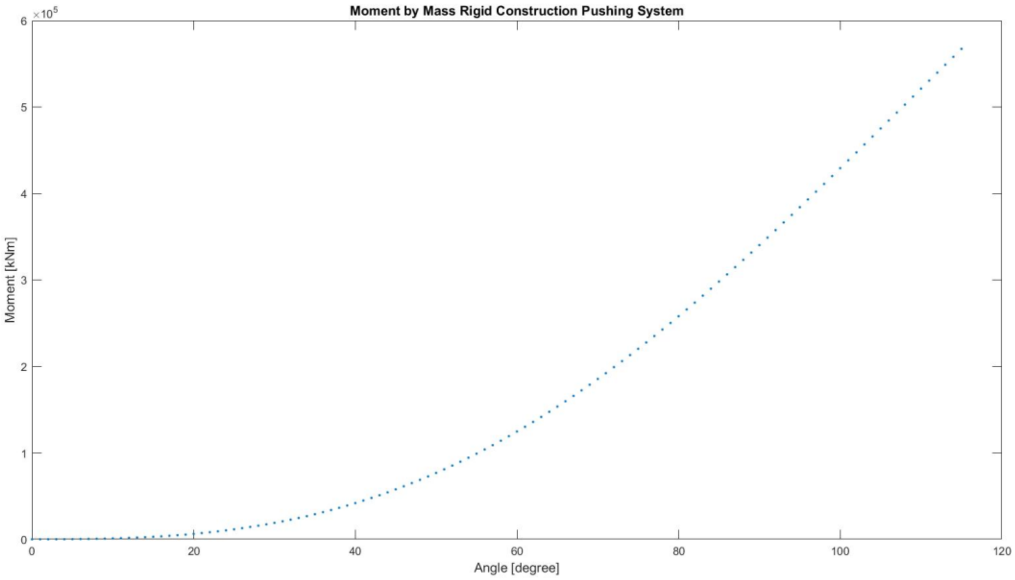


Figure 153: Static (Moment) Force, Mass Rigid Construction Pushing System

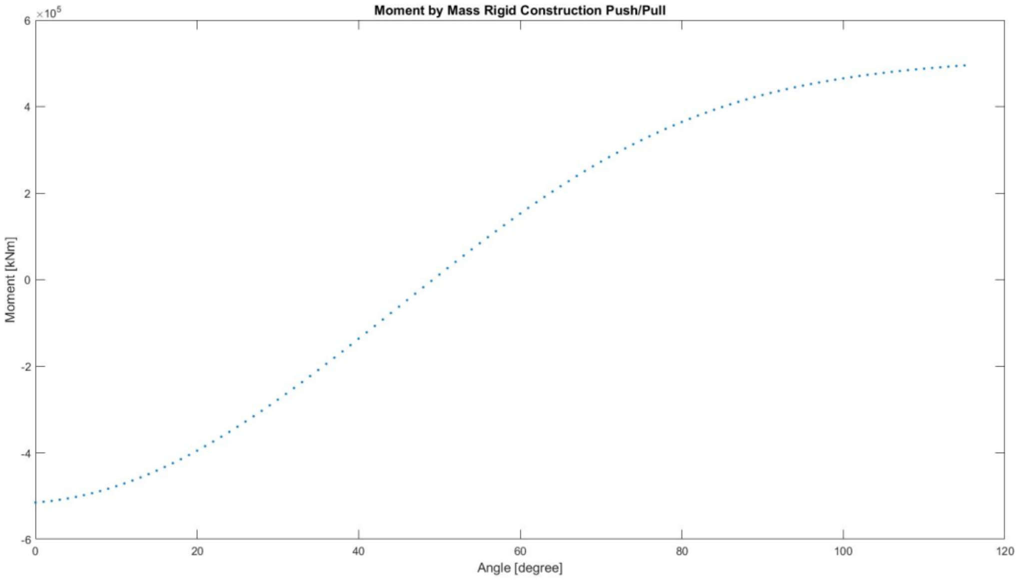


Figure 154: Static (Moment) Force, Mass Rigid Construction Push/Pull System

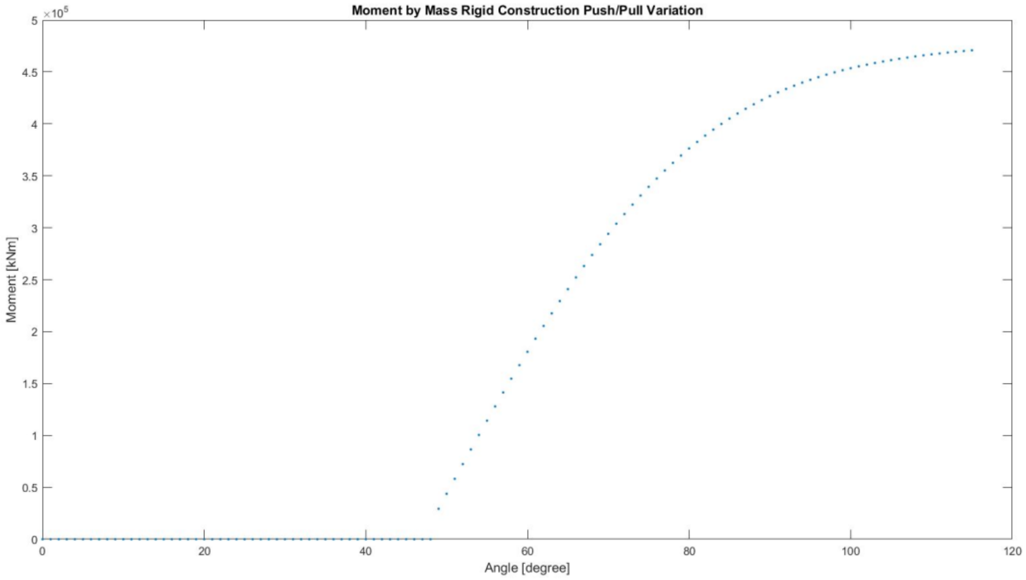


Figure 155: Static (Moment) Force, Mass Rigid Construction Push/Pull Variant System

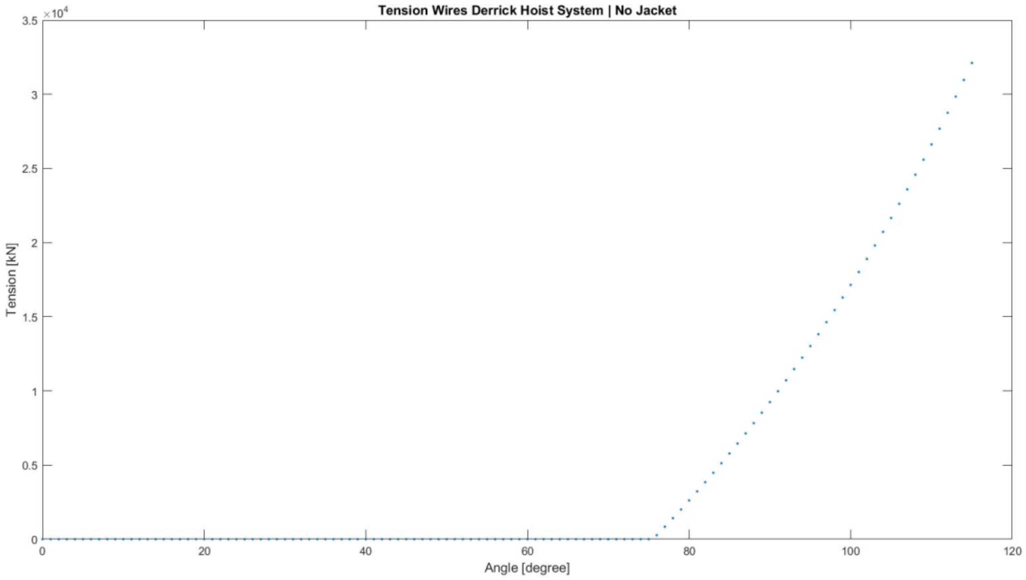


Figure 156: Static (Moment) Force, Derrick Hoist System (No jacket)

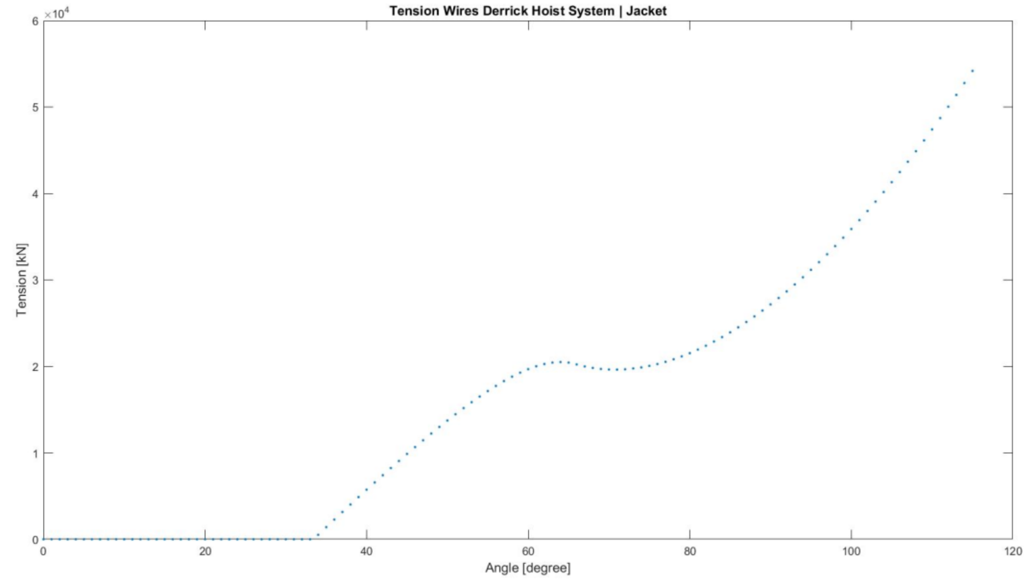


Figure 157: Static (Moment) Force, Derrick Hoist System (jacket)

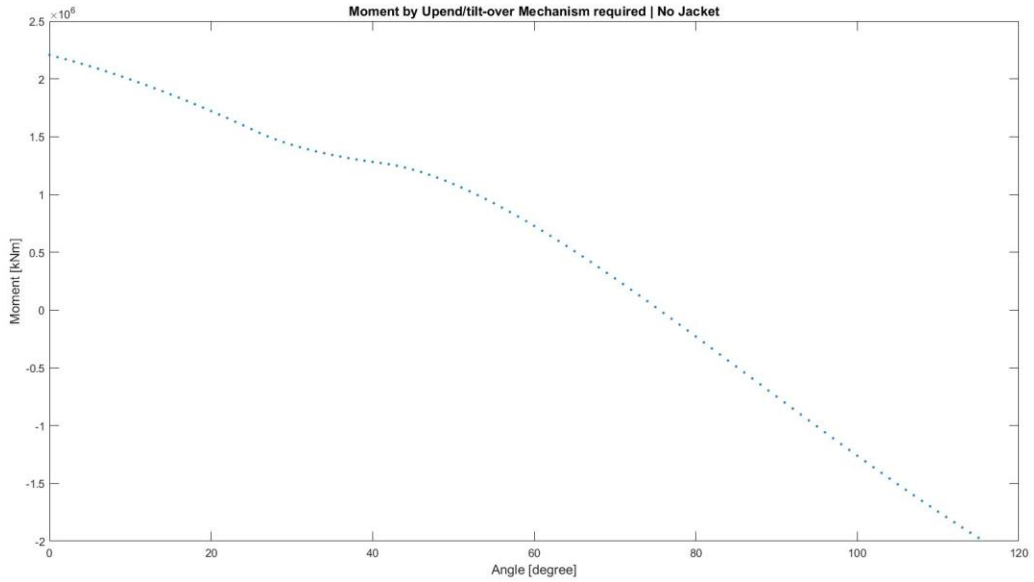


Figure 158: Static (Moment) Force, Upend/Tilt-over Mechanism (No Jacket)

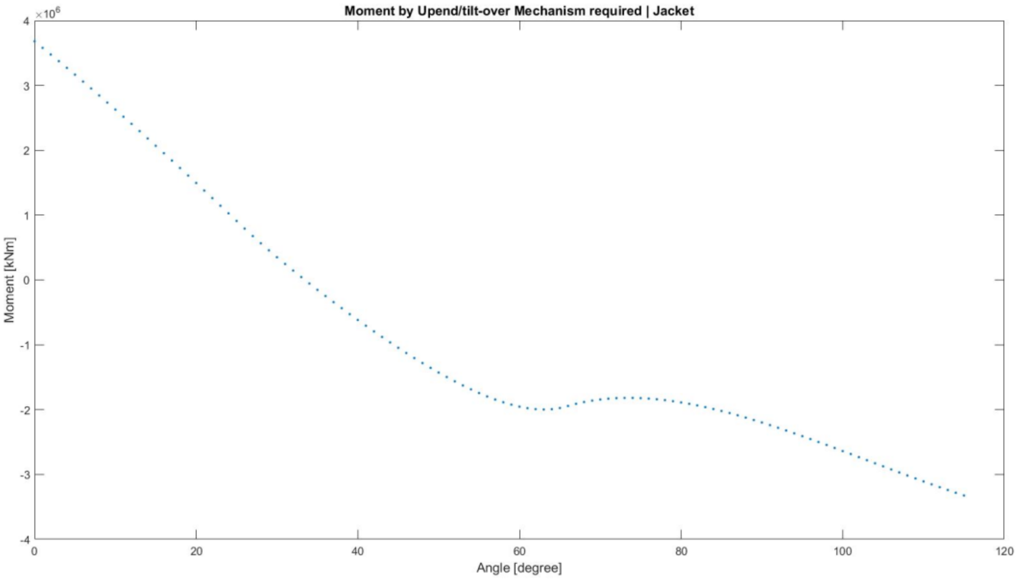


Figure 159: Static (Moment) Force, Upend/Tilt-over Mechanism (Jacket)

E.2 Static Forces per Concept (No Jacket)

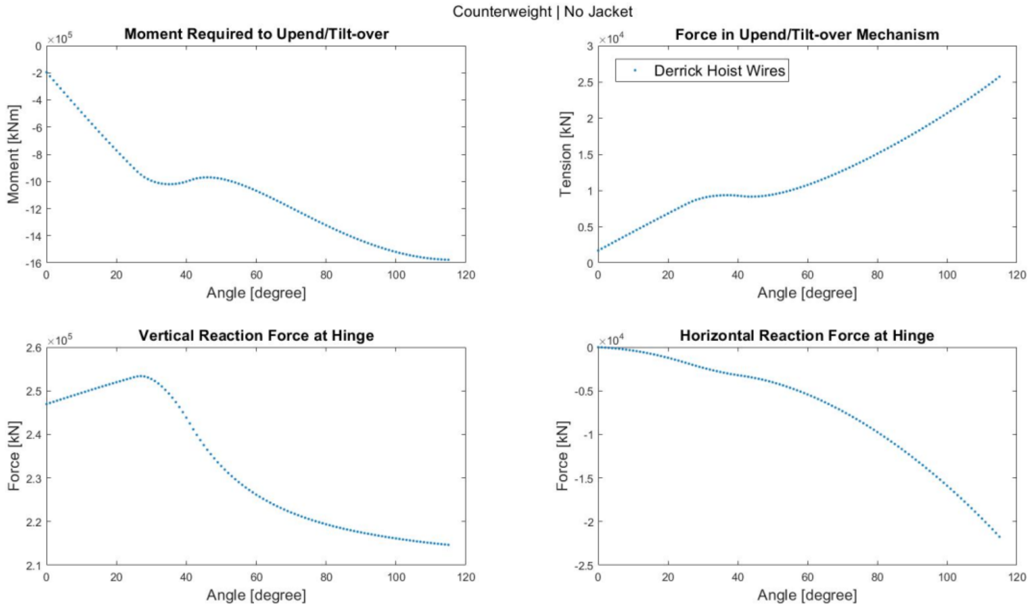


Figure 160: Static (Moment) Forces, Concept Counterweight (No Jacket)

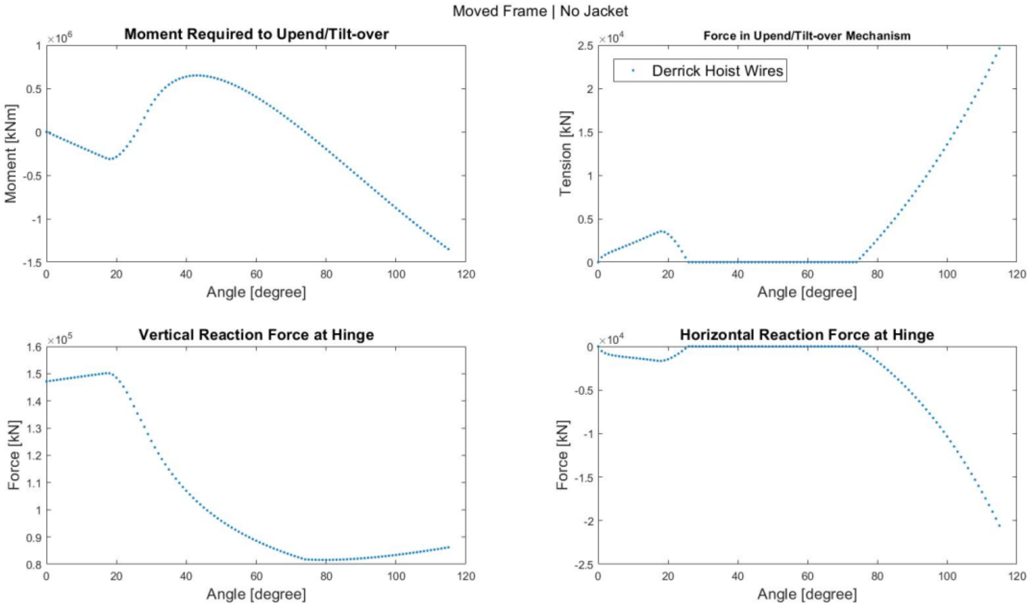


Figure 161: Static (Moment) Forces, Concept Moving frame (No Jacket)

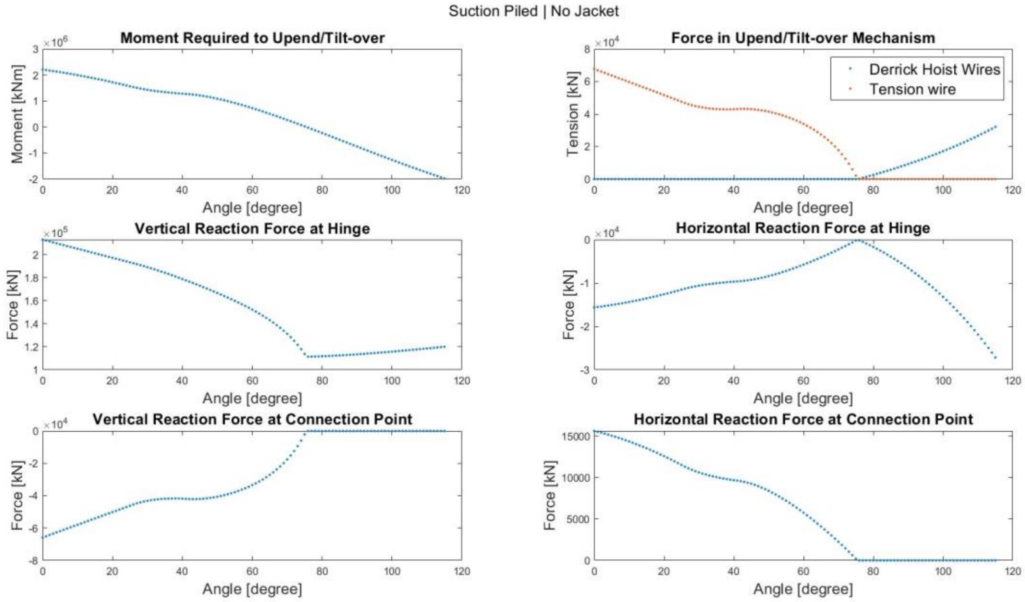


Figure 162: Static (Moment) Forces, Concept Suction Piled (No Jacket)

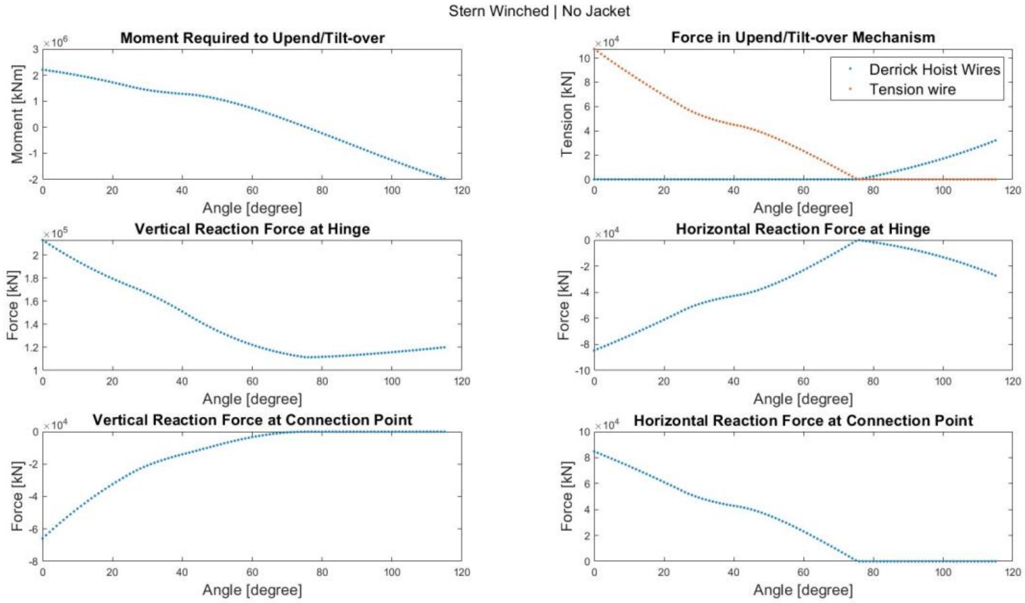


Figure 163: Static (Moment) Forces, Concept Stern Winch (No Jacket)

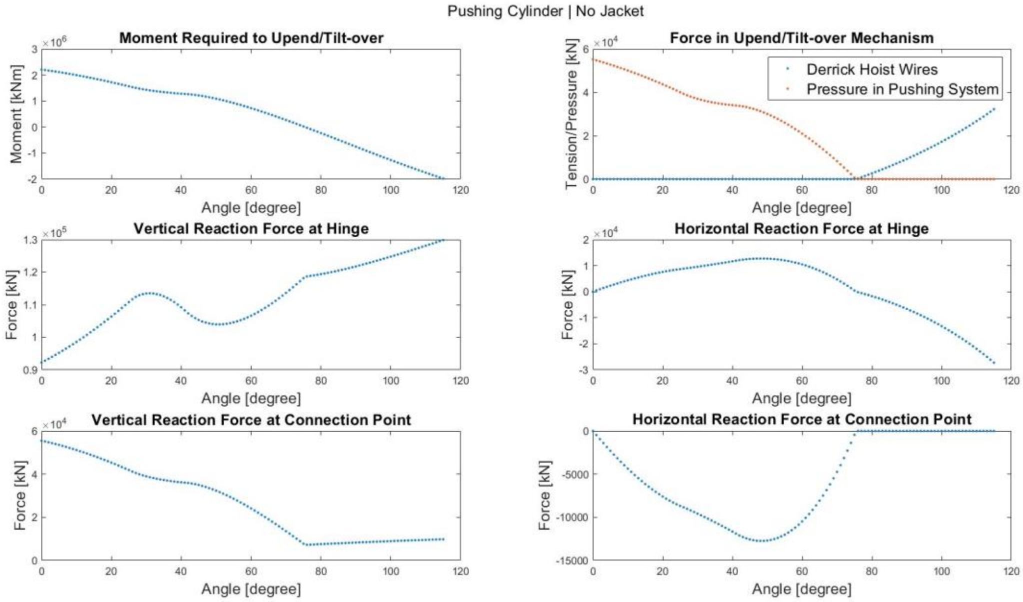


Figure 164: Static (Moment) Forces, Concept Pushing System (No Jacket)

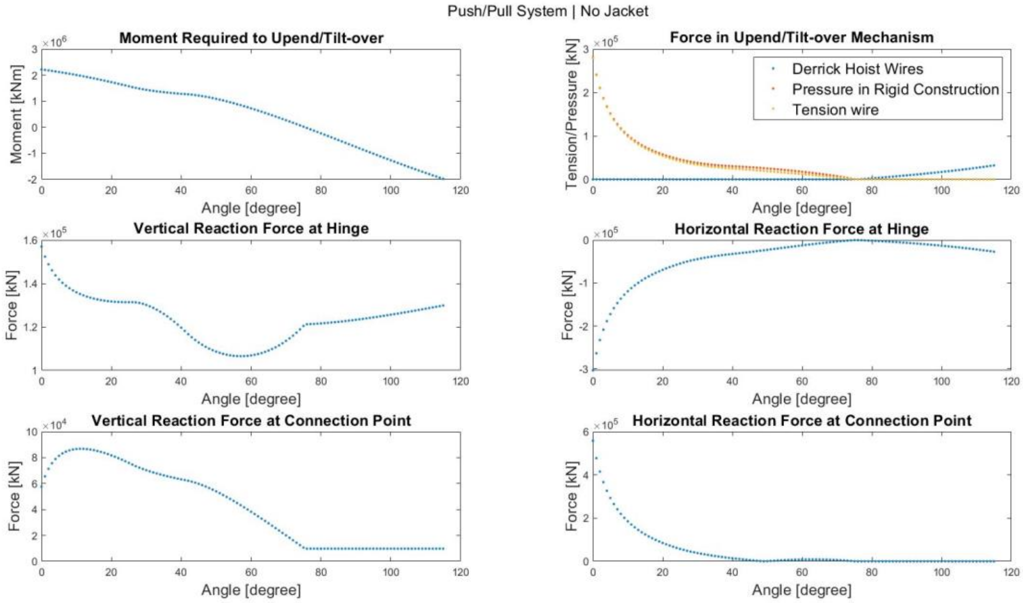


Figure 165: Static (Moment) Forces, Concept Push/Pull System (No Jacket)

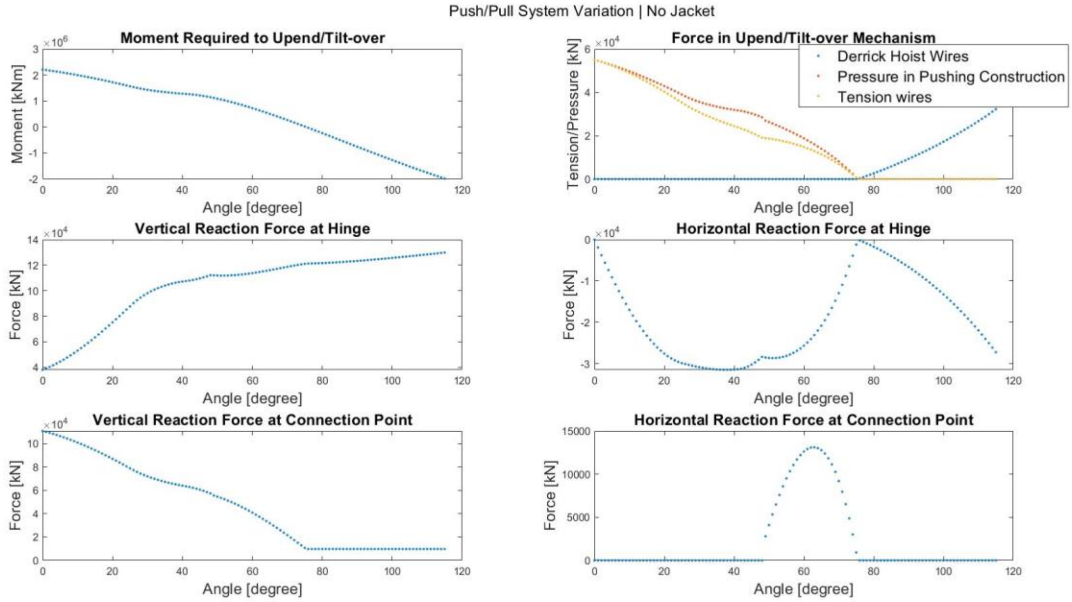


Figure 166: Static (Moment) Forces, Concept Push/Pull Variant System (No Jacket)

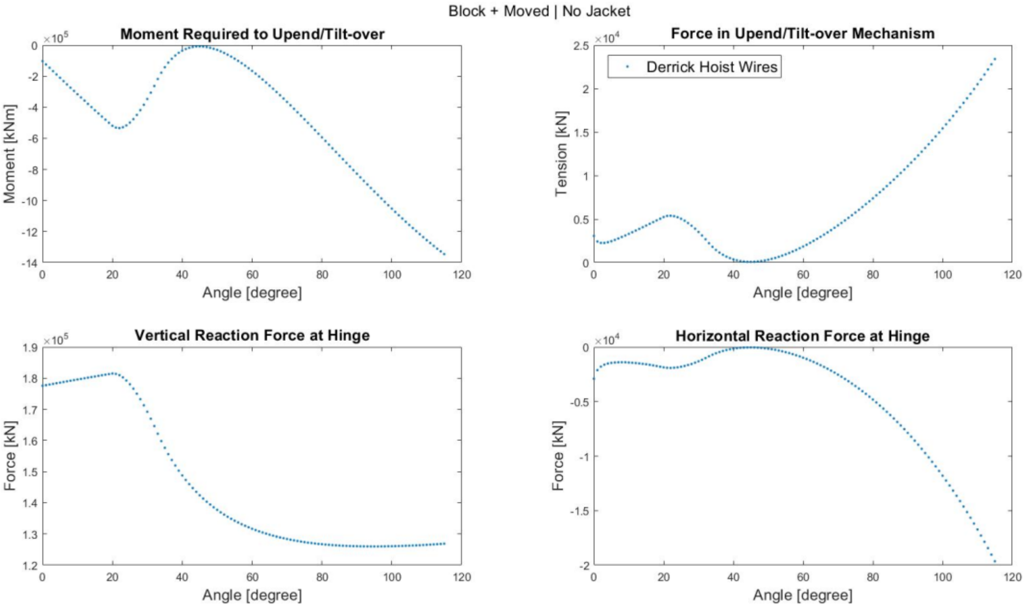


Figure 167: Static (Moment) Forces, Concept Counterweight + Moved Frame (No Jacket)

E.3 Static Forces per Concept (Jacket)

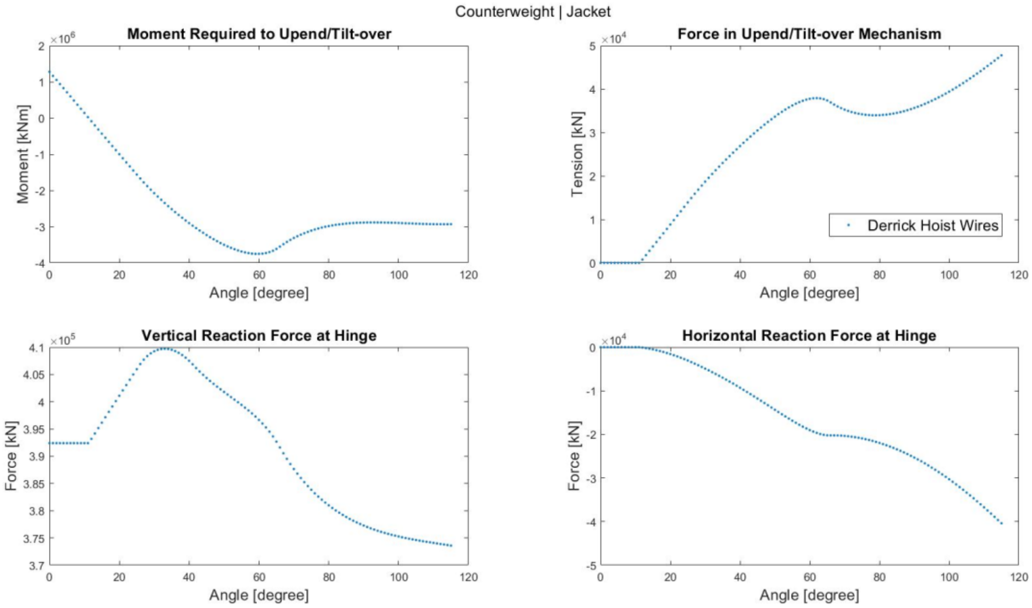


Figure 168: Static (Moment) Forces, Concept Counterweight (Jacket)

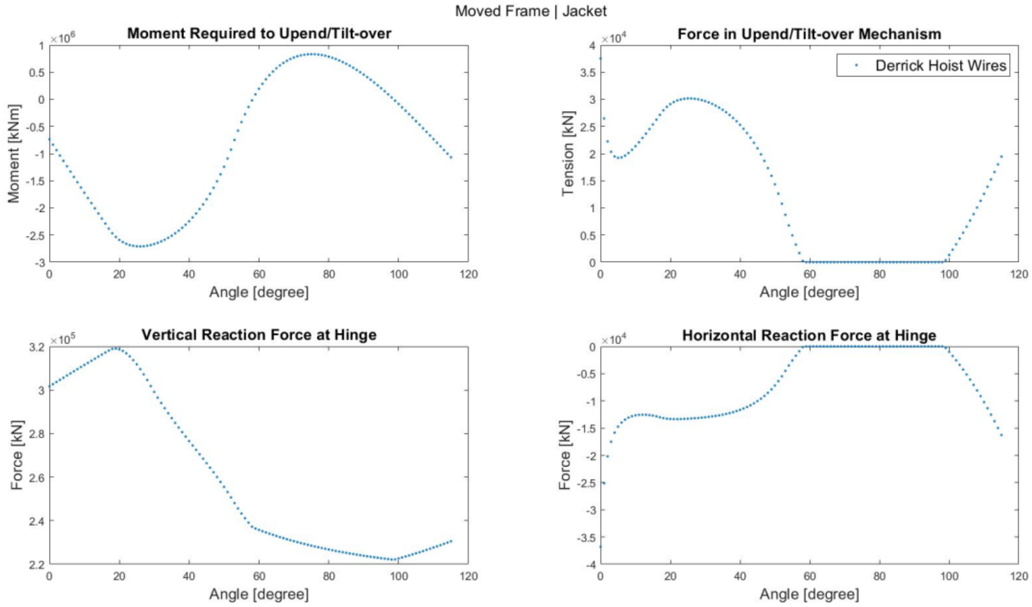


Figure 169: Static (Moment) Forces, Concept Moving frame (Jacket)

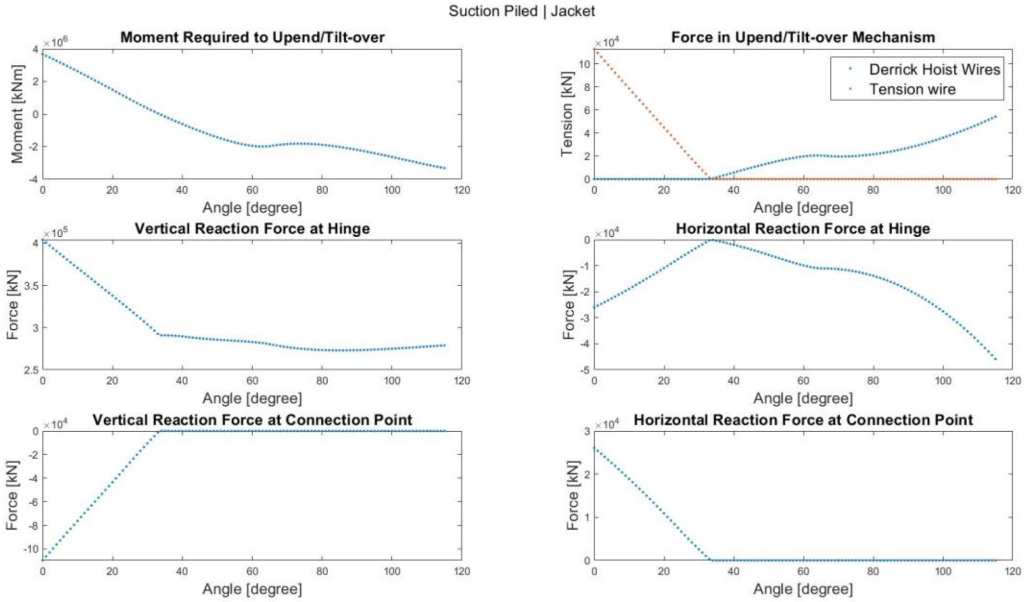


Figure 170: Static (Moment) Forces, Concept Suction Piled (Jacket)

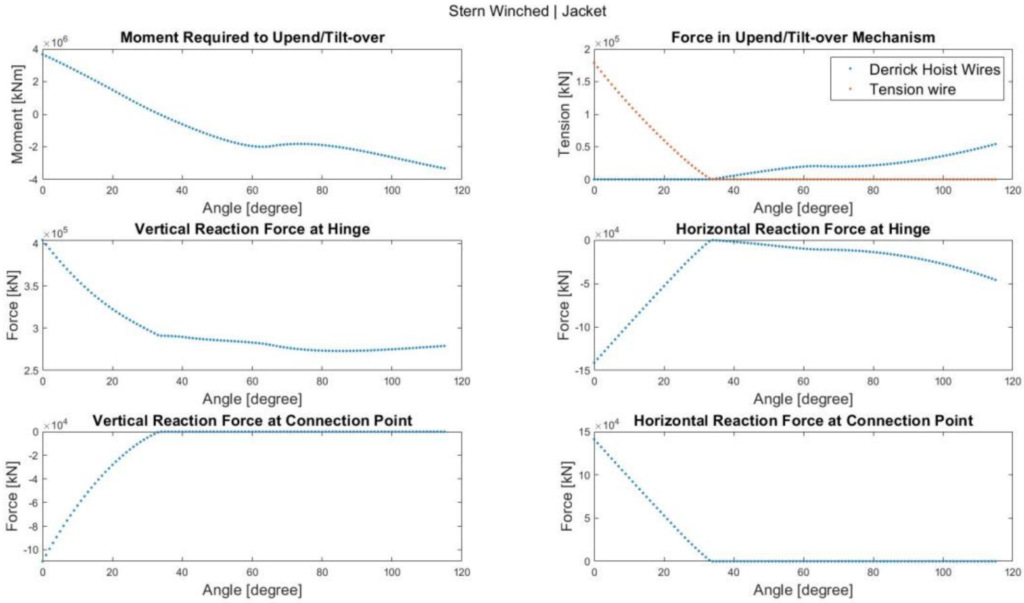


Figure 171: Static (Moment) Forces, Concept Stern Winch (Jacket)

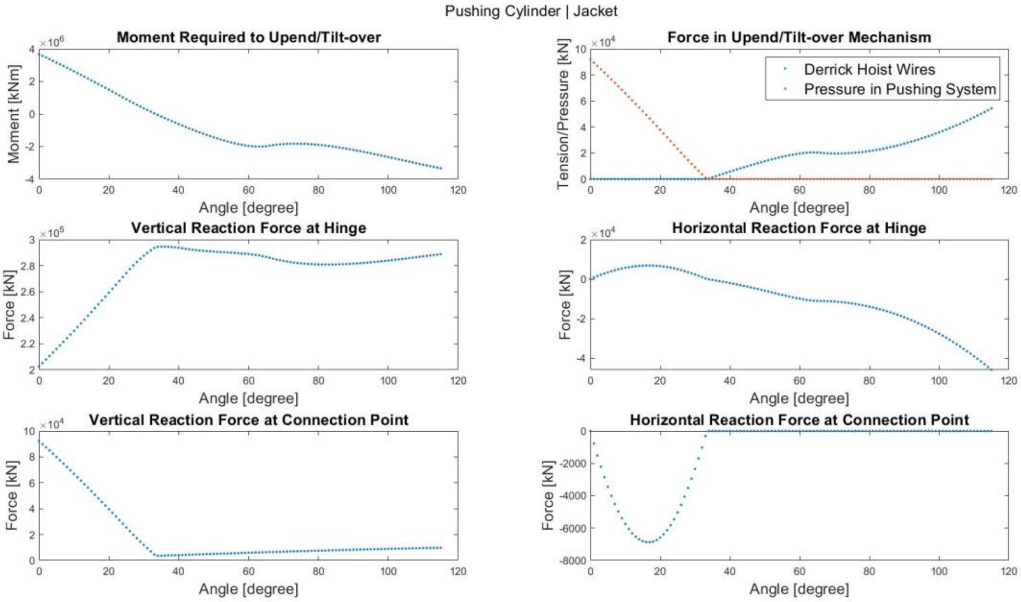


Figure 172: Static (Moment) Forces, Concept Pushing System (Jacket)

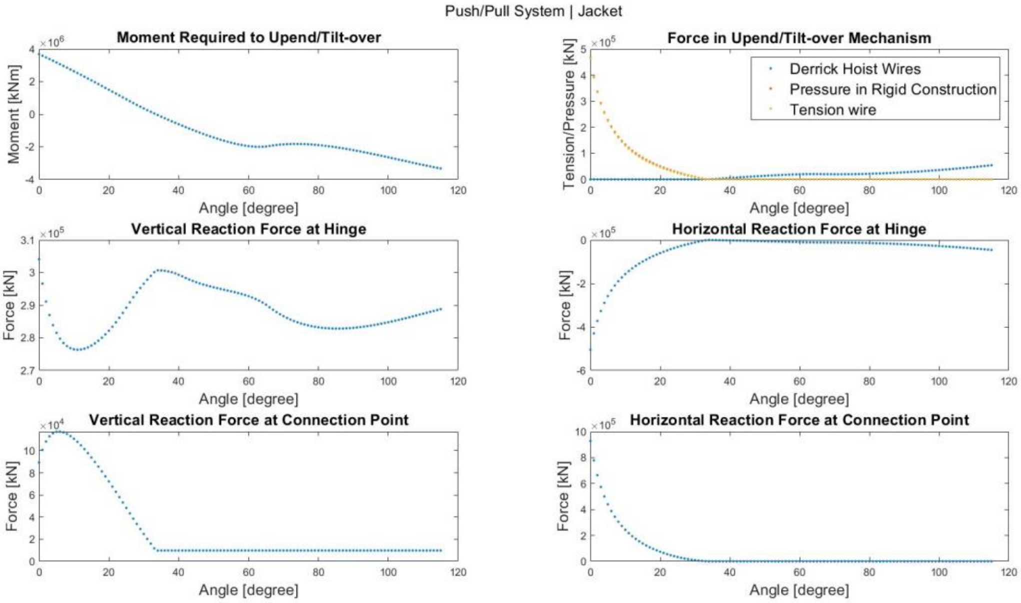


Figure 173: Static (Moment) Forces, Concept Push/Pull System (Jacket)

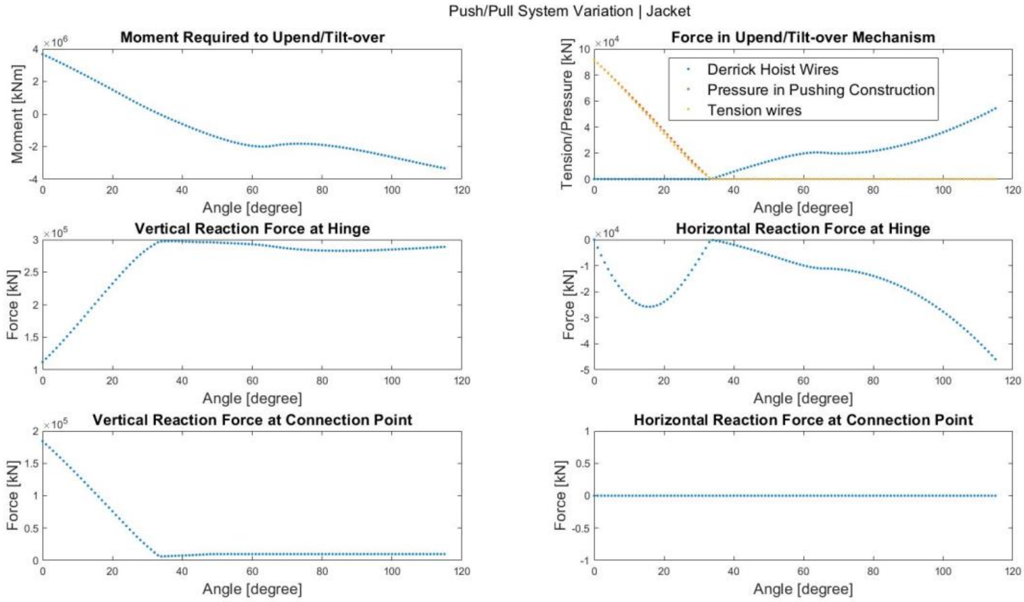


Figure 174: Static (Moment) Forces, Concept Push/Pull Variant System (Jacket)

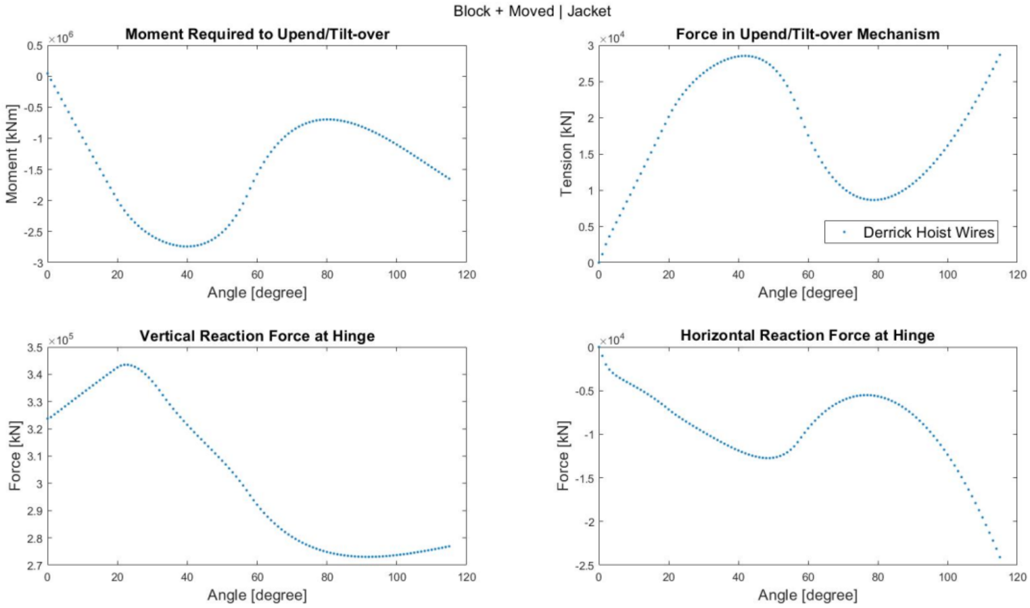


Figure 175: Static (Moment) Forces, Concept Counterweight + Moved Frame (Jacket)

E.4 Static Forces Concept Comparison (No Jacket)

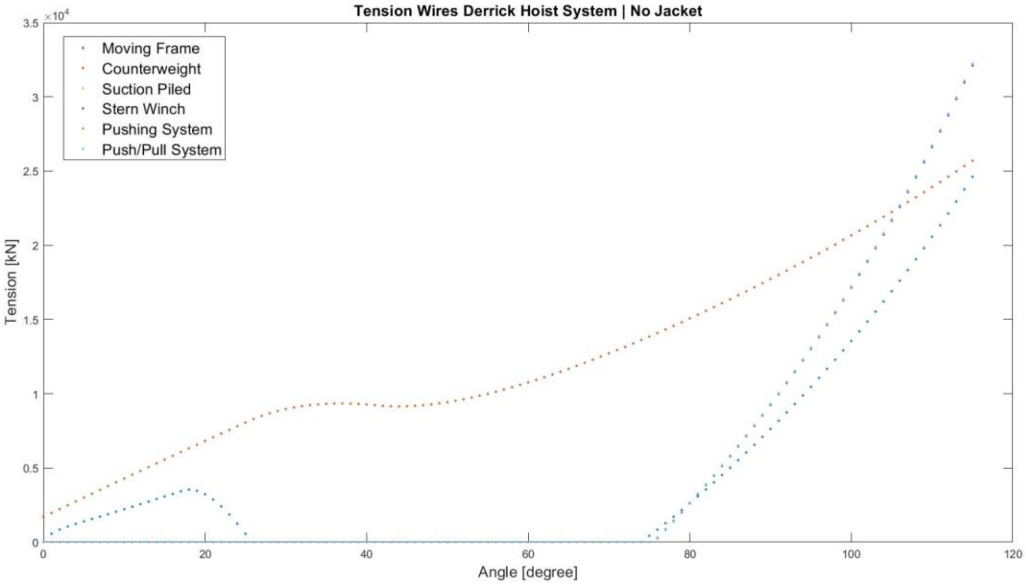


Figure 176: Static (Moment) Forces, Comparison Tension in Derrick Hoist System (No Jacket)

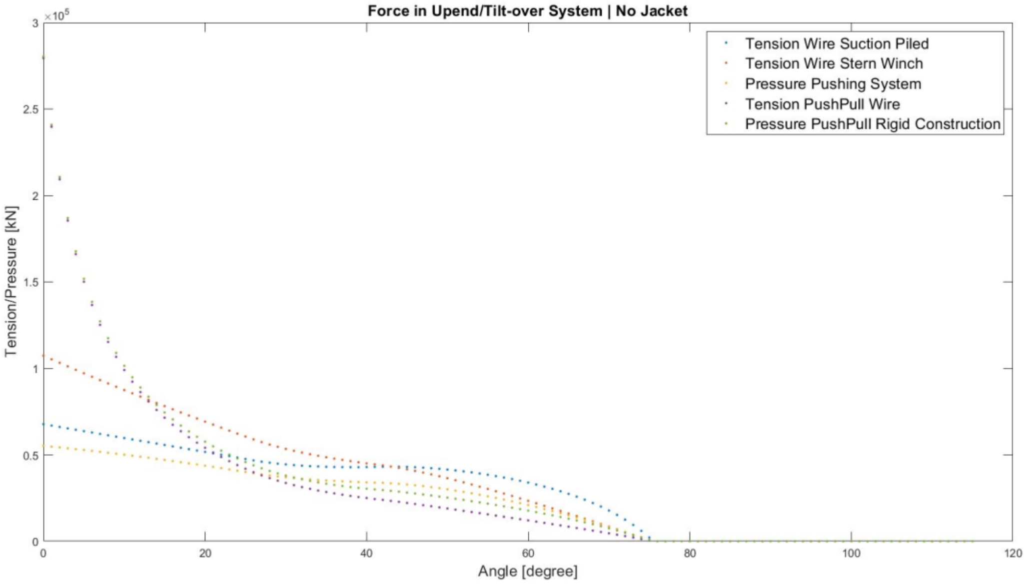


Figure 177: Static (Moment) Forces, Comparison Tension/Pressure in Upend/Tilt-over Component (No Jacket)

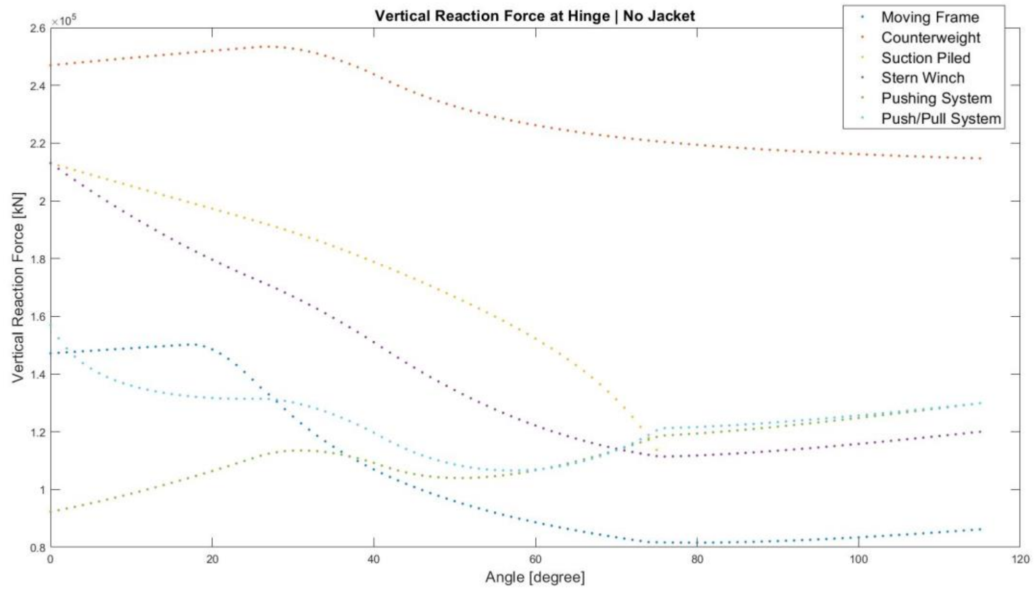


Figure 178: Static (Moment) Forces, Comparison Vertical Reaction Force Hinge (No Jacket)

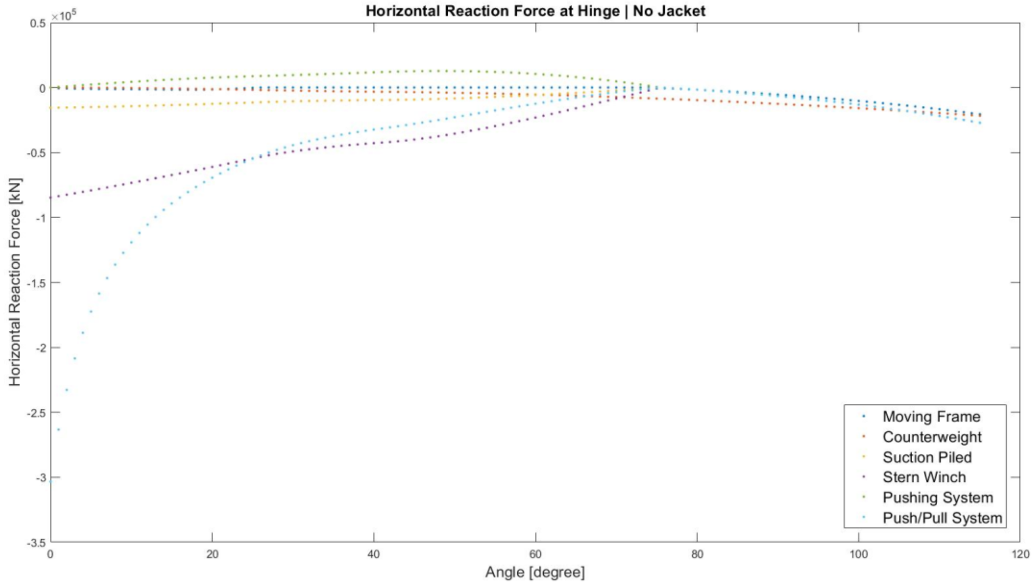


Figure 179: Static (Moment) Forces, Comparison Horizontal Reaction Force Hinge (No Jacket)

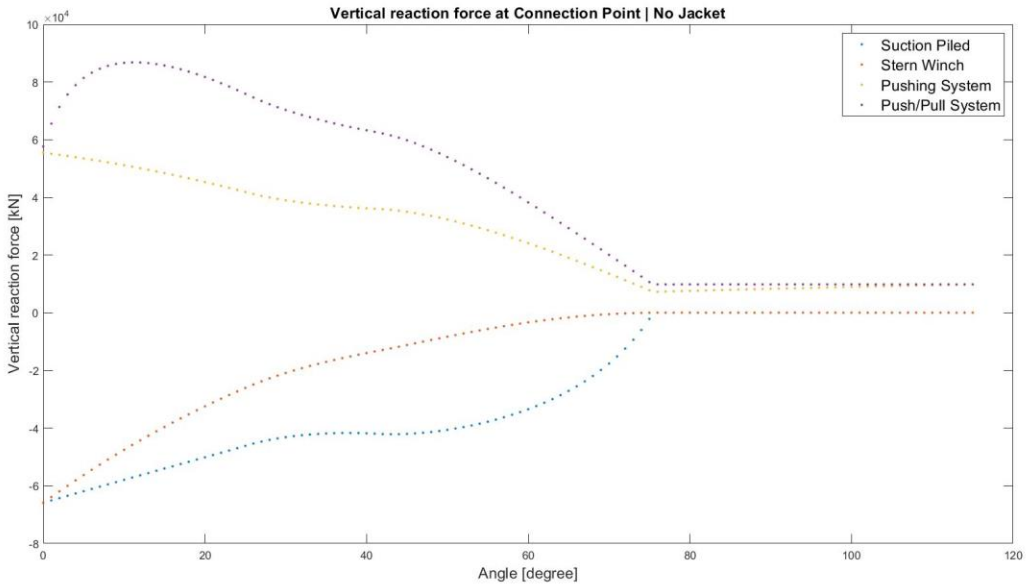


Figure 180: Static (Moment) Forces, Comparison Vertical Reaction Force Support (No Jacket)

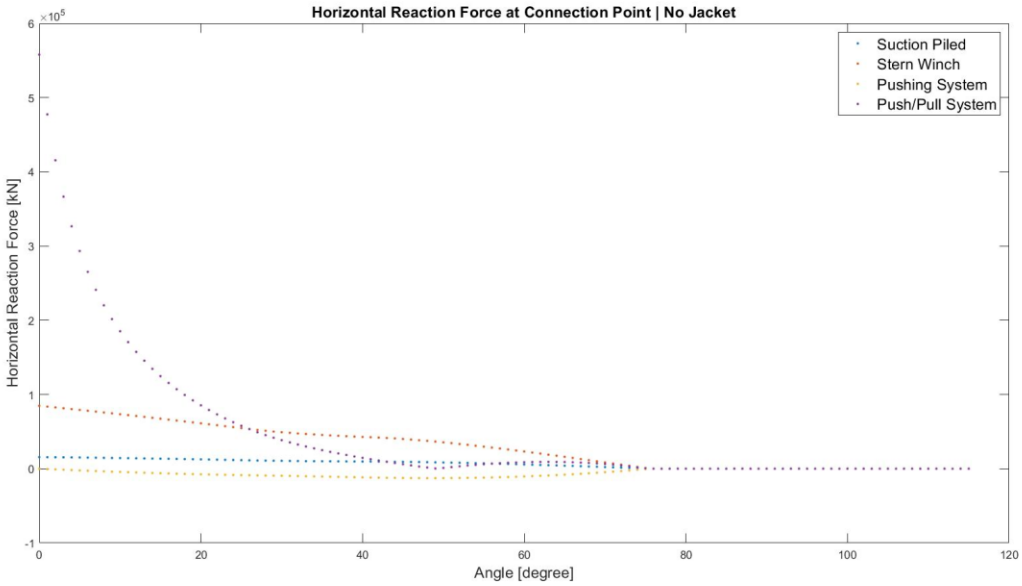


Figure 181: Static (Moment) Forces, Comparison Horizontal Reaction Force Support (No Jacket)

E.5 Static Forces Concept Comparison (Jacket)

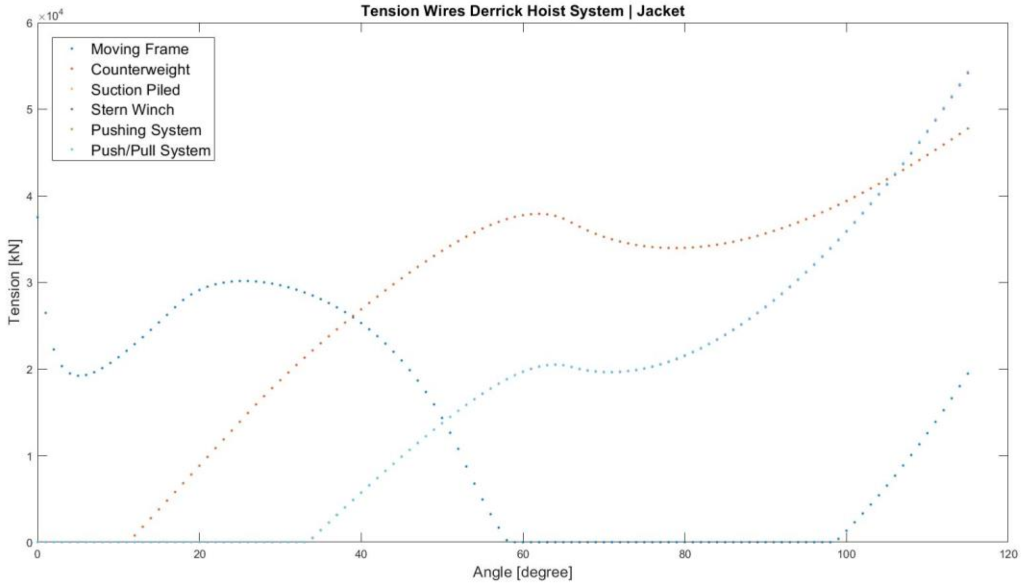


Figure 182: Static (Moment) Forces, Comparison Tension in Derrick Hoist System (Jacket)

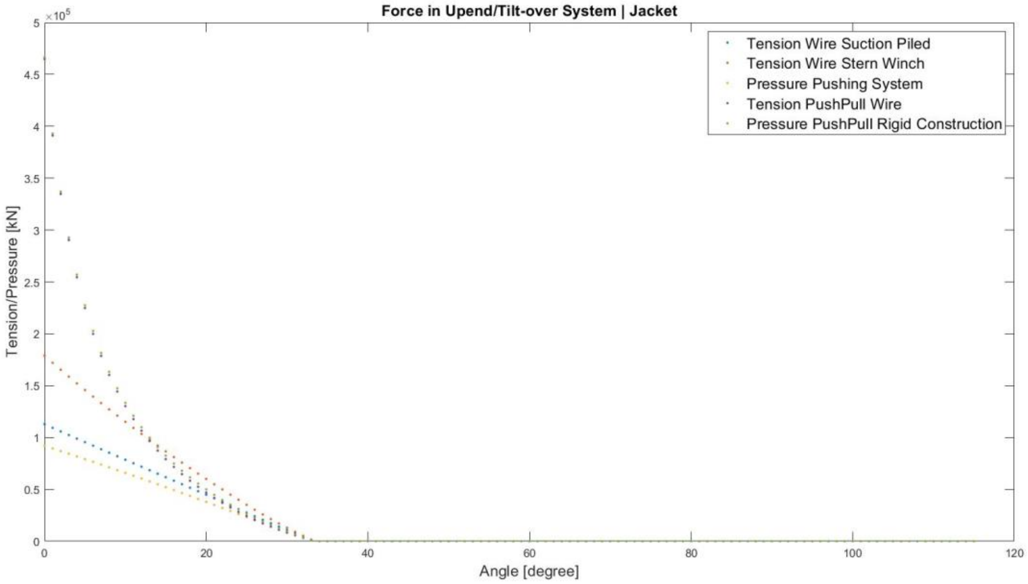


Figure 183: Static (Moment) Forces, Comparison Tension/Pressure in Upend/Tilt-over Component (Jacket)

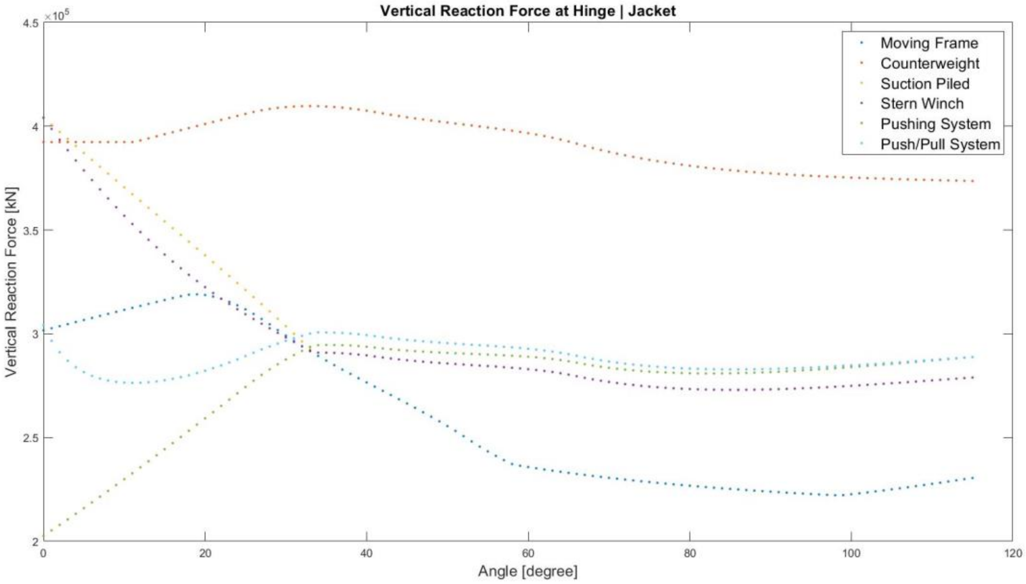


Figure 184: Static (Moment) Forces, Comparison Vertical Reaction Force Hinge (Jacket)

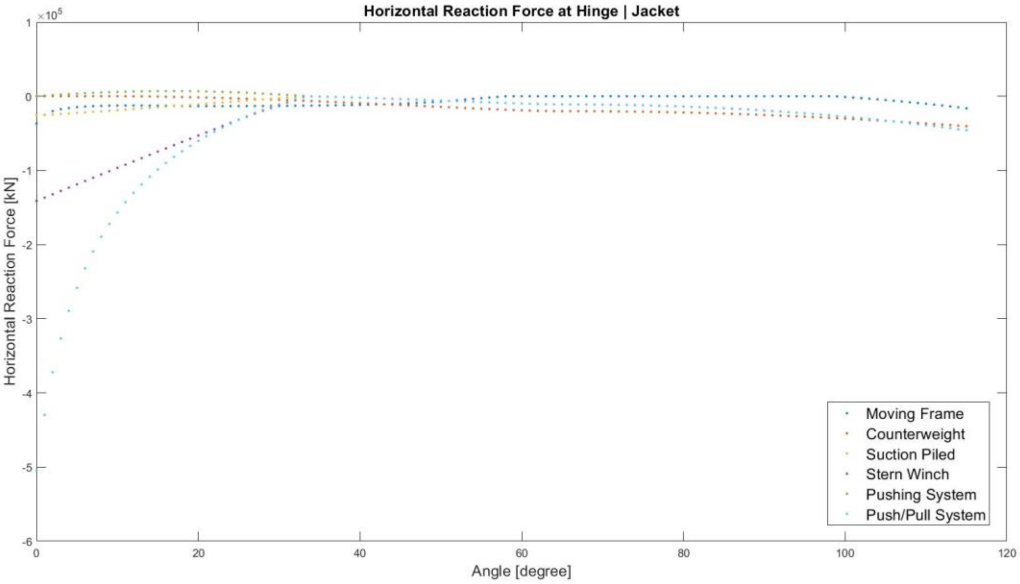


Figure 185: Static (Moment) Forces, Comparison Horizontal Reaction Force Hinge (Jacket)

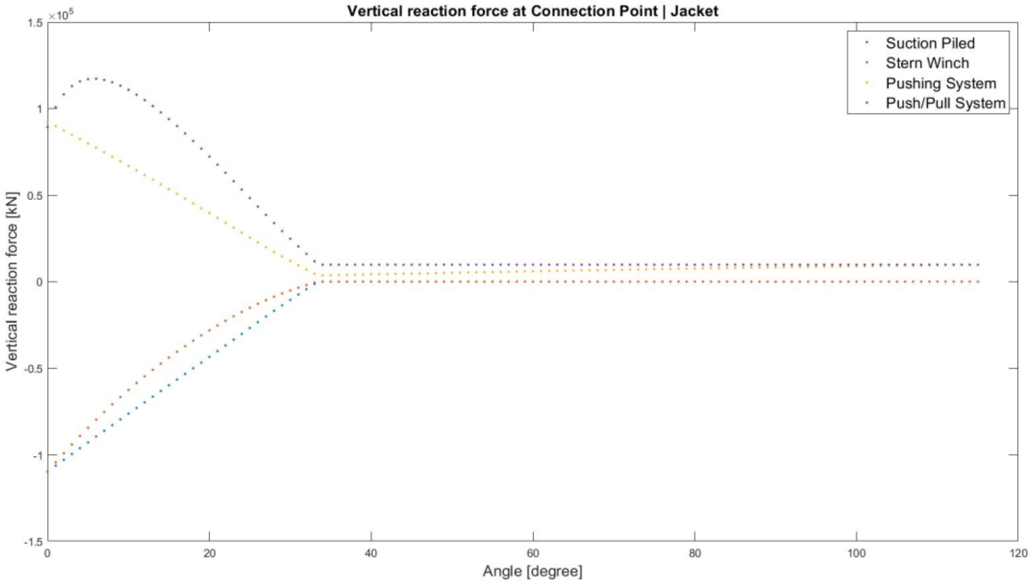


Figure 186: Static (Moment) Forces, Comparison Vertical Reaction Force Support (Jacket)

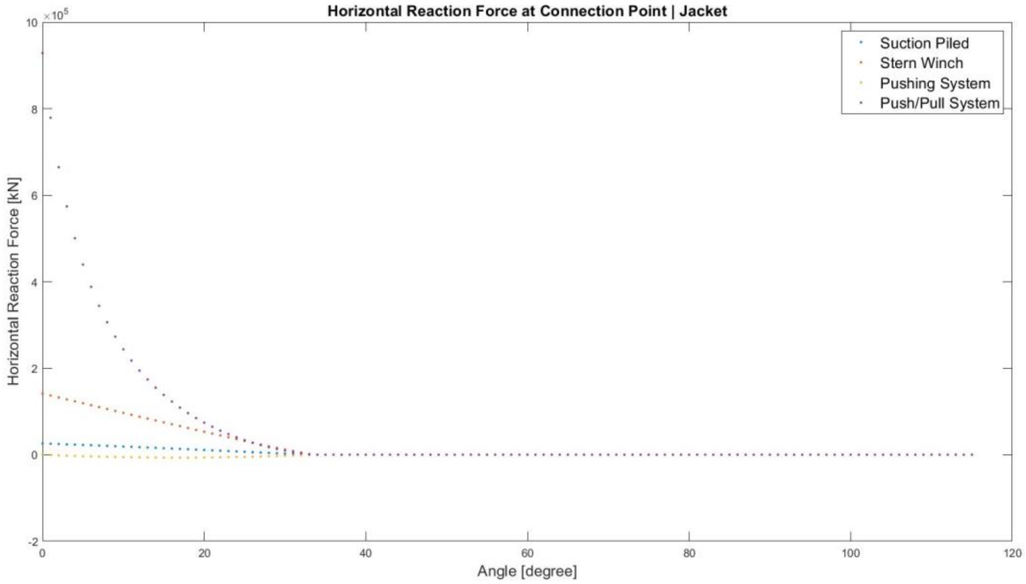


Figure 187: Static (Moment) Forces, Comparison Horizontal Reaction Force Support (Jacket)

F. Results Static Forces Optimisation (Chapter 6)

F.1 Static Forces Concept Comparison Variant (No Jacket)

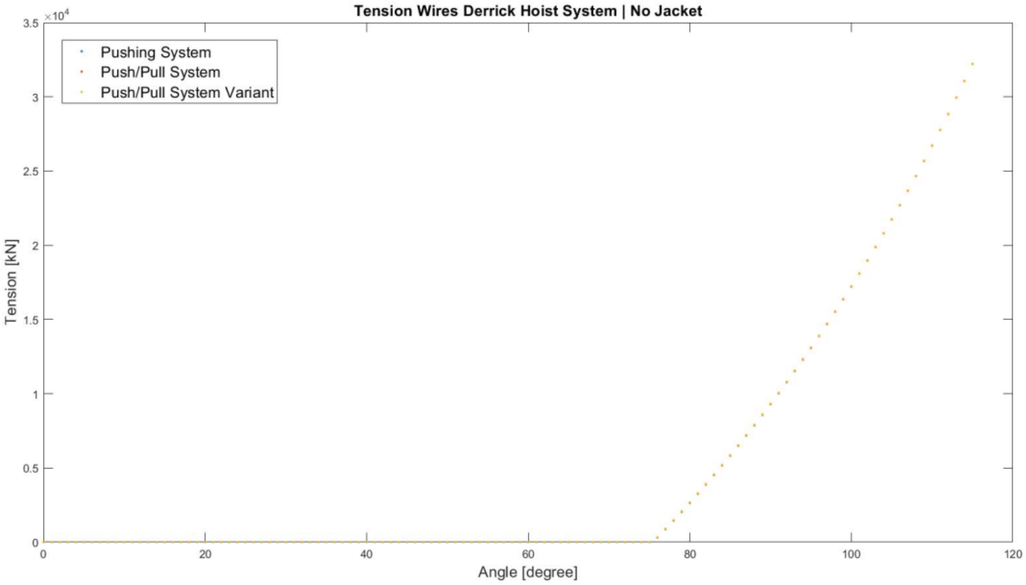


Figure 188: Static (Moment) Forces, Comparison Variant Tension in Derrick Hoist System (No Jacket)

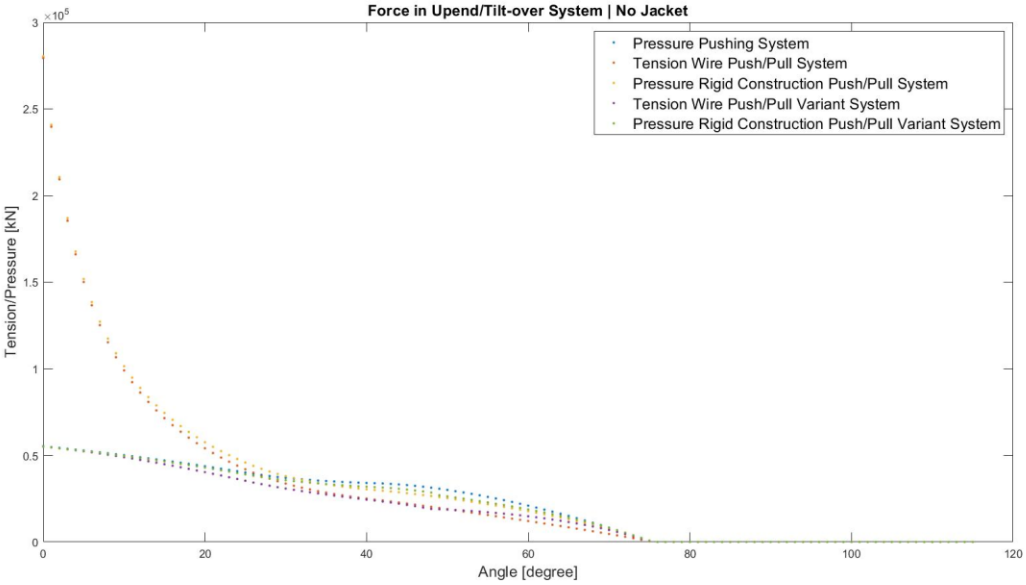


Figure 189: Static (Moment) Forces, Comparison Variant Tension/Pressure in Upend/Tilt-over Component (No Jacket)

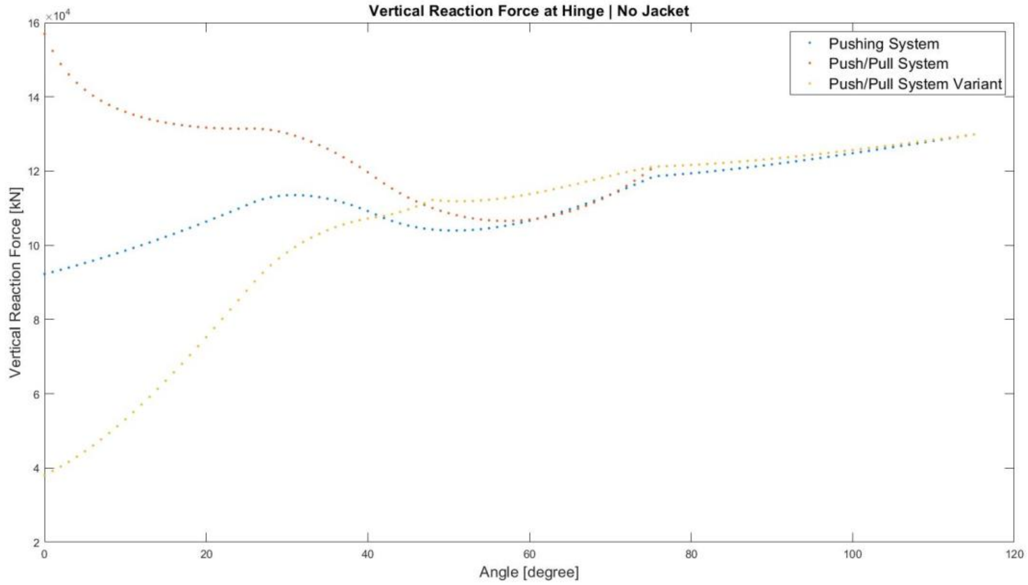


Figure 190: Static (Moment) Forces, Comparison Variant Vertical Reaction Force Hinge (No Jacket)

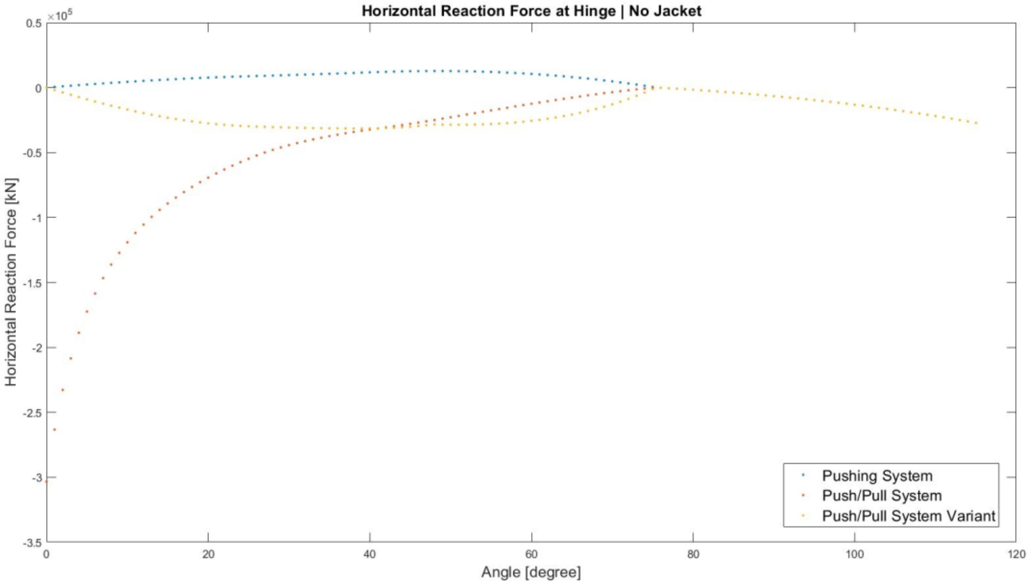


Figure 191: Static (Moment) Forces, Comparison Variant Horizontal Reaction Force Hinge (No Jacket)

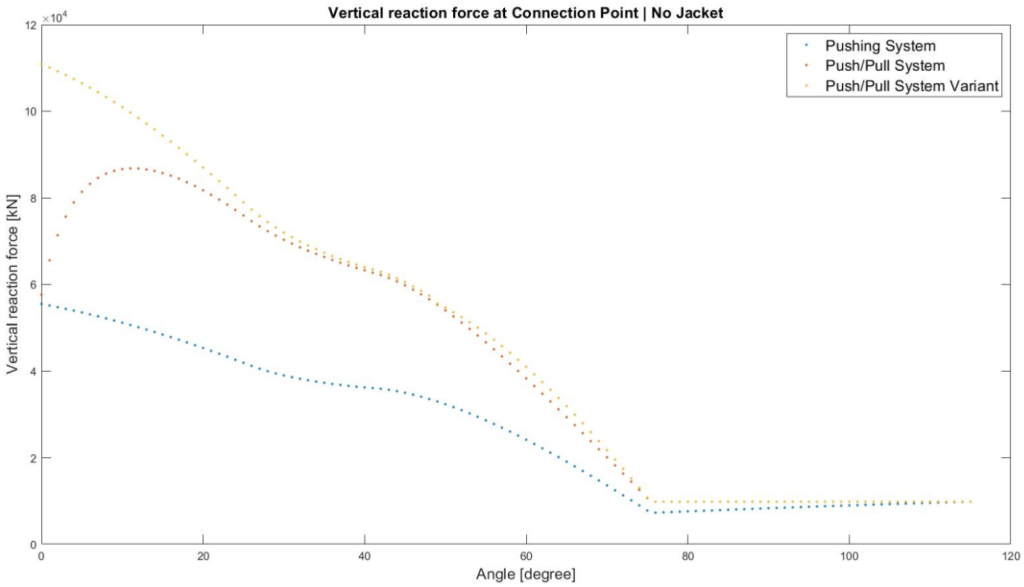


Figure 192: Static (Moment) Forces, Comparison Variant Vertical Reaction Force Support (No Jacket)

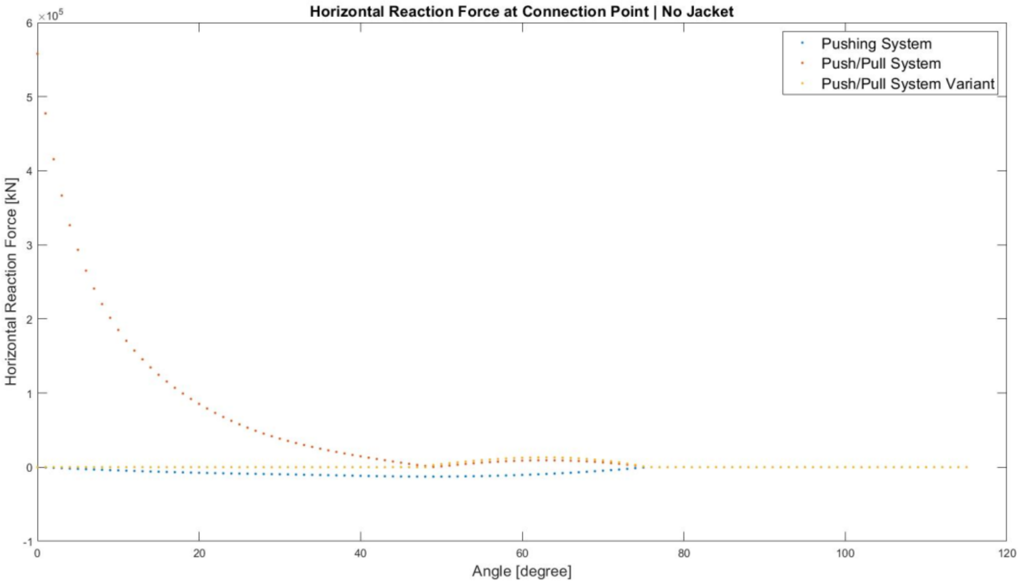


Figure 193: Static (Moment) Forces, Comparison Variant Horizontal Reaction Force Support (No Jacket)

F.2 Static Forces Concept Comparison Variant (Jacket)

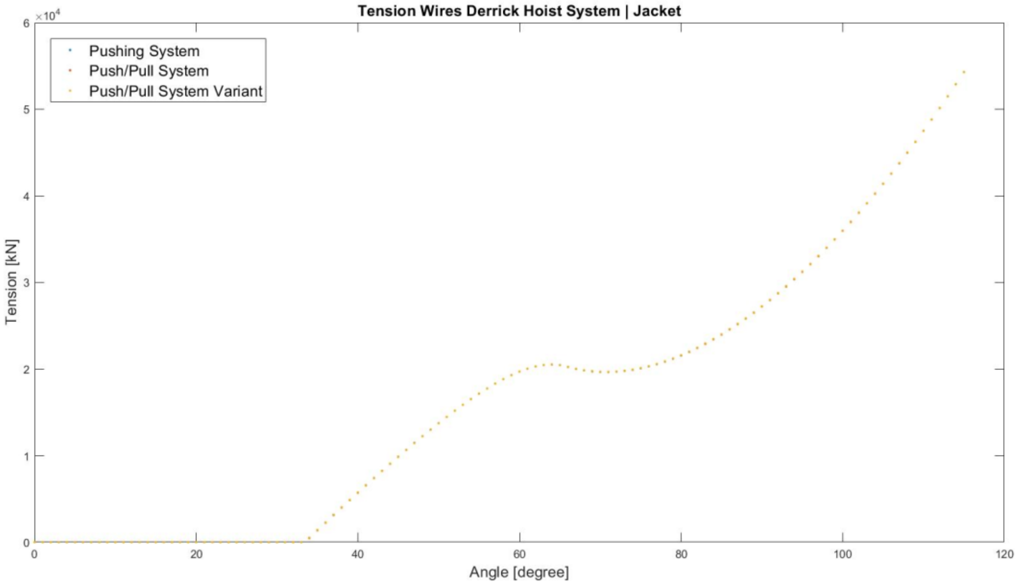


Figure 194: Static (Moment) Forces, Comparison Variant Tension in Derrick Hoist System (Jacket)

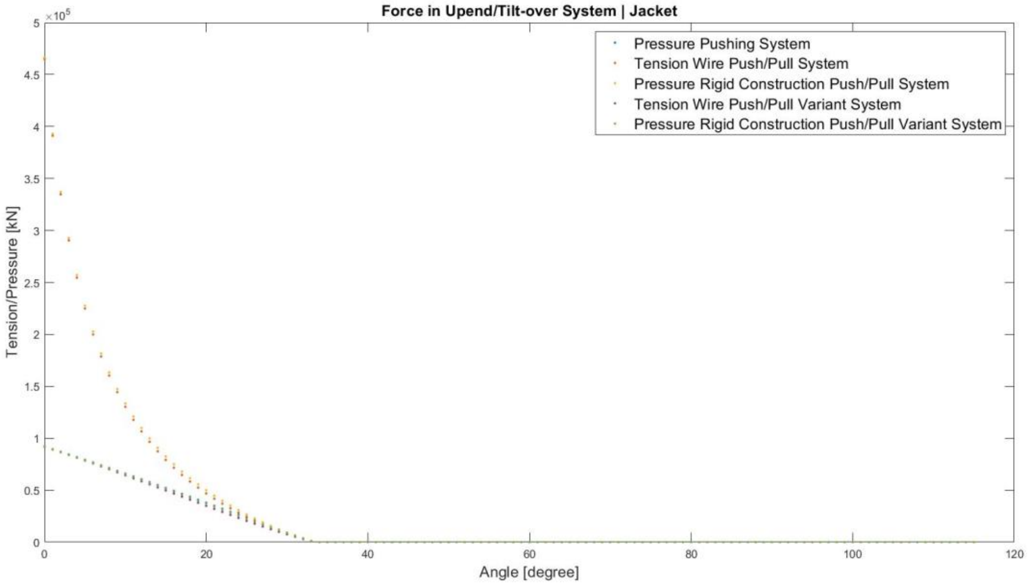


Figure 195: Static (Moment) Forces, Comparison Variant Tension/Pressure in Upend/Tilt-over Component (Jacket)

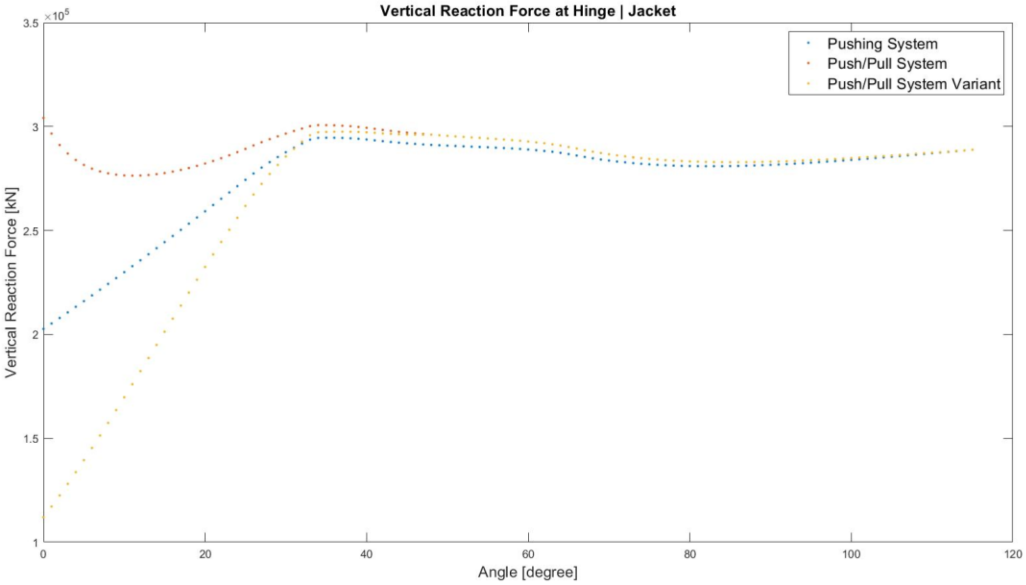


Figure 196: Static (Moment) Forces, Comparison Variant Vertical Reaction Force Hinge (Jacket)

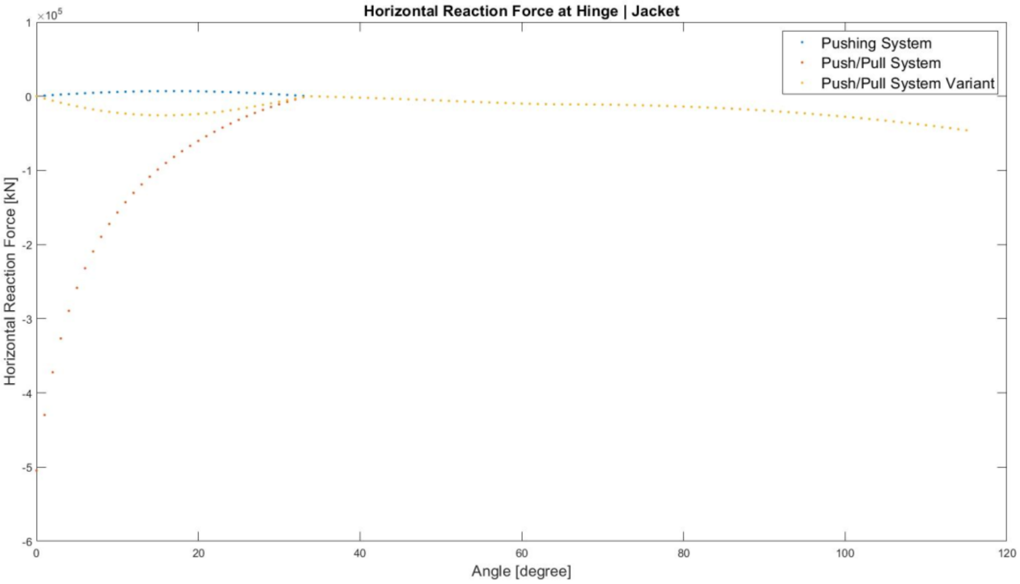


Figure 197: Static (Moment) Forces, Comparison Variant Horizontal Reaction Force Hinge (Jacket)

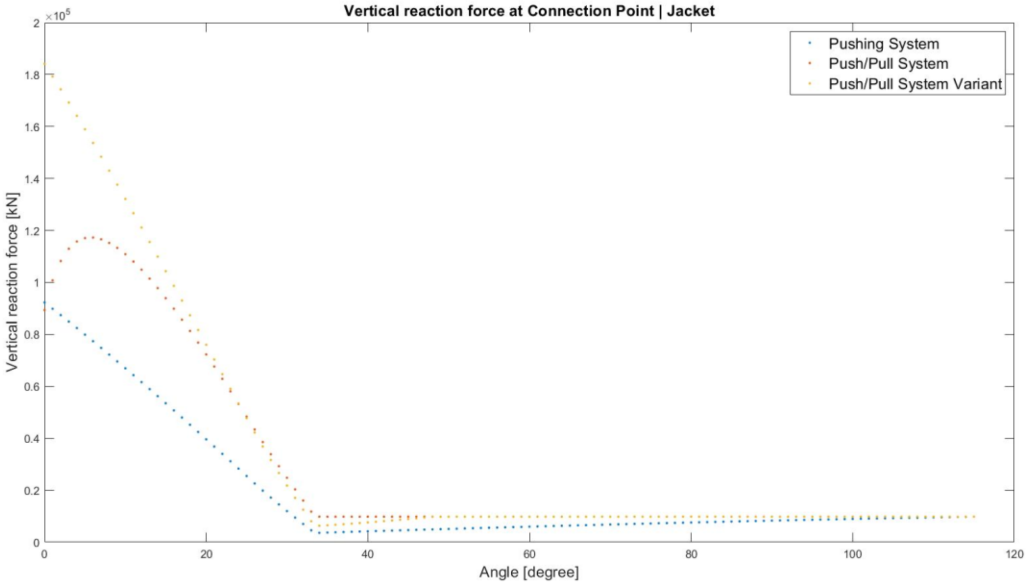


Figure 198: Static (Moment) Forces, Comparison Variant Vertical Reaction Force Support (Jacket)

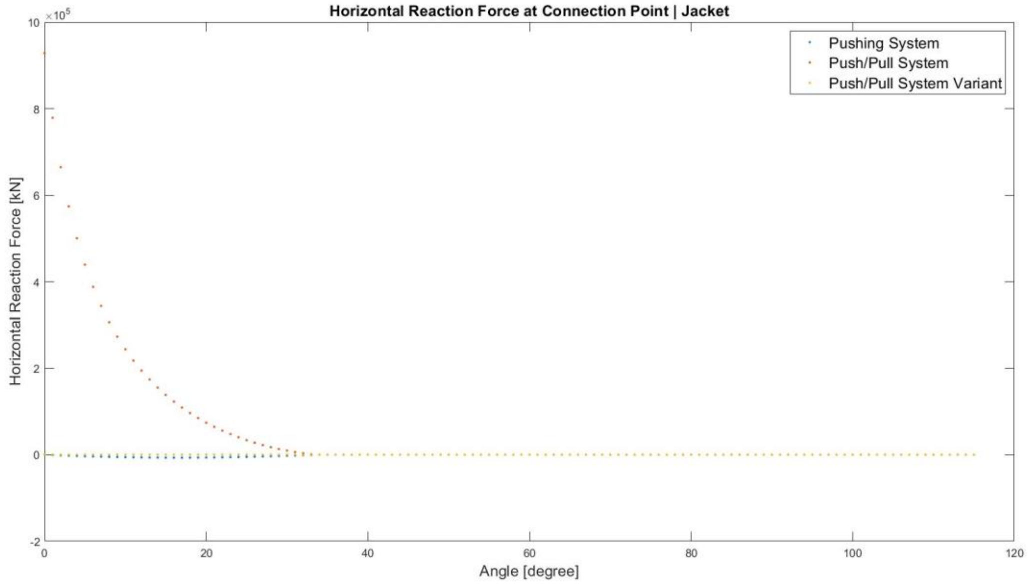


Figure 199: Static (Moment) Forces, Comparison Variant Horizontal Reaction Force Support (Jacket)

F.3 Individually Forces Moved Centre of Gravity

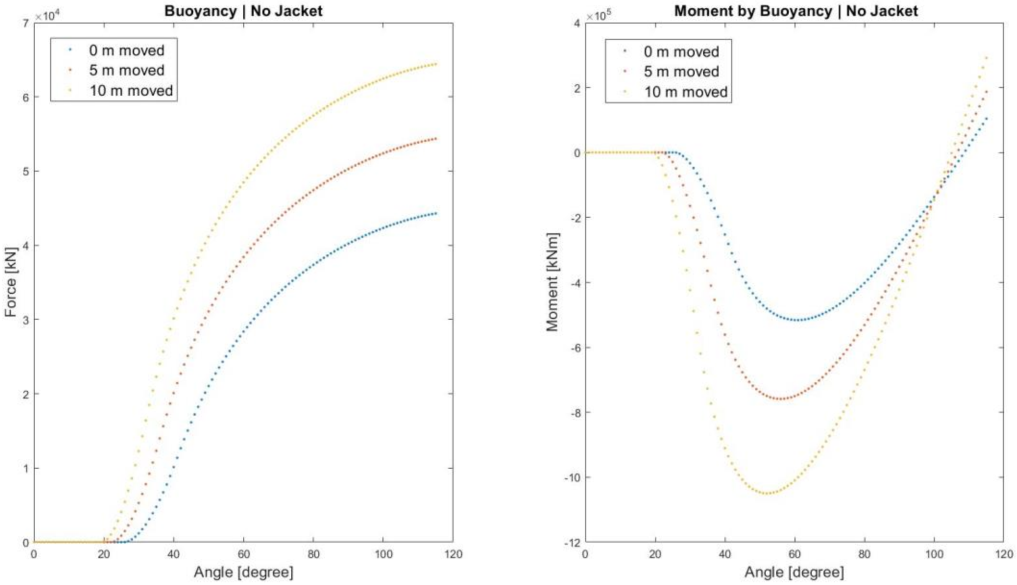


Figure 200: Static (Moment) Force, Buoyancy (Moved)

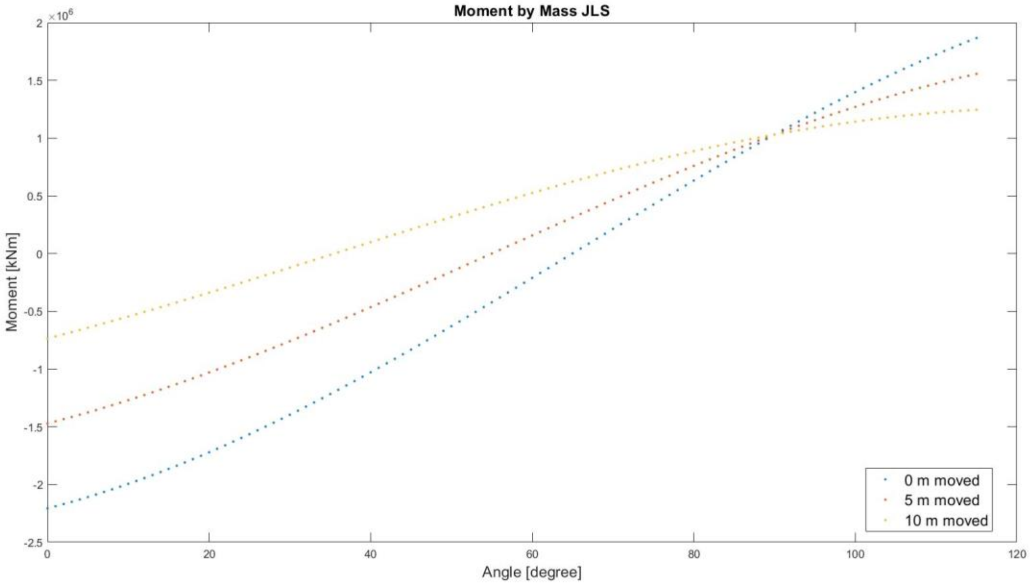


Figure 201: Static (Moment) Force, Mass JLS (Moved)

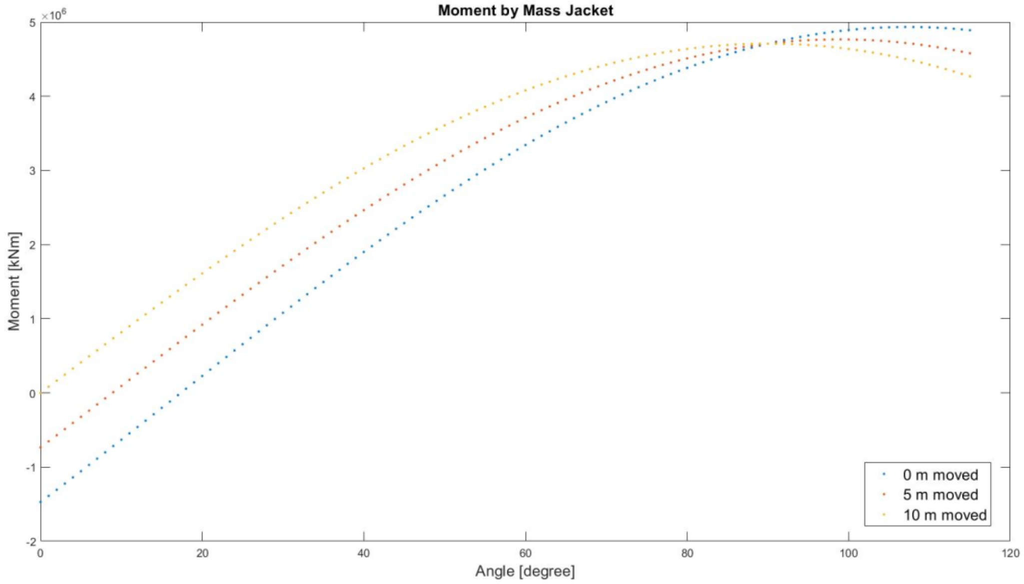


Figure 202: Static (Moment) Force, Mass jacket (Moved)

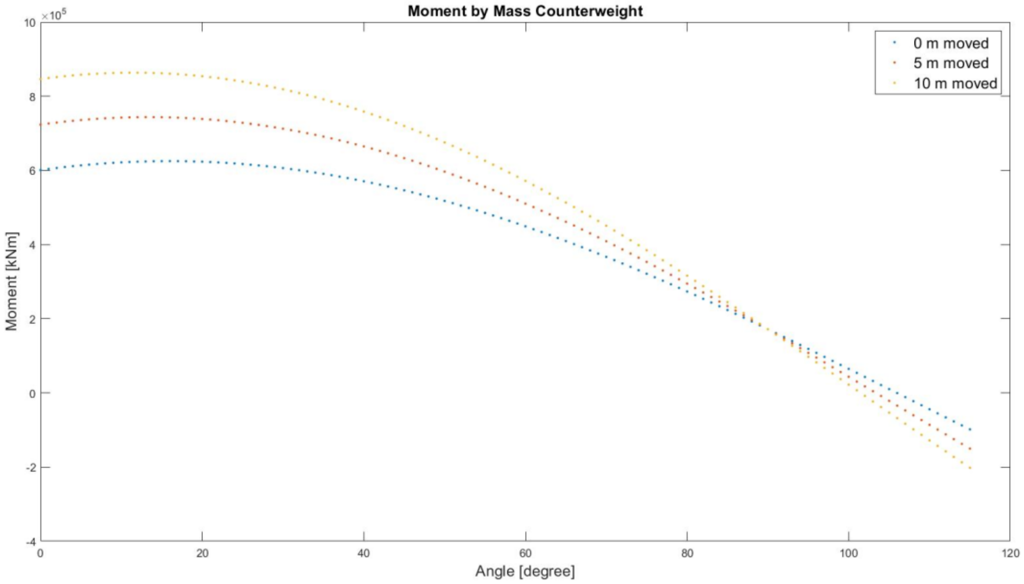


Figure 203: Static (Moment) Force, Mass Counterweight (Moved)

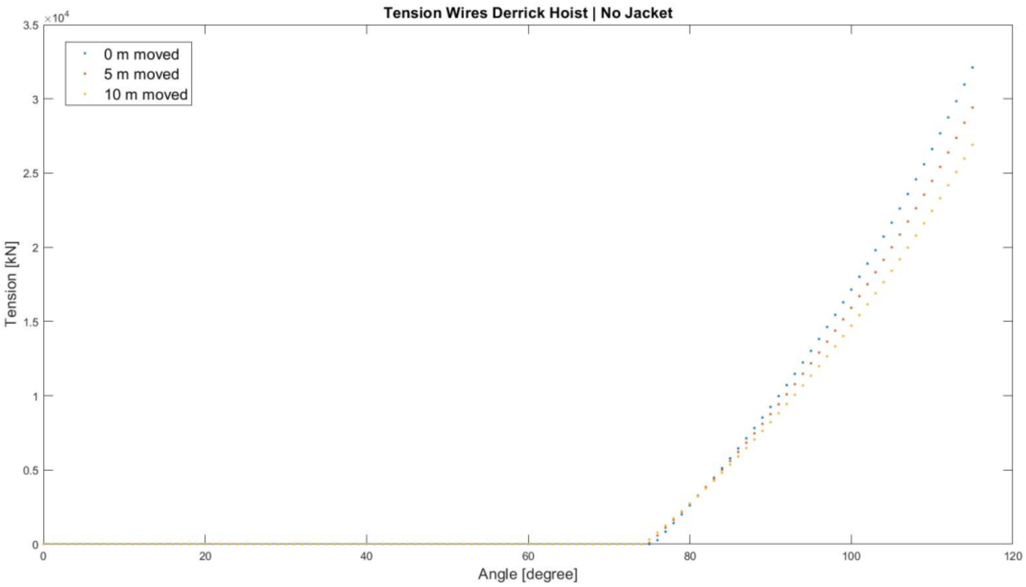


Figure 204: Static (Moment) Force, Derrick Hoist System (No jacket) (Moved)

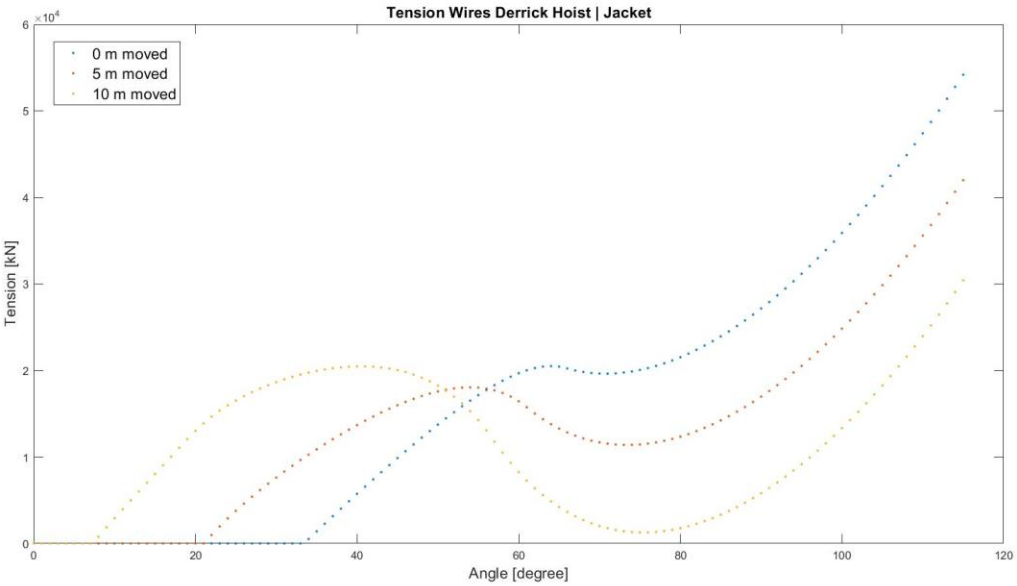


Figure 205: Static (Moment) Force, Derrick Hoist System (jacket) (Moved)

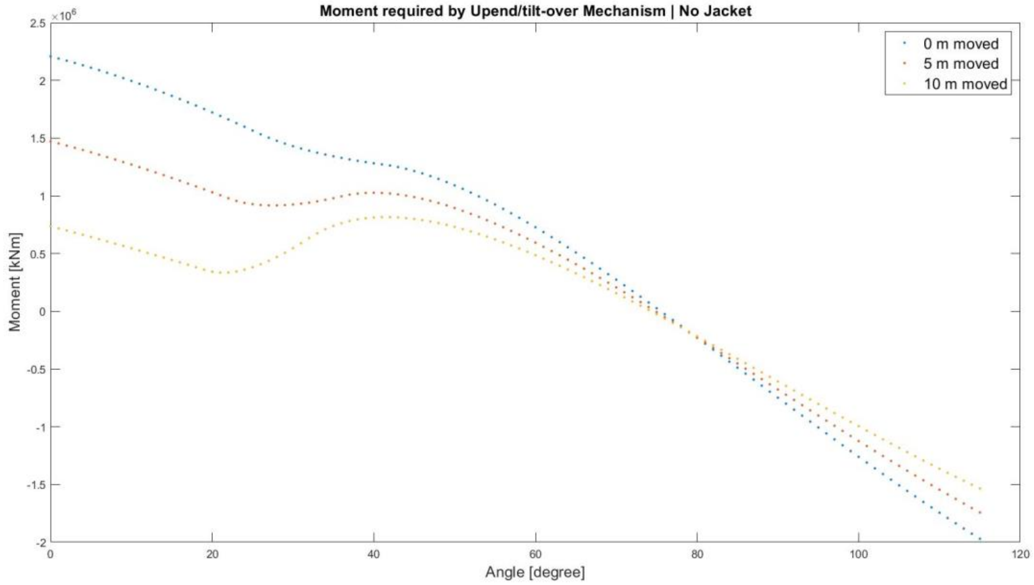


Figure 206: Static (Moment) Force, Upend/Tilt-over Mechanism (No Jacket) (Moved)

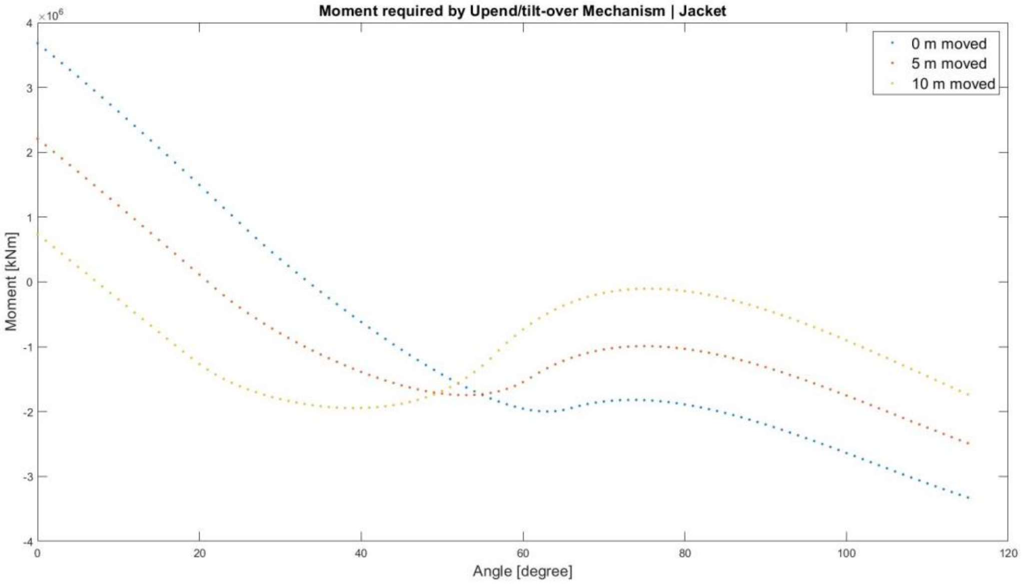


Figure 207: Static (Moment) Force Upend/Tilt-over Mechanism (Jacket) (Moved)

F.4 Static Forces Concept Comparison Variation, Optimisation (No Jacket)

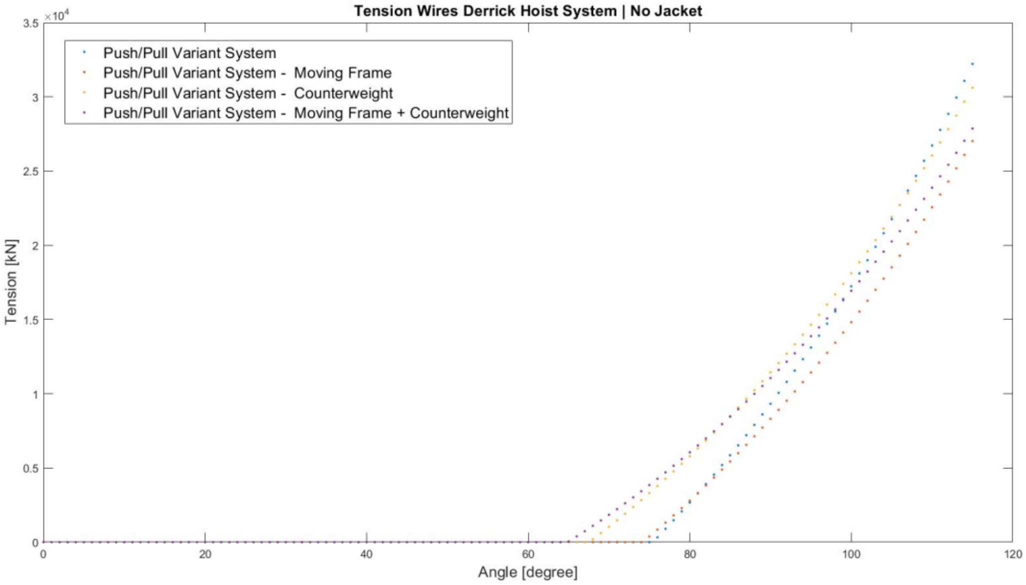


Figure 208: Static (Moment) Forces Optimisation, Comparison Tension in Derrick Hoist System (No Jacket)

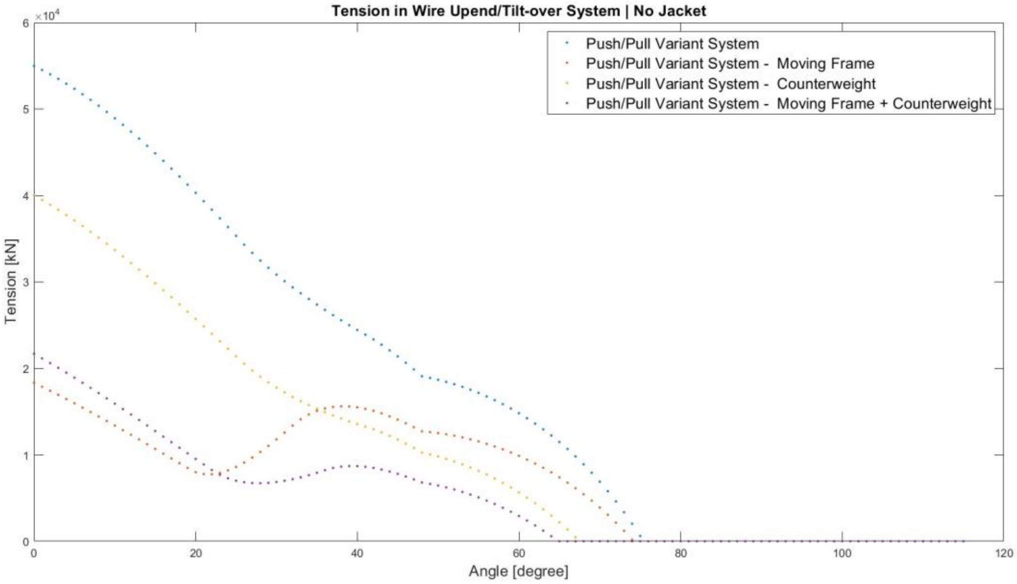


Figure 209: Static (Moment) Forces Optimisation, Comparison Tension in Upend/Tilt-over Component (No Jacket)

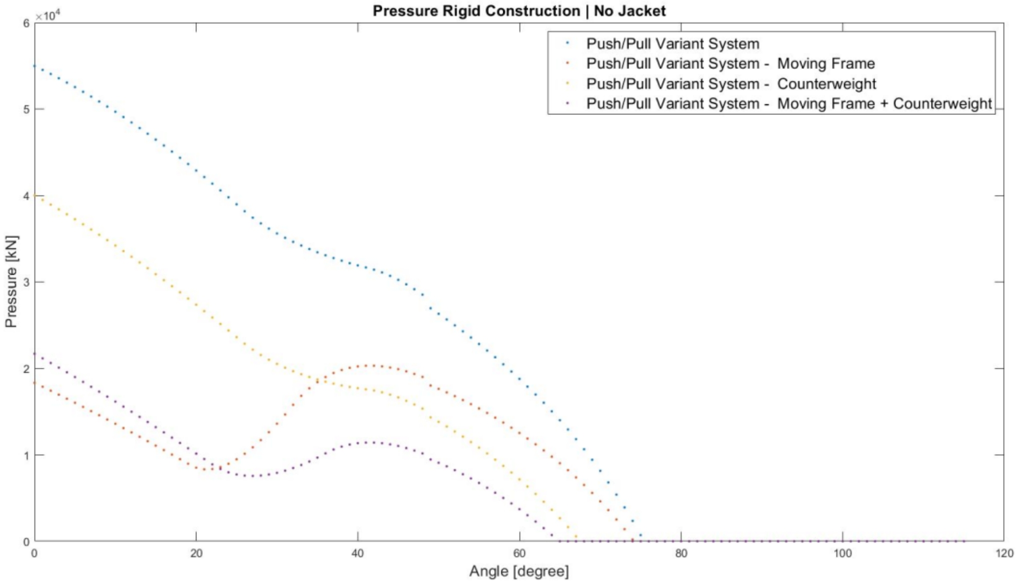


Figure 210: Static (Moment) Forces Optimisation, Comparison Tension/Pressure in Upend/Tilt-over Component (No Jacket)

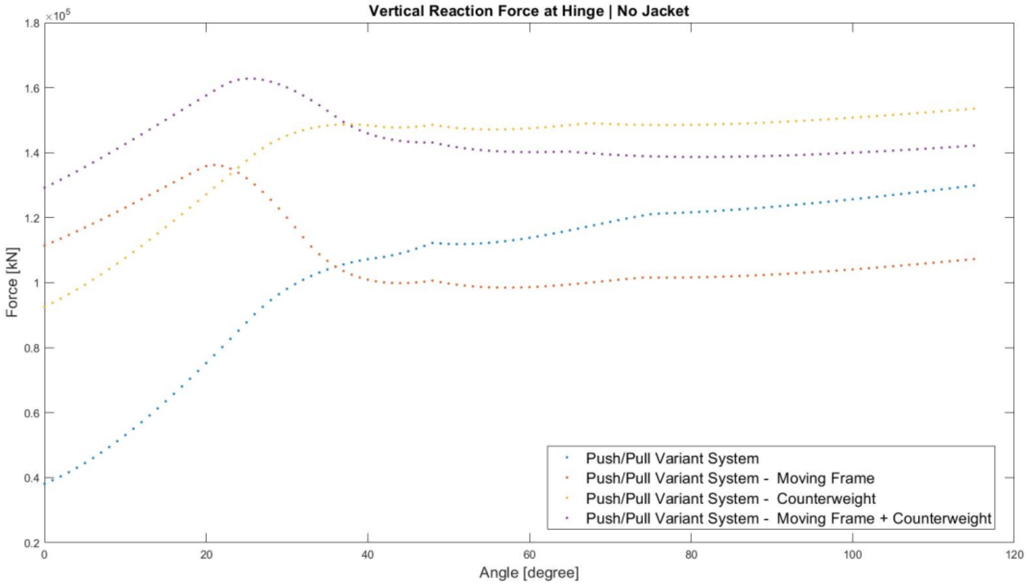


Figure 211: Static (Moment) Forces Optimisation, Comparison Vertical Reaction Force Hinge (No Jacket)

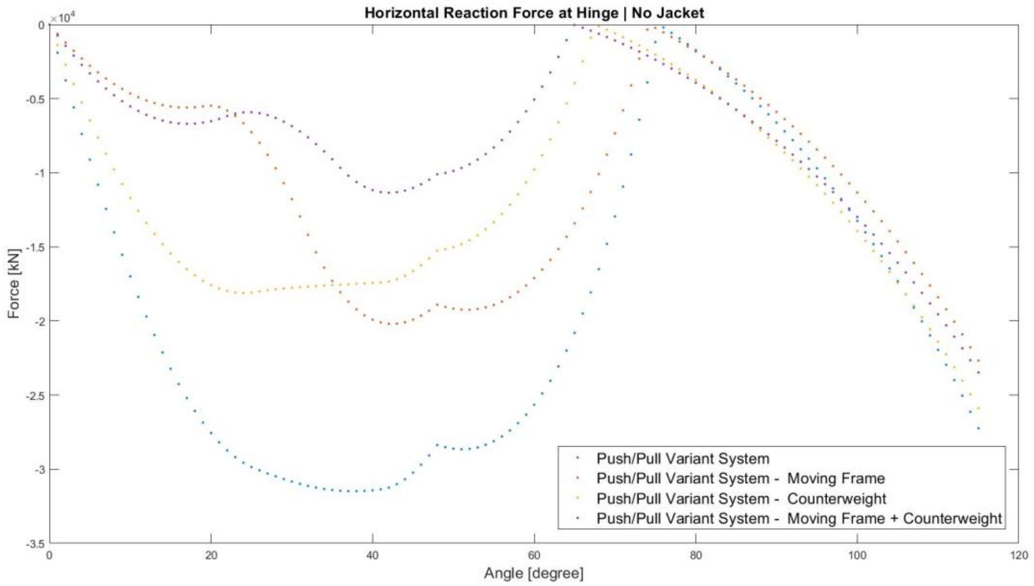


Figure 212: Static (Moment) Forces Optimisation, Comparison Horizontal Reaction Force Hinge (No Jacket)

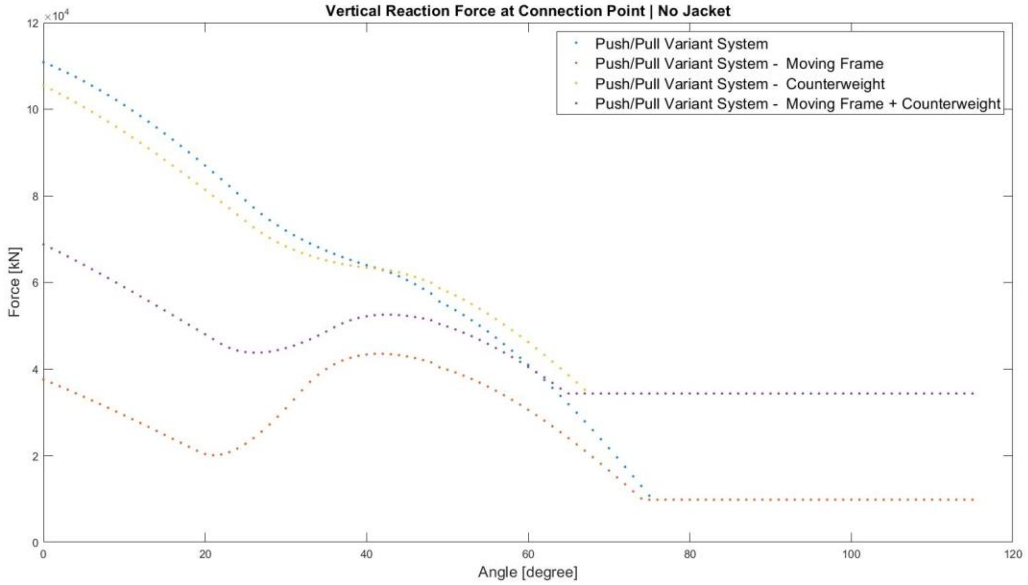


Figure 213: Static (Moment) Forces Optimisation, Comparison Vertical Reaction Force Support (No Jacket)

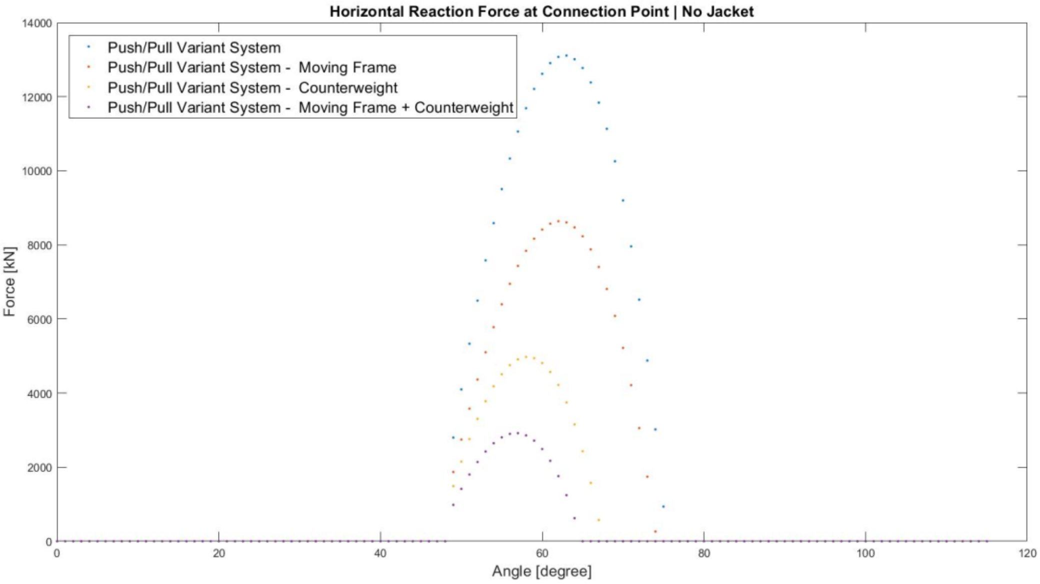


Figure 214: Static (Moment) Forces Optimisation, Comparison Horizontal Reaction Force Support (No Jacket)

F.5 Static Forces Concept Comparison Variation, Optimisation (Jacket)

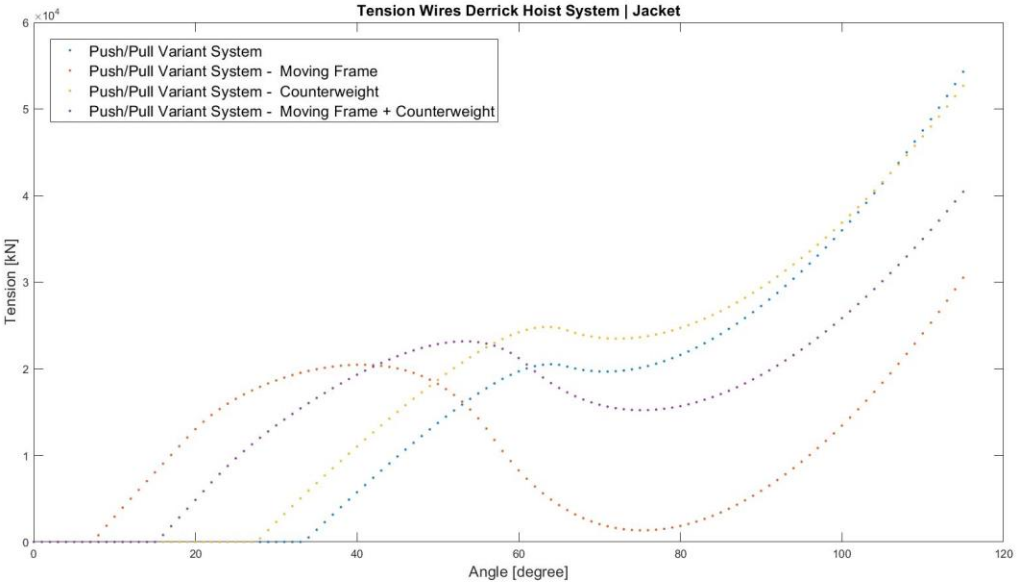


Figure 215: Static (Moment) Forces Optimisation, Comparison Tension in Derrick Hoist System (Jacket)

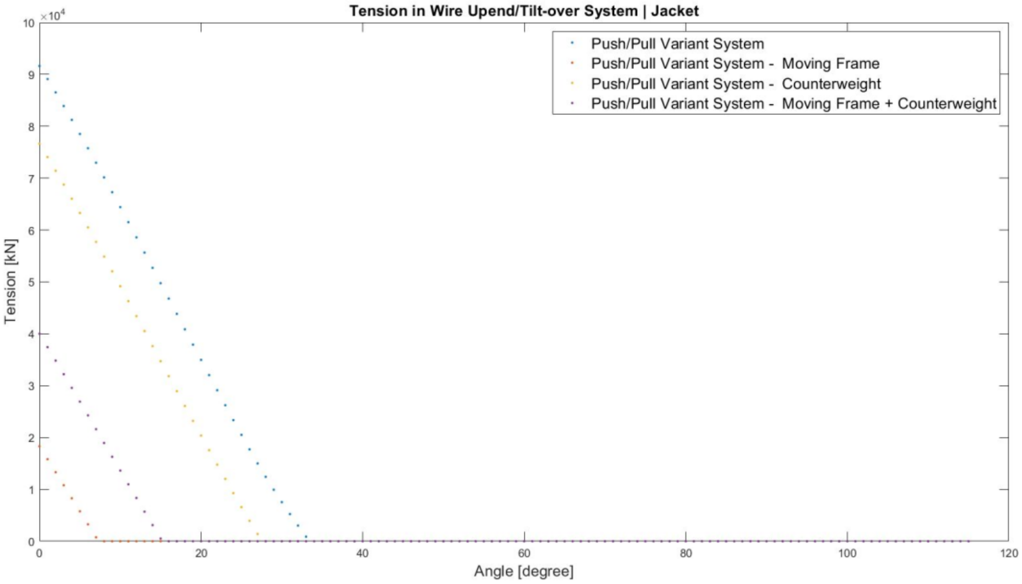


Figure 216: Static (Moment) Forces Optimisation, Comparison Tension in Upend/Tilt-over Component (Jacket)

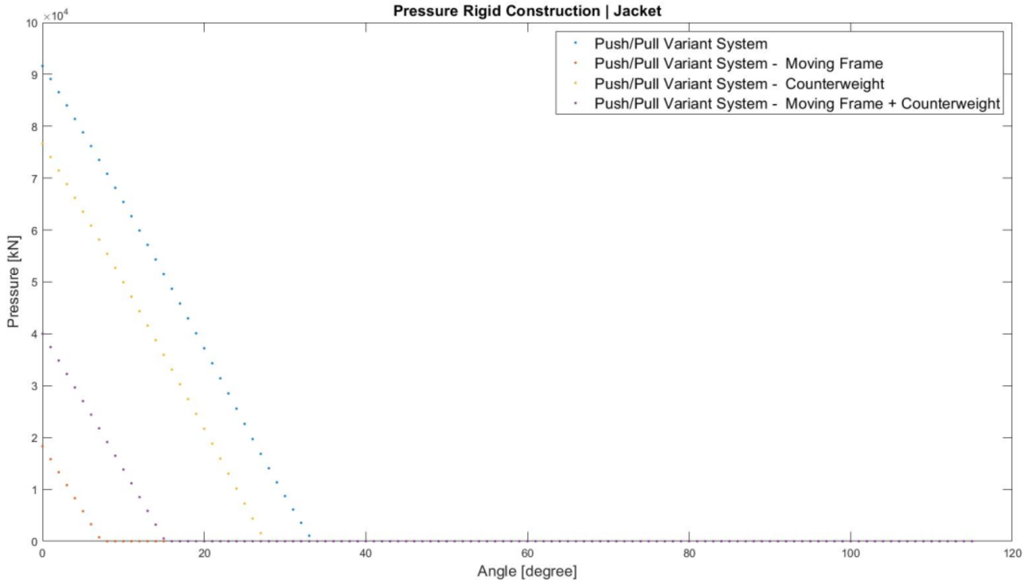


Figure 217: Static (Moment) Forces Optimisation, Comparison Pressure in Upend/Tilt-over Component (Jacket)

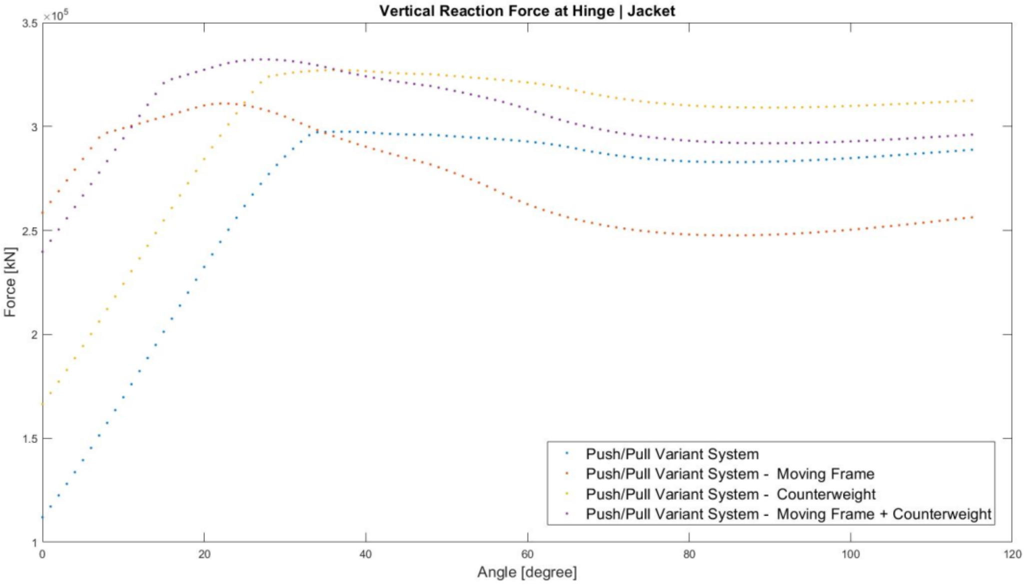


Figure 218: Static (Moment) Forces Optimisation, Comparison Vertical Reaction Force Hinge (Jacket)

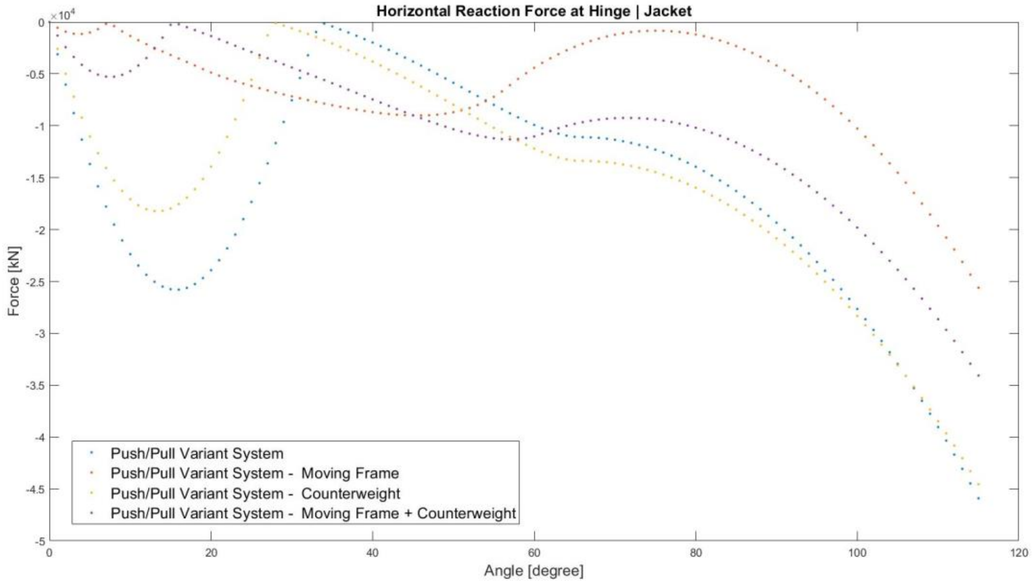


Figure 219: Static (Moment) Forces Optimisation, Comparison Horizontal Reaction Force Hinge (Jacket)

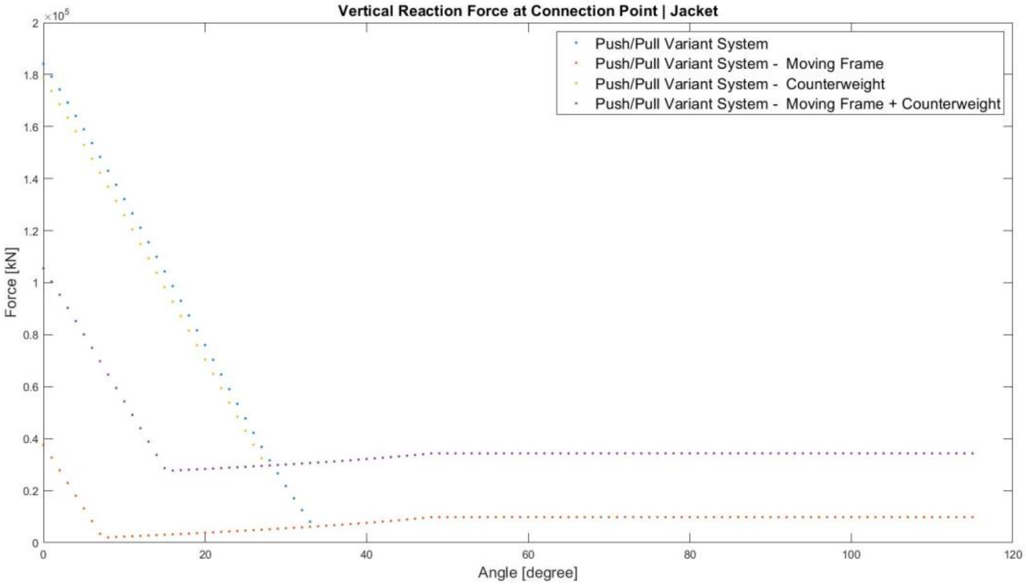


Figure 220: Static (Moment) Forces Optimisation, Comparison Vertical Reaction Force Support (Jacket)

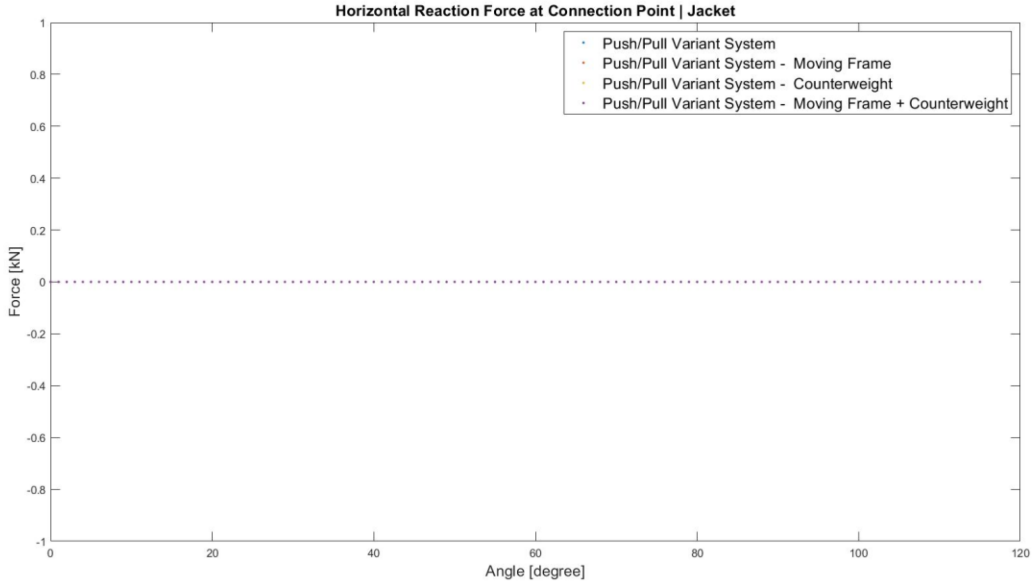


Figure 221: Static (Moment) Forces Optimisation, Comparison Horizontal Reaction Force Support (Jacket)

G. Response Spectra

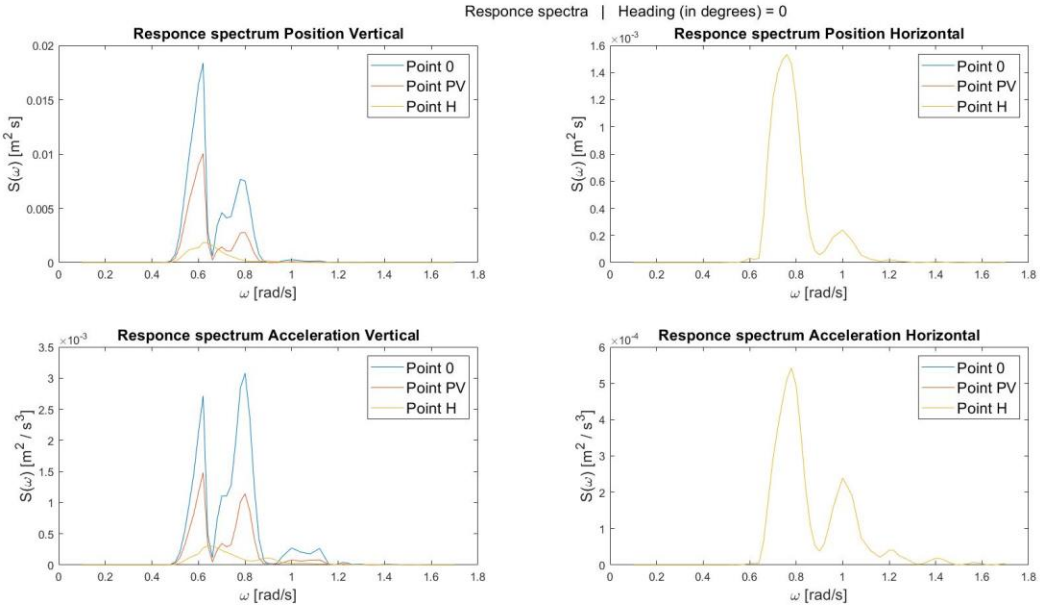


Figure 222: Response Spectra Heading of 0 degrees

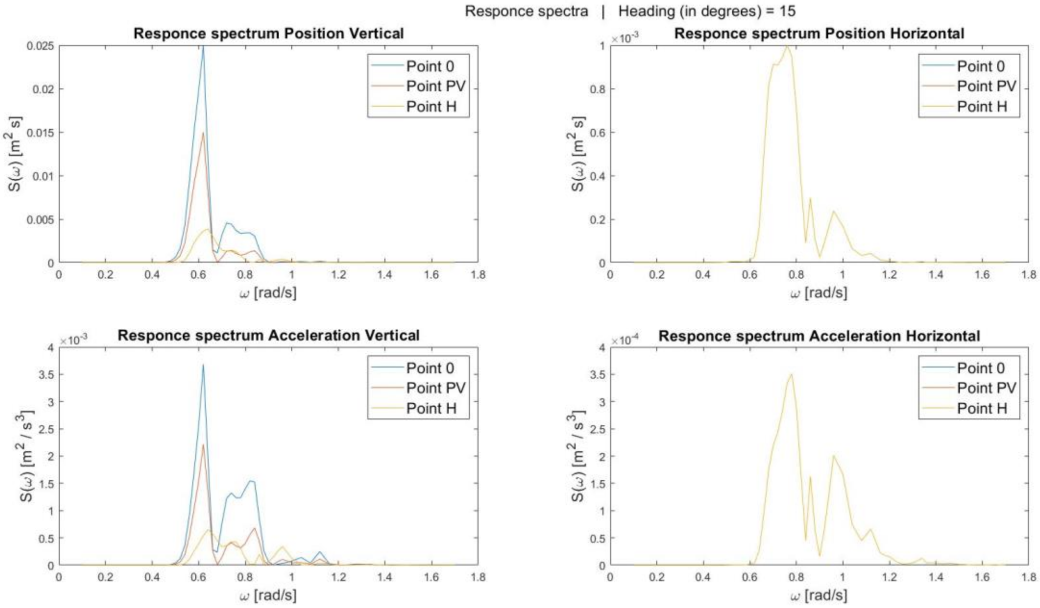


Figure 223: Response Spectra Heading of 15 degrees

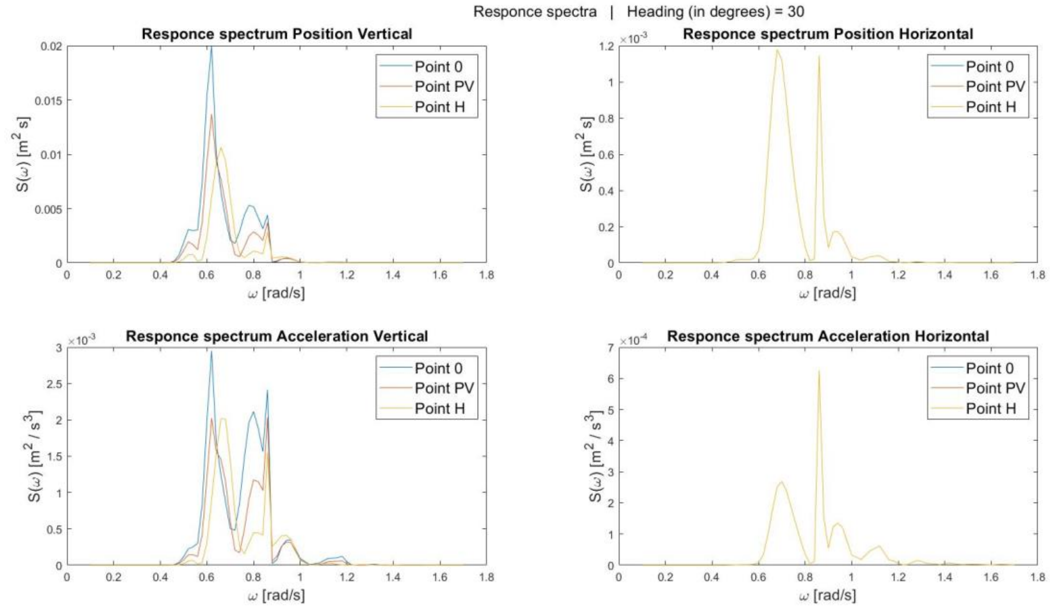


Figure 224: Response Spectra Heading of 30 degrees

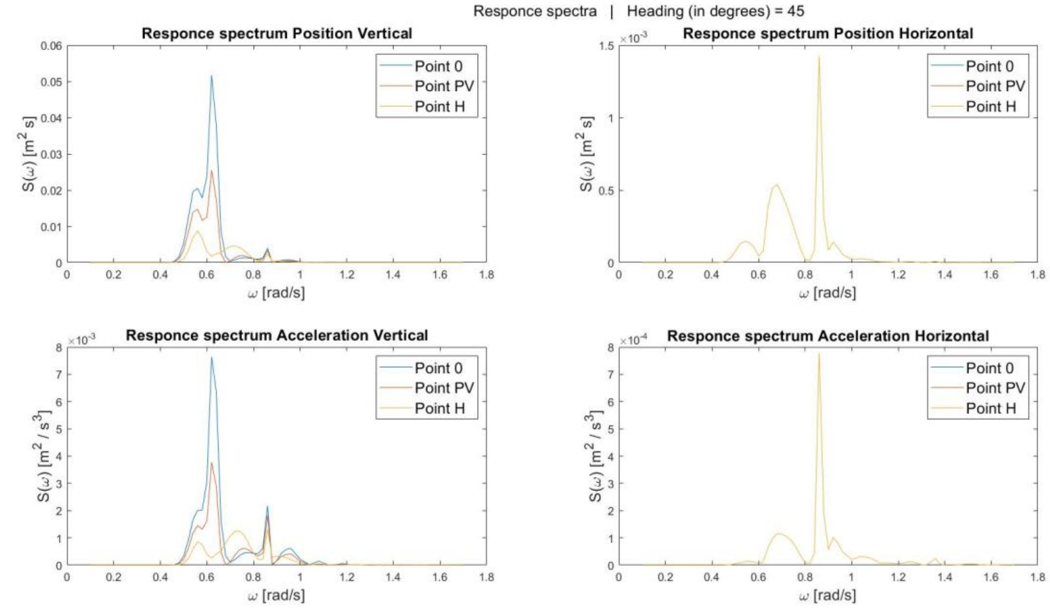


Figure 225: Response Spectra Heading of 45 degrees

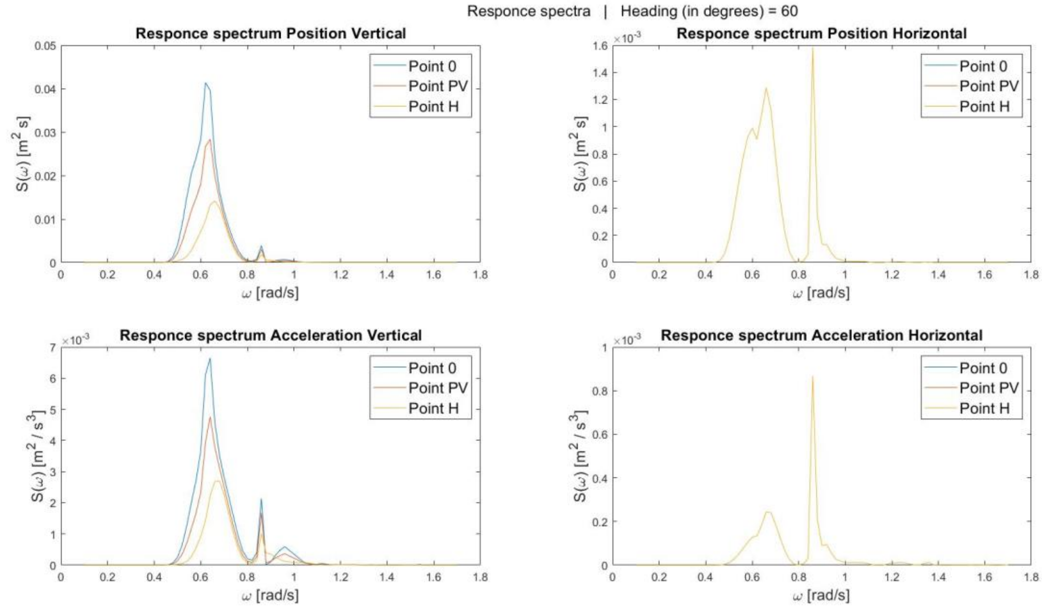


Figure 226: Response Spectra Heading of 60 degrees

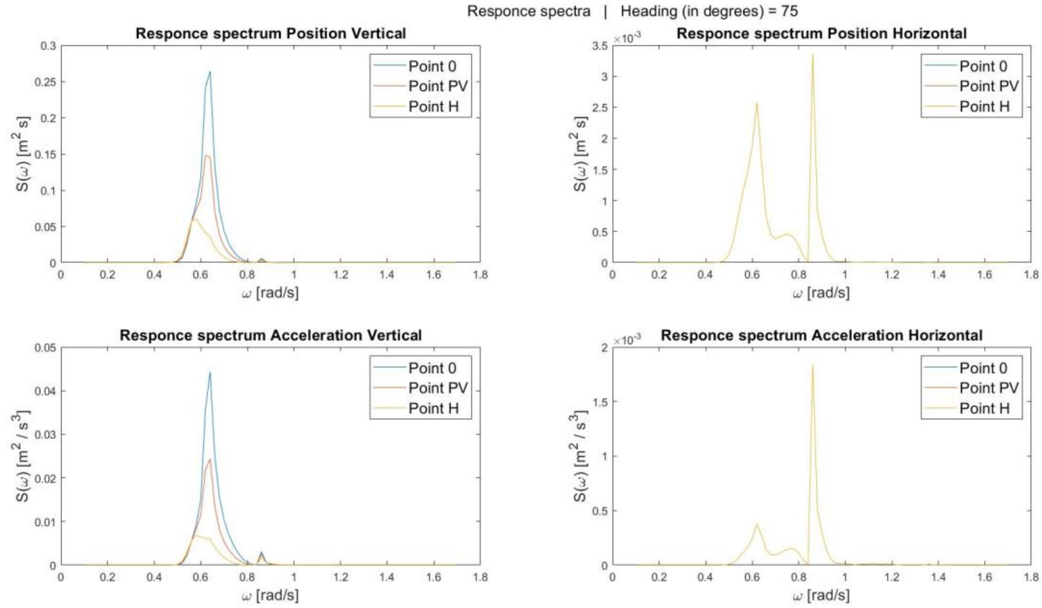


Figure 227: Response Spectra Heading of 75 degrees

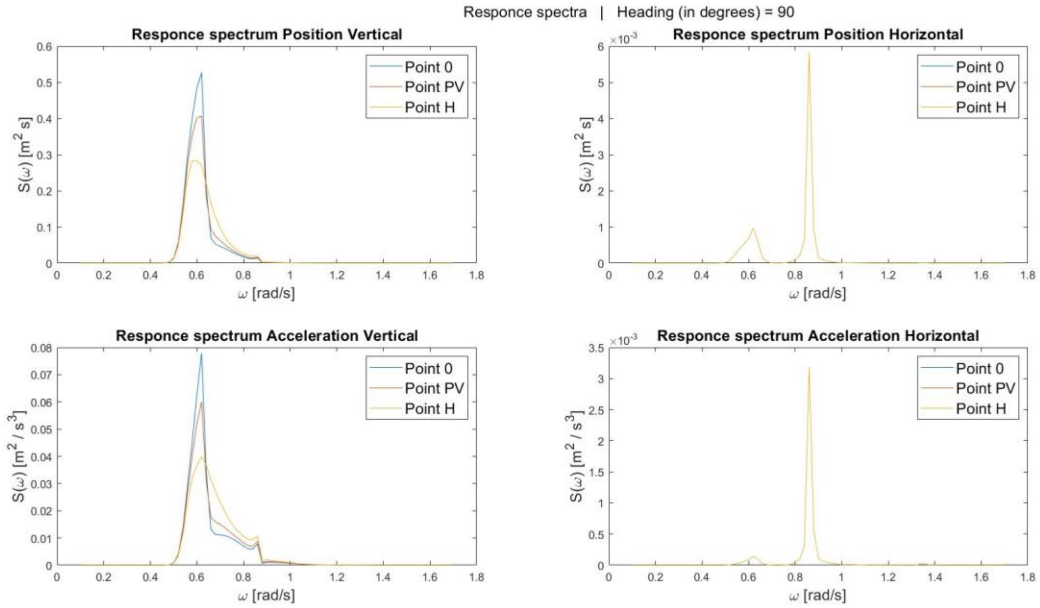


Figure 228: Response Spectra Heading of 90 degrees

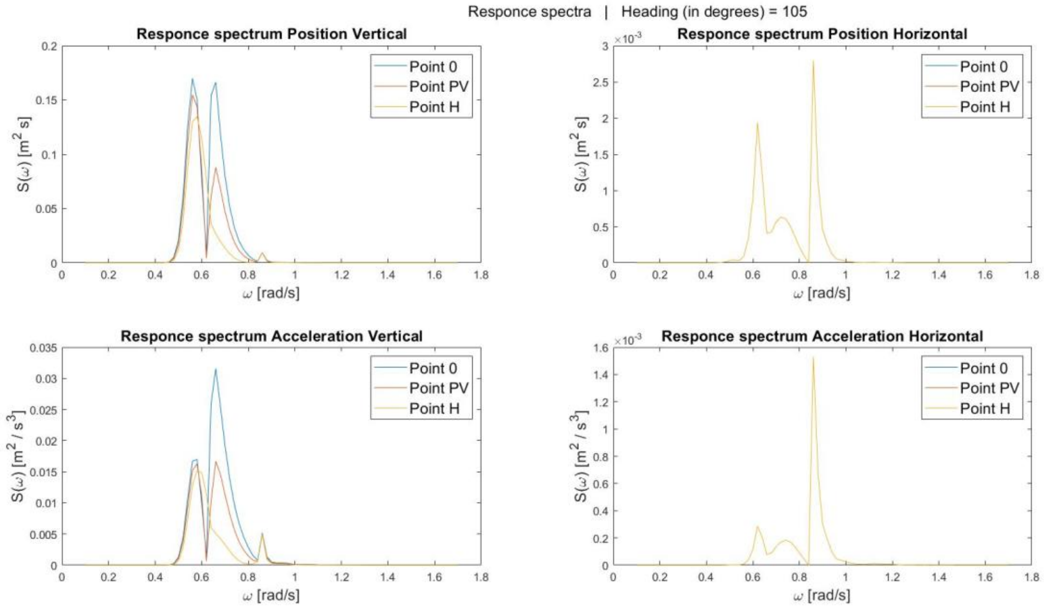


Figure 229: Response Spectra Heading of 105 degrees

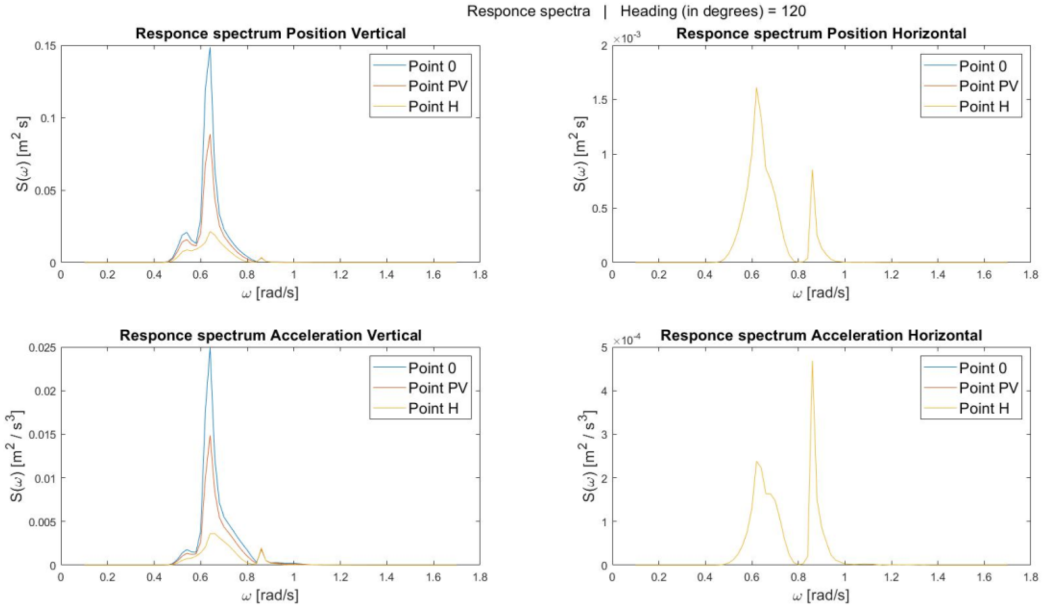


Figure 230: Response Spectra Heading of 120 degrees

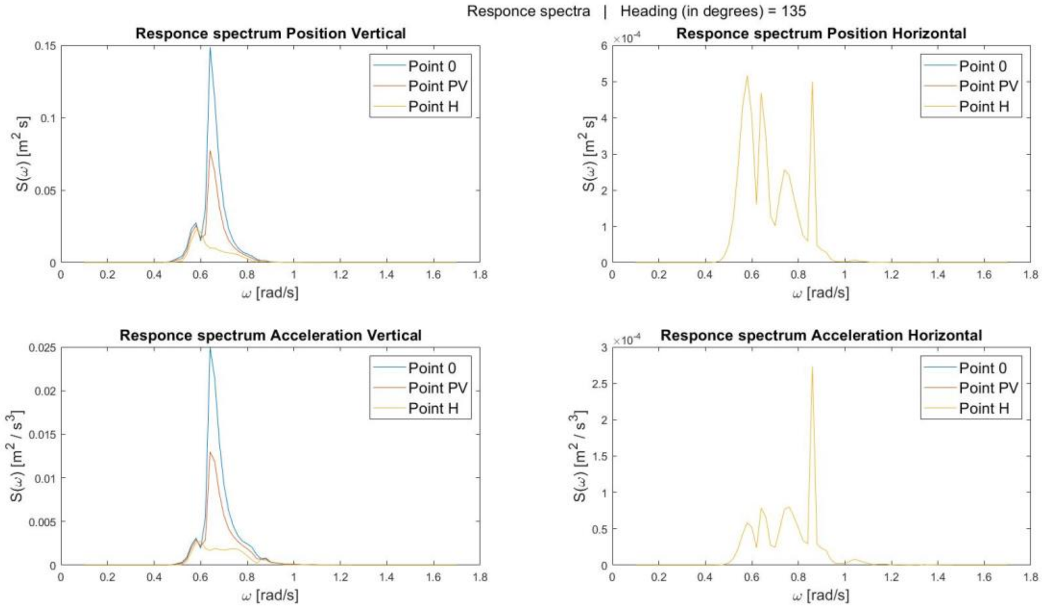


Figure 231: Response Spectra Heading of 135 degrees

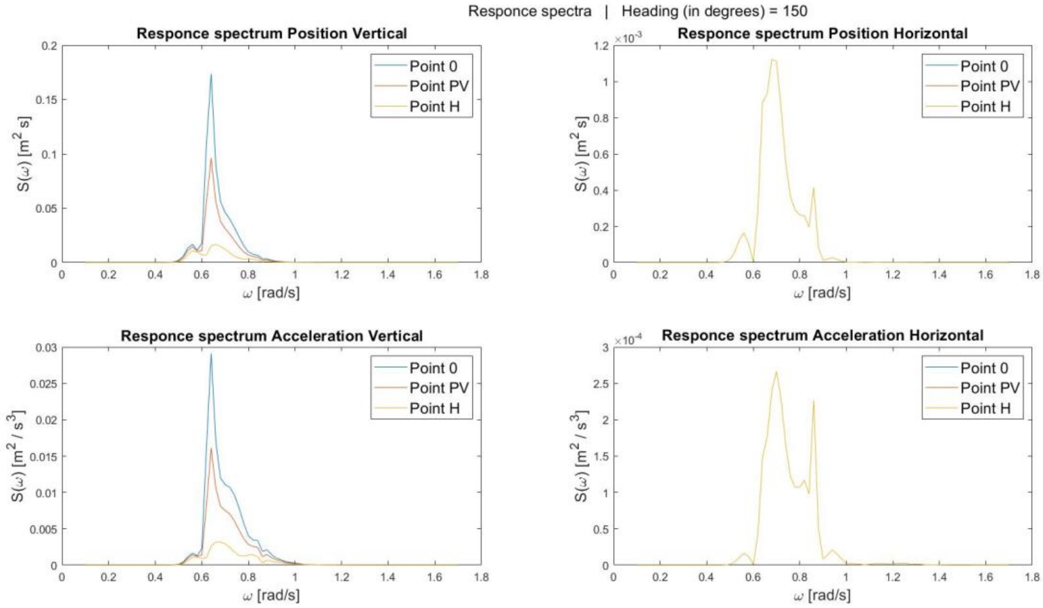


Figure 232: Response Spectra Heading of 150 degrees

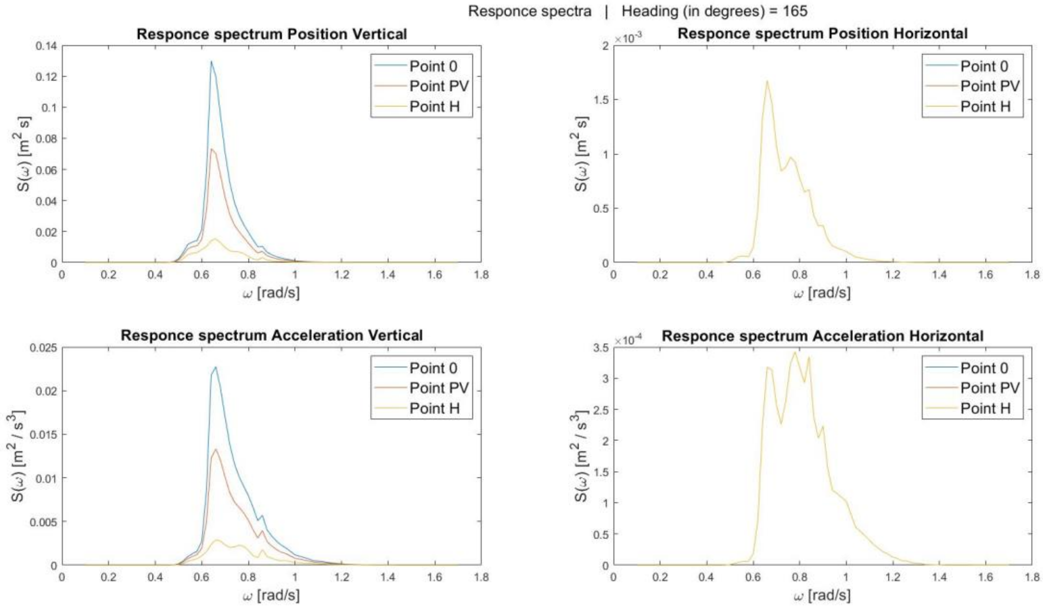


Figure 233: Response Spectra Heading of 165 degrees

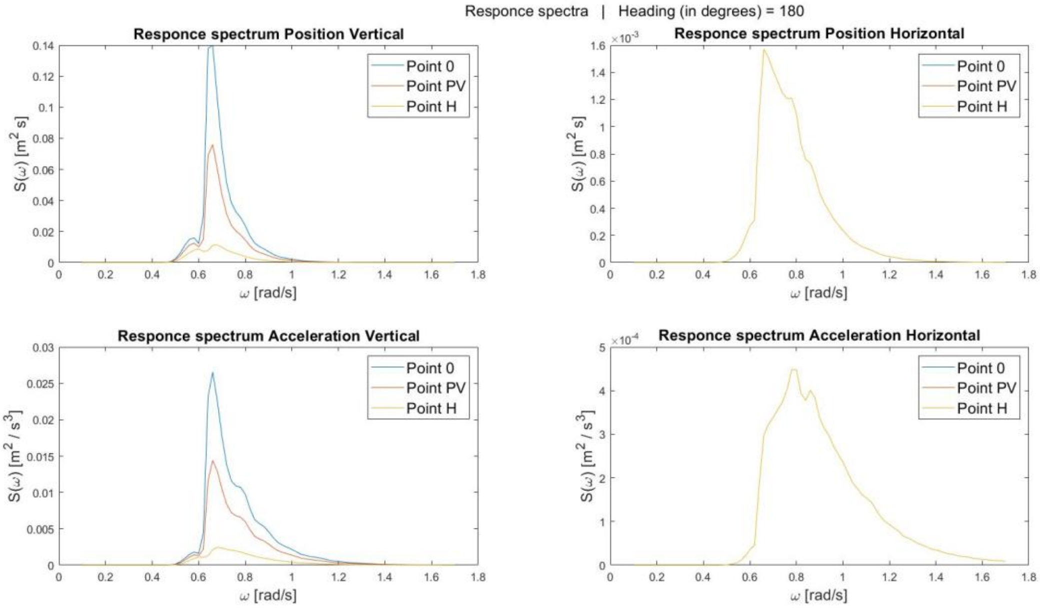


Figure 234: Response Spectra Heading of 180 degrees

H. Natural Frequency and Stability Mathematically

The general method of mathematically determining the Natural Frequency, for linear systems), is elaborated below. First the undamped free vibration homogeneous solution is stated (NDOF):

$$\mathbf{J} \cdot \underline{\ddot{\theta}} + \mathbf{K} \cdot \underline{\theta} = \underline{0}$$

In which the displacement vector, describing the synchronic harmonic motion (constant amplitude and period), is described by:

$$\underline{\theta}(t) = \underline{\hat{\theta}} \cdot \sin(\omega t + \phi)$$

Where .... represents:

$\underline{\hat{\Theta}}$ the eigenvector (unknown amplitude vector)
ω the natural frequency (unknown circular frequency)
ϕ the unknown phase angle

The displacement vector substituted in the homogeneous solution results in a homogenous set of equations which satisfies at any moment in time [49]:

$$\left(-\omega_i^2 \mathbf{J} + \mathbf{K}\right) \cdot \underline{\theta} \cdot \sin(\omega t + \phi) = \underline{0} \qquad \text{(i = angle theta for1 – 115)}$$

This results in the generalised eigenvalue problem (the time function is not equal to zero at every moment in time) described by [49].:

$$\left(-\omega_i^2 \mathbf{J} + \mathbf{K}\right) \cdot \underline{\theta} = \underline{0} \qquad \text{(i = angle theta for1 – 115)}$$

To find the characteristic polynomial (ω_i^2), the determinant of the eigen value problem is set to zero. This results in the characteristic equation:

$$\det\left(-\omega_i^2 \mathbf{J} + \mathbf{K}\right) = 0 \qquad \text{(i = angle theta for1 – 115)}$$

In this thesis project the system is described by a single degree of freedom. This results in one characteristic polynomial, representing the natural frequency, and two values representing the eigenvector. The stability of the system (described in paragraph 7.6)) is fully described by the character of the roots of the characteristic polynomial. In other words, the eigenvector.

In order to apply the method described above, the equation of motions must be linearized around the static equilibrium for each initial angle of theta. This is done by applying the Taylor series. The Taylor series is described by [56]

$$f(a) + \frac{f'(a)}{1!} \cdot (x - a) + \frac{f''(a)}{2!} \cdot (x - a)^2 + 0^3$$

and numerical by [57]:

$$Q(h) = \frac{f(x + h) - 2f(x) + f(x - h)}{h^2}$$

The results of the natural frequencies determined mathematically do not match with the natural frequencies determined experimentally. The reason for the discrepancies is the constraints in the equation of motions. The springs are supposed to exert a force to the system only when stretched. This constraint is not included in the general formulation of the equation of motion. This is included in the script that is used in the MATLAB ODE45 solver. As a result, the experimentally values are assumed as representative.

I. Vessel Motion with and without Jacket Lift System

In assumption 7 (paragraph 7.3.2 (page 127)) it is assumed that the motions of Pioneering Spirit are not significantly influenced by the Jacket Lift System with or without Jacket. As already mentioned in the explanation of the assumption on page 127, this is based on the ratio between the mass of the Jacket Lift System and Pioneering Spirit. The mass of the Jacket Lift System with lifting equipment and a jacket applied on the system is assumed on a maximum of 30 000 mt. The mass of Pioneering Spirit with a draft of 17 meters is about 571 925 mt. The ratio of the masses is 5.25%.

$$\frac{\text{Mass Jacket Lift System with Jacket}}{\text{Mass Pioneering Spirit}} = \frac{30\ 000}{571\ 925} = 0.0525$$

This statement is based on experience in the maritime sector but is not very accurate. A more advanced method is to look at the hydrostatic restoring moment [58]. The hydrostatic restoring moment depends on the density of the water (ρ), gravitation (g), moment of inertia of the waterplane area (I_L) and the trim angle (θ_y). The trim angle of Pioneering Spirit due to the Jacket Lift System can be calculated by calculating the moment around the centre of gravity of Pioneering Spirit due to the mass of the Jacket Lift System with or without jacket. The hydrostatic restoring moment is calculated by [58]:

$$M_{ry} = -\rho \cdot g \cdot I_L \cdot \theta_y \qquad \text{[kNm]}$$

Where:

ρ	= Density of the water	[kg/m³]
g	= Gravitational acceleration	[m/s²]
I_L	= Moment of inertia of the waterplane area of Pioneering Spirit	[m⁴]
θ_y	= Trim angle of Pioneering Spirit	[°]

The moment of inertia of the waterplane area is calculated by [58]:

$$I_L = \iint_{A_w} y^2 dA \qquad \text{[m}^4\text{]}$$

Where:

A_w	= Waterplane area	[m²]

The moment of inertia of the waterplane area of Pioneering Spirit is 369 717 664 [m⁴].

The moment around the centre of gravity of Pioneering Spirit as a result of the mass of the Jacket Lift System with jacket applied to the most far position on the stern of Pioneering Spirit is:

$$M_{JLS+Jacket} = M_{JLS+Jacket} \cdot y_{JLS+Jacket} \qquad \text{[kNm]}$$

Where:

$M_{JLS+Jacket}$	= 30 000	[mt]
$y_{JLS+Jacket}$	= 175	[m]

Result:

$M_{JLS+Jacket}$ = 5 250 000 [kNm]

The entire mass is applied at the most far position from the centre of gravity of Pioneering Spirit, towards the stern, and the maximum possible mass is used. This is the position and configuration that causes the largest moment.

This substituted in the hydrostatic restoring moment results in a trim angle of 0.0014 °. This angle is negligibly small. The assumption is a reasonable assumption to make.

J. Ratio Displacement Theta and Phi + Displacement Roller/Slider

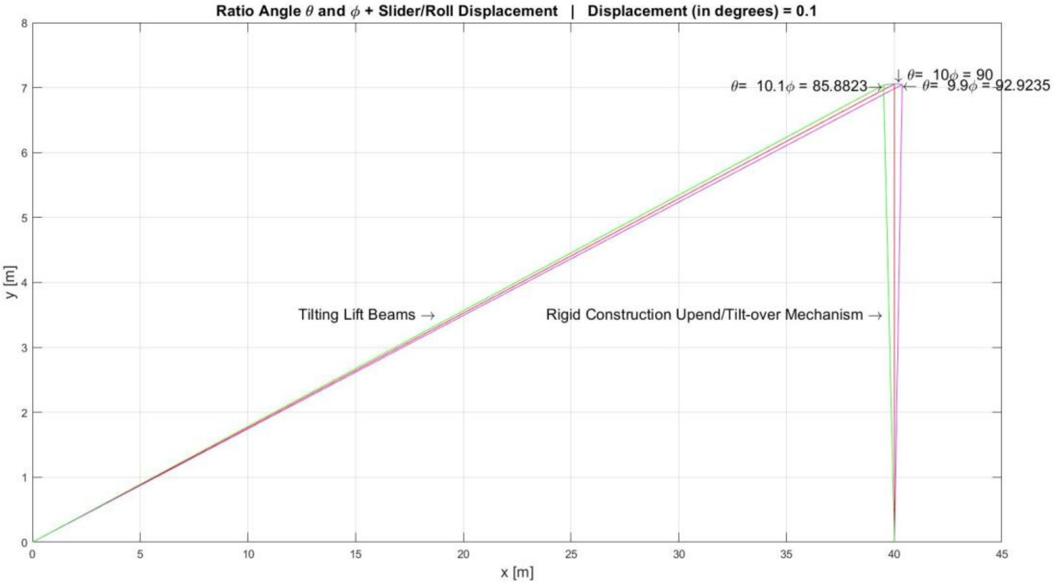


Figure 235: Ratio Displacement Theta and Phi + Displacement Roller/Slider (Theta = 10)

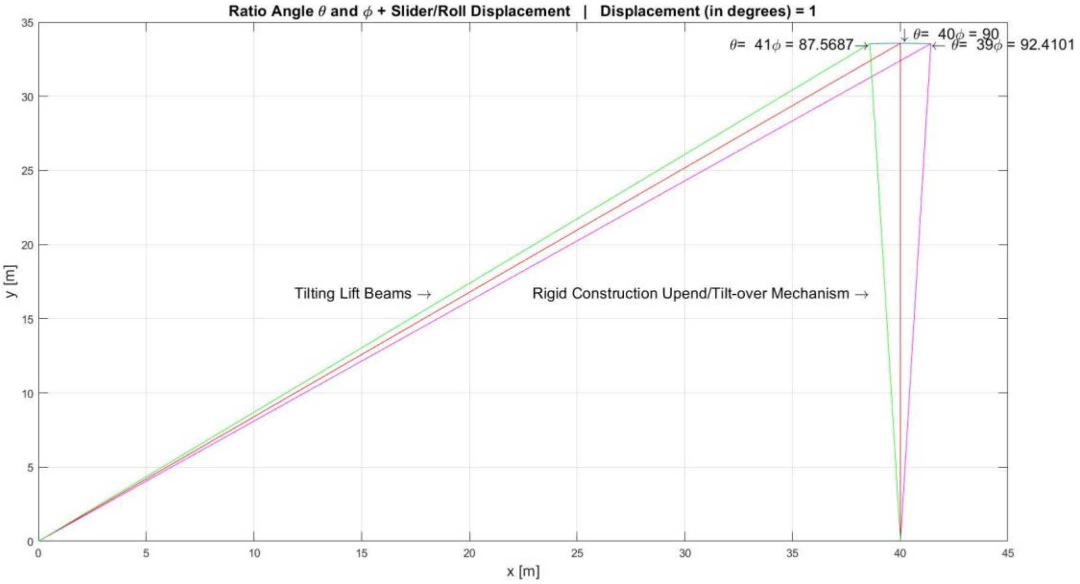


Figure 236: Ratio Displacement Theta and Phi + Displacement Roller/Slider (Theta = 40)

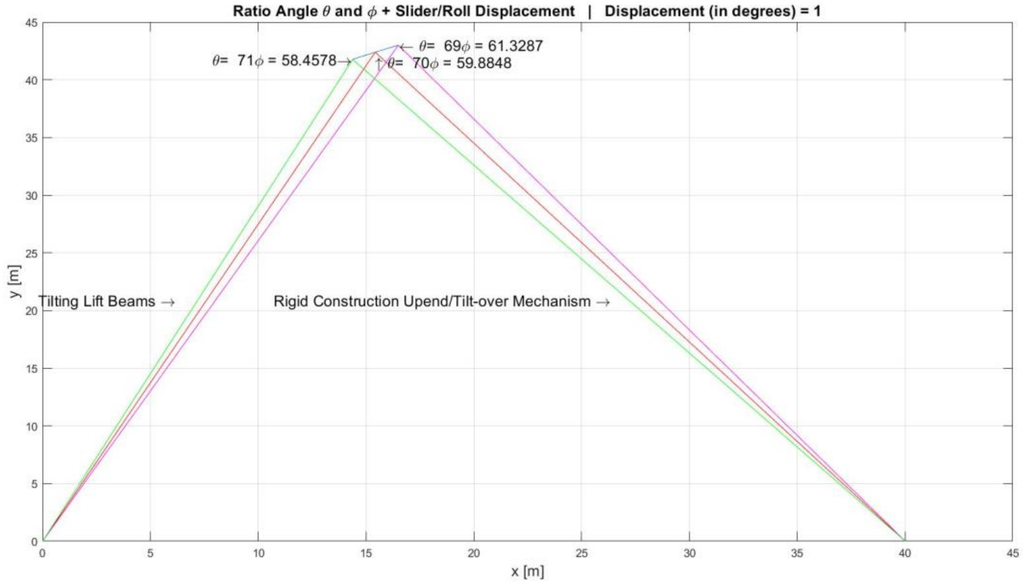


Figure 237: Ratio Displacement Theta and Phi + Displacement Roller/Slider (Theta = 70)

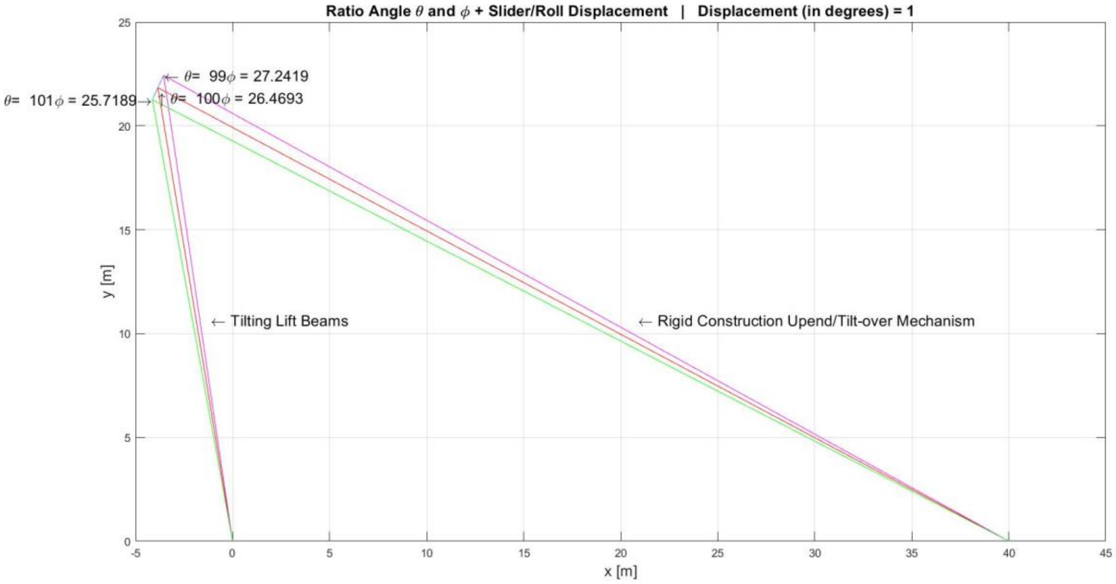


Figure 238: Ratio Displacement Theta and Phi + Displacement Roller/Slider (Theta = 100)

K. List of Figures

Bibliography

[1] U. K. Shell, “Brent Delta Platform Lift,” 2017. [Online]. Available: http://www.shell.co.uk/sustainability/decommissioning/brent-field-decommissioning/brent-delta-topside-lift.html. [Accessed 6 June 2017].

[2] TurkStream, “TurkStream,” 2017. [Online]. Available: http://turkstream.info/press/news/2017/164/. [Accessed 3 July 2017].

[3] Allseas, “Basis of Design Pieter Schelte,” Delft, 2010.

[4] O. &. G. UK, “The Decommissioning of Steel Piled Jackets in the North Sea Region,” Oil & Gas UK, 2012.

[5] O. &. G. UK, “Decommissioning Insight Report 2016,” 2016.

[6] Rien Elling et al., Rapportagetechnieken, 3th ed., Delft: Noordhoff Uitgevers bv, 2004.

[7] Allseas, “History,” 2017. [Online]. Available: https://allseas.com/company/history/. [Accessed 16 May 2017].

[8] Allseas, “Company,” 2017. [Online]. Available: https://allseas.com/company/. [Accessed 16 May 2017].

[9] Allseas, “Brent Delta Topsides Removal,” 2017. [Online]. Available: https://allseas.com/project/brent-delta-topsides-removal/. [Accessed 16 May 2017].

[10] Allseas, “Activities,” 2017. [Online]. Available: https://allseas.com/activities/pipelines-and-subsea/. [Accessed 16 May 2017].

[11] Heavyliftnews, “allseas-aquires-volstad-shipping-newbuild,” 2017. [Online]. Available: http://www.heavyliftnews.com/news/allseas-aquires-volstad-shipping-newbuild. [Accessed 23 6 2017].

[12] Allseas, “Equipment,” 2017. [Online]. Available: https://allseas.com/equipment/. [Accessed 16 May 2017].

[13] E. Heerema, “Mission Statement,” Allseas, Delft, 2015.

[14] P. J. H. Vugts, Handbook of Bottom Founded Offshore Structures, 1 ed., Delft: TU Delft, 2002.

[15] Sliggers, *Course: OE4606-Introduction_to_Offshore/BFOS,* Delft: TUDelft, 2016.

[16] I. 19902:2007, Petroleum and natural gas industries -- Fixed steel offshore structures, 2011.

[17] M. Fadly, “foundations,” 2010. [Online]. Available: http://betaindex.yolasite.com/structural-modeling/foundations. [Accessed 11 Oktober 2017].

[18] O. &. G. UK, “Decommissioning Insight 2017,” 2017.

[19] OSPAR, “About OSPAR,” [Online]. Available: https://www.ospar.org/about. [Accessed 14 September 2018].

[20] Ospar, “OSPAR Decision,” [Online]. Available: https://www.ospar.org/work-areas/oic/installations. [Accessed 14 September 2017].

[21] Offshore-Technology, “Hutton Field,” [Online]. Available: https://www.offshore-technology.com/projects/hutton-field/. [Accessed 18 August 2017].

[22] U. Shell, “Sustainability,” 2017. [Online]. Available: http://www.shell.co.uk/sustainability/decommissioning/brent-field-decommissioning/jacket.html. [Accessed 05 Oktober 2017].

[23] Ingenia, “Murchison_case_study,” Ingenia, 2013.

[24] E. T. Offshore, “murchison,” 2017. [Online]. Available: http://www.offshoreenergytoday.com/murchison-removed-2-years-ahead-of-schedule/. [Accessed 05 Oktober 2017].

[25] Kvaerner, “Kvaerner Jackets,” 2014. [Online]. Available: http://www.kvaerner.no/en/. [Accessed 05 Oktober 2017].

[26] Statoil, “Johan-sverdrup,” 2017. [Online]. Available: https://www.statoil.com/en/what-we-do/johan-sverdrup.html. [Accessed 05 Oktober 2017].

[27] Kvaerner, “Johan-Sverdrup-jacket,” 2015. [Online]. Available: http://www.kvaerner.no/en/toolsmenu/Media/Press-releases/2015/Kvarner-ASA-Kvaerner-wins-its-third-Johan-Sverdrup-jacket-contract-/. [Accessed 05 Oktober 2017].

[28] SEBok, “System Requirements,” 2017. [Online]. Available: http://sebokwiki.org/wiki/System_Requirements. [Accessed 24 August 2017].

[29] G. Koelsch, Requirements Writing for System Engineering, First ed., Herndon, Verginia, USA: Apress, 2016.

[30] U. Steel, “Bracings for Sea Fastening of barge,” [Online]. Available: http://uniquesteeluae.com/products-Services.php?Mid=2&Sid=2. [Accessed 29 September 2017].

[31] O. E. Today, “Heerema places Culzean jacket on seabed for Maersk Oil,” 2017. [Online]. Available: https://www.offshoreenergytoday.com/photo-heerema-places-culzean-jacket-on-seabed-for-maersk-oil/. [Accessed 17 August 2017].

[32] ESDEP_Course, “WG 15_A Installation”.

[33] GL Noble Denton, “Guidelines For Marine Lifting & Lowering Operations,” GL Noble Denton, 2010.

[34] Cambridge.dictionary. [Online]. Available: https://dictionary.cambridge.org/dictionary/english/buoyancy. [Accessed 21 September 2017].

[35] “OffshorePost,” 2017. [Online]. Available: http://www.offshorepost.com/650-workers-and-24-vessels-to-go-at-boskalis/. [Accessed 16 August 2017].

[36] H. Welleman et al., Basisboek Toegepaste Mechanica, 2nd ed., Den hoorn: Thiememeulenhoff, 2005.

[37] P. d. i. J. Blaauwendraad, Dynamica van Systemen, Delft: TUDelft, 2016.

[38] J. Journée, W. Massie and R. Huijsmans, Offshore Hydromechanics, 1st ed., Delft: Delft University of Technology, 2015.

[39] T. J. v. d. Boom, Introduction Modeling and Control, Delft: TUDelft, 2012.

[40] F. M. White, Fluid Mechanics, 7th ed., Mc Graw Hill, 2011.

[41] W. I. Nortier and P. d. Koning, Toegepaste Vloeistofmechanica, 7th ed., Groningen/Houten: Stam Techniek, 1996.

[42] S. Jonkman, R. Steenbergen, O. Morales-Nápoles, A. Vrouwenvelder and J. Vrijling, Probabilistic Design: Risk and Reliability Analysis in Civil Engineering, 4th ed., Delft: Delft Univeristy of Technology, 2017.

[43] IMCA, Guideline for Lifting Operations, IMCA SEL 019, IMCA M 187 ed., The International Marine Contractors Association, 2007.

[44] Lloyd's Register, Code for Lifting Appliances in a Marine Environment, 1 feb 2014 ed., Lloyd's Register, 2013.

[45] Redaelli, “Wire Ropes for Offshore,” Redaelli, Cologno Monzese, 2011.

[46] R. C. Hibbeler, Engineering Mechanics: Dynamics, 12th ed., Pearson Education Inc, 2010.

[47] A. Metrikine, *Course: Structural Dynamics,* Delft: Delft University of Technology, 2018.

[48] A. Metrikine, Dynamics, Slender Structures and an Introduction to Continuum Mechanics, Delft: Delft University of Technology, 2006.

[49] J. Spijkers, A. Vrouwenvelder and E. Klaver, Dynamics of Structures; Part 1 Vibration of Strucutres, Delft: Delft University of Technology, 2006.

[50] R. Jazar, Advanced Vibrations, Springer, 2013.

[51] MathWorks, “ode45,” [Online]. Available: https://nl.mathworks.com/help/matlab/ref/ode45.html. [Accessed 16 April 2018].

[52] J. d. Haan, *Course: Floating Offshore Structures,* Delft: Delft Univeristy of Technology , 2017.

[53] L. Holthuijsen, Waves in Oceanic and Coastal Waters, Cambridge University Press, 2007.

[54] P. Naaijen, *Course: Motions & Loading of Structures in Waves,* Delft: Delft University of Technology, 2017.

[55] S. Rao, Mechanical Vibrations, Harlow: Pearson, 2017.

[56] J. Stewart, Calculus Early Transcendentals, Toronto: Brooks/Cole, 2012.

[57] C. Vuik, P. van Beek, F. Vermolen and J. van Kan, Numerieke Methoden voor Differentiaalvergelijkingen, Delft: VSSD, 2007.

[58] J. Pinkster, *Course: Hydromechanics 1,* Delft: Delft University of Technology, 2015.

[59] Allseas, “Pioneering Spirit,” 2017. [Online]. Available: https://allseas.com/equipment/pioneering-spirit/. [Accessed 16 May 2017].

[60] M. Tissier and A. Reniers, *Course: Ocean Waves,* Delft: Delft University of Technology, 2017.

[61] W. Boyce and R. DiPrima, Elementary Differential Equations and Boundary Value Problems, New York: Wiley, 2012.

[62] J. Hoving, *OE4651 Bottom Founded Structures - Course,* Delft: TU Delft, 2015.