Dynamic analysis of a subsea cable during cable installation

Improving operability of the cable installation for shallow and deep water

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Technische Universiteit Delft

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by

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Abstract

DELFT UNIVERSITY OF TECHNOLOGY
TIDEWAY OFFSHORE SOLUTIONS

Master of Science Offshore and Dredging Engineering
Dynamic Analysis of a subsea cable during cable installation
by N. C. Bui

The investigation into the dynamic behavior of a cable during installation was done with the aim of improving cable installation for safety, operational and commercial value. In order to increase the operational limit of the vessel during cable installation, the investigation into improvement systems was desired. The workability of a vessel during cable laying operations is governed by the cable integrity design criteria such as maximum tension, touch-down-point tension, side-wall-pressure and the minimum bending radius. In practice during cable-laying the touch-down-point tension and minimum bend radius cannot be measured. Therefore a dynamic analysis of the subsea cable is required to determine the cable motions and tension fluctuations. The main objective of this Master Thesis is to develop and investigate two cable lay improvement systems. Both systems are modeled in OrcaFlex software to analyze its improved effect on the workability during cable laying operations.

The cable integrity design conditions are compensated by either active force control at the tensioner systems or by active position control near the departure point on the chute. By controlling one of the two parameters the catenary shape is stabilized and therefore the fluctuating tension and cable motions are controlled. Force control is developed in OrcaFlex by a Tensioner System controlling the tensions in the load cells at a target value, position control is controlling the chute-end location with an Active Heave Compensated Chute System. To actively control the improvement systems, a Proportional-Integral-Derivative (PID)-Controller is used in OrcaFlex as external function where the performance dependents on the defined PID-Parameters.

To optimize the improvement systems further, first simplified 1-Degree Of Freedom (DOF) analytical position controlled models are developed to identify the initial guess PID-Parameters. Subsequently, a 6-DOF position (left picture) and force (right picture) controlled models in OrcaFlex, was developed and simulated using the obtained initial guess PID-Parameters. In OrcaFlex the PID-Parameters are further adjusted using regular wave theory to achieve the full performance capacity of the improvement systems based on data obtained from existing systems on the market. Finally a detailed numerical model is developed and analyzed for irregular wave heights to obtain the workability plots. The numerical models are subjected to environmental and hydrodynamic loads during a three-hour simulation.

Results show that the force and position controlled systems are able to improve the cable integrity design conditions significantly, but more for the position controlled system. The force controlled system is limited by the pay-out velocity for deep water and by cable compression and the minimum bending radius at shallow water, whereas the position controlled system is limited by the stroke of the cylinder. Also it has been found that the controller performance for the force controlled system must be adjusted for different range of waterdepth, while the position controlled system maintains the same performance. Furthermore, the position controlled system is able to hold the catenary shape nearly still, significantly more that it does for the tension controlled system. In conclusion an increased workability during cable installation can be achieved with one of the improvement systems.

Preface

First of all, I would like to thank my graduation committee for their excellent help, input, discussions and comments on the work done; Andrei Metrikine, Joao barbosa, Antonio Laguna, Connie Visser, Gowtham Natarajan and Mohamed Hassan. Also the support of a friend Luuc Duijm is highly appropriated for his knowledge on OrcaFlex and control system.

secondly, I am grateful to my girlfriend (Dewi Wesselman), family, friends and housemates for their support and understanding. Special thanks to Erik Heeres for borrowing his Laptop when mine broke down after 4 months research. Also the information received for the tensioner system and hydraulic cylinder was made possible by IHC SAS bv and Bosch Group Rexroth.

Finally, many thanks to Tideway Offshore Solutions for the opportunity to graduate at their company on a very interesting topic and the provided data to develop an innovative solution to improve the workability of a vessel during cable installation. Without all that, this report would not have been made possible.

N. C. Bui
Delft, October 2016

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List of Acronyms

CT	Constant Tension.
DOF	Degree of Freedom.
HCC	Heave Compensated Chute.
LVS	Living Stone Vessel.
MBR	Minimum Bend Radius.
PID	Proportional-Integral-Derivative.
PS	Port-Side.
ROV	Remotely Operating Vehicle.
SB	Star-Board.
SWP	Side Wall Pressure.
TDP	Touch-down-point.
TT	Top Tension.
TW	Tideway Offshore Solutions.

Chapter 1

Introduction

For the last few decades the demand for submarine cables for signal and power transmission has increased significantly. One of the driving reasons for this is the advantage of optical fiber technology which made communication system based on optical fiber cables possible. Since the first submarine communication cable was laid in the 1850s, the oceans and seas are rapidly being crossed by a large number of these cable communication systems. Modern cables nowadays use optical fiber technology to carry digital data, which include telephone, internet and private data traffic. In the Offshore industry submarine power cables are installed between countries and two offshore installations; like oil and gas platforms, ocean science observations and also to transfer power from offshore windfarms to shore, e.g. wind, wave and tidal systems, [12].

However to ensure a safe operation of submarine cable installation from a cable lay vessel can be a challenging issue in ocean engineering. Even though lots of data is available like depth-profile and environmental data, the analysis of submarine cable tension and profile during laying operations in water is still very important. With these analysis predictions can be made which will guarantee a safe working environment, as well as improving operational efficiency. Therefore the cable integrity analysis in subsea cables has been of great interest to engineering researchers, [13].

As well as, submarine power cable installation projects are laid from relative shallow water for wind turbines to deep water for retrieving oil and gas resources in increasingly deeper waters. Because of this, the cable lay technology is constantly evolving to keep up with these advances. The main drive in the offshore submarine cable lay industry today concerns installing cable connections for wind turbines throughout Europe, e.g., North Sea, [1].

Figure 1.1: A subsea cable cut in half for inspection

1.1. Tideway Offshore Solutions

Tideway has specialized knowledge, experience and techniques required for the installation of submarine power cables, rock placement, seabed preparation, landfall construction, offshore dredging and deep sea harvesting.Tideway Offshore Solutions (TW) executes its offshore activities with several vessels; Tideway RollingStone(TRS), Flinstones(FS), Seahorse(SH), and Livingstone (LVS) (under construction). The submarine power cable installation is executed using a cable lay vessel equipped with a cable-lay system. This activity is considered the core of the MSc Thesis.

1.2. Problem Description

Consider a submarine cable being installed on the seabed between an offshore platform and onshore construction. During installation operations if an unexpected high wave is encountered due to a peak wave, high tension fluctuations can occur in the submarine cable and possible exceed the allowable limits of the cable. It is therefore very important to investigate such effects to predict the influences on the cable during installation at sea in a safe manner.

With development in the offshore field, cables are required to be installed at much greater depth compared to a decade ago. This increases the importance of installation analysis of the cables to be carried out accurately, such that the installation is done in a safe manner and at the highest workability possible. Also with increasing complexity of offshore cable installation and the desire for higher workability, the investigation of improving cable installation for safety, operational and commercial value was deemed necessary. In order to increase the operational limit of the vessel during cable installation, the investigation into improvement systems was desired.

With current technology the cable lay vessel is able to perform cable laying in a safe working environment with a limited extent in workability. Therefore it is interesting to investigate how to increase the workability of the vessel while still maintaining the safe working environment within its boundaries. In deep water depth the high top tension is governing, because of the high downward weight on the cable. In shallow water applications the top tension will most likely not be the governing parameter. An example of exceeding a cable maximum axial tensile (Extreme case) is shown in figure 1.2. Submarine cables have a very high tensile load capacity and such break failure will not happen, instead the internal armor will deform and bird-caging of a cable could occur.

Plenty of research has already been done in the field of dynamic behavior of the submarine cable coupled with the vessel during installation. Yet the interaction of such coupled system with an improvement system to increase the workability is not. Tideway therefore wants to perform more extensive research on the effect on implementing an improvement system in the cable-lay system of the Living Stone Vessel (LVS) to increase the workability while maintaining the safe working environment.

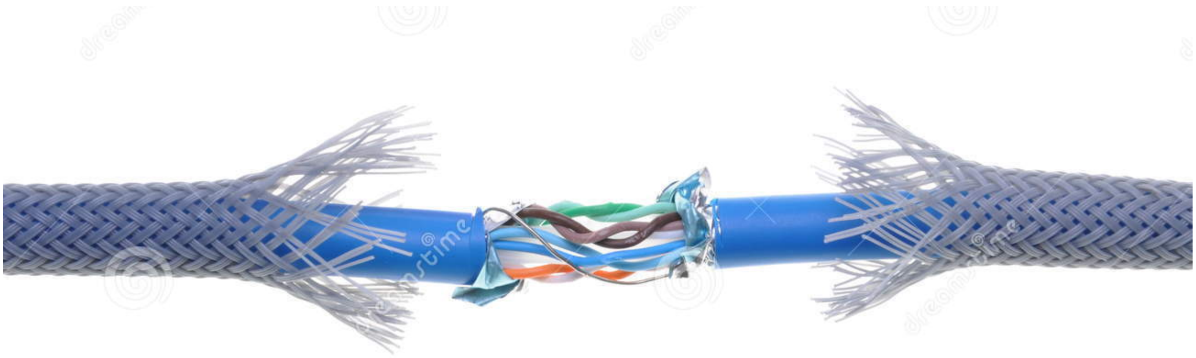

Figure 1.2: Example of a small computer network power cable damage due to high tensile loads, source: https://www.dreamstime.com

1.3. Problem Statement

The problem is defined as:

"The increasing demand for offshore wind energy and offshore cable installation is creating a desire for higher workability in a safety, operational and commercial value"

1.4. Research Objectives

In order to have a successful marine operations, a good understanding of the dynamic behavior of the cable structure, vessel, improvement system and environmental condition is required. The main focus of this Thesis will be to develop a stable model for subsea cable installation for various input conditions. Additionally different possibilities of improvement systems will be evaluated to increase the workability during cable installation. Simulations are performed for different water depths, significant wave heights, wave headings and different cable properties. A 3D non-linear time domain model based on exact kinematics is used for the numerical modeling of the submarine cable dynamics. The static and dynamics results are acquired by analysis and simulations in a software called OrcaFlex. Below are proposed the main and sub objectives of the MSc thesis to be achieved.

"To develop a detailed model for dynamic analysis of subsea cables during installation and investigate the effect of the different improvement systems to increase the workability"

1.4.1. Sub-Objectives

1. Determine and study on the influence of the environmental and hydrodynamic loads on the system.
2. Develop a morphological overview based on the market research to mitigate for the high tension fluctuations in the cable.
3. Identify the factors that influence and contribute to the high fluctuating tensions in the submarine cables, with the focus on the vessel motions and cable integrity problems.
4. Develop simplistic analytical models of the improvement systems to determine the parameters input for the numerical model in OrcaFlex.
5. Create the final OrcaFlex models with improvement systems implemented to analyze the performance of the improvement systems.
6. Develop and analyze the workability of the improvement systems in a full dynamic 3-hour simulation, to see whether it has the desired results compared to the non-improvement systems.

1.5. Approach of the project

To achieve the main objective of the MSc Thesis topic, the research study can be evaluated into 3 different stages. Figure 1.3 illustrates the approach that is used in this MSc Thesis report.

The first stage is to develop analytical models of the improvement systems with as main purpose to find the controller initial guess PID-Parameters. The improvement systems have been chosen based on a morphological overview developed and are actively controlled. In the analytical model the systems are assumed to be positioned controlled as a single linear spring-mass-damper system of 1-Degree of Freedom (DOF). The external forces acting on the systems are considered static. By use of a closed-loop-system with a feedback loop and Proportional-Integral-Derivative (PID)-Controller, a critical damped system can be developed to obtain the initial guess PID-Parameters.

The second stage is to develop numerical models in OrcaFlex of the improvement systems which are performing with the same capability as the design criteria. In the numerical models the systems are influenced in the 6-DOF by dynamic forces like the vessel response and cable tensions. For an active control, the PID-Parameters found in the analytical model are used as initial guess PID-Parameter input to the PID-controller external function in OrcaFlex. Two different controlling actions are evaluated, a force control and position control. Further tuning inside OrcaFlex is required to obtain the maximum system performance.

In the final stage of the approach, the final improvement systems developed in OrcaFlex are analyzed for results for a full workability analysis. This means in all directions and different significant wave heights and periods. The results will be analyzed for how much the cable integrity design conditions have been improved and conclusions will be made based on the influence of such system during cable-laying for deep and shallow waterdepths.

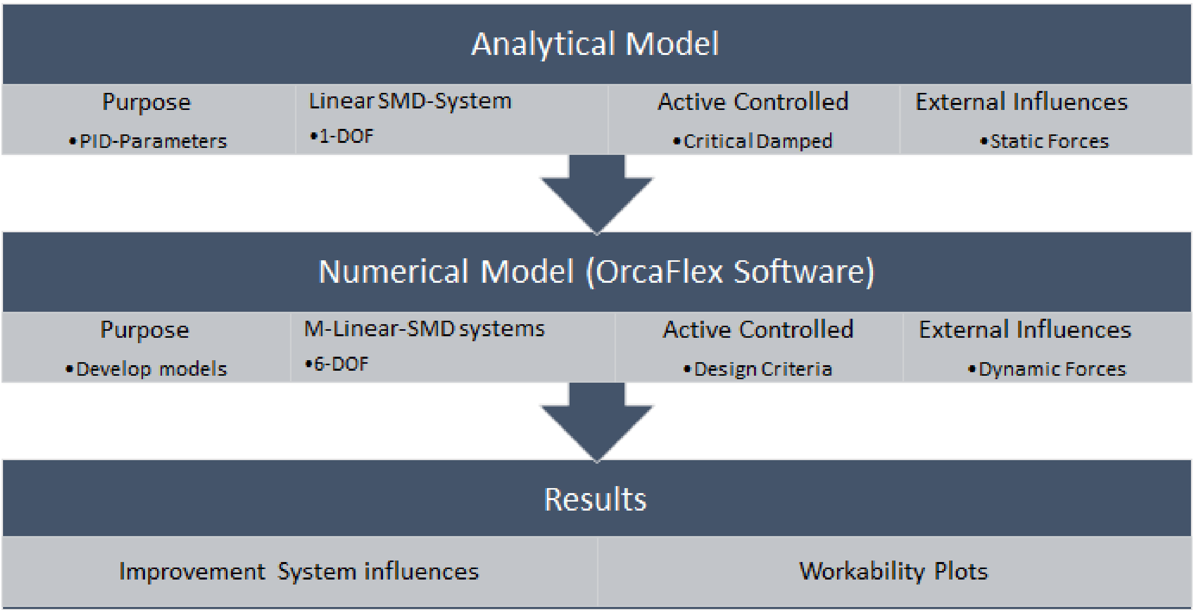

Figure 1.3: Approach of the MSc Thesis divided into three main steps; Analytical Model, Numerical model and results

Chapter 2

Offshore cable installation

This chapter provides an insight into the cable lay vessel(dimensions), cable lay methods(normal installation) and required cable lay equipment.

2.1. Living Stone vessel

"Tideway Offshore Solutions is currently building the world's most advanced subsea cable installation/trenching vessel 'Living Stone'. The vessel is equipped with two turntables below deck, each having a 5,000 tons cable capacity. Together the turntables can carry and transport more than 200 km of cable that can be installed in a single trip. Ample deck space of 3,500 m2 facilitates a revolutionary cable handling system with innovative and reliable cable handling tools for cable ends, connections and cable protection systems. Furthermore, the 'Living Stone' can be equipped with a third carrousel above deck with an additional load capacity of 2,000 tons and a 600 tons crane. A system developed in-house by Tideway enables the 'Living Stone' to install cables faster and more efficiently in longer lengths and with less offshore joints than any other cable installation vessel. The vessel will serve transport and installation projects as well as offshore power cable installations, interconnectors for the future European Supergrid amongst others.

The 'Living Stone' features DP3 (Dynamic Positioning 3) capability and has been designed as an environmentally friendly vessel with dual fuel engines with LNG being its prime fuel. The 'Living Stone' has a Green Passport and the Clean Design Notation awarded to owners and operators who choose to design and operate their vessels in an environmentally sustainable approach". The information above is cited from a press release about the 'Living Stone' by DEME[10]. Below in the figure 2.1 shows an illustration of the profile of the vessel and table 2.1 gives the vessel properties. The Tideway vessel structure properties and RAOs are obtained from an analysis done in AQWA [7], [4].

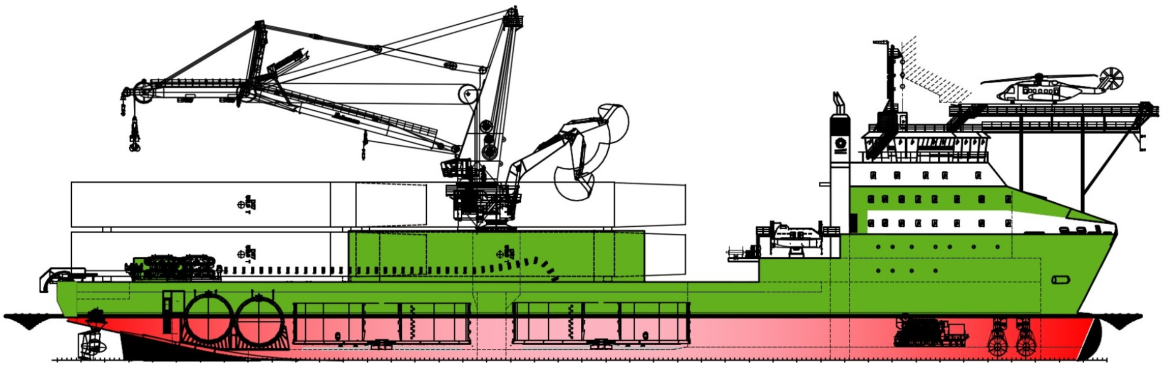

Figure 2.1: Livingstone vessel profile

Length overall, Loa	-	[m]	**Depth(moulded), D**	-	[m]
Length between perpendiculars, Lpp	-	[m]	**Operational draught, T**	-	[m]
Breadth(moulded),B	-	[m]	**Ship maximum speed, V**	-	[knots]

Table 2.1: Living Stone vessel properties, source:[7]

2.2. Cable Lay Methods

Submarine cable installation is basically deploying the cable from the cable lay vessel onto the seabed floor. This is done while the vessel is moving with a specific velocity forwards and the cable is payed-out simultaneously by the tensioner system. After the cable is placed on the seabed, it will need to be protected against dangerous hazards. The risk of damage is minimized and prevented of impact, by burial of the cables at a safe depth. The cable can be laid directly into the trench or the burial of cables can be done by jetting machines. Jetting machines uses a high pressure jet to increase the pore pressure. As result, the weight of the cable will cause it to bury itself. Also burial can be achieved by ploughing. In this method the cable is placed in a trench opened by a plough and back-filled by a plough mechanism. In short, it is very important to maintain the cable integrity and fulfill the tight lay tolerance during operations.

In this section the different cable lay installation types, subsea power cable projects, subsea cable properties and horizontal or semi-vertical cable lay is studied and explained. All the cable lay method information is obtained from a cable lay guideline written by Tideway Offshore Solutions[11] and the DNV-RP-J301[11].

2.2.1. Cable-Lay installation Stages

There are several types of installation possibilities, and every project requires its own type of installation. First there is Starting Cable installation by connecting the cable to the 1st end, next is the normal cable installation, Ending cable installation by connecting the cable to the 2nd end and at last the cable is trenched to protect it from dangerous hazards. In this MSc Thesis the focus is only on "cable installation type" with a normal installation. Below are the steps listed of subsea cables during "normal Installation" operations,

Normal Installation

1. `Preparations on board Cable Lay Vessel`
   Official checks of the documentation and too see if the equipment is working properly.

2. `Verify Cable Touchdown Position`
   After the preparations on the vessel, the subsea cable is verified if the configuration is in line with the dynamic analysis. Checks are done on the layback length, touch-down-point, top tension, and departure angle, to maintain the cable s integrity. The lateral cable position and its position regarding the planned route is important to maintain the cable's tight lay tolerance.

3. `Start/Continue Cable Installation`
   After approval of previous steps the cable lay vessel can start tracking a planned course and speed according to the Offshore Installation Manager(OIM). Simultaneously with the speed of the vessel, the tensioner pays out the subsea cable with a speed depending on the mode of the tensioner. The cable storage system works together with the tensioner as a complete system. During installation all cable parameters should be monitored constantly and accurately. These are explained in Chapter 3.

4. `Verify Cable position on seabed`
   After installation of the subsea cable on the seabed, the position of the cable along the route is verified if it is within allowable tolerance. If the position of the subsea cable is accepted to be within allowable tolerance, the cable-lay can continue. In case the subsea cable is not within allowable tolerance, the subsea cable must be relocated.

2.2.2. Subsea power cable projects

The type of subsea cable to be installed and the choice of cable installation equipment are based on the expected scope of work. The expected scope of work can either be in shallow or deep waterdepths, calm or rough sea states and type cable between onshore and on/off-shore structure. Below are the different types of cable installation project indicated, each with its own different scope of work. The information is party obtained from the Offshore Wind Program Board, [8].

Infield power cables installation project

A connection between 2 offshore wind turbine generator with a first and second end pull-in into the structure. Infield cables are relatively small in diameter compared with export cables. The wind turbines are generally grounded to the seabed and are therefore in relatively shallow waterdepth. Figure 2.2 illustrates an infield power cable connection between two wind turbines offshore with the subsea cable trenched into the seabed. Cables between three offshore structures is called an inter line.

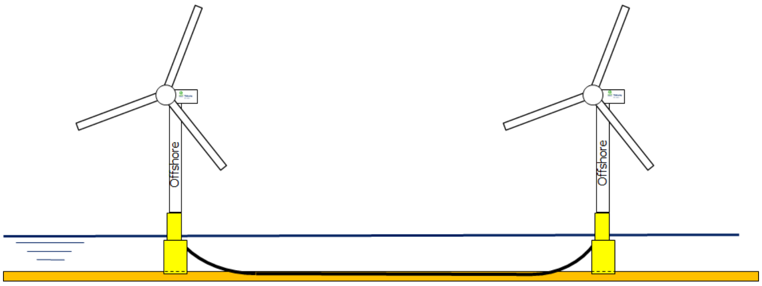

Figure 2.2: An infield cable connected between two offshore wind turbine structures. The cable is buried beneath the seabed

Export power cables installation project

An connection between an offshore structure and onshore structure with 1 pull-in onshore and 1 pull-in on the platform. Export cables are usually used for these types of projects, because of the long distance. The cable are generally heavier cables than infield and require more operational effort from the vessel equipment. The offshore structure can be either on a jacket structure or on a floating structure. These types of projects are mostly executed in deeper waters compared infield projects. An illustration is shown in figure 2.3 between the offshore structure with an onshore structure.

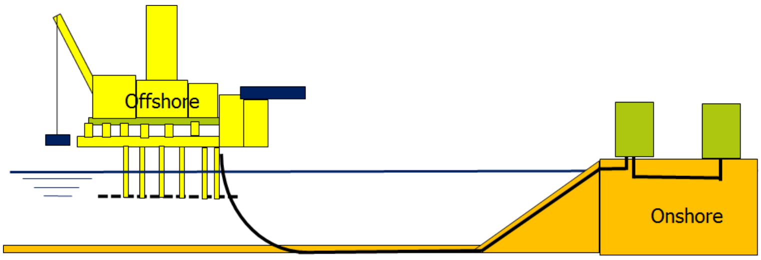

Figure 2.3: An export cable connection between an offshore platform and an onshore structure. The cable is buried beneath the seabed

Interconnector cable installation project

An interconnection is the connection between two onshore structures or offshore structures. The cable ends are connected to the HVDC converter stations on each side of the land, allowing two countries to trade power. An illustration of this type of submarine cable project is shown in figure 2.4.

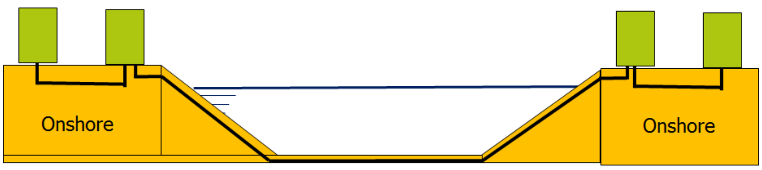

Figure 2.4: An interconnection between an offshore platform and an onshore structure. The cable is buried beneath the seabed

Cable repair/decommissioning project

Repairs are executed when a cable is damaged. The repairs are done by removing the damaged/bad cable section and replacing it by a new cable section with two joints. The cable is reeled into a cable storage from the seabed for removal or repair. This type of project requires a small cable storage capacity.

When the cable is out of service, the cable is removed from the seabed and require therefore large cable storage capacity.

2.2.3. Subsea power cable properties

Generally Alternating Current [AC] power cables are used for infield. Direct Current [DC] are power cables used for interconnector cables and export cables. There are two types of cables; HVAC and HVDC. Different from the AC cables, the HVDC cables require Voltage Source Converter stations at both ends of the power cable. The HVDC is a highly efficient for transmitting large amounts of electricity over a long distance, [2].

Below in the figure 2.5 shows an illustration of the cross-section of an AC cable. The subsea cables consist of several cores inside the cable to transfer the electrical signals. The outer layer is of non-metallic material. Next we have the armor which is twisted around the core of the cable which enables the cable on bending in the lateral or vertical plane without getting damaged. Inside the core there are cables to transfer the electrical impulses and are surrounded by fillers to prevent the cable to deform.

The cable specifications which influence the dynamic behavior of the cable are obtained from the cable manufactures. Below are the parameters given which are required to complete the dynamic analysis in OrcaFlex [9]. OrcaFlex is a numerical software used to perform dynamic analysis in the offshore industry. This will be more explained in detail in chapter 5.

- Axial[kN], Torsional[kN.m2], bending stiffness [kN.m2]
- Geometry [mm]
- Mass per unit length [kg/m]
- Cable Limitations; Top Tension (TT) [kN], Side Wall Pressure (SWP) [kN/m],Minimum Bend Radius (MBR) [m] , Touch-down-point (TDP) [kN]

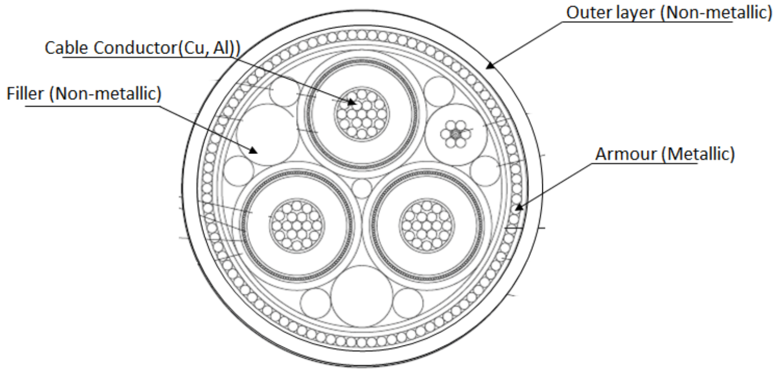

Figure 2.5: An interconnection between an offshore platform and an onshore structure. The cable is buried beneath the seabed, [2]

2.2.4. Horizontal and vertical tensioner cable lay

The most common installation method is the horizontal tensioner. The tensioner is placed on deck close to the chute to hold the cable under tension and control the lay-speed, cable configuration and prevent cable damage. To prevent damage a controlled pay-out or pull-in is required. The chute can either be placed at the aft or at the Port-Side (PS)/Star-Board (SB)-center of the vessel and is function is to guide the cable from the vessel to the seabed.

Vertical cable lay is a more complex cable lay method, because of the large steel structure and many hydraulics required. The cable is laid in an almost vertically shape into the water by an inclined ramp. The vertical tensioner method eliminates the issue of the sidewall pressure and Minimum bend radius on the subsea cable. An illustration of the horizontal and semi-vertical tensioner cable lay is shown in the right picture of figure 2.6.

Figure 2.6: Left you see an illustration of a horizontal tensioner cable lay vessel, source: Germany: NSW Charters Cable Laying Vessel MV Aura. Right illustration you see a semi-vertical tensioner cable lay vessel, source: Subsea 7 reel-lay vessel seven Oceans.

2.3. Cable installation equipment

This section contains general information about cable lay system equipment required to operate and execute a cable installation. The entire structure generally consist of the cable storage, cable highway, cable tensioner and chute. An example of a deck-layout is illustrated in figure 2.7. The type of subsea cable to be installed and the choice of equipment are based on the expected scope of work. All the cable lay equipment information is obtained from a cable lay guideline written by Tideway Offshore Solutions[11] and the DNV-RP-J301[11].

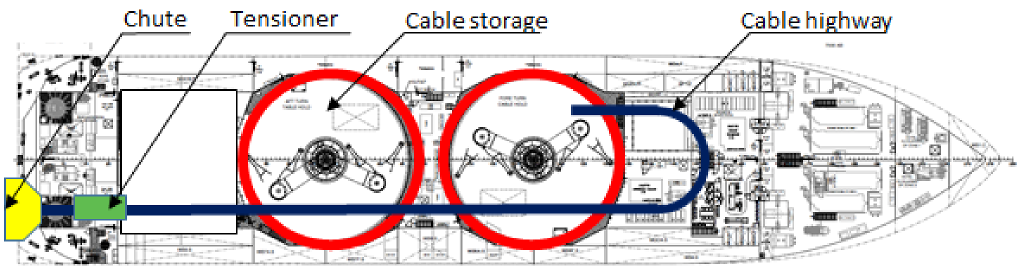

Figure 2.7: Top view of a Living Stone with an example of how the cable lay deck-layout could look like

2.3.1. Cable storage

There exist various systems on the market to storage a large amount of submarine cable on a vessel. Infield power cables are relatively lighter than export and interconnector cables and may therefor be split in sections and stored onto separate systems. Export and interconnector cables on the other hand are relatively large in length and heavy in weight and preferred not to be split in sections. The cables are loaded onboard by spooling the cable onto a storage system, lifting a pre-loaded storage system onboard or with skidding operations of a full storage system. Each cable storage system has its own advantages and disadvantages which are listed below.

1. `Turntable`
   Different from the carousel, a turntable rotate the storage basket where the cable is spooled onto, each layer is stored on top of the layer before. Advantages of this system are the storage of multiple cables and evenly spread deck load. A disadvantage of this system are the turning speed of the turntable must be kept under tension by continuously adjusting and the cable needs to enter the turntable tensionless to prevent pulling the outer layer inside. See number 1 in figure 2.8 for the illustration.

2. `Carousel`
   The carousel is circular construction where the cable is spooled around a vertical core (layer by layer), beginning from the inner-core towards the outer core. Advantages are the large storage capacity and easy loading. A disadvantage is that the cable must always be kept under tension to prevent it from sliding off the vertical core. See number 2 in figure 2.8 for the illustration.

3. `Reel`
   reel is powered by a drive system and horizontal level winder. Reel has a lot of practicable benefits for short cable installation. A cable can be stored on its own reel onshore and lifted on board when they are needed. A reel provides a lot of flexibility in installation sequence. Advantages are the easy loading of multiple smaller cables on their own reel, less deck requirement and flexible in installation sequence. A downside is the required back tension and low capacity. See number 3 figure 2.8 for the illustration.

4. `Static Tank`
   In a static tank, the cable is spooled with a turning loading arm in a fixed basket. These method of cable storage is only allowed for cables with a small minimum bending radius and if the cable is able to rotate around its own axis within a certain distance. Due to this setup it requires a lot of deck space and therefore less preferable. See number 4 in figure 2.8 for the illustration.

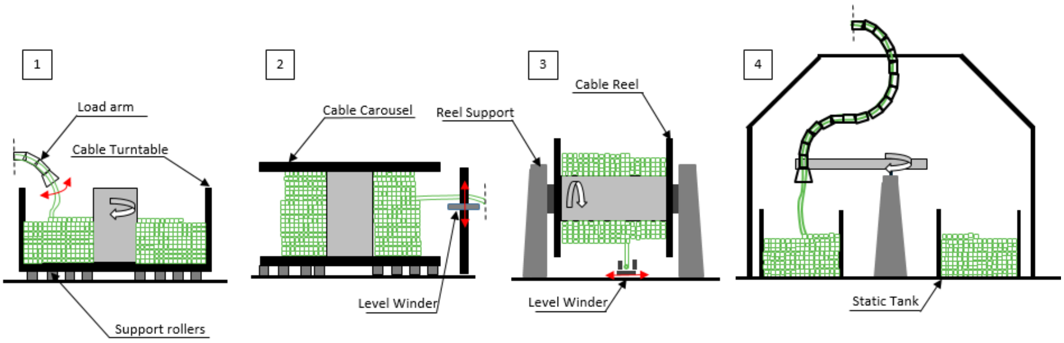

Figure 2.8: Different cable storage principles; (1) Turntable, (2) Carousel, (3) Cable Reel, and (4) Static Tank

2.3.2. Cable highway

The subsea cable is rolled out from the storage system and guided over a cable highway towards the tensioner system. The cable highway holds the cable in position while maintaining the minimum bend radius to guide it towards the Chute by a pull force from the tensioner system.

To prevent the cable go into slack or create high tensions between the carousel and tensioner, a slack compensation system is required or good communication between the employees handling the equipment. For the slack compensation system, slack management quadrants are placed on rails to compensate for the shortage or surplus of cable length during operations.

1. `Longitudinal motion compensator`
   The quadrant moves in the surge direction relative to the vessel axis and compensate for the excessive length of cable by moving up and down the cable highway over rails. The advantages of this compensations is less bending along the cable highway. An illustration of this type of compensation system is shown as number 1 in figure **??**.

2.3.3. Cable tensioner systems

Tensioner systems are required to install the cable in a controlled and safe manner. The tensioner holds the cable under a specified tension by friction. The tensioners pulls the cable through the cable highway and controls the cable configuration during the installation operations by adjusting the pay-out and pull-in velocity. Besides, the tensioners should be able to measure and log the calibrated tension, pay-out & pull-in distance & velocities.

On the market there are several types of cable lay tensioner systems available with different holding capability, but the three most common are listed below.

1. `Tracked cable tensioner`
   This type of tensioner has a relative high holding capacity, suitable for various types of cables and has a pay-out and pull-in rate. The tensioners can either be executed with 2 or 4 horizontal/vertical trackpads. An illustration is shown in figure 2.9, left picture. By rotating the trackpads the cable will be payed-out or pulled-in and the hydraulics between the upper and lower pad can be adjusted manually according to the required holding force.

2. `Linear Belt cable engine`
   A belt cable engine has a relatively low holding capacity and is therefore not preferred when installing export cable. This type of tensioner is very suitable for telecom and fiber-optic cables.

3. `Linear wheel cable engine`
   This type of tensioner is suitable for power cables, telecom and fiber-optic cables. An advantage of this system is the ability of extending the holding capacity of the linear wheel cable engine. This is done by adding more wheels into the system. The wheels have also more grip compared to a belt.

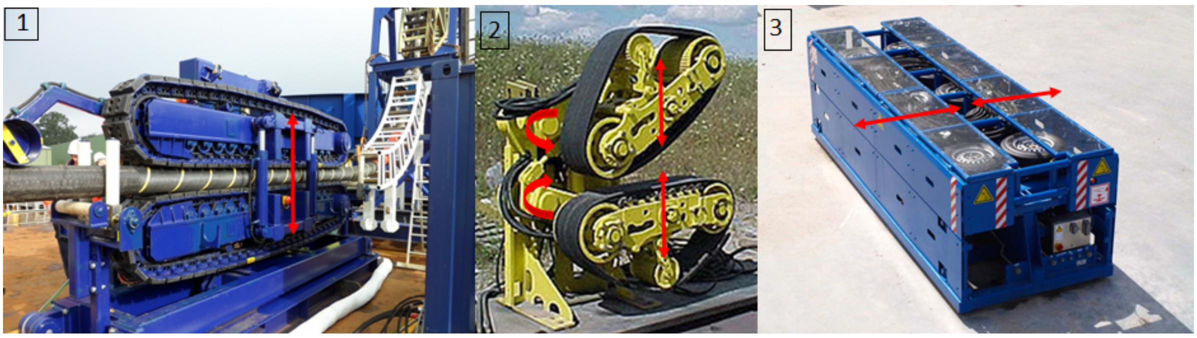

Figure 2.9: (1) 10t baricon tracked tensioners, source: 4equipment, (2) Linear Belt Engine, source: Timberland equipment limited, (3) Linear wheel cable engine, source: Hulst Innovation cable equipment B.V.

Tensioner operation modes

The tensioner systems are able to operate in two different control modes; Speed Mode Tension Mode, and Render mode, [6]. Each mode is used for different purposes and it also influences the required cable equipment. Below are only the modes listed which are of importance in this MSc Thesis;

- `Speed Mode`
  The speed mode is the operational mode to control the speed. This mode is used when the cable installation is preferred to be controlled manually. The operator can adjust the pay-out or pull-in velocities, based on the actual measured tension at the tensioner system load cells. This type of operation makes the cable sensitive for high peak tensions, because of human responds delay.

- `Tension Mode`
  During laying operations when the tensioner system is in tension mode, the system automatically pays-out faster when the target value is exceeded and pays-out slower when the tension is below the value. In this mode the torque and speed can be automatically adjusted by active control.

Tensioner system parts

A tensioner design is based on the client expected scope of work regarding the cable installation operations. The main parts which differs a tensioner holding capacity from another are the type of motor, gearbox, sprocket diameter and trackpads.

- `Motor`
  The tensioner electric motor is the core unit in a tensioner system to deliver the required torque to the trackpads to pay-out or pull-in of the cable. For active control an actuator sends an electric signal to the motor to adjust the motor torque accordingly.

- `Gearbox`
  The gearbox is a transmission of the speed and torque from the motor to the sprocket. It reduces the engine speed to the sprocket speed, increasing the torque in the process.

- `Sprocket`
  A sprocket is used to transfer rotational motion from the gearbox to the chain and trackpads. The diameter of the sprocket defines the gear ratio of the chain drive which is directly connected to the trackpads.

- `Trackpads`
  The trackpads are connected to the chains which are driven by the rotating sprockets. To prevent the cable from slipping during installation, the whole drive train with the track-pads are hydraulically adjusted by squeezing the two systems together.

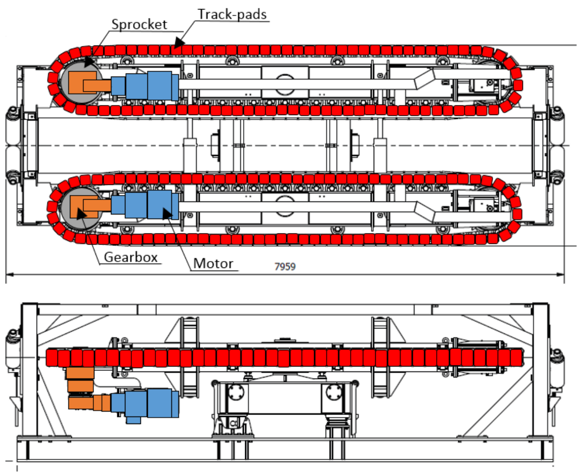

Figure 2.10: Highlighted in color, Red: track-pads, Blue: Motor, Orange: Gearbox, ref: Tideway Drawings

2.3.4. Chute
The chute is used to guide the subsea cable safely overboarding from the cable lay vessel towards the seabed. Its design depends on the cable limitation and installation type. Two types of chute designs are listed below.

- `Flared Chute`
  A flared chute has a v-shape open channel to guide the subsea cable (see number 1 on figure 2.11). Having a flared chute enables freely circular rotation of the vessel.

- `Straight Chute`
  The straight chute is a very simple and easy design(Illustrated in figure 2.11 as number 2). The disadvantage is the circular rotation of the vessel compared to a flared chute. A straight chute can also be constructed with rollers for a frictionless chute (number 3).

Figure 2.11: These are pictures of existing Chute types, Flared Chute(1), Straight Chute fixed(2), Straight Chute Rotating wheel(3), [11]

2.3.5. Possible improvement systems
A study is done on the possible systems to improve the workability of the vessel during cable installation operations. Several systems have been found and are listed and elaborated below.

(1) Constant Tension System, Constant Tension (CT)
A constant tension system is simply the 'Tension mode' from a tensioner system. The tension is compensated for by active control of the measured force by load cells. The actual measured tension at the load cells are compared with the target force value and as output of the system the trackpads of the system will rotate with a specified pay-out or pull-in velocity. To use such system it requires either slack-management or good communication between the carousel and tensioner operators. An illustration to set the 'Tension mode' is shown in the left picture of figure 2.12. This type of improvement system indirectly reduces the cable motions and result in lower tension fluctuation in the cable. In the PID Setup Control screen different parameters can be specified such as the Gain, Integral, Derivative. These parameters will be elaborated in Chapter[4].

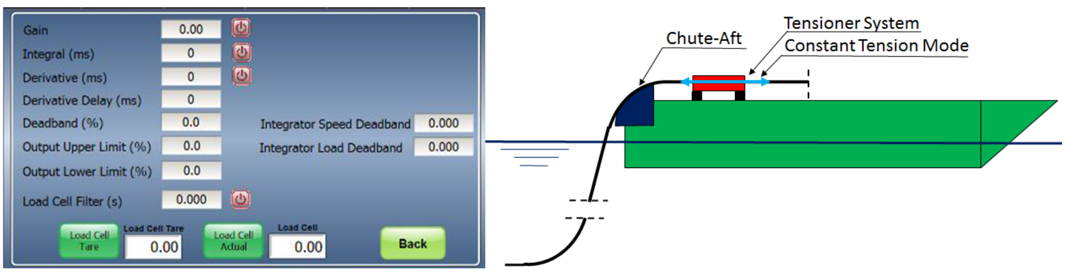

Figure 2.12: PID Setup Screen of a tensioner on Tension Control, [6].

(2) Heave Compensated Chute, HCC
The HCC system is designed and constructed by KCI[5]. It is a semi-active system to compensate for the heave displacement by force control of the piston length. Technical details about the construction or dynamics are not given, only an artist impression and picture is found for the rough estimations.

Figure 2.13: Left you see a realistic HCC build on a vessel and right you see an artist impression of the HCC, [5]

(3) Catenary cable stabilizer with depressor

The catenary cable stabilizer is a concept design of Subsea7 to improve the catenary shape during operations,[3]. The depressor on the catenary will act as an weight element with a bell-mouth on both ends and is lowered from the vessel by two winches towards the TDP. The main purpose of this improvement system is to control the TDP of the cable. This results in a more controlled layback length of the cable and reduces the peak tensions at the TDP. This type of improvement system is especially of interest for deep waterdepth projects, uneven seabed, long cables, strong current and where the length of the Remotely Operating Vehicle (ROV) reaches its limit.

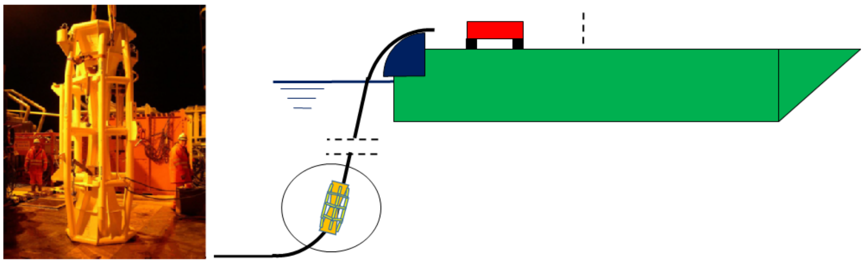

Figure 2.14: Depressor, left figure shows a realistic build depressor on a vessel, and right when the depressor is deployed along the cable catenary line.[3]

(4) Cable installation PS/SB Center

The chute can be placed at the aft or PS/SB center of the vessel. The main advantage of a PS/SB center location compared to the aft location is the overall reduction of the heave and pitch motions during operations. This solution is illustrated in figure 2.15.

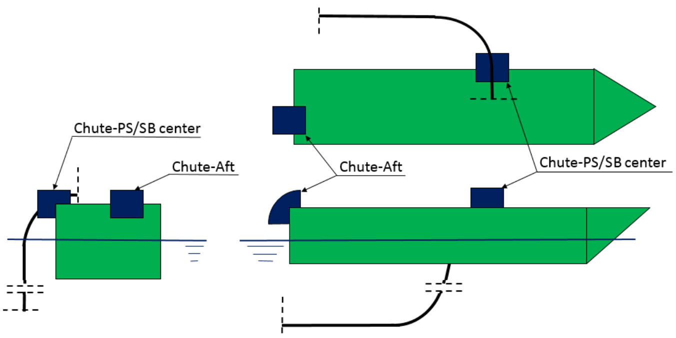

Figure 2.15: Location of the chute at the aft-SB and center-PS of the vessel.

Chapter 3

General Cable Lay mechanics

This chapter gives a description about the cable mechanical problems in general and influences due to environmental loads, hydrodynamic loads and vessel response on the cable. First the cable lay definitions are explained then the caternary equations are presented. These will be used in the analytical models to define the static tension in the cable. After, the cable integrity design conditions are presented and explained about their occurrence and where they are influenced by. Two improvement systems are presented for further analysis. For the investigation of environmental loads and hydrodynamic loads only waves are taken into account to determine the particle velocity profile, wave spectrum, drag and inertia coefficient. Furthermore the vessel response calculations are presented to calculate the maximum heave motion of the chute location. These are all calculations to define the input parameters for the analytical and numerical models.

> *The content of this chapter is confidential. Contact the author or company for detailed information.*

3.1. Cable Lay Definitions

3.2. Cable Installation Loads

3.2.1. Static Calculations

3.2.2. Dynamic Calculations

3.3. Cable Integrity Design conditions

3.4. Cable motions

3.4.1. Tension fluctuations: Analytically explained

3.4.2. Tension fluctuations: Numerically simulated

3.5. Concept improvement system

3.5.1. Improved system 1: CT Tensioner System

3.5.2. Improved system 2: HCC System

3.6. Environmental Loads

3.6.1. Fluid Particle Velocity from waves for analysis

3.6.2. Wave spectra for analysis

3.7. Hydrodynamic Loads

3.7.1. Drag Force

3.7.2. Inertia Force

3.8. Operational loads

3.8.1. Vessel Response equations

3.8.2. Chute Heave response

3.8.3. Chute maximum heave response

3.9. Chapter summary

Chapter 4

Analytical Analysis of Improvement Systems

This chapter outlines the analytical analysis of the improvement systems, tensioner system and HCC system. First is explained how an active controller works, second the analytical models are developed for further analysis in chapter 6 to define the critical damped system PID-Parameters.

The content of this chapter is confidential. Contact the author or company for detailed information.

4.1. Control Theory

4.1.1. Open-Loop-System

4.1.2. Closed-Loop-System

4.1.3. Transferfunction: General Theory

4.1.4. PID-Controller Theory

4.2. Analytical Model: CT Tensioner System

4.2.1. Tensioner System modeling

4.2.2. Vessel response influences

4.2.3. Cable static force influences

4.2.4. Force actuator

4.2.5. Equation of Motion: Tensioner system

4.2.6. Transferfunction: CT Tensioner system

4.3. Analytical Model: Heave Compensated Chute System

4.3.1. Motion compensated Cylinder modeling

4.3.2. Vessel response influences

4.3.3. Cable static force influences

4.3.4. Force Actuator

4.3.5. HCC System: Equation of Motion

4.3.6. Transferfunction HCC System

4.4. Chapter summary

Chapter 5

Numerical Analysis of Improvement systems

This chapter contains general information about the software OrcaFlex, developed by Orcina. First are the governing OrcaFlex model objects discussed on their physical behaviour and interaction with other objects, with the main focus on the winch object. The winch object is used to physically model a tensioner system to actively control the force and motion compensated cylinder to actively control the position in OrcaFlex software. Before finalizing the final models, a simple model is developed in OrcaFlex and validated against a realistic project: "Thornton bank Project". The results for the validation can be found in Appendix D.6.2.

> *The content of this chapter is confidential. Contact the author or company for detailed information.*

5.1. General OrcaFlex software description

5.2. OrcaFlex Objects and external influences modeling

5.2.1. Line Object

5.2.2. Winch Object

5.2.3. Shapes

5.2.4. Vessel object; "Living Stone"

5.3. Simulation model: Static Analysis

5.4. Simulation model: Dynamic Analysis

5.4.1. Solution method

5.4.2. Explicit solver

5.4.3. Implicit solver

5.4.4. Stages

5.5. OrcaFlex modeling: CT Model

5.5.1. Modeling of the flared chute

5.5.2. Modeling of the active force controlled tensioner system

5.5.3. Final Mode: CT Model

5.6. OrcaFlex modeling: AHCC Model

5.6.1. Modeling of the Chute Structure

5.6.2. Modeling of the Frame Structure

5.6.3. Modeling an active positioned controlled cylinder

5.6.4. Final model: AHCC Model

5.7. Chapter summary

Chapter 6

Model Analysis: Tensioner System

The transferfunctions of the tensioner system and the PID-controller are determined in chapter[4]. These will be used as input for the open and closed loop-system to analyze its stability and safety margin for a critical damped system. As result from the analysis from the analytical Tensioner system, a set of PID-parameters are defined. These will be used as input for the External Function(PID-controller) of the numerical CT Model to develop an active system in OrcaFlex and determine the operation efficiency of the winch object in OrcaFlex.

The analytical model and numerical model in OrcaFlex are two complete different systems, but only using the same set of initial guess PID-parameters. The main difference between the analytical and numerical model are the non-linearities included in the numerical model for the cable dynamics and vessel dynamics. Whereas the analytical model assumes the cable to be a static force and only exerted by the maximum vessel heave motions. Furthermore the numerical model, models the tensioner system by a massless spring and damper system with coefficients set to OrcaFlex default values. The analytical model, models the tensioner system as a mass-spring-damper system with input parameters for the mass, spring and damper coefficients obtained from IHC SAS bv C.2.

Here will also be analyzed how the performance of the numerical tensioner system behave and if its able to become stable when using the initial guess parameters. Based on this analysis will be determined if further tuning of the PID-Parameters inside OrcaFlex is required to obtain a performance which uses the full capacity of the system. At last the final model with the tuned PID-Parameters will be analyzed for its tensioner system behavior, reduction of the cable motion and improvement if its able to keep the cable integrity values within the design conditions.

> *The content of this chapter is confidential. Contact the author or company for detailed information.*

6.1. Analytical analysis

6.1.1. System Response

6.1.2. Open-loop-system

6.1.3. Closed-loop-system

6.1.4. Concluding remarks on analytical analysis: Tensioner system

6.2. Numerical CT Model Analysis: OrcaFlex software

6.2.1. Tuned PID-Parameter analysis

6.2.2. Tensioner system performance analysis

6.2.3. Final Constant Tension System analysis

6.3. Chapter summary

6.3.1. Analytical CT Model

6.3.2. Numerical CT Model

Chapter 7

Model Analysis: Heave Compensated Chute System

The transferfunctions of the HCC system and the PID-controller are determined in chapter[4]. These the transferfunctions will be used as input for the open and closed loop-system to analytically model a position controlled critical damped system system for its its stability and safety margin. Same approach as the tensioner system will be used to model the final numerical models PID-parameters. The PID-parameters from the analytical models are used as input for the numerical model in OrcaFlex (See chapter 6. In the numerical model the velocity of the piston length control is constantly adjusted to keep the actual chute end z-location on its target height value.

The main difference between the analytical and numerical model are the included non-linearities in the numerical model for the cable dynamics and vessel dynamics. Whereas the analytical model assumes the cable to be a static force and only exerted by the maximum vessel heave motions. In the numerical model the motion compensated cylinder is developed as a massless spring and damper system with coefficients set to OrcaFlex default values. The analytical model develops the motion compensated cylinder as a mass-spring-damper system with input parameters for the mass, spring and damper coefficients obtained from Bosch Rexboth C.1.

The performance of the cylinder is analyzed in the numerical model analysis for its stability and how well it can keep the chute-end location on its z location when using the initial PID-Parameters. If the chute is still deviating significantly from the target height and the system is not using the full capacity, the PID-Parameters are further tuned inside OrcaFlex. Furthermore the final model cylinder is analyzed for its performance, improving behavior and whether the cable integrity are below its design conditions

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7.1. Analytical analysis

7.1.1. System Response

7.1.2. Open-loop-system

7.1.3. Closed-loop-system

7.1.4. Concluding remarks on analytical analysis: HCC system

7.2. Numerical HCC Model Analysis: OrcaFlex software

7.2.1. Tuned PID-Parameter analysis

7.2.2. Final Heave Compensated Chute System analysis

7.3. Chapter summary

7.3.1. Analytical AHCC Model

7.3.2. Numerical AHCC Model

Chapter 8

Workability Analysis CT Tensioner System and AHCC System

In this chapter the CT Model and AHCC Model are dynamically analyzed in irregular sea states for different wave headings, waterdepths of 30 and 600[m]. significant wave heights with its corresponding peak period obtained from the JONSWAP Spectrum in OrcaFlex software. The systems in the models are using the full capacity of the design criteria by setting the controller with the tuned PID-Controller.

A realistic case 'Johan Sverdrup Project' is used to analyze the CT Model and AHCC Model for its workability during cable lay installation operations. The case information can be found in Appendix [B.1]. The considered case is about the installation of the HCDC Export cable between the onshore DVHC converter station at Haugneset and the Johan Sverdrup Riser Platform. The platform is located at approximately 155[km] distance from the coast of Stavanger. Through the subsea cable, a 100[MW] power is supplied from onshore to offshore high voltage direct current module on the Riser Platform. The route from the onshore station towards the offshore Riser Platform, Johan Sverdrup has a depth which varies from 0 till approximately 600 [m]. The deep waterdepth of 600[m] and shallow waterdepth of 30[m] is considered for the full dynamic analysis.

From this analysis should become clear which improvement system maintains the cable integrity within its design condition for the highest possible sea state for deep and shallow waterdepths. The cable integrity will be analyzed and verified for the four criteria mentioned in Chapter [3], top tension, Side-Wall-Pressure, Touch-Down-Point and Minimum Bend Radius. At last a total workability plot will be developed.

> *The content of this chapter is confidential. Contact the author or company for detailed information.*

8.1. General Model: Workability Analysis

8.2. Workability CT Model Analysis

8.2.1. CT Model: Top Tension of the cable

8.3. Workability HCC Model Analysis

8.3.1. AHCC Model: Top Tension of the cable

8.4. Workability plots

8.5. Chapter summary

Chapter 9

Conclusions

The main objective of this thesis was to develop a detailed model for dynamic analysis of a subsea cable during installation in OrcaFlex software and investigate the effect of the different improvement systems. This could lead to an increased workability of the Living Stone during cable lay operations by maintaining the cable integrity design criteria(TT, SWP, TDP and MBR). First an analytical model was developed of the improvement systems to control the position of the cable and chute of a linear SMD-System of only 1-DOF. The purpose of the analytical model is only to define the initial guess PID-Parameters used as input for the external function of the numerical model in OrcaFlex. Second the numerical CT and HCC models were developed in OrcaFlex. The CT Model actively controls the actual measured tension of the cable at the top and the HCC Model actively controls the actual measured heave displacement of the Chute end location. Inside OrcaFlex the PID-Parameters are further tuned to guarantee the systems are performing according to the full capability of a real system. Finally it is of important the improvement systems can be used for different environmental cases. The conclusion is divided into three parts; Analytical model, numerical model and the final results of both improvement systems. At the end final conclusions are drawn for the improvement system.

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Chapter 10

Recommendations

From the conclusions, results and observations in this MSc Thesis, the following recommendations are suggested to obtain a more accurate workability plot and realistic performance of the systems.

The content of this chapter is confidential. Contact the author or company for detailed information.

Appendix A

Tideway Flinstone Vessel Visit: Cable Repair project

The content of this chapter is confidential

Appendix B

Project cases

B.1. Project: Johan Sverdrup

The content of this section is confidential

B.2. Project: Thornton Bank

The content of this section is confidential

Appendix C

Product information

C.1. Hydraulic Cylinder

The content of this section is confidential

C.1.1. Hydraulic Cylinder Calculator

The content of this subsection is confidential

C.2. Tensioner System

The content of this section is confidential

C.3. Export Cable properties

The content of this section is confidential

C.4. Flared chute structure

The content of this section is confidential

C.5. Heave compensated Chute Structure

The content of this section is confidential

Appendix D

Model Analysis Sensitivity study's

D.1. CT system Deadband
The content of this section is confidential

D.2. CT system Friction
The content of this section is confidential

D.3. HCC system Friction
The content of this section is confidential

D.4. OrcaFlex Friction
The content of this section is confidential

D.5. OrcaFlex Contact normal Stiffness
The content of this section is confidential

D.6. OrcaFlex Contact shear Stiffness
The content of this section is confidential

D.6.1. OrcaFlex Line segmentation
The content of this subsection is confidential

D.6.2. OrcaFlex model validation
The content of this subsection is confidential

Appendix E

Workability Analysis Results

E.1. General Model
The content of this section is confidential

E.2. CT Model
The content of this section is confidential

E.3. AHCC Model
The content of this section is confidential

Appendix F

Morphological Overview decision making

F.1. Procedure

The content of this section is confidential

F.2. Basic design criteria

The content of this section is confidential

F.2.1. Partial Functions & Various possibilities

The content of this subsection is confidential

Appendix G

Chute port-side-center vessel

Appendix H

Transferfunction: Mitigation Solutions

H.1. Transferfunction: Tensioner System

H.2. Transferfunction:Heave Compensated Chute System

Appendix I

External Function in Python: PID-Controller

I.1. CT Tensioner System External Function

I.2. HCC System External Function

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