# MASTER'S THESIS

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<td>Supervisor: Erlend Hovland (Aercy Norway AS)</td>
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**Title of Master's Thesis:** Passive Heave Compensation of Heavy Modules  
**Norwegian title:** Passiv hivkompensering av tunge moduler

**ECTS:** 30

| Subject headings: | Pages: 108  
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**Stavanger, 16-6/2008**

**Date/year**
Preface

This report contains my work done by with my master thesis during spring 2008. The thesis is mandatory at University of Stavanger in fulfilling master degree in offshore technology.
Aim is to acknowledge the expertise the student have after its education.
The thesis contains issues related to the subsea engineering industry, where the focus is on vessel response and performance of a passive heave compensation system.

Thesis is performed in cooperation with subsea engineering company Acergy, where naval discipline leader Erlend Hovland has been teaching supervisor.
The thesis takes a broad look at heavy module installation and tries to look at this aspect in a new way, with implementing already known compensation technology from drilling industry to the subsea industry.
The student has to use advanced marine engineering software in aim of finding the results that are needed. In evaluating the concept software's like MOSES and MathCAD are used.

Many people have been involved in the thesis where the two supervisors have to be mentioned specially:
- Arnfinn Nergaard, Professor University of Stavanger
- Erlend Hovland, Naval Discipline Manager Acergy Norway AS

In addition several colleagues at Acergy have come with important contributions and the whole naval discipline should have a special thanks.

Stavanger, 16th June 2008
Sten Magne Eng Jakobsen
Abstract

New subsea technology has increased size and weight of installed modules significantly. This thesis looks at heavy module installation from barge, through moonpool with use of passive heave compensation.

An installation barge is designed with moonpool used as working platform for installation. Motion responses for barge are analyzed with use of marine engineering software MOSES. Responses found shows a significantly impact from moonpool, and it doubtingly if software is capable of calculate actual barge. Motion response found is used in operational analysis of compensator.

Mathematical models of first and second order are established to evaluate chosen passive compensator. Models calculate residual motion of module under a given harmonic force with respect to frequency $\omega$.

Two first order models are established with use of different theories, transfer function and motion of equation. System is simplified and evaluated model results correspond well. Transfer function model is evaluated for varying variables. Results show that resonance frequency has a large impact on compensator performance. Resonance frequency is determined by compensator stiffness and module mass, following compensator stiffness are important for compensator performance. One second order model is evaluated and includes some of the simplifications made for first order system. The second model gives a more accurate view of the physical situation.

Calculations show that all three models correlate well, where largest difference between models is in resonance area. The passive compensator works best for high $\omega$, in contrast to compared semi-active compensator. Calculations shows that model for motion of equation are most conservative, while the second order models gives largest changes for changing water depth.

Results are based on theoretical evaluations and model test should be performed to conclude if models represents physical situation.

Designed system should fulfil installation criteria’s for modules given by a max velocity for landing. Evaluated barge has largest velocities for lowest values of $\omega$. Without compensation the barge Hs for installation is below 1m Hs, and defined as low. Compensator with evaluated inputs is not able to reduce the highest velocities, and does not increase the weather window significantly. Compensator does not increase weather window for operation, and inputs should be analysed. System should be designed to meet barges motion response.
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<tr>
<td>CFD</td>
<td>Computational Fluid Analysis</td>
</tr>
<tr>
<td>COG</td>
<td>Centre of Gravity</td>
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<tr>
<td>DAF</td>
<td>Dynamical Amplification Factor</td>
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<tr>
<td>DP</td>
<td>Dynamic Positioning</td>
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<td>GPV</td>
<td>Gas Pressure Vessels</td>
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<td>GRP</td>
<td>Glass Reinforced Plastic</td>
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<tr>
<td>Hs</td>
<td>Average height of the one-third largest waves</td>
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<td>IMR</td>
<td>Inspection, Maintenance and Repair</td>
</tr>
<tr>
<td>JONSWAP</td>
<td>Wave Spectrum</td>
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<tr>
<td>MHS</td>
<td>Module Handling System</td>
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<tr>
<td>MOSES</td>
<td>Marine Analysis Software</td>
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<tr>
<td>MRU</td>
<td>Motion Response Unit</td>
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<td>NCS</td>
<td>Norwegian Continental Shelf</td>
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<td>OCV</td>
<td>Offshore Construction Vessel</td>
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<tr>
<td>RAO</td>
<td>Response Amplitude Operator</td>
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<tr>
<td>ROV</td>
<td>Remotely Operated Vehicle</td>
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<tr>
<td>SEMI</td>
<td>Semi Submersible</td>
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<tr>
<td>SSCV</td>
<td>Semi Submersible Crane Vessel</td>
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<tr>
<td>SWL</td>
<td>Safety Weight Load</td>
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<td>Tordis SSBI</td>
<td>Tordis Subsea Boost and Injection</td>
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1. **INTRODUCTION**

1.1 **MARINE OPERATIONS**

Marine operations play a vital in offshore oil and gas field developments where the need for advanced solutions in deep water constantly increases.

Demand for energy has grown rapidly the last 40 years, and a big part of the energy today is produced from non-renewable sources like oil and gas. This has forced through an enormous development in the industry with increased resources on research and development.

The early fields like Ekofisk where developed in shallow waters with topside structures. We now see large new gas fields like Ormen Lange that are developed with a subsea to shore tieback solution.

In a technical aspect we are now able to develop smaller and more advanced fields, with respect to both drilling and subsea technology.

Due to the high transformation of the requirements and expectations, the business demand for marine operations has increased.

Due to high development in the business demands for marine operations has increased.
- Heavy structures to be installed
- Advanced pipe design with heating and “pipe in pipe”
- Larger depths
- Remote locations
- New equipment e.g. subsea processing and pressure boosting

The growth in the market has driven the day rates to all time high, and new ships are constantly entering the market. The market is dominated by a few operators as Technip, Acergy, Allseas, Subsea 7 and Saipem, but smaller contractors are also entering the market. Deep Ocean is a Norwegian example of a company that recently has expanded, partly due to contracts with StatoilHydro.

Typical marine operations on an offshore field development can be:
- Seismic survey
- Pipe lay
- Module installation
- Inspection, maintenance and repair
- Survey
All operations are performed with highly specialized vessels outfitted with advanced equipment and personnel for these tasks.

From an economical point of view, marine operations have been topic to changes both in negative and positive way. The price on materials and personnel has increased rapidly and has made the projects more costly and more difficult to plan. In the same way the oil price has increased to record levels make the projects more profitable.

The main consideration for an offshore field development is always the net present value (NPV) of the project, and in order to attain a NPG as high as possible the cost has to be kept to a minimum.

The offshore business is based on tendering, where the responsibility are transferred from the developer and on to the contractor. This will in a monopoly market create high prices for the developer, while higher competition in the market will push the price down and the interest will increase.

Offshore operations are highly exposed to competition, which gives an attitude of constantly development of the business.

Figure 1.1: Picture shows Acergy Piper during pipe lay close to Sleipner field centre. Several marine operations are in action; pipe lay, anchor handling, extra pushing tugs, pipe supply vessel (outside picture) and a survey vessel to monitor touchdown (outside picture). [1]
1.2 HEAVY LIFT OPERATIONS

The first offshore fields where developed in shallow waters with topside structures due to lack of large offshore cranes. The installed modules were small, the offshore completion work was time demanding and costly, but the enormous reservoirs justified the developments.

The search for more cost effective solutions increased the lifting capacities, and semi submersible crane vessels (SSCV’s) were developed. With lifting capacities up to 14,200 tons (Heerema Thailf) these vessels changed the way of how to develop offshore fields. It was now possible to complete whole deck structures at shore, with only a small amount of offshore completion work. This new way of construction reduced considerably the development cost a made development of new technology possible.

As all the discovered large oil and gas fields in shallow waters have already been developed, new technology has been introduced to be able to produce from smaller and more complex fields. The subsea technology has been developed to be reliable and cost efficient, and offshore field developments are now in a large extent dependent of it. Developed from simple x-mas trees with small amount of functions and short control distance, we nowadays are able to install subsea to shore fields with distances up to 140 km. The control and monitoring systems allow us to produce a subsea field in the same way as we operate a platform field, although there might be some drawbacks to the reservoir performance. In the same way as the platforms became larger the subsea structures also became larger. As an example Ormen Lange has 8 well slots and a weight of 1150 tons [2].

This thesis will take into account the latest technology developments, and look at a barge for heavy module installation. Up to now such installations have been performed with SSCV’s or monohull vessels with large offshore cranes. Such vessels are very expensive to hire and have also very limited availability. Both types of vessels are thoroughly described in the following subchapters.
1.2.1 Monohull Vessels

Vessels designed to perform offshore construction work can be defined in two ways.

The first group of vessels is typically up to 170m long and can perform installation work up to 400 tons. They have high transit speeds up to 18 knots and are designed to operate in harsh weather environments. Work typically performed is:

- Smaller installation work
- IMR
- Reeling and flexible pipe lay
- Umbilical installation

Due to the flexible design and high transit speed, the vessels are capable of working in remote areas.

The Skandi Acergy, as viewed in figure 1.2 is a new built vessels that is a perfect example of this first group of vessels. With a maximum speed of 18 knots and 350 ton subsea lift crane capacity in addition to the possibility of reeling and flexible pipe lay, the vessels performs a universal working platform for marine operations.

The second group of vessels consists of flat bottomed vessels equipped with DP capabilities, and are made for operating in calm environments. Typical areas for use of these vessels are; West Africa, Asian waters and the Gulf of Mexico.

Due to the size combined with the shape of the hull a vessel like Sapura 3000 (figure 1.3) will perform badly in harsh environments. The strengths of these vessels are high crane capacity, large deck space and pipe lay possibilities. The size of the vessel, the transit speed are important factors to take into consideration when evaluating the different vessels and making the cost decisions.
1.2.2 Semi Submersible Crane Vessels

The need for cost reduction in offshore field developments forced through the development of semi submersible crane vessels (SSCV). These vessels are self propelled DP capable semi submersible rigs equipped with heavy lift cranes that can perform lifts up to 14,200 tons. Today there are two main contractors in this business; Heerema and Saipem, and they operate the two largest SSCV’s in the world.

SSCV’s are essential in the modern structure of offshore field developments. With capabilities of operating all over the world they perform both topside and subsea lifts, and have in the last few years also been involved in decommission work. Based on the design they perform very well during lifting operations, and the large displacement is also an advantage during pipe lay in deep waters with large top tension requirements.

SSCV’s where originally designed for lift of modules like jackets and topsides, but following the development in the subsea part of the industry these vessels also perform installation of large subsea modules. In autumn 2007 Saipem 7000 installed the TORDIS IOR template in NCS with a max weight of 1250 tons [3].

In contrast to the specification for this thesis, the SSCV’s usually do not have possibilities for heave compensation.

Figure 1.4: Heerema Marine Contractor vessel Thialf [4]
1.2.3 Barges

Barges offer a cheap way for transportation of offshore structures, and have been used since the early years of the industry. They are cheap to build, and with only a small amount of equipment located on board the off-hire rate is low.

Barges are designed in many ways but the common characteristics is the flat bottomed hull, as a box, where the hull is divided into compartments for both structural and ballasting purposes.

As a cargo mover the barge represents large load capabilities to a low cost, but the limitations are high. Barges are designed to lift large loads, and will perform badly in other situations for example while towing.

Looking at the behaviour in waves a barge will perform badly, based on simple calculations of the heave period.

Heave period is a simple mass/water plane ratio that defines the heave resonant period. The lower this period becomes, the worse the barge will perform in waves. Barges consist of small mass, and the water plane area is very large, which gives a low heave period. For instance a SEMI will have a much larger mass, while the water plane area is reduced with use of pontoons and columns. This simple argument is why drilling rigs used in the North Sea are based on SEMI’s.

The thesis looks at heavy module handling in both the North Sea and in West African waters, two areas with different weather conditions.

In the North Sea a barge will only be usable through the summer months, while it can be used throughout the year in West Africa.
1.2.4 Wet Tow

Module installations offshore are challenging operations both while in air and in the splash zone. Often the module faces the largest forces in its lifetime during installation.

To increase the operational window and reduce risk for cost overrun, new concepts have been developed, where Subsea 7 have patented a method for wet tow of heavy templates. The templates will be transported on a barge to a nearby fjord, deployed in calm environments, and wet stored for later pickup by a construction vessel. By use of relatively small monohull vessels the module can be wet towed to its location, avoiding offshore lifts.

In stead of an offshore crane the concept uses a standard offshore winch for the lift. A lift wire is routed through moonpool and is used for pickup of the template, which are locked into a rigging also mounted in the moonpool. Located on site the winch takes over the lift again, now mounted with an in-line passive heave compensator, and the template are submerged to the seabed. The system was first used the summer of 2007 on Tyrihans field in northern North-Sea, during installation of 4 x 260 Te templates [5].

The illustration below presents how the lifting arrangement is located above the moonpool of the offshore construction vessel Botnica. The lift wire from the winch is routed over a fairlead and down through the moonpool. To increase the lifting capacity of the winch the wire are routed through a subsea sheave and is finally connected to a passive heave compensator attached to a frame above the moonpool.

The concept lets relatively small offshore construction vessels install large templates to an affordable cost, but it requires relatively large weather windows to perform such operation. The operation is performed in a safe manner, with all critical operations done by use of ROV.

Figure 1.5: Wet tow system – Subsea 7 [5]
2. OBJECTIVE OF WORK

The development of the subsea technology have forced through new ways of thinking in the oil and gas business. New technology makes it possible to move processing and compression equipment subsea. Fields developed are at increasing water depths, and the new technology represents heavy equipment located on seabed. This thesis looks at heavy module installation in Norwegian and West African waters, from barge through moonpool with compensation system.

Task:

“Passive heave compensation of heavy modules”

This thesis is divided into 6 main sections:

1) Select a barge concept suitable for the operation
2) Calculate motion response of the barge
3) Discuss and select a passive compensator concept
4) Establish mathematical models for calculation of residual motion
5) Comparison and evaluation of mathematical models
6) Operational study

The barge and its technical systems should be able to meet requirements for the next decade. Specifications for the systems will be based on SSBI Tordis installed by StatoilHydro autumn 2007. The module is representative for the latest technology used.

Module specifications [1]:

**Tordis SSBI:**

<table>
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<th>Value</th>
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<tr>
<td>Length</td>
<td>47m</td>
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<tr>
<td>Breadth</td>
<td>21m</td>
</tr>
<tr>
<td>Height</td>
<td>18m</td>
</tr>
<tr>
<td>Mass</td>
<td>1000 tons</td>
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Operational criteria:

Max landing velocity: 0.5 m/s
3. SELECTION OF BARGE CONCEPT

Barge design should be made according to objective of work.

3.1 DESIGN BASIS

Specifications for barge:
- Approved stability
- Capable of mobilizing two modules at one time
- Constructed with moonpool
- Minimizing moonpool water elevation
- Removable module handling system

Moonpool specifications:
- Length: 50m
- Breadth: 30m

Specifications of module handling system:
- Height: Module + rigging
- Lifting capacity: 1000 tons
- Lifting points: 2

Operational requirements:

Barge should be capable of working in the North Sea and West African waters. Areas are represented with two locations:

North Sea field: Kristin – operated by StatoilHydro
Water depth: 350m

West Africa field: Girassol – operated by Total
Water depth: 1300m

Weather data for given locations should be evaluated with use of JONSWAP wave spectrum. Spectrum input variables should be adjusted to meet the wave statistics for area.
3.2 DESIGN CONSIDERATIONS

3.2.1 Stability

Several subjects are to be considered when planning offshore operations. This section looks at barge stability and barge response function in waves.

Stability checks are used to calculate if barge is capable of performing planned operations. Main considerations are buoyancy and keeping stable equilibrium during all phases of operation.

Vessels motions, velocities and acceleration are used in operational studies of vessels. These data are inputs in calculating forces that cargo, seafastening and barge has to withstand. Data are also called vessels Response Amplitude Operators, RAO’s.

**Buoyancy** can be expressed by Archimedes law which tells us that a body submerged in a fluid experiences an upward buoyant force equal to [6]:

\[ F_v = \rho g \nabla \]

In which:
- \( F_v \) = buoyant force
- \( \nabla \) = volume of the submerged part of the object
- \( g \) is gravity acceleration
- \( \rho \) is sea water density

From this law we can define object placed in water in three ways. Some will float, some will sink and some will neither float nor sink.

The objects floating are called positive buoyant, those sinking are called negative buoyant and the last one not floating or sinking are called neutrally buoyant.

An object is floating when the buoyant force is larger then the exposed load on the object. An object is sinking when the exposed load is larger than the buoyant force.

Neutral buoyant is the condition when the exposed force is equal to buoyant force, and the object is in a stable condition.
**Static floating stability** is of interest for ship designers and owners, and represents:

“Up-righting properties of the structure when it is brought out of equilibrium or balance by a disturbance in the form of a force and/or moment” [7].

A rectangular barge will have two kinds of stability, longitudinal and transverse stability.
The longitudinal stability rotates around the transverse axis and is measured in meters or degree. When a vessel is in horizontal stability we say it floats without trim. Transversal stability rotates around the longitudinal axis and measured in meters or degree. The inclination of vessels is defined as heel.
Stability checks use the transversal stability to check the vessels sea keeping capabilities. The same calculations also can be used for the longitudinal stability.
This section will take a closer look at so called undamaged stability for a simple rectangular shaped barge. The output from the stability check is the calculated GM.

Calculations to follow represent small angels of inclinations and do not implement dynamically effects from forces and response.

When a stable floating body is disturbed to an external force \((M_n)\) it will start to heel. This heel will affect the submerged shape of the body and the centre of buoyancy will move \((B)\), where \(B_0\) becomes the new centre of buoyancy.
Drawing a vertical line from the new centre of buoyancy, a point will be created where the line crosses the centre line of the barge. This point is called the fake metacentre \(M\).
Distance between point \(G\) and \(M\) \((GM)\) is a common expression in defining vessel stability.

![Figure 3.1: Transversal stability](image-url)
When GM is above zero a new force that tends up righting the vessel are created when with vessel heel. This force, $M_r$, is created by the couple between the force of gravity and the force of buoyancy.

$M_r$ can be written as:

$$M_r = \Delta GM \sin(\phi)$$

For small angels of inclination, $\sin(\phi) \approx \phi$, then we have:

$$M_r = \Delta GM \phi$$

$M_r$ is the force that tries to keep vessel in an equilibrium condition.

Based on the calculated GM the vessel stability can be analyzed in the following way [8]. Statements also explain the $M_r$ influence to the stability.

- $GM > 0 \Rightarrow M_r > 0$: The vessel will go back to its original position when the external influence is removed. It is in the stable equilibrium.
- $GM = 0 \Rightarrow M_r = 0$: The vessel is in a condition of neutral equilibrium
- $GM < 0 \Rightarrow M_r < 0$: The vessel is in a condition of unstable equilibrium. It will continue to incline even if the external influence is removed.

GM specifications are given in standards used for vessel design.

**The vessels RAO’s** gives a response spectrum for all 6 degrees of freedom.
Numbers have to be calculated by use of marine software, and are given as a ratio of heave motion.
Theory behind motion response is quite involved and will not be described. RAO’s are created for different headings and for different wave periods.
3.2.2 Moonpool

Size and location
The moonpool design should meet the given requirements, 50m x 30m. Compared to other moonpool designs the requirements are large, standard sized moonpools have a size of 7.2m x 7.2m [1].

Preferred location of moonpool is in centre of roll and pitch motions, in centre of barge. This is to minimize the heave motions of the crane hook. The requirement for mobilization of two modules at one time demands a hull length that is at least 3 times moonpool length. Barge breadth should be as slender as possible, but be able to keep structural strength.

Design is in this report simplified. Chosen design has to be prepared more thoroughly for work beyond motions response.

Moonpool design will affect barge operational capabilities in several ways. When designing a moonpool several issues have to be discussed in order to find the most preferable design.

Two issues are discussed:
- Water column elevation
- Damping
Water column elevation
The new DNV standard for offshore operations includes a section for moonpool calculations. This includes a graph for investigation of the water column excitation in moonpool.
Input data are based on model test for offshore vessels with standard sized moonpools. Tests are performed at MARINTEK [10].

Figure 3.2: Moonpool RAO for different designs [10]

- T is wave period
- T0 is moonpool resonance period
- RAO is amplitude ratio of relative water plug elevation to incoming wave elevation
- Curves for different restrictions in moonpool

The graph illustrates water elevation with different types of restrictions in moonpool.
It is discussable if the standard can be used for the moonpool design in this report. Designed moonpool is large compared to the evaluated moonpools in reference. To find the exact moonpool water elevation test should be performed in proper CFD analysis or with use of model tests. Water motions inside moonpool are important to establish when calculating marine forces on modules during lowering. Elevation should be as low as possible to keep drag and added mass forces on module to a minimum. Hydrodynamic coefficients are not evaluated in this thses and it is assumed that forces on module in moonpool will not be the limiting factor for operations.
**Damping**

Moonpools are a challenge when designing offshore construction vessels. It complicates the structural design and will often increase the drag factor for the hull.

A moonpool can also make a positive effect to vessel response. In Sphaier [11] the moonpool influence to vessel RAO’s are evaluated.

Figure 3.3 compares the vertical motion for different water entrance openings. Tests are performed with use of a monocolumn SPAR platform. Curves presents amplification of vertical motion with changed water entrance area in bottom.

![Figure 3.3: Damping in circular moonpool [18]](image)

Where:
- Wave periods in seconds, x-axis
- Amplification of vertical motion, y-axis
- Spar external diameter, 95m
- Internal diameter, 69m

As observed the amplification change with varying water entrance area. Reduction is low when restriction in opening, and most interesting observation is when D=47, half of monocolumn diameter. With this restriction the damping is considerable, and the response is reduced to just above one.

The observations will be useful during evaluations in chapter 4.
3.2.3 Module handling

An important part of the installation system presented in this thesis is the module handling system. The system will not be detail analyzed but one solution is briefly discussed. This will make it easier for the reader to get a full overview over heavy module installation.

The process for transporting the module from yard to installation location can be described in three steps: mobilization, onboard handling and installation.

Mobilization

Mobilization is the process where the vessel arrives to quay in preparing for the next project to be performed. Equipment is lifted on board the vessel with use of its own crane, or by use of harbour cranes.

The design weight for the system presented in this report is 1000 tons which gives lifting related problems. Some large yards are capable of doing such large lifts, but it is reasonable to believe that the mobilization have to be performed by skidding.

Skidding is a technique where the module is placed on greased steel beams. Module is skidded on beams with use of hydraulic jacks or winches. System is well known in industry where heavy topside modules are skidded onto barges and installed with large crane vessels offshore.

Figure 3.4 shows skid way in yard and it is also possible to see a barge with mounted skid ways.

Skidding is proposed as a good alternative for mobilization of the installation barge.

Figure 3.4: Skidding ways in yard [1]
After module is skidded onboard the vessel it has to be sea fastened due to prevailing rules and regulations. This can be e.g. DNV or Noble Denton. The necessary sea fastening is calculated from accelerations analyzed for the barge. Barge will not leave quay before weather forecasts are according to calculated criterias.

**On board handling**

Installation barge is equipped with a moonpool that complicates the module handling. It is assumed that with use of moonpool hatches and skidding beams it will be possible to use skidding to place module inside the module handling system above the moonpool.

Offshore module handling could be performed in this sequence:

- Safety meeting with all involved personnel
- Preparation of all included equipment
- Removing of sea fastening
- Skidding into moonpool
- Mounting of lifting system
- Lock cursor frame
- Lift module
- Lower moonpool hatches
- Deploy module subsea
Installation
The barge is to be equipped with a module handling system located above the moonpool, a system designed to lift and control the module during installation.

The idea of a module handing system comes from the subsea IMR industry. Handling systems have been used for safe and efficient operation for many years. Existing systems are mounted above moonpools with a dimension of 7.2m x 7.2m and are usually rated up to 50 tons (PSV Far Saga [1]). The moonpool can be closed with hatches including skidding beams. This allows the module to be transported into the moonpool area without lifting. While lifting the module a cursor frame will guide the module until it is complete submerged.

Figure 3.5 shows the MHS installed on Normand Flower operated by subsea contractor Deep Ocean. System is rated to 30 tons and contains 5 storage locations for modules.

The MHS designed for the installation barge will be based on the same principles as the IMR handling systems. Dimensions of module and lifting system will require a different larger design.

Some parameters are important to implement in the system.

Design parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cursor frame</td>
<td>Lock position of module during lift - adjustable</td>
</tr>
<tr>
<td>Adjustable lifting point locations</td>
<td>Adjustable to module size</td>
</tr>
<tr>
<td>Safe wire routing</td>
<td>Wire to be routed in safe distance from personnel</td>
</tr>
<tr>
<td>Moonpool hatches with skidding ways</td>
<td>Allows skidding of module into moonpool area</td>
</tr>
<tr>
<td>Allows for both 1, 2 and 4 point lift</td>
<td>Adjustable to module size</td>
</tr>
</tbody>
</table>

**Table 3.1:** Design parameters
Rigging height
Cranes and lifting equipment are usually designed for one or two lifting points. Rigging are used to transfer forces into the actual lifting points on module and can be considerably high. This is due to decomposed forces that occur due to an angle between sling and module. Avoiding large loads in the rigging it's an issue to keep the angle relative the module as high as possible, where this will increase the rigging height significantly.

The competitors for this concept are all based on cranes which allows for high rigging height. Figure 3.6 shows lift of Tordis SSBI from Saipem 7000, a 4 point lift with rigging that allows Saipem to use both cranes.

The barge designed is to be fitted with a module handling system kept as low as possible. Large height of this system increases the weight considerably. It will also react negative on vessel stability, GM. Keeping rigging height low will be necessary in project planning.

Lifting operations at offshore location is dangerous due to swing in module. Standard way to avoid this to use tugger winches connected to the module, where such operations need very good planning. The risk for all included personnel and equipment are also considerably high. With low rigging height the probability for swing in lifting system becomes smaller.

Module handling system should be designed with cursor frame for module locking. It should also be designed for use of low rigging height.

Figure 3.6: Lift of Tordis SSBI with use of Saipem 7000 [1]
3.3 BARGE DESIGN

Initial requirements have to be met when designing barge. At this stage several assumptions are made and the design can only be used for calculating the response.

Because of the moonpool explained in chapter 2, the size of the barge is large. Due to the required ability to mobilize the two modules at the same time, the length of the barge will be at least three times the moonpool length.

**Chosen barge concept:**

- Length: 180m
- Breadth: 60m
- Moonpool length: 50m
- Moonpool breadth: 30m

**Figure 3.7:** 3D model of barge

All auxiliary equipments will be located between the module handling system and the quarters. Compensators will also be mounted in this area (see chapter 5.2 for specifications).
The chosen barge design is particularly large. This large barge design compared with standard North Sea barges might look strange for the reader.

<table>
<thead>
<tr>
<th></th>
<th>Installation barge</th>
<th>300 feet North Sea Barge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>180m</td>
<td>91m</td>
</tr>
<tr>
<td><strong>Breadth</strong></td>
<td>60m</td>
<td>27m</td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td>11m</td>
<td>6m</td>
</tr>
</tbody>
</table>

**Table 3.2:** Comparison of barge size

The large size can be explained by:
- The moonpool located in centre of pitch and roll motions
- Large modules
- Mobilizing of two modules at same time
- A large deck area required for lifting equipment [12]

In addition to this the module handling system will be removable. This allows the barge to be used for transport of large equipment, e.g. platform bridges.
4. **CALCULATE MOTION RESPONSE OF THE BARGE**

The RAO’s and motions response for the designed barge are calculated. Marine analysis software MOSES is used for the calculations.

The wanted results from calculations are:
- Stability
- Barge RAO’s
- Motion characteristics
- Comparison of analysis with and without moonpool

The software has capability to take use of two different methods for calculations; strip-theory and 3D-diffraction theory [13].

**Strip theory** is in MOSES the most convenient way to find the RAO’s. By dividing the underwater part of the vessel into a number of strips with an infinite width, two-dimensional added mass and damping coefficients could be found for every strip. The 3D added mass and damping coefficients are found by taking the 2D coefficients and integrate them over the length of the ship. Using strip theory implies that the variation of flow in the cross-sectional plane is much larger than the variation in the longitudinal direction. This will not be true at the ends of the hull. Strip theory is basically a high frequency theory. This means that if headway speed is included, the theory will fail when the vessel is going in waves from behind. Strip theory is also most applicable for low Froude numbers, Fn<0.4. The basic assumptions for strip theory are
- Linear response between ship and waves
- Slender body, \( L \gg B \)
- All viscous effects are neglected
- No lift generated by the hull itself

**3D-diffraction theory** can not be solved analytically, so we need to use numerical methods to find the ship motions. First the geometry has to be divided into several panels. A source is then placed in each panel, and the strength of the source is found by the boundary condition. This represents the normal component of the panels forced motion. In other words; zero relatively fluid motion at the panel. The fluid velocity in this relation is the sum of all the other sources placed on the geometry. When the source strength is known, the velocity potential can be found, and further on the dynamic pressure, forces, damping and added mass for
each panel. Basic assumptions for Diffraction theory are the same as for potential theory.

The fluid needs to be:
- Incompressible
- Inviscid (ideal fluid)
- Irrotational

Based on the shape of the hull and by following the software supplier’s recommendation, 3D diffraction theory is used for calculations. Strip theory is not able to handle two hulls close to each other, and this is the actual case for the moonpool.

**MOSES modelling**

It takes some time to be familiar with MOSES modelling. There are several ways to model a vessel in MOSES, and the modelling is based on two different techniques; block function and frame function.

The block function is a quite simple technique where the vessel is modelled with different blocks that are combined with each others. The figure below illustrates how the barge is made of two blocks, one barge block and one block that is used for the cut-out of the moonpool.

![Simple block model of the barge](image)

**Figure 4.1:** Simple block model of the barge

In the second method the vessel is modelled in the same way that vessels have been defined in several hundred years; with the use of frames. By defining the different frames of the vessels, the program draws lines from frame to frame and the hull shape is defined. To show how this function can be used for a relatively advanced vessel, the figure below shows the hull of IMR vessel PSV Far Saga [1].
Because of the program’s capabilities, special design elements like roll dampers and cofferdams will not be calculated. This is because MOSES is not able to calculate viscous effects. The first, damping in roll movements, will not create any challenges in this project due to the large width of the barge, the cross-section stability will be very high for a wide flat bottom barge. The last, damping created in cofferdams, is a positive effect that creates damping in both the barge and for moonpool water elevation. The damping effect is not taken into consideration during any calculation, but is described in section 3.2.2.

Figure 4.2: Frame function explanation, MOSES model of FAR SAGA [1]
**MESH control** is important to get realistic results with the use of the 3D diffraction theory. The programmer defines maximum distance between the nodes, and the program creates the mesh over the whole structure. The most accurate results are calculated using square panels, and it may be necessary to implement more planes in the model to straighten the mesh. In addition the program has capability to reduce the amount of nodes that will occur when different blocks are combined.

The program inputs for the barge are:
- Max nodes distance: 4m
- Min nodes distance: 0.09m

The barge was first modelled after using the block method with a single cut-out for the moonpool. Some extra planes were added to straighten the mesh. The figure below shows the barge with mesh used.

![Figure 4.3: MOSES model – barge with mesh 1134 panels](image)

Using this method there were experienced some problems with negative damping and negative added mass. The problem was located at periods up to 6 seconds when the barge was modelled by the use of blocks only. Several of the techniques described in the previous section were tried with no luck; redefined mesh, increased number of panels, applying more planes in the model and decreasing the draft. Still the results were not approved and the model was rejected.

The barge was now modelled with the use of frame theory. The moonpool were still created as a block and extracted from the frame-defined hull. After some tryouts it now was possible to create the results without any negative damping. The results for the barge were approved, and a complete RAO report is presented in appendix D.
4.1.1 MOSES-analysis results

The following section contains analyses performed to show the barge capability. The section includes:

- RAO’s for different headings
- Barge with and without moonpool
- RAO’s for lifting points

![Diagram showing wave heading relative to vessel](image)

**Figure 4.4** Wave heading relative to vessel

Figure 4.4 shows how the wave directions are defined in MOSES. The system of the coordinates has its origin in the bow, with x-axis positive backwards, z-axis upwards and y-axis towards starboard side.

To establish radii of gyration for roll $r_{44}$, pitch $r_{55}$ and yaw $r_{66}$, the formulas given in Faltinsen [24] have been used.

\[
\begin{align*}
r_{44} &= 0.34 \times Bm \\
r_{55} &= r_{66} = 0.27 \times Lpp
\end{align*}
\]

Where Bm is width and Lpp is the overall length of the barge.

As described in chapter 3.2.1 the barge stability is explained by use of calculated GM.

The GM for the installation barge needs a little explanation.

In general barges have large GM’s since width of vessels is large compared to the height. A low height gives the vessel a low centre of gravity, while a wide vessel will give a high metacentre height.

The installation barge is equipped with a moonpool that will affect the GM in a positive way. The moonpool will change the radii of gyration in a positive way since masses are moved out on the edges. The moonpool also reduces the displacement of the vessel.
At the other end the buoyancy centre B will be moved to a higher level which will decrease the GM.

If we look at the sum of these elements the GM for the installation barge without cargo and equipment should be satisfying.

The GM is not calculated with cargo, but since the weight of the cargo is assumed to be small related to the barge displacement the GM will not be affected that much.

<table>
<thead>
<tr>
<th>Input to MOSES</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_{44} )</td>
<td>20.4m</td>
</tr>
<tr>
<td>( r_{55} )</td>
<td>48.6m</td>
</tr>
<tr>
<td>( r_{66} )</td>
<td>48.6m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calculated by MOSES</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GM</td>
<td>46.5m</td>
</tr>
</tbody>
</table>

*Table 4.1: MOSES data*

RAO’s are created for three different places on the barge, COG and both lifting points used. The COG is used to compare the barge with and without the moonpool.

RAO’s for lifting points are used to find motion response used for operational studies of compensation system.

Lifting points are located mid ship five meters from moonpool edges, at 70m and 110m while the COG is assumed to be in the central point of the barge at 90m.

Assumptions used for calculations:
- Draft 7m
- COG in mid ship, centre of barge, \( z=5 \)
- Ballasting used to keep COG at origin during operation

*[Figure 4.5: Calculated points]*
The graph in figure 4.6 shows COG heave RAO’s for the three headings.

![Figure 4.6: Heave RAO for COG, 3 different headings](image)

As observed response for 0 and 180 degree are identical. From figure 4.5 this is explained by the symmetrical design of barge.

Responses are different when comparing 0 and 90 degree headings, which have to be considered during planning.

It is normal to take account for this by require a specific vessel heading for operation.

This can not be done for the moonpool barge as it has two lifting points. Modules are installed with a specific heading where is required.

Operations from moonpool barge have to be planned for worst case heading.

The sharp peaks occurring make the RAO results quite unusual. The analysed barge is 180 meter long and the dynamical situation for such a large vessel should not create peaks as observed.

Table 4.2 tries to explain the unusual results.

<table>
<thead>
<tr>
<th>Period [s]</th>
<th>Omega [rad/s]</th>
<th>Wave length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>1.14</td>
<td>47</td>
</tr>
<tr>
<td>5.75</td>
<td>1.09</td>
<td>52</td>
</tr>
<tr>
<td>8.25</td>
<td>0.76</td>
<td>106</td>
</tr>
<tr>
<td>8.75</td>
<td>0.72</td>
<td>120</td>
</tr>
<tr>
<td>9.75</td>
<td>0.64</td>
<td>148</td>
</tr>
<tr>
<td>11</td>
<td>0.57</td>
<td>189</td>
</tr>
</tbody>
</table>

*Table 4.2: Wave lengths for different periods*
Barge responds differently for different calculated wave periods. The vessel response closes towards 1 as wave period increase.

Looking at the graph for 90 degree heading there is a peak at 5.75s with corresponding wave period of 52m.

The width of the barge is 60m, and the peak can be explained by the barge response to a wave length equal to the width.

Next peak in 90 degree heading is located at 8.25s which corresponds to 106m length. This point does not match any physical dimensions.

Only 0.5s after the peak at 8.25s there is a low value at 8.75s, corresponding to 120m wave length. The wave length at this point is exactly twice the width of the barge, where this should not have any impact.

After this point the response for the barge is getting closer to zero, which it should do for large periods.

The 0 and 180 degree curves are also affected by sharp peaks. The first peak is located at 5.5s which corresponds to 47m wave length. For the 90 degree heading this can be related to the width of the barge, but has no physical correspondence with the 0 and 180 degree heading.

The next peak is located at 8.25s which corresponds to the high peak in 90 degree heading. The reason why peaks are located at this specific point is not discovered.

A low value for the 0 and 180 degree curves is found at a period of 11s. This value corresponds to 189m wave length which is close to the length of the barge.

As seen for the 90 degree heading there was a low value where the wave length met the width of barge.

It seems like the barge response will get low values when wave length meet physical dimension in the corresponding direction.
Figure 4.7 shows how the moonpool affects the RAO for the barge.

As explained in the moonpool section chapter 3.2.2 a vessel with a moonpool will be affected by mainly damping and excitation forces from the moonpool. The moonpool water column resonance period is calculated in appendix C using MARINTEK calculations [10], where the calculations give a resonance period of 10 seconds.

It is assumed that when wave periods meet the moonpool resonance period the response will increase. For a 90 degree heading this is not the case, as the moonpool lowers the results from 8 sec until 15 sec.

The moonpool affect to 90 degree heading changes results in a positive way since the response does not exceed much above 1 at any given period.

Curves for 0 degree heading vary quite much. The curve for the barge without the moonpool looks like a regression line for the moonpool barge.

The calculated resonance period for the moonpool is 10s, a period that is explaining any of the peaks that we observe.

Figure 4.7: Heave RAO for barge with and without moonpool
The moonpool barge is to be equipped with two lifting points located inside the moonpool, figure 4.5.
The two lifting points are located at 70m and 110m from the bow, where the heave response will differ from the COG results. Figure 4.8 shows heave RAO for both lifting points for 0 degree and 90 degree wave heading.
As observed response curves for 90 degree heading corresponds 100%, which is expected due to the design.
The two other graphs show that RAO’s will be different for the two lifting points with the same heading.
This requires that the lifting winches and the compensators are individual devices and operations should be planned according to the highest values.

![Graph showing heave RAO for both lifting points](image)

**Figure 4.8:** Heave RAO for both lifting points
The barge response compared to other large vessels is evaluated below.

<table>
<thead>
<tr>
<th>Type</th>
<th>Installation Barge</th>
<th>Skandi Acergy</th>
<th>Alvheim FPSO</th>
<th>Acergy Piper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Barge</td>
<td>Monohull construction vessel</td>
<td>Monohull FPSO operating in North Sea</td>
<td>World wide S-lay pipe lay SEMI</td>
</tr>
<tr>
<td>Length</td>
<td>180m</td>
<td>157m</td>
<td>233m</td>
<td>167m</td>
</tr>
<tr>
<td>Breadth</td>
<td>60m</td>
<td>27m</td>
<td>42m</td>
<td>58m</td>
</tr>
<tr>
<td>Displacement</td>
<td>66700 ton</td>
<td>17000 ton</td>
<td>104000 ton</td>
<td>53500 ton</td>
</tr>
</tbody>
</table>

**Table 4.3:** Main specifications for compared vessels

The vessels compared are large of size. These should be representative vessels when comparing vessels in heavy module installation. All input data is based on analysis done by 3D diffraction theory.

The curves in figure 4.9 show how the different vessels perform with heading 0 degree.

The two monohull vessels have some small peaks with low periods, but still the results are quite similar. The barge results coincide quite well with the results from the two monohull vessels, where the barge has a large peak due to its moonpool. The SEMI pipe lay vessel Acergy Piper shows clearly its capabilities compared to the monohull vessels. The Piper has a larger natural period due to a smaller cross-sectional area in the water line. This can clearly be observed in the graph as the SEMI’s response is lower for all periods up to 17 seconds.

**Figure 4.9:** RAO comparison at 0 degree
Figure 4.10 shows the response for the mentioned vessels in 90 degree wave heading.

The vessels performance correlates in the same way as for figure 4.9.

It is observed that the two monohull vessels get a response peak over 1, while the installation barge stays below 1 for almost all periods. It is presented in figure 4.7 that it’s the moonpool that affects the barge in this way. The curve for the barge without the moonpool, figure 4.7, correlates closely to the two monohull vessels. Acergy Piper shows also in this graph why a SEMI design is well suited for offshore operations. Response stays below 1 up to 18 seconds wave period which is larger than for the other vessels.

**Figure 4.10:** RAO comparison at 90 degree
The motion response is calculated as it is needed for the compensator evaluation. The motion response is motions, velocities and accelerations for a vessel in a given wave spectrum. The barge motion response is calculated by the use of JONSWAP wave spectrum, both for the North Sea and West Africa. The JONSWAP spectrum can be found as an input in the MOSES software, and will create maximum responses for the different areas, based on a change in the gamma factor.

The RAO’s used for all analysis later in this report are from the barge without the moonpool. This is done because results from the moonpool analysis can not be qualified due to limitations in the software. The motion response is calculated for lifting point 110m from the stern.

The installation barge in North Sea waters:

<table>
<thead>
<tr>
<th>Velocity and Acceleration analysis - Kristin</th>
</tr>
</thead>
<tbody>
<tr>
<td>JONSWAP height: 1 m</td>
</tr>
<tr>
<td>Gamma factor 1 (peaked ness factor)</td>
</tr>
<tr>
<td>Max values</td>
</tr>
<tr>
<td>Motions</td>
</tr>
<tr>
<td>Velocities</td>
</tr>
<tr>
<td>Accelerations</td>
</tr>
</tbody>
</table>

**Table 4.4:** JONSWAP analysis North Sea waters

The installation barge in West Africa waters:

<table>
<thead>
<tr>
<th>Velocity and Acceleration analysis - Girassol</th>
</tr>
</thead>
<tbody>
<tr>
<td>JONSWAP height: 1 m</td>
</tr>
<tr>
<td>Gamma factor 2</td>
</tr>
<tr>
<td>Max values</td>
</tr>
<tr>
<td>Motions</td>
</tr>
<tr>
<td>Velocities</td>
</tr>
<tr>
<td>Accelerations</td>
</tr>
</tbody>
</table>

**Table 4.5:** JONSWAP analysis West African waters

The tables give the maximum motions, velocities and accelerations for the installation barge in the different areas. As observed the only difference between a gamma 1 and a gamma 2 spectrum is a slight change in the results and earlier peaks. The results from the spectra are linear and can be multiplied with any given sea state to get the motions results for that actual given case.
5. DISCUSS AND SELECT A PASSIVE COMPENSATOR CONCEPT

5.1 HEAVE COMPENSATION

All marine operations are affected by their environment like weather and waves. Weather condition has to be monitored in order to perform safe operations. Since work has to be stopped when weather exceeds a pre-set value, all marine contractors are aiming for setting this value at a highest possible level. In addition to monitoring of the weather a well detailed planning of the operations is a crucial success factor.

Different vessels have different response to waves. Hull designs like barges, SEMI’s, catamarans and trimarans react differently. Responses are possible to calculate with the use of marine software (e.g. MOSES) and response for the chosen barge is calculated in chapter 4.
Designing a vessel for offshore installation work requires calculations for vessel motion response. The motion response is used to calculate the highest feasible sea state.

Drilling engineers where designing at an early stage heave compensation systems. The aim was to increase the weather windows for operations. The design purpose for these systems is simple, keeping equipment stable related to seabed.

Floating drilling units are working all year round and are very expensive to operate. Downtime related to weather limitations is very expensive due to high day rates. Working all year round means that the wave height can be very large during winter storms, e.g. in the North Sea. The SEMI’s are build to have minimum heave response to the waves, but heave motion of drilling rig will still be considerably high.
As the oil fields are developed on deeper waters, the weight of equipment has increased. The state of the art compensation systems are capable to compensate up to 1000 tons of weight.

Wave height and weight are the main challenges for drill-string compensation systems.
Heave compensation in subsea construction is a well known technology, and compared to the drilling industry there is less weight. Vessels used can be divided in two sections as explained in chapter 1, where the largest vessels generally do not have heave compensation systems. Smaller vessels working with smaller structures and weights up to 400 tons are in contrast mainly designed with compensation systems.

A subsea lift can be divided in several phases:

1. Landing of load on seabed
   a. Splash zone
   b. Landing phase
   c. Hook release

2. Picking-up load from seabed
   a. Engaging hook to load
   b. Lifting load of seabed
   c. Splash zone

While installing modules larger than the standard moonpool size (7.2m x 7.2m) there is no alternative to over side deployment. Large forces will occur on structure in the splash zone. A heave compensation system can reduce these forces, e.g. forces from drag and added mass. The compensation system will then monitor the maximum potential power in the wire and spool out wire when the load increases above a preset value.

When landing on seabed a heave compensator will try to keep the module in a constant distance from sea bed. This phase is critical due to large forces on the impact with sea bed. Operators use a maximum velocity restriction for landing the modules. A much used maximum landing speed is 0.5 m/s, as will be used on the Gjøa template summer 2008 [14].

During the hook release it is important to prevent snap loads in wire, hook or installed equipment. A compensation system can in this case be used to monitor vessel movement, and start feeding out wire while the vessel is on the top of the wave.
The last phase described is a constant tension used while lowering and retrieving equipment in soft soil.

Templates have in many cases large suction anchors to keep the module stable on the seabed. Using a constant tension system the penetration of these suction anchors will be controllable. This is important to avoid wash-out around the anchors.

Wash-out is a problem and has occurred several times in the North Sea [15]. The system will also help stabilizing high suction anchors during landing penetration.

Figure 5.1: Wash out during installation [15]
Heave compensation can in general be divided into three kinds of system; passive, semi-active and active systems. Generally compensation is based on two kinds of equipment; cylinder or winch. Since knowledge of these systems is quite important to evaluate work done the following section contains a brief overview.

5.1.1 Passive heave compensation

Passive heave compensation is based on a cylinder working towards an accumulator. This gives the system a spring-damper effect. The system is designed to hold the static load which can be adjusted with pressure in the accumulator. The volume of gas determines how much the pressure increases in compensation mode, e.g. the spring stiffness in system. Passive compensation system can be designed in two different ways, cylinder based and winch based.

1

The system can be made as a cylinder filled with gas. In this case the cylinder is mounted in-line, between the crane hook and the module. The system is defined as a subsea compensator, and the technology is known as a Cranemaster© [16]

There are several configurations of a compensator and it is possible to connect additional bottles of gas to increase the gas volume. From the supplier Cranemaster© there can be supplied compensators from 12 to 400 tons.

The main challenge for the subsea compensator is the restricted gas volume and not the possibility of adjustment of gas pressure during operation.

Figure 5.2: Passive heave compensator
For compensators mounted on vessels large gas volumes can be installed. These compensators generally use hydraulic fluid between the compensating cylinder and accumulator.

Figure 5.3 shows a simple sketch of the system, the gas volume of the accumulator will be increased with the use of gas cylinders (GPV).

Compensators mounted on vessel generally have larger gas volumes, and thus softer spring stiffness. This gives a better compensation. Earlier several modes for compensation were mentioned for use in special cases of installation. These modes require changes in gas pressure and gas volume which are difficult do to. In general the gas volume is fixed and therefore the gas pressure has to be changed with compressors. Due to the large gas volumes the change of the gas pressure takes time, and it is not recommended to be performed during operation.

Passive compensators work with the use of stored energy, and have no energy consumption during operation. This requires pre-charged accumulators prior to operation.
5.1.2 Active Heave Compensation

An active compensator system holds both static weight of load and compensate for motion in one single hydraulic system. Compensation can be performed both by cylinder and by winch. In both cases the hydraulic system will require high flow levels. Flow levels can be up to several thousands of litre pr. minute for heavy lift systems. Active compensation systems can also be based on electrical winches.

The systems are controlled by signals from the MRU (motion reference unit), measuring heave of vessel. High flow in the system is very difficult to control and the system will easily come in an unstable position. As shown in figure 5.4 the cylinder holds the whole load, and is compensating for motion.

![Figure 5.4: Active heave compensation - cylinder](image-url)
5.1.3 Semi-active compensation system

Semi-active systems use advantages from both passive and active systems. A passive cylinder carries the load and an active controlled cylinder helps the non-ideal spring to overcome the friction losses. This adds additional movement to ensure proper compensation.

If the static load will vary in mass, as it most usually does, the pressure in the accumulator has to be adjusted from one load case to another. Such an operation could be relative time demanding, and will not be performed during operation.

The semi-active compensator can be designed with different set ups, both cylinder and winch based concepts.

The winch based system uses several hydraulic motors with variable displacement who are connected to the winch drum. During lowering and hoisting all engines are connected to the hydraulic circuit. In compensation mode several of the motors are connected to an accumulator system with GPV’s. The variable displacement in the engines adjusts the weight to be compensated. The other engines who are still connected to the hydraulic circuit perform the compensation motion. According to crane constructor Hydralift [17], a semi-active system will be able to reduce the power requirement with up to 75 % related to an equal rated active system.

Figure 5.5: Semi-active compensation system
A semi-active cylinder can be created in several ways, divided between several cylinders or a combined cylinder.

Figure 5.7 shows the cylinder designed for use on 125 tons heave compensation system mounted on Acergy Eagle [1]. The cylinder is designed with two pistons. The largest one is used as an accumulator piston while the smallest one, still connected with the same rod, is used for the active part. Such cylinders are well known, and are widely used in drilling packages.

Figure 5.6: Semi-active winch compensation system [17]

Figure 5.7: Acergy Eagle compensation system – semi-active [1]
Another way to construct a system is with use of two or more cylinders connected to a common steel bar. As shown in figure 5.8 there are two cylinders in passive mode, used to hold the static weight of the load. The third cylinder performs the compensation motion. This system is used by crane constructor Hydralift [17].

**Figure 5.8:** Semi-active cyllindre compensation – Hydralift model [17]
5.2 CHosen Concept

Design case for the passive heave compensator is landing phase.

Heave compensator shall be designed to minimize motion from module.

Chosen concept for passive heave compensation:

Figure 5.9: Landing phase

Figure 5.10: Chosen concept mounted on barge
ALL calculations for compensation system are based on TWO systems. This means e.g. that each system is designed for half module weight.

Compensation concept is given in the objectives for thesis, pure passive compensation.

Figure 5.11 shows the selected passive heave compensation system.

System is designed to keep large units like cylinder and accumulator on and below deck. To minimize piston area system is designed for force on piston side in cylinder where several sheaves are used to achieve this. The two systems will be located beside each other, and lifting wires are routed through module handling system to specific lifting point.

Compared to active and semi-active systems the compensator has positive qualities. Especially for heavy loads:

- No energy consumption during operation
- Simpler system

Figure 5.11: Chosen compensator concept
Force in cylinder is calculated according to figure 5.12.

F1 represents wire force
F2 represents winch holdback force
F3 is force in cylinder

\[ F_3 = F_1 + F_2 \]

F1 and F2 will be the same, and the force to be carried by cylinder is 2 times wire force.

Figure 5.12: Force in cylinder

Velocities are needed for calculations, and defined below

Figure 5.13: Velocities in system
Velocities:
- Barge velocity, \( V_B \), calculated in chapter 4.
- Winch velocity, \( V_W \),
- Module, \( V_M \),
- Compensator velocity, \( V_C \),

Barge velocities are calculated for the installation barge in chapter 4.

Module speed while lowering:
\[ V_M = V_B + V_W \]

Module speed in compensation mode, standstill:
\[ V_M = V_B + V_C \]

Module speed at landing:
\[ V_M = V_B + V_C + V_W \]

The compensator velocity is of interest for calculations performed. At 100 % compensation velocity in compensator will be:
\[ V_C = 2 \cdot V_B \]

The passive compensator is designed with hydraulic oil as medium between cylinder and accumulator. It is the piston area and hydraulic pressure that carries the load.

At static load the cylinder should be at mid-stroke. Accumulator gas pressure should be pre charged to this requirement.

All calculations performed are also shown in appendix A.

Static load are sum of module and wire force:

Wire weight is found in data sheet for chosen wire. The argument and calculations for wire are shown in chapter 6.3, defining variables.

Wire weight:
\[ W_{\text{weight}} := 100.5 \, \frac{\text{kg}}{\text{m}} \]

Module weight:
\[ W_{\text{module}} := 500 \, \text{ton} \]
North Sea – Kristin:

Water depth: \( WD_{Kris} := 350 \text{ m} \)

Wire weight: \( W_{wireK} := W_{wire} \cdot WD_{Kris} \)

\( W_{wireK} = 35 \text{ ton} \)

Static load: \( F_{Kris} := 2(W_{module} + W_{wireK}) \cdot a \)

\( F_{Kris} = 10500 \text{ kN} \)

West Africa – Girassol:

Water depth: \( WD_{Gira} := 1300 \text{ m} \)

Wire weight: \( W_{wireG} := W_{wire} \cdot WD_{Gira} \)

\( W_{wireG} = 131 \text{ ton} \)

Static load: \( F_{Gira} := 2(W_{module} + W_{wireG}) \cdot a \)

\( F_{Gira} = 12373 \text{ kN} \)

Static load in cylinder is multiplied with 2 according to figure 5.12.
6. MATHEMATICAL MODELS

Mathematical models for the compensator are established to find the residual motion of the module. There are defined two first order models and one second order where results are compared. Input motion is represented with amplitude and frequency $\omega$ from the barge.

6.1 1. ORDER MATHEMATICAL MODELS

To find residual motion of the module, two first order mathematical models are established.

The two models are created with use of different theories, one with use of transfer function theory and one as a simple spring-damper system from motion of equation.

Both first order models use the system described in figure 6.1.

Output from models is module response:

$$\text{Response} := \frac{x_1}{X}$$

![Figure 6.1: First order system](image)

Variables in model:
- $X\sin(\omega t)$ is barge motion
- $x_1$ is module motion
- $v_1$ is module motion
- $c_{\text{drag}}$ is drag motion on module
- $k_c$ is compensator stiffness
- $c_c$ is compensator damping
- $\mu_cN$ is mechanical friction in system
- $M$ is module mass
System equations do not contain elements for friction. To include friction it needs to be calculated as an equivalent damping and added to the compensator damping. Figure 6.2 show the change that this affects to system:

![Figure 6.2: New compensator variables.](image)

Where:
- $C_c$ is compensator damping + equivalent friction damping
- $K_c$ is compensator stiffness

Simplifications for model are:
- The wire is infinite stiff, all masses moves together
- Mass of compensator is very small compared to the module weight, it is therefore included in this weight.
- Mass of wire is included into module weight
- Wire stiffness is much higher than compensator stiffness, wire as a spring is therefore not included.
- Friction is calculated as equivalent damping
### 6.1.1 Transfer function model

The transfer function model is according to the model given in reference [18], page 175.

\[
\text{Response} := \left[ 1 + \left( \frac{\omega}{\omega_0} \right)^2 \frac{c_c^2}{k_c \cdot M} \right]^{-\frac{1}{2}} \left[ 1 - \left( \frac{\omega}{\omega_0} \right)^2 \right]^2 + \left( \frac{\omega}{\omega_0} \right)^2 \frac{(c_c + c_d)^2}{k_c \cdot M}
\]

Where:
- Response is \( \frac{x_1}{x} \), ref figure 6.1
- \( M \) is mass of module, compensator and wire
- \( \omega \) is barge period
- \( \omega_0 \) is un-dampened natural frequency
- \( k_c \) is compensator spring constant
- \( c_c \) is compensator damping
- \( c_d \) is drag damping on module

Un-damped natural frequency is found from equation:

\[
\omega_0 := \frac{k_c}{\sqrt{M}}
\]

From the above expressions it can be concluded that to obtain efficient heave compensation:
- The natural frequency, \( \omega_0 \) should be as low as possible
- The heave compensator damping should be as low as possible, unless resonant motions are expected
- As the natural frequency is calculated by mass of load, a passive compensator system will perform better with a heavy load than a light load.

Model will not be further explained in this report.
6.1.2 Harmonic motion model

Compensator model can also be calculated using motion of equation. The theory and background for this method can be found in reference [19]. System use same first order model as described in figure 6.1.

![Free body diagram](image)

**Figure 6.3:** Free body diagram

System can be described as a free body diagram:

Where:
- \( X \) is barge motion
- \( x_1 \) is module motion
- \( M \) is module mass
- \( k_c \) is compensator damping
- \( C \) is defined as = Compensator damping (\( C_c \)) – drag damping (\( C_d \))

Motion of equation becomes:

\[
mx_1 + c(\dot{X} - \dot{x}_1) + k(X - x_1) = 0
\]

If \( X = X \sin(\omega t) \), new equation becomes

\[
m\ddot{x}_1 + c\ddot{x} + k_c x_1 = k_c X + c\dot{X} = k_c X \sin(\omega t) + c\omega X \cos(\omega t)
\]

The theory behind solving this equation is quite involved and will not be thoroughly explained. The solved solution is found in reference [19], page 240.

\[
\frac{x_1}{X} = \sqrt{\frac{1 + (2\zeta r)^2}{(1-r^2)^2 + (2\zeta r)^2}}
\]
Definition of variables:

Natural frequency of system:
$$\omega_n := \sqrt{\frac{k_c}{M}}$$

Frequency ratio:
$$r := \frac{\omega}{\omega_n}$$

Critical damping:
$$c_{\text{crit}} := 2M \cdot \omega_n$$

Damping ratio:
$$\zeta := \frac{c_c - c_d}{c_{\text{crit}}}$$

Critical damping factor can be explained from the motion of equation [19]:

$$M\ddot{x} + c\dot{x} + k_c x = 0$$

We assume a solution on form:
$$x(t) = Ce^{st}$$

Where C and s is undetermined constants. Inserting this into motion of equation it leads to the characteristic equation

$$Ms^2 + cs + k_c = 0$$

The root of which are:

$$s_{1,2} = -\frac{c}{2M} \pm \sqrt{\frac{c^2}{4M^2} - \frac{k_c}{M}} = -\frac{c}{2M} \pm \sqrt{\left(\frac{c}{2M}\right)^2 - \frac{k_c}{M}}$$

The critical damping $$c_{\text{crit}}$$ is defined as the value of the damping constant c for which the square root in equation above becomes zero.

$$\left(\frac{c}{2M}\right)^2 - \frac{k_c}{M} = 0$$
Or

\[ c_{\text{crit}} = 2M \sqrt{\frac{k_c}{M}} = 2\sqrt{k_c M} = 2M \omega_n \]

Response function for system under harmonic motion:

\[ \text{Response}_{\text{hmotion}} = \frac{1 + (2\zeta \tau)^2}{\sqrt{(1 - \tau)^2 + (2\zeta \tau)^2}} \]

Where:

- Response is \( \frac{x_1}{X} \)
- M is module mass
- \( \omega \) is barge period
- \( \omega_n \) is un-dampened natural frequency
- \( k_c \) is compensator spring constant
- \( c_c \) is compensator damping
- \( c_d \) is drag damping on module
- \( c_{\text{crit}} \) is critical damping

This function expresses the first order system described in figure 6.1 by use of motion of equation.

The results from the functions should correspond to the results from the other first order function, as both express the same system.
6.2 2. ORDER MATHEMATICAL MODEL

The second order mathematical model is an expansion of the first order model. This model includes some of the simplifications that are set for the first order model.

Model is defined as a second order model since two masses are included, mass of the moving parts in compensator and the module itself. Crane wire mass is included into the module mass.

This model is more correct to the physical problem. More variables are used to define the physical situation in a compensator system.

Compared to the first order system, the second order system includes both compensator mass and crane wire stiffness.

Variables in model:
- $X\sin(\omega t)$ is barge motion
- $x_1$ is compensator motion
- $x_1$ is compensator motion
- $x_2$ is module motion
- $v_2$ is module motion
- $c_{\text{drag}}$ is drag motion on module
- $k_c$ is compensator stiffness
- $c_c$ is compensator damping
- $\mu N$ is mechanical friction in system
- $k_w$ is crane wire stiffness
- $M_c$ is compensator mass
- $M$ is module and wire mass
Simplifications for model are:
- Mass of wire is included into module weight
- Friction is calculated as equivalent damping

As for the first order system it is not possible to implement friction into the model. To include friction it needs to be calculated as an equivalent damping and added to the compensator damping. New system is viewed in figure 6.2.

System can be expressed with free body diagrams:

\[
\begin{align*}
0 & = -k_0 x_1 - k_w (x_2 - x_1) + \ddot{x}_1 \\
0 & = -k_0 x_2 - k_w (x_2 - x_1) + \ddot{x}_2 \\
F_c(t) & \text{ is a time dependent vertical force on top of compensator.}
\end{align*}
\]

The following statement shows that giving excitation, \( X \sin(\omega \cdot t) \), as input to system (figure 6.4) is equivalent to applying a harmonic force of magnitude \( X \) to the mass.
Then $F_c(t)$ is given by:

$$F_c(t) = X \sin(\omega \cdot t) \cdot k_c + X \omega \cos(\omega \cdot t) \cdot c_c$$

Where:

- $X$ is vertical motion of barge
- $\omega$ is motion frequency
- $k_c$ is compensator stiffness
- $c_c$ is compensator damping

System written on matrix form:

$$M \ddot{x} + C \dot{x} + kx = F_c(t)$$

$$M_{\text{matrix}} = \begin{pmatrix} M_c & 0 \\ 0 & M \end{pmatrix}$$

$$C_{\text{matrix}} = \begin{pmatrix} c_c & 0 \\ 0 & c_d \end{pmatrix}$$

$$K_{\text{matrix}} = \begin{pmatrix} k_c + k_w & -k_w \\ -k_w & k_w \end{pmatrix}$$

$$F_{\text{matrix}} = \begin{pmatrix} X \sin(\omega t) \cdot k_c + X \cos(\omega t) \cdot c_c \\ 0 \end{pmatrix}$$

The forced motion to system is caused by barge, and is expressed in matrix $F$. Motion is defined with use of vertical barge motion, $X$, and the response for barge is defined by:

$$\text{Response} = \frac{x^2}{X}$$
In order to solve the system, mathematical software MathCAD is used. The second order differential equations are replaced by four first order differential equations.

\[
\begin{pmatrix}
M_c & 0 \\
0 & M
\end{pmatrix}
\begin{pmatrix}
\ddot{x}_1 \\
\ddot{x}_2
\end{pmatrix}
+ \begin{pmatrix}
c_c & 0 \\
0 & c_d
\end{pmatrix}
\begin{pmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{pmatrix}
+ \begin{pmatrix}
k_c + k_w & -k_w \\
-k_w & k_w
\end{pmatrix}
\begin{pmatrix}
x_1 \\
x_2
\end{pmatrix}
= \begin{pmatrix}
X \sin(\omega \cdot t) \cdot k_c + X \omega \cos(\omega \cdot t) \\
0
\end{pmatrix}
\]

For the new system with four coupled first order equations we introduce new variables:

\[
y_0 = x_1 \quad y_1 = \dot{x}_1 \quad y_2 = x_2 \quad y_3 = \dot{x}_2
\]

\[
M_c \ddot{x}_2 + c_c \ddot{x}_1 + (k_c + k_w)x = (X \cdot k_c \cdot \sin(\omega \cdot t) + X \cdot c_c \cdot \omega \cos(\omega \cdot t))
\]

Or

\[
\dot{y}_1 = \frac{(Xk_c \omega \sin(\omega \cdot t) + Xc_c \cdot \omega \cos(\omega \cdot t))}{M_c}
- \frac{c_c}{M_c} y_2
- \frac{(k_c + k_w)}{M_c} y_0
+ \frac{k_w}{M_c} y_2
\]

and

\[
M\ddot{x}_2 + c_d \ddot{x}_2 - k_w x_1 + k_w x_2 = 0
\]

Or

\[
\dot{y}_3 = -\frac{c_d}{M} y_3
- \frac{k_w}{M} y_0
- \frac{k_w}{M} y_2
\]

System has initial conditions:

\[
y_0(0) = 0 \quad y_1(0) = 0 \quad y_2(0) = 0 \quad y_3(0) = 0
\]

System is solved in analysis chapter 7.1.3.
6.3 DEFINING VARIABLES

In order to solve the system numerically variables has to be defined. Variables for module mass and added mass are calculated inputs from Tordis module while the rest of the variables will not represent an actual case. These values are assumed. Analysis with varying variables will determine the module response due to changing input parameters.

Compensator mass

Compensator mass combines:
- Assumed mass for hydraulic oil
- Assumed mass for pistons, rod and wire sheave (ref figure 5.11)

The mass of the compensator system is difficult to predict since the hydraulic system is not established. Assumed weights for model are:
- Mass of oil: $M_{oil} := 3\text{ton}$
- Mass of steel components: $M_{steel} := 3\text{ton}$

The assumed mass of compensator mass will be.

$$M_{comp} := M_{steel} + M_{oil}$$
$$M_{comp} = 6\text{ton}$$

Compensator mass is very small compared to module mass.
Drag damping

Drag force are viscous forces around the submerged module. Force is acting in opposite way of module motion.

Drag force can be calculated after formula given in DNV Marine Operations [20]:

\[ F_d = 0.5 \cdot \rho \cdot C_d \cdot A_p \cdot v_r^2 \]  \[ N \]

Where:
- \( \rho \) is sea water density
- \( C_d \) drag coefficient
- \( A_p \) is area of object projected on a horizontal plane
- \( v_r \) is characteristic vertical relative velocity between object and water particles. \( v_r \) is velocity in module after compensation.

As seen in mathematical models the drag force is modelled as a damper to the module. Barge motion will try to pull the module upwards and drag force will hold back. Opposite the drag force will restrict gravity force to lower the module. The force is proportional to velocity squared.

Calculating the drag damping force from the module is very much work and are not performed in this thesis.

It is assumed a value of \( C_d = 500 \frac{kN_s}{m} \) for calculations to follow.

Analysis performed will show how the system works with the assumed value. In addition the value is changed looking for drag impact on module response.
**Compensator damping**

Compensator damping is time demanding to calculate. As seen in the mathematical models the damping is a sum of friction in the compensator system and the compensator damping.

**Friction**

Friction is a value that is not dependant on motion, velocity or acceleration. Friction force is defined by:

\[ F_f = \mu \cdot fN \]

Where:
- \( \mu \) is friction factor between mass and base
- \( fN \) is friction force acting in plane of contact.

Friction forces will occur in:
- Cylinder
- Accumulator
- Wire
- Wire sheaves

All mentioned places of friction are lubricated surfaces and the friction force is assumed to be small.

**Viscous**

Viscous damping in compensator is related to the hydraulic oil and accumulator gas.

At this preliminary stage viscous damping is not possible to calculate.

Compensator damping is assumed to be small compared to drag damping.

Input value for compensator damping is:

\[ C_c = 20 \frac{kNs}{m} \]

Chosen value will be evaluated in analysis.
Compensator spring stiffness

In a passive compensator the spring stiffness is important as it defines the force needed for compensation. The chosen passive system use a gas accumulator design the spring in the compensator.

A compensator system is defined as a quick accumulator system [25]. This means that the compression and expansion takes place during t< 15 sec. A quick accumulator system is an adiabatic process assuming no heat exchange with surroundings.

For an adiabatic process we have equation:

\[ p_1 \cdot V_1^\kappa = p_2 \cdot V_2^\kappa \]

Where:
- \( p_1 \) is maximum gas pressure at full charged accumulator
- \( V_1 \) is volume of gas at maximum pressure
- \( p_2 \) is minimum operating pressure
- \( V_2 \) is volume of gas at pressure \( p_2 \)
- \( \kappa \) is factor for linearity

Figure 6.6 shows the pressure/stroke curves for a 400 ton Cranemaster© [16] at four different loads. The curves indicate the non-linearity in the compensator caused by energy build-up in gas. An increase in \( \kappa \)-factor will increase the steepness more, and a decrease will flatten the curve. When \( \kappa = 1 \) the system is linear.

Spring stiffness used in calculations is assumed to be linear.

Assumed value used is \( k_c = 1000 \frac{kN}{m} \)

Figure 6.6: Cranemaster© load curve [16]
Crane wire stiffness

After consulting with Viking Mooring in Stavanger a non rotating crane wire are chosen, Fleexpack 21. Recommended safety factor from supplier is $SF_{wire} = 3$ of SWL; this factor is used in calculations and is not further discussed. The chosen wire is frequently used by companies like Acergy, Subsea7, Hydramarine and Saipem for subsea lifting operations.

Specs for wire Flexpack 21:

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>MBF (kN)</th>
<th>M tons</th>
<th>S tons</th>
<th>Air (kg/m)</th>
<th>Water (kg/m)</th>
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<td>2260</td>
<td>124.8</td>
<td>108.6</td>
</tr>
</tbody>
</table>

Table 6.1: Flexpack 21 specifications [23]

As given in specifications, design water depth is 350 and 1300m.

Wire weight: $W_{weight} := 103.2 \frac{kg}{m}$

Module weight: $W_{module} := 500$ ton

**North Sea – Kristin:**

Water depth: $WD_{Kristin} := 350$ m

Wire weight: $W_{wireK} := W_{weight} \cdot WD_{Kristin}$

$M_{wireK} = 36$ ton

**West Africa – Girassol:**

Water depth: $WD_{Girassol} := 1300$ m

Wire weight: $W_{wireG} := W_{weight} \cdot WD_{Girassol}$

$W_{wireG} = 134$ ton
Design load for wire are sum of module and wire mass. Design water depth for system is 1300m and the wire has to be calculated for this depth. Weights for Girassol are therefore used.

\[ F_{\text{wire}} = (M_{\text{module}} + M_{\text{wire}}) \cdot 9.81 \frac{m}{s^2} \]

\[ F_{\text{wire}} = 6219 \text{kN} \]

\[ \text{Design load} = F_{\text{wire}} \cdot SF_{\text{wire}} \]

\[ \text{Design load} = 18658 \text{kN} \]

Wire chosen for installation system is with diameter of 154mm, ref table 6.1.

Crane wire stiffness:

\[ k_{\text{wire}} = \frac{E \cdot A}{L} \]

Where:

- \( E \) is modulus of elasticity for wire. Table 6.1 gives 210 GPa
- \( A \) is cross sectional area of wire
- \( L \) is wire length

Wire cross sectional area:

\[ A_{cw} := \left( \frac{154 \text{mm}}{2} \right)^2 \cdot \pi \]

\[ A_{cw} = 0.019 \text{ m}^2 \]

Crane wire stiffness for Kristin and Girassol field:

\[ k_{w_{\text{Kristin}}} := \left( \frac{E \cdot A_{cw}}{WD_{\text{Kristin}}} \right) \]

\[ k_{w_{\text{Kristin}}} = 11176 \frac{\text{kN}}{\text{m}} \]

\[ k_{w_{\text{Girassol}}} := \left( \frac{E \cdot A_{cw}}{WD_{\text{Girassol}}} \right) \]

\[ k_{w_{\text{Girassol}}} = 3009 \frac{\text{kN}}{\text{m}} \]
Module mass in calculations

Due to the simplifications in the mathematical models, module mass is a value of several variables.

For the first order systems the module mass includes:
- \( M_m \) is module mass
- \( M_{comp} \) is mass of compensator
- \( M_a \) is added mass
- \( M_{wire\text{K}} \) or \( M_{wire\text{G}} \) is mass of crane wire

For second order systems the module mass includes:
- \( M_m \) is module mass
- \( M_{wire\text{K}} \) or \( M_{wire\text{G}} \) is mass of crane wire
- \( M_a \) is added mass

Added mass is further discussed below.

Masses:

\[
M_m = 500\text{ton} \\
M_{comp} = 6\text{ton} \\
M_a = 1600\text{ton}
\]

Kristin Field, first order:

\[
M_m = 500\text{ton} \\
M_{comp} = 6\text{ton} \\
M_a = 1600\text{ton} \\
M_{K1} := M_m + M_{comp} + M_a + M_{wire\text{K}} \\
M_{K1} = 2142\text{ton}
\]

Girassol field, first order:

\[
M_m = 500\text{ton} \\
M_{comp} = 6\text{ton} \\
M_a = 1600\text{ton} \\
M_{G1} := M_m + M_{comp} + M_a + M_{wire\text{G}} \\
M_{G1} = 2240\text{ton}
\]
Kristin Field, second order:

\[ M_m = 500 \text{ton} \]
\[ M_a = 1600 \text{ton} \]
\[ M_K2 := M_m + M_a + M_{\text{wireK}} \]
\[ M_{K2} = 2136 \text{ ton} \]

Girassol field, second order:

\[ M_m = 500 \text{ton} \]
\[ M_a = 1600 \text{ton} \]
\[ M_G2 := M_m + M_a + M_{\text{wireC}} \]
\[ M_{G2} = 2234 \text{ ton} \]

As for the drag force discussed earlier the added mass is a force that reacts on the module. Added mass can be calculated using DNV standard for Marine Operations [20]:

\[ m_{\text{add}} = \rho V C_m \]

Where:
- \( \rho \) is sea water density
- \( V \) is volume of displaced water
- \( C_m \) is added mass coefficient as a function of depth

Finding the actual added mass for the module is time demanding, and are not performed in this thesis.

Added mass calculated for Tordis SSBI, as calculated by Rune Stigedal [21].

Added mass for Tordis SSBI: \( M_a = 1600 \text{ton} \)
7. COMPARISON AND EVALUATION OF MATHEMATICAL MODELS

The two first order models described in chapter 5.1 are calculated in appendix A, and the results from the analyses are presented below.

Analysis shows residual motion in the module after compensation.
Input motion amplitude $X = 1$ for all models

7.1 1. ORDER SYSTEM – TRANSFER FUNCTION

Residual motion is given on form:

$$\text{Response} = \frac{x_1}{X}$$

The system is under a motion with variation frequency, and the response shows the residual motion for the given frequency.
Due to its simplification the system is evaluated without crane wire stiffness. The crane wire mass and compensator mass is included into the module mass.

Evaluations to follow uses mass of module for Kristin field. A comparison of Kristin and Girassol field is presented later in chapter.

Un-dampened natural frequency:

$$\omega_0 := \sqrt{\frac{k_c}{M}} \quad \omega_0 = 0.68 \frac{1}{s} \quad T_0 := \frac{2\pi}{\omega_0} \quad T_0 = 9.19 \ s$$
Following response are calculated with initial input data defined in chapter 6.3.

Equation is given:

\[
\text{Response } (\omega) := \sqrt{\frac{1 + \left(\frac{\omega}{\omega_0}\right)^2 \frac{c_c^2}{k_c \cdot M}}{1 - \left(\frac{\omega}{\omega_0}\right)^2 + \left(\frac{\omega}{\omega_0}\right)^2 \frac{(c_c + c_d)^2}{k_c \cdot M}}}
\]

Input data, Kristin field.

Mass: \( M = 2141 \text{ton} \)

Compensator damping: \( c_c = 20 \frac{\text{kN-s}}{m} \)

Drag damping: \( c_d = 500 \frac{\text{kN-s}}{m} \)

Compensator stiffness: \( k_c = 1000 \frac{\text{kN}}{m} \)

As seen the drag damping only occur in the denominator. It follows that the drag damping \( c_d \) should be as high as possible to reduce the response.
The response becomes:

![Graph showing response transfer function](image)

**Figure 7.1**: Response transfer function

The figure shows the response of the compensator. The peak corresponds to undamped natural frequency for the system.

Peak is high above 1 and system should never be used for these frequencies.

Dotted lines shows where the response becomes 1 for frequencies below this point the compensator will not work.

Compensator limit:

\[
\omega = 0.934 \frac{\text{rad}}{s} \text{ at response } = 1
\]

\[
T = \frac{2\pi}{\omega}
\]

\[
T = 6.72s
\]

As observed from the graph compensator will close towards 1 as the omega decreases. This is according to the physical system:

Long waves $\rightarrow$ slow motions $\rightarrow$ compensator will not react $\rightarrow$ Response $=1$
The compensator system should work for varying water depths. Two cases are used in this report, Kristin field in the North Sea and Girassol in West Africa. The crane wire stiffness is seen as infinite stiff, the only difference in first order model is larger module mass.

Observed is a small change in peak position due to changed natural period of system. The height of the peak in resonance increases a little due to higher mass in motion.

As calculated earlier the systems crane wire stiffness is changing for these two water depths. The model is not able to calculate the variation from this change. Results for this evaluation should be compared to result from second order model, where it is possible to implement crane wire stiffness.

Compensator efficiency varies with for different inputs. Below the response is evaluated for changing compensator stiffness, compensator damping, drag damping and mass of module:
The input data for evaluations are Kristin field.

Input values are changed with a scaling factor.

**Figure 7.2:** Response with varying water depth
Varying compensator stiffness

The compensator stiffness has a large impact on the response. Both peak height and peak position change. Change in position can be explained by the natural frequency.

The natural frequency is calculated with use of stiffness, and for analysis k4 we get a new resonant frequency:

\[
\omega_0 := \frac{k_c}{\sqrt{M}} \quad \omega_{0k4} := \frac{k_{c4}}{\sqrt{M}} \quad \omega_{0k4} = 0.37 \frac{1}{s}
\]

This corresponds to observed values. The compensator limit changes much due to the stiffness in system. New limit in analysis k4:

\[
\omega = 0.471 \frac{rad}{s} \quad T = \frac{2\pi}{\omega} \quad T = 13 \text{ second}
\]

This new limit increases the operational window for the compensator and observed is that the compensator spring stiffness plays a vital role for compensator performance.

Figure 7.3: Varying compensator stiffness
Varying compensator damping

As observed the forces acting in the system is not affected by the compensator damping unless in the resonance area. Compensator damping is low compared to drag damping and the observed changes in compensator are low.

Compensator damping only affects frequencies close to resonance. This correspond to the given statement that compensator damping should be as low as possible to prevent resonant motions.
Varying drag damping

\[
\text{Variation}_d := \begin{pmatrix}
2c_d \\
3c_d \\
0.5c_d \\
0.3c_d \\
0.1c_d
\end{pmatrix}
\]

The experienced drag on module is able to affect the compensator response much. Results in resonance area varies from above 10 and as low as just above 1.

As seen in figure 7.6 an increase in drag of factor 3 will move the limit of compensator to:

\[
\omega = 0.654 \frac{rad}{s} \text{ at response } = 1
\]

\[
T = \frac{2\pi}{\omega}
\]

\[
T = 10.0 s
\]

This value is increasing the operational window of compensator.
Changes in module mass

Compensator response varies much due to varying module mass. X-axis value changes with resonance period, while y-axis value changes with swinging mass. A high mass is preferable to reduce resonant frequency, while a low mass is preferable to limit motion in resonance.

In analysis M2 the mass is multiplied 3 times.

The response is 1 at $\omega = 0.552 \frac{rad}{s}$

This gives:

Increased mass changes operational frequency considerably.

$$\omega = 0.552 \frac{rad}{s} \text{ at response } = 1$$

$$T = \frac{2\pi}{\omega}$$

$$T = 11.4s.$$
7.2  1. ORDER SYSTEM – HARMONIC MOTION MODEL

The theory for the model is presented in chapter 6.2 and will not be discussed. Input values are same as for the transfer function model:

\[
\omega_n := \sqrt{\frac{k_c}{M}} \quad \omega_n = 0.68 \frac{1}{s} \quad T_n := \frac{2\pi}{\omega_n} \quad T_n = 9.19s
\]

Where \( \omega_n \) is natural frequency

Frequency ratio: \( r(\omega) := \frac{\omega}{\omega_n} \)

Critical damping: \( c_{\text{crit}} := 2M\omega_n \quad c_{\text{crit}} = 2927 \text{kN} \cdot s \text{m}^{-1} \)

Damping ratio: \( \zeta := \frac{c - c_d}{c_{\text{crit}}} \quad \zeta = -0.16 \)

The system is under harmonic motion, and the response is defined as:

Response h motion = \( \frac{x_1}{X} \)

\[
\text{Response h motion}(\omega) := \sqrt{1 + \left[ 2\zeta \left( \frac{\omega}{\omega_n} \right)^2 \right]^{\frac{1}{2}} - \left[ \left( 1 - \left( \frac{\omega}{\omega_n} \right)^2 \right)^2 + \left( 2\zeta \frac{\omega}{\omega_n} \right)^2 \right]^{\frac{1}{2}}}
\]

The results for the system should correspond to the values calculated for the other first order system. The models evaluate the same physical system with the same inputs.
Figure shows the calculated results for both transfer function model, and harmonically motion model. The models are closely correlated where harmonic motion model are slightly more conservative.

The model is calculated with varying compensator stiffness.

The results are closely correlated for the transfer function, but peak in resonance are lower. This peak difference is due to differences in damping. Motion of equation model uses a function for critical damping to express the damping ratio. Drag damping is therefore included in both numerator and denominator. Transfer function model only include drag in denominator.
7.3  2. ORDER MODEL

Equations representing the mathematical model of second order are presented in chapter 6.2.
The numerical problem is solved by using Mathematical software MathCAD.
Results for first order models are run with continuous $\omega$ while the results for the second order model are plotted for a given number of $\omega$.
All calculations are presented in appendix B.

Initial conditions for the model are set to zero; the system is under harmonically motion, see figure 5.1, with motion amplitude $X=1$.

Input data are for Kristin field. See chapter 5.2 for more details:
\[
\begin{align*}
M_c &= 6\text{ton} \\
M &= 2135\text{ton} \\
C_c &= 20\frac{kN\text{s}}{m} \\
C_d &= 500\frac{kN\text{s}}{m} \\
k_c &= 1000\frac{kN}{m} \\
k_w &= 11167\frac{kN}{m}
\end{align*}
\]
\[
\omega_{\text{range}} = \begin{pmatrix}
1.571 \\
1.047 \\
0.785 \\
0.628 \\
0.524 \\
0.449 \\
0.393 \\
0.349 \\
0.314 \\
0.286
\end{pmatrix} \frac{1}{s}
\]

An important indicator for how the system will perform in different wave conditions is the eigenfrequencies for each part of the system.
Eigenfrequencies represents natural frequency for undamped free vibration of system, and can be found by evaluating the eigenvalues for a second order mathematical system, [19]:

Eigenvalues are found by creating a dynamical matrix $D$:
\[
D := M_{\text{matrix}}^{-1}K_{\text{matrix}}
\]
Eigenvalues are calculated using software MathCAD:

\[ e_{\text{val}} := \text{eigenvals}(D) \]

With result:

\[ e_{\text{val}} = \begin{pmatrix} 2032.635 \\ 0.429 \end{pmatrix} \]

Resonance values are square root of eigenvalues:

\[ \text{resonans val} := \sqrt{e_{\text{val}}} \]

With result:

\[ \text{resonans val} = \begin{pmatrix} 45.085 \\ 0.655 \end{pmatrix} \]

As seen the eigenvalue for the two different systems are quite different. The lowest value, \( \omega = 0.66 \) is likely to occur as this represents barge motion of 9.5 seconds. When motion from barge meets the resonance frequency peak amplitude is expected.

Response is defined as:

\[ \text{Res} = \frac{x_1}{X} \]
Response function for the second order mathematical model, Kristin field:

Figure shows that the compensator will work well for high motion frequencies. Peak for evaluated values are found at $\omega = 0.628$, this is the closest value to the natural frequency that are evaluated.

To qualify if the highest peak is found in resonance, 5 iterations are performed

\[
\begin{pmatrix}
0.635 \\
0.645 \\
0.655 \\
0.665 \\
0.675 \\
\end{pmatrix} \quad \text{Value}_{\text{peak}} := \begin{pmatrix} 6.19 \\ 6.44 \\ 6.44 \\ 6.22 \\ 5.83 \end{pmatrix}
\]

Matrices show that the second order system will have peak response at resonance frequency.

As observed the compensator closes towards 1 for low frequencies. For low frequencies the motion will be so slow that the system will not be able to react. The slowness in the system due to the damping and the compensator stiffness is too high.
The intersection point of dotted lines indicates value for response equal to 1. This value of omega represents the lowest value of omega where the compensator will work. If system excitation has lower frequencies the compensator will not be able to compensate the motion.

\[ \omega = 0.97 \frac{rad}{s} \text{ at response } = 1 \]

\[ T = \frac{2\pi}{\omega} \]

\[ T = 6.5 \]

As observed the given input data gives a compensator limit at period of 6.5s. Value corresponds close to the value found for the fist order mathematical model.

The second order system is under harmonic motion which gives the possibility to evaluate time to system come stable. Figure 5.13 shows that the system use several periods converging to a stable position.

![System under harmonic motion](image)

**Figure 7.11:** System under harmonic motion

Where:
- \( X_2(t1) \) is motion of module with respect to \( t1 \)
- \( t1 \) is steps: 1 step is \( t_1 = \frac{T1}{1000} \) where T1 is 1000
Such a lag in the system is not preferable, and can mainly be described by two phenomena’s:

- Drag damping
- System response to motion

The drag damping is positive in the system as it both decrease resonant motion and reduce the time for the system to become stable.

Figure below shows Response of module \(x_2\) for drag damping multiplied with 3.

![Figure 7.12: System under harmonic motion – increased damping](image)

As observed the time for system to come stable is reduced from approximately 100 steps to 50 steps. The system becomes more stable with high drag damping. Damping effect in resonance is evaluated later during the section of varying variables.

The black box in figure 7.12 shows that the peak of the curve is not following a harmonic motion. In order to try to explain the occurring phenomena, the output signal from the compensator system is analyzed with Fourier theory.
Analysing the output signal into waves with specific frequencies allows us to find which frequencies that occurs in the signal.

Any periodic function $x(t)$ of period $\tau$, can be expressed in the form of a complex Fourier series:

$$x(t) = \sum_{n=-\infty}^{\infty} c_n \cdot e^{in\omega_0 t}$$

where $\omega_0$ is the fundamental frequency given by

$$\omega_0 = \frac{2\pi}{\tau}$$

and the complex Fourier coefficients can be expressed by:

$$c_n = \frac{1}{\tau} \int_{-\tau/2}^{\tau/2} x(t) \cdot e^{-in\omega_0 t} dt$$

The analysed data (see figure 7.12) are based on an example frequency $\omega = 1.047$.

Resonant frequency for system is:

$$\text{resonant val} = \left( \begin{array}{c} 45.085 \\ 0.655 \end{array} \right)$$

The software used for calculations are MathCAD and program need to solve the problem numerically.
Where:
- \( f \) is \( x_2 \)
- \( V_k \) is read-off values for Fourier analysis

Input data for Fourier analysis, \( V_k \) is from the last figure:

By use of Fourier theory and pre-defined functions in the program Fourier frequencies are found.

Figure 7.14: Numerical input to the Fourier analysis

Figure 7.15: Fourier analysis output
The peaks are located at:

\[
f_1 = 0.10156 \\
f_2 = 0.16406
\]

\[
\omega_1 = 2\pi \cdot f_1 = 0.638 \\
\omega_2 = 2\pi \cdot f_2 = 1.031
\]

The two found frequencies correlate closely to the motion frequency and the system resonance frequency.

Analysis shows that the output signal is dominated by two frequencies. One frequency is of course the motion frequency to system, while the other are calculated to be the resonance frequency.

Conclusion becomes that system is affected by resonance frequency for other frequencies than resonance. A low resonance frequency is both positive to system response and reduces influence to harmonic motion.

Second order system is analyzed with varying input.

Below there are shown figures for changes in the compensator stiffness, compensator damping, drag damping and the module mass.

In those cases where the resonance frequencies change these are also shown.

**Varying compensator stiffness**

![Varying compensator stiffness](image)

*Figure 7.16: Varying compensator stiffness*
Varying compensator damping

**Figure 7.17:** Varying compensator damping

Varying drag damping

**Figure 7.18:** Varying drag damping
Varying module mass

\[ \text{Res}_{\text{val2M}} := \begin{pmatrix} 45.058 \\ 0.463 \end{pmatrix} \quad \text{Res}_{\text{val3M}} := \begin{pmatrix} 45.049 \\ 0.378 \end{pmatrix} \quad \text{Res}_{\text{val0.5M}} := \begin{pmatrix} 45.058 \\ 0.856 \end{pmatrix} \quad \text{Res}_{\text{val0.3M}} := \begin{pmatrix} 45.058 \\ 1.193 \end{pmatrix} \]

Figure 7.19: Varying module mass

Varying compensator mass

\[ \text{Res}_{\text{val2Mc}} := \begin{pmatrix} 31.917 \\ 0.654 \end{pmatrix} \quad \text{Res}_{\text{val3Mc}} := \begin{pmatrix} 26.091 \\ 0.653 \end{pmatrix} \quad \text{Res}_{\text{val0.5Mc}} := \begin{pmatrix} 63.722 \\ 0.655 \end{pmatrix} \quad \text{Res}_{\text{val0.3Mc}} := \begin{pmatrix} 78.028 \\ 0.655 \end{pmatrix} \]

Figure 7.20: Varying compensator mass
Analysis performed shows how the changing variables affects the system. The responses are quite the same as for the first order models.

It can be concluded that the performance of system highly depends on the resonance frequency. It is the compensator stiffness and the mass of module that has the largest effect on the compensator performance. The resonance frequencies for system are found by calculating the eigenvalues, which gives possibility to evaluate the coupled system. The resonance frequency decides for which frequency the peak will occur and with that for which frequencies the response will be below zero.

Both drag and compensator damping affects the system for frequencies close to the resonance frequency only and decreases the time for system to come stable.

For varying compensator mass the system compensator does not change response at all. Compensator mass are small compared to the module mass and are not able to change the response.
One of the benefits with the second order model is the possibility to implement crane wire stiffness.

Requirements for the barge are operations at Kristin field and Girassol field, 350m WD and 1300m WD.

\[ M = 2231 \text{ton} \]
\[ k_w = 3009 \frac{kN}{m} \]

All calculations presented above are performed with crane wire stiffness and crane wire weight for Kristin field.

Results from the calculations at Girassol field are:

As observed the crane wire stiffness does affect both position on x-axis and the peak value. Red curve is Kristin and Blue is Girassol.

Resonance period is calculated to be \( \omega = 0.592 \) where this value is not evaluated in the interval. To qualify that resonance frequency gives highest peak 5 iterations shows:

\[
\begin{align*}
\omega_{\text{iterate}} & = \begin{pmatrix} 0.55 \\ 0.56 \\ 0.57 \\ 0.58 \\ 0.59 \end{pmatrix} \\
\text{Res}_{\text{Girassol}} & = \begin{pmatrix} 2.50 \\ 2.55 \\ 2.50 \\ 2.46 \\ 2.45 \end{pmatrix}
\end{align*}
\]

Figure 7.21: Varying water depth

As observed the crane wire stiffness does affect both position on x-axis and the peak value. Red curve is Kristin and Blue is Girassol.

Resonance period is calculated to be \( \omega = 0.592 \) where this value is not evaluated in the interval. To qualify that resonance frequency gives highest peak 5 iterations shows:

Compensator response changes due to the varying water depth and the crane wire mass. Analysis shows that assuming crane wire stiffness to be infinite stiff will give a more conservative compensator response.
7.4 COMPARISON OF MODELS

This report contains 3 analyses of the different mathematical models. All calculations are presented in the previous chapters.

Figure 7.22 show response for the three models with input data specified in chapter 6.3

- Red line is the second order model
- Blue line is the transfer function model
- Green line is the harmonic motion model

As seen the values corresponds closely to each other. The harmonic model is the most conservative.

It can be concluded from this graph that all three models are usable in finding the residual motion for the module. As seen in analysis of the different models, the results when changing variables also corresponds well. Harmonic motion model gives a lower peak in resonance than for the other models.

Results are based on theoretical evaluations of a physical system. Due to lack of experienced data for passive compensator, results are not compared to physical performance of a constructed system.

Model test should be performed to qualify the models before design and construction of system.

Figure 7.22: Comparison of models
For a given installation case it is not possible to change all kinds of input data that done in this report.

Fixed inputs are:
- Module mass
- Drag damping, calculated from module
- Compensator damping, value for given designed system
- Wire stiffness, wire is designed for the given system
- Compensator mass, value for designed system

The only variable that can be changed is the compensator stiffness. According to 6.1.3 compensator stiffness is defined by pressure and volume of gas in accumulator. Gas pressure is changed due to module weight, and volume is changed to get the required compensator stiffness.

Figure 7.23 show how changes in stiffness varying response for the three evaluated systems:

![Figure 7.23: Compensator stiffness times 3](image)

Figure show the response for compensator 3 times higher than defined in chapter 6.3.

Evaluated compensator stiffness: \( k_c = 3000 \frac{kN}{m} \)

With this stiffness the compensator becomes useless, as response is above 1 for all evaluated values.
Figure 7.24 shows the response with compensator stiffness 70% lower than in defined value in chapter 6.3.

Evaluated compensator stiffness: \( k_c = 300 \frac{kN}{m} \)

As observed the three models correlates for the evaluated frequencies. The second order model is more conservative with low compensator stiffness.

**Figure 7.24:** 70 % lower compensator stiffness
The method of passive compensation has been thorough investigated in this report, and limitations have been discovered. The system works best with heavy module weight and when exposed to high frequencies.

Most systems in the industry today are semi-active, and generally these systems should perform better. As explained in chapter 5.1.3 these systems are based on passive systems to hold the static load, but uses an active part to improve the compensation performance.

Figure 7.23 shows measured data for a semi-active heave compensation system found in reference [18].

![Figure 7.23](image)

**Figure 7.25: Performance of Active Heave Compensator [18]**

Where:
- Y-axis is computed response between vertical load motion and top motion
- X-axis is frequencies given in hertz

The figure can not be used to compare the actual residual motion; as we do not know enough about the system. System performance gives a clear indicator that system has a different characteristic.

The semi-active system works best for low frequencies, and will in some cases amplify the motions in regions where the passive compensation will work very well.

This is in contrast to the passive compensator that works best for high frequencies.
7.5 TENSION RELATION DURING COMPENSATION

The previous subchapters presented the efficiency of the compensator with changing variables. This section will give an overview of how the tension variates in crane wire.

Figure 7.26 shows how stroke is executed due to tension in system. Position $S_1$ shows system with static load. Up to this point position changes is due to the wire stiffness. Position change from $S_1$ up to $S_2$ requires a small change in tension, which corresponds to the purpose of a compensator. Position change is determined by the stiffness of the compensator spring. $S_2$ represents the maximum stroke of compensator, and a position change beyond this point will be in the lifting wire. Point $S_2$ should never be reached during operation.

A compensation cycle between $S_1$ and $S_2$ can be presented simplified with figure 7.27. The figure includes both damping and friction and shows how the tension in crane wire is due to stroke of compensator.

A simplified case for the modelled compensator is presented in figure 7.28. The compensator damping is not calculated, and the compensator stiffness is linear. This is according to assumption presented in chapter 6.3.
Model input:
- Kristin field 350m WD
- Crane wire stiffness $k_w = 11167 \frac{kN}{m}$
- Compensator stiffness $k_c = 1000 \frac{kN}{m}$
- Static hook load: Module mass + crane wire weight

$$M_M = 500ton$$
$$M_{CW} = 35ton$$
$$F = (500ton + 35ton) \cdot 9.81 \frac{m}{s^2}$$
$$F = 5248kN$$

Calculations are performed in appendix A.

Tension in lift wire is calculated including both wire and compensator stiffness. The damping influence will affect the shown graph in the same way as for figure 5.21.

Where:
- $F_0$ is zero
- $F_1$ is static load
- $F_2$ is compensation mid
- $F_3$ is compensation end
- $F_4$ is override of compensator

$$F = \begin{bmatrix} 0 \\ 5250 \\ 6250 \\ 7250 \\ 12500 \end{bmatrix} \text{kN} \quad E = \begin{bmatrix} 0 \\ 1.75 \\ 2.75 \\ 3.75 \\ 5.5 \end{bmatrix} \text{m}$$

**Figure 7.28:** Tension during compensation
8. OPERATIONAL STUDY

All analysis’s in this chapter is performed according to the results from the second order model presented in chapter 7.1.3.

8.1 WAVE ENERGY SPECTRUM

The operational requirement is to perform installation operations in the North Sea and outside West Africa.

The weather conditions for these areas are different, the North Sea is dominated by more short waves than West Africa. Operational performance is calculated for the Kristin field in North Sea and the Girassol field outside West Africa.

When evaluating each field the sea state is the only variable since it is seen as the limiting factor. Wind and current loads are not evaluated in this analysis.

All the weather information is based on information from Acergy internally and unpublished documents and weather-reports supplied by clients, so no references to published papers are therefore given.

In order to evaluate the system performance at the two fields, the wave energy calculations and the wave height probability analysis are used.

The energy in a wave spectrum can be defined with the JONSWAP spectrum, where the energy is a variable of the wave frequency.

The JONSWAP function can be defined with the following formula.

\[
S(f) = 0.3125H_{mo}^2T_p\left(\frac{f}{f_p}\right)^{-5} \exp(-1.25(\frac{f}{f_p})^{-4})(1 - 0.287 \ln \gamma)\gamma^{\frac{f}{\sigma}}
\]

Where:

- \( f \) is frequency \( f_p = \frac{1}{T_p} \)
- \( \sigma = 0.07 \) for \( f \leq f_p \) and \( \sigma = 0.09 \) for \( f > f_p \)
- \( \gamma \) (gamma) is the peakedness parameter (see below)
- \( H_{mo} \) is significant wave height
- \( T_p \) is spectral peak period
The JONSWAP analysis method is usable for both the North Sea and for West Africa.

The following inputs are used for the two areas.

<table>
<thead>
<tr>
<th></th>
<th>North Sea</th>
<th>West Africa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma factor</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$H_m$</td>
<td>2m</td>
<td>2m</td>
</tr>
<tr>
<td>$T_p$</td>
<td>11s</td>
<td>15s</td>
</tr>
</tbody>
</table>

Table 8.1: JONSWAP spectra input

The JONSWAP spectra for the two areas becomes – simplified by $\sigma=0.07$ for all values. The curves show the energy in the waves, $S(f)$ is for North Sea while $S_2(f)$ is for West Africa.

Figure 8.1: JONSWAP spectra for North Sea and West Africa, 2m $H_s$
8.2 KRISTIN FIELD

MOSES software calculates the velocity for the barge in the JONSWAP spectrum with respect to frequencies.

The motion response for the barge at the Kristin field:

Figure 8.2 shows the heave velocity for the barge at the Kristin field at 1m wave height. The graph shows velocity for:
- The heave velocity
- The summed velocity of heave and pitch

The pitch velocity should be included into design sea state as lifting point is different to barge centre in longitudinal direction. This will take into account for the situations were barge responds to both maximum heave and maximum pitch.

As observed the pitch velocity contributes much in 0 degree heading.

Maximum seabed landing speed is 0.5 m/s.

The idea for the compensator is to reduce heave and velocity of module to increase operational Hs. Compensator response is dimensionless and can be used to find module velocity after compensation.
Compensator response, second order, for Kristin field with initial inputs:

\[
T_p := \begin{pmatrix}
4 \\
6 \\
8 \\
10 \\
12 \\
14 \\
16 \\
18 \\
20 \\
22
\end{pmatrix}, \quad \text{Res} := \begin{pmatrix}
0.2 \\
0.59 \\
1.6 \\
2.7 \\
2.13 \\
1.67 \\
1.47 \\
1.34 \\
1.26 \\
1.21
\end{pmatrix}
\]

As discussed earlier the compensator does not work for periods above 6.7 seconds. Observed from figure 8.2 this does not increase the operational window since compensator does not reduce the largest velocities.

For a 70% reduction in compensator stiffness the response becomes:

\[
T_p := \begin{pmatrix}
4 \\
6 \\
8 \\
10 \\
12 \\
14 \\
16 \\
18 \\
20 \\
22
\end{pmatrix}, \quad \text{Res}_{0.3, 2\text{order}} := \begin{pmatrix}
0.06 \\
0.134 \\
0.25 \\
0.44 \\
0.71 \\
1.07 \\
1.39 \\
1.57 \\
1.58 \\
1.53
\end{pmatrix}
\]

As observed the response for compensator changes and compensator limit are now just below 14s.

Figure 8.3 shows the heave velocities at Kristin with compensator.
Both 0 degree and 90 degree heading are implemented with compensator.
As observed the compensator reduces velocity for values up to 12 seconds and reduction is quite large. As the compensator does not work for periods from 14 seconds and above, it will not be used for these periods. Problem is that compensator is not able to reduce the velocity for high periods, where large velocities occur.

Given compensator does not increase the operational window significantly. This makes a compensator that does not work. As seen from analysis in chapter 7 it is possible to increase compensator performance by adjusting variables. Compensator stiffness should be designed to match performance of working platform, in this case the barge.
8.3 GIRASSOL FIELD

Motion response for barge at Girassol field, from MOSES analysis:

![Figure 8.4: West Africa – Girassol field](image)

Figure shows velocities for barge at Girassol location outside West Africa at 1m Hs. The numbers are closely related to the ones for the North Sea.

As observed the barge is not usable for module installations because of high velocities.

By including a compensator we should be able to increase the weather window for barge. Two variables for compensator stiffness are used; define value and 70% reduction.

\[
\begin{bmatrix}
4 \\
6 \\
8 \\
10 \\
12 \\
14 \\
16 \\
18 \\
20 \\
22
\end{bmatrix}
\begin{bmatrix}
0.15 \\
0.41 \\
0.98 \\
2.12 \\
2.50 \\
1.98 \\
1.66 \\
1.45 \\
1.36 \\
1.28
\end{bmatrix}
\begin{bmatrix}
0.05 \\
0.12 \\
0.22 \\
0.39 \\
0.61 \\
0.92 \\
1.51 \\
1.6 \\
1.6 \\
1.58
\end{bmatrix}
\]

\[T_p :=\]

\[\text{Res}_{\text{Girassol}} :=\]

\[\text{Res}_{0.3\text{Girassol}} :=\]
As observed compensator with initial defined variables have poor performance. The compensator does not work for periods above 8 seconds. With 70% decreased compensator stiffness the result looks quite different. Compensator now works for periods up to 14 seconds, which is 2 seconds higher than for the North Sea. Figure 8.5 shows compensator performance for 0 and 90 degree heading at Girassol field.

**Figure 8.5:** Girassol field – with compensator

As observed highest velocity is at the same period for the North Sea, but the value is higher. Figure 8.6 shows operational compensator at Girassol field, performance of the compensator is set to be 1 above limit.

**Figure 8.6:** Girassol field – Operational compensator
As observed in figure the compensator is able to qualify 1m Hs as the operational window. Observations give that the velocity are low up to 12 second, while it close to 0.5 m/s for above periods.

The graph in figure 8.7 shows the probability for actual Hs in the summer months (June, July and August) and on an all year basis.

![Figure 8.7: Hs probability, Girassol and Kristin field](image)

As observed the sea state is much rougher in the North Sea than outside West Africa. An installation criterion of 1m Hs. is very low in the North Sea, while it gives almost 50% probability of installation outside West Africa.

It is possible to increase operational weather window by setting a criteria for maximum wave period. Following the JONSWAP spectrums in figure 8.1 this will work best for the North Sea since peak period is lower there than for West Africa (see table 8.1).

Compensator performance should be designed to meet requirements for operation. The compensator defined with input data from chapter 6.3 does not for either in the North Sea or in West Africa. By decreasing compensator stiffness performance can be improved.
9. CONCLUSIONS

9.1 BARGE DESIGN

The barge designed in this report is well suited for heavy lift operations. With its large size it is possible to mobilize to off modules at one time, and the moonpool reduces hydrodynamic forces on module. The barge is suited with a module handling system for safe and efficient handling.

The RAO’s for the barge is evaluated by use of marine calculation software MOSES, where the results are not the way that we could predict. Much work is done in to quality assurance for the presented RAO’s, but still the results are strange. The results for both 0 and 90 degree heading have some peaks that the author is not capable of establish reasonable arguments fro. The results are compared to both wavelengths and calculations for the moonpool, but the results still are strange.

When the barge is evaluated without a moonpool, the results look very good and are easily comparable to other large vessels. Software has its limitations and the analyses show that the program may not be capable of calculating RAO’s for vessels with such large moonpools.

This statement follows indications given by colleagues when performing the work.

Barge with and without moonpool is calculated for motion response in North Sea and West African areas. Since the responses for barge with moonpool can not be qualified, results from barge without moonpool are used in operational analysis. Compared to other monohull vessels responses are closely correlated an data gives a realistic overview of the actual situation.

Much work is still left designing a barge for moonpool installation of large modules, but calculated values are usable to evaluate heave compensator system presented in this report.
9.2 PASSIVE HEAVE COMPENSATOR SYSTEM

The weight of the installed subsea modules have increased with the technology development. The report discusses the installation of a 1000 ton module from a barge, through the moonpool with passive compensation.

Mathematical models for passive heave compensation designed in chapter 5 have been proven to work well. Two different systems are evaluated; two first order system and one second order system.

The input data is a combination of calculated and assumed values. The scope of work requirements used for installation of the Tordis module has been used as reference for the input data.
Some values are assumed to be able to calculate the mathematical models.
The values are used for numerical calculation of compensator, where the residual motion is evaluated for varying variables.
The motion input is harmonic and represents the excitation of system from the barge.

The first order system is evaluated by two models and is simplified to only include one mass. This allows the use of relatively simple modelling techniques, but the flexibility has decreased. The models can only be evaluated for infinite stiff crane wire.
The models used are described by two different theories, transfer functions and motion of equation.
The two models correlate closely and the motion of equation proves to be most conservative. The models are evaluated with defined input data and results in a compensator that only works for high frequencies. The limit for the compensator is set to be where the residual motion is equal to the excited motion.
Damping motion from the drag and the compensator affect response only in resonance and have a small impact below response of 1.
Further the resonance frequency is decided by the crane wire stiffness and the module mass has a big impact on the system. The resonance frequency should be as low as possible. A low resonance frequency gives a good compensator performance.

The second order system implements some of the assumptions in the first order model, and a more physical correct result is expected.
The Model uses more variables in the system design and is represented by two masses. The model implements the crane wire stiffness, not covered by the first order models.

The calculated results show a close correlation between the three models. The compensator works best for high frequencies and some differences are found in the resonance area. The performance of the model follows the same as for the first order model, but the drag impact on the system stability is also evaluated with this model. A high drag damping makes the system more stable as it requires less time to come into a stable harmonic motion.

In the time domain analysis for single frequency, analysis has been used to explain the residual motion. It follows that the natural frequencies occur in the output signal for frequencies different from the resonance. This affects the system stability.

All models evaluated give almost the same response for the analysed passive compensator. The evaluated compensator works best for high frequencies. The second order model is expected to be the most accurate as it implements more variables, while the harmonic motion gives the most conservative result.

The results are not compared to measurements of a physical constructed compensator. The mathematical models should be evaluated with models test before it is used to design a compensator.

Compared to the measurements of a semi-active system the passive compensator works best for opposite frequencies. The evaluated semi-active compensator proves to work best for low frequencies.
9.3 OPERATIONAL

The operational analysis is performed by use of JONSWAP wave spectra's for the two areas North Sea and West Africa. The barges design works very well for installation operations in calm weather at the two specific locations.

In the North Sea the barges response to waves are reduced by the very large size of the barge. The waves that occur in the North Sea have a lower peak value compared to West Africa where this fits the response curves for both barge and compensation system well.

In planning operation
10. REFERENCES


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http://www.oiltech.no/pdf/Akkumulatorbok_Oiltech.pdf
10.1 ADDITIONAL REFERENCES IN APPENDIXES

Appendix A – 1. Order Mathematical Models:

Appendix B – 2. Order Mathematical Model:

Appendix C – Moonpool Calculations:

Appendix D – Moonpool barge RAO’s and Motion Characteristics:
[9] RAO and vessel motion report made with marine analysis program MOSES. Ultramarine Inc.
Appendix A

1. Order Mathematical Models
Appendix A
1. Order Mathematical Models

References:

/2/ Nielsen F.G., Lecture Notes SIN 1546 Marine Operations, NTNU 2003
/3/ Personal communication with Professor Jasna B. Jakobsen, May 2008
/4/ Personal communication with colleague Rune Stigedal, May 2008
/5/ Personal communication with colleague Gabriel Grødem, May 2008

1. Input

Motion amplitude
\[ \Lambda_m := 1 \]

Mass of module
\[ M_m := 500000 \text{kg} \]

Added mass
\[ M_a := 1600000 \text{kg} \]

Compensator stiffness
\[ k_c := 1000 \frac{\text{KN}}{\text{m}} \]

System design period
\[ T_p := \begin{pmatrix} 4 \\ 6 \\ 8 \\ 10 \\ 12 \\ 14 \\ 16 \\ 18 \\ 20 \\ 22 \end{pmatrix} \text{s} \]

Heave velocity of barge
\[ V_H := \begin{pmatrix} 0.06 \\ 0.24 \\ 0.43 \\ 0.55 \\ 0.54 \\ 0.52 \\ 0.49 \\ 0.45 \\ 0.41 \\ 0.38 \end{pmatrix} \text{m/s} \]

reference RAO in appendix D
1.1 Calculation of mass of compensator system

The mass of compensator system is total weight the elements that moves during compensation, including:
- sheave
- piston
- piston rod
- accumulator piston
- hydraulic oil

Assumed weight of steel components:
\[ M_{\text{steel}} := 3 \text{ ton} \]

Assumed weight of oil
\[ M_{\text{oil}} := 3 \text{ ton} \]

Mass of compensation system
\[ M_{\text{comp}} := M_{\text{steel}} + M_{\text{oil}} \]
\[ M_{\text{comp}} = 6 \text{ ton} \]

1.2 Crane wire

In the dynamical model the crane wire is seen as a spring with a defined wire stiffness, where the spring constant varies with water depth.

\[ k_{\text{wire}} = \frac{E \cdot A}{L} \]

Input crane wire:

Young modulus:
\[ E := 2.1 \cdot 10^8 \frac{\text{kN}}{\text{m}^2} \]

Area
\[ A_{\text{cw}} := \left( \frac{154 \text{mm}}{2} \right)^2 \cdot \pi \quad A_{\text{cw}} = 0.019 \text{ m}^2 \]

Weight:
\[ W_{\text{wire}} := 103.2 \frac{\text{kg}}{\text{m}} \]
North Sea - Kristin field

\[ WD_{Kristin} := 350 \text{m} \]
\[ M_{wireK} := W_{wire} \cdot WD_{Kristin} \]
\[ k_{w_{Kristin}} := \frac{E \cdot A_{cw}}{WD_{Kristin}} \]
\[ k_{w_{Kristin}} = 11176 \frac{kN}{m} \]

West Africa - Girassol Field:

\[ WD_{Girassol} := 1300 \text{m} \]
\[ M_{wireG} := W_{wire} \cdot WD_{Girassol} \]
\[ k_{w_{Girassol}} := \frac{E \cdot A_{cw}}{WD_{Girassol}} \]
\[ k_{w_{Girassol}} = 3009 \frac{kN}{m} \]

1.3 Module Mass

First order systems:
- Module mass
- Compensator mass
- Added mass

Second order systems:
- Module mass
- Added mass

North Sea - Kristin field

\[ M_m = 500 \text{ton} \]
\[ M_{comp} = 6 \text{ton} \]
\[ M_a = 1600 \text{ton} \]
\[ M_{K1} := M_m + M_{comp} + M_a + M_{wireK} \]
\[ M_{K1} = 2142 \text{ton} \]

North Sea - Kristin field

\[ M_m = 500 \text{ton} \]
\[ M_{comp} = 6 \text{ton} \]
\[ M_a = 1600 \text{ton} \]
\[ M_{K2} := M_m + M_a + M_{wireK} \]
\[ M_{K2} = 2136 \text{ton} \]
West Africa - Girassol Field:

\[ M_m = 500 \text{ ton} \]
\[ M_{\text{comp}} = 6 \text{ ton} \]
\[ M_a = 1600 \text{ ton} \]

\[ M_{G1} := M_m + M_{\text{comp}} + M_a + M_{\text{wireG}} \]
\[ M_{G1} = 2240 \text{ ton} \]

\[ M_{G2} := M_m + M_a + M_{\text{wireG}} \]
\[ M_{G2} = 2234 \text{ ton} \]

1.4 Compensator damping

Equivalent damping related to mechanical friction in system

\[ c_c := 20 \frac{\text{kN} \cdot \text{s}}{\text{m}} \]

1.5 Drag damping on module

\[ c_d := 500 \frac{\text{kN} \cdot \text{s}}{\text{m}} \]
2. 1.-Order System - Transfer Function

\[ M := M_{KI} \]

Approximately undamped natural frequency

\[ \omega_0 := \frac{k_c}{\sqrt{M}} \quad \omega_0 = 0.68 \frac{1}{s} \quad T_0 := \frac{2\pi}{\omega_0} \quad T_0 = 9.2 \text{s} \]

Residual motion in module

The residual motion in module is expressed with the response function showed below.

\[
\text{Response}(\omega) := \sqrt{\frac{1 + \left(\frac{\omega}{\omega_0}\right)^2 \frac{c_c^2}{k_c M}}{1 - \left(\frac{\omega}{\omega_0}\right)^2 + \left(\frac{\omega}{\omega_0}\right)^2 \frac{(c_c + c_d)^2}{k_c M}}} 
\]
2.1 Girassol field

$$\omega_0 G := \sqrt{\frac{k_c}{M_{G1}}}$$

$$\text{Response}_G(\omega) := \frac{1 + \left(\frac{\omega}{\omega_0}\right)^2 \frac{c_c}{k_c M_{G1}}}{\sqrt{1 - \left(\frac{\omega}{\omega_0}\right)^2 + \left(\frac{\omega}{\omega_0}\right)^2 \frac{(c_c + c_d)^2}{k_c M_{G1}}}}$$
3. 1.-order system - harmonic motion model

Since the stiffness of crane wire are much larger than compensator stiffness we use the stiffness factor for the compensator.

\[
\omega_n := \frac{k_c}{\sqrt{M}} \quad \omega_n = 0.68 \, \text{s} \quad T_n := \frac{2\pi}{\omega_n} \quad T_n = 9.2 \, \text{s}
\]

\[
r(\omega) := \frac{\omega}{\omega_n}
\]

\[
c_{\text{crit}} := 2 \cdot M \cdot \omega_n \quad c_{\text{crit}} = 2927 \, \text{kN} \cdot \text{s/m}
\]

\[
\zeta := \frac{c_c - c_d}{c_{\text{crit}}} \quad \zeta = -0.16
\]

\[
\text{Response}_{\text{hmotion}}(\omega) := \frac{1}{\sqrt{1 + \left[2\zeta \left(\frac{\omega}{\omega_n}\right)\right]^2}}
\]

\[
\left[1 + \left(\frac{\omega}{\omega_n}\right)^2\right] + \left(2\zeta \left(\frac{\omega}{\omega_n}\right)\right)^2
\]
4. 2.-order system

In order to solve the 2. order dynamical system, the system is divided into 4 differential equations.

$$M_{\text{matrix}} = \begin{pmatrix} M_c & 0 \\ 0 & M \end{pmatrix} \quad y_0(0) = 0$$

$$C_{\text{matrix}} = \begin{pmatrix} c_c & 0 \\ 0 & c_d \end{pmatrix} \quad y_1(0) = 0$$

$$K_{\text{matrix}} = \begin{pmatrix} k_c + k_w & -k_w \\ -k_w & k_w \end{pmatrix} \quad y_2(0) = 0$$

$$F_{\text{matrix}} = X \sin(\omega t) \cdot k_c + X \cos(\omega t) \cdot c_c \quad y_3(0) = 0$$

Given:

$$\frac{d}{du} y_0(u) = y_1(u)$$

$$\frac{d}{du} y_1(u) = \frac{X k_c \sin(\omega u) + X c_c \cos(\omega u)}{M_c} - \frac{c_c}{M_c} y_1(u) - \left( \frac{k_c + k_w}{M_c} \right) y_0(u) + \left( \frac{k_w}{M_c} \right) y_2(u)$$

$$\frac{d}{du} y_2(u) = y_3(u)$$

$$\frac{d}{du} y_3(u) = -\frac{c_d}{M} y_3(u) + \left( \frac{k_w}{M} \right) y_0(u) - \left( \frac{k_w}{M} \right) y_2(u)$$

The response from the 2.order dynamical model is showed in table and graph below.

$$T_p = \begin{pmatrix} 4 \\ 6 \\ 8 \\ 10 \\ 12 \\ 14 \\ 16 \\ 18 \\ 20 \\ 22 \end{pmatrix} \quad \omega_{\text{range}} := \frac{2 \pi}{T_p} \quad \omega_{\text{range}} = \begin{pmatrix} 1.571 \\ 1.047 \\ 0.785 \\ 0.628 \\ 0.524 \\ 0.449 \\ 0.393 \\ 0.349 \\ 0.314 \\ 0.286 \end{pmatrix} \quad \frac{1}{s}$$
### Table

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### Diagram

![Graph](image-url)
5. Analysis

5.1 Variations in compensator stiffness

5.11 Analysis 1

\[ k_{c1} := 2 \cdot k_c \]

\[ \omega_{0k1} := \frac{k_{c1}}{\sqrt{M}} \]

\[ \text{Analysisk}_1(\omega) := \frac{1 + \left(\frac{\omega}{\omega_{0k1}}\right)^2 \frac{c_c^2}{k_{c1} \cdot M}}{\sqrt{1 - \left(\frac{\omega}{\omega_{0k1}}\right)^2}^2 + \left(\frac{\omega}{\omega_{0k1}}\right)^2 \frac{(c_c + c_d)^2}{k_{c1} \cdot M}} \]

5.12 Analysis 2

\[ k_{c2} := 3 \cdot k_c \]

\[ \omega_{0k2} := \frac{k_{c2}}{\sqrt{M}} \]

\[ \text{Analysisk}_2(\omega) := \frac{1 + \left(\frac{\omega}{\omega_{0k2}}\right)^2 \frac{c_c^2}{k_{c2} \cdot M}}{\sqrt{1 - \left(\frac{\omega}{\omega_{0k2}}\right)^2}^2 + \left(\frac{\omega}{\omega_{0k2}}\right)^2 \frac{(c_c + c_d)^2}{k_{c2} \cdot M}} \]

5.13 Analysis 3

\[ k_{c3} := 0.5 \cdot k_c \]

\[ \omega_{0k3} := \frac{k_{c3}}{\sqrt{M}} \]

\[ \text{Analysisk}_3(\omega) := \frac{1 + \left(\frac{\omega}{\omega_{0k3}}\right)^2 \frac{c_c^2}{k_{c3} \cdot M}}{\sqrt{1 - \left(\frac{\omega}{\omega_{0k3}}\right)^2}^2 + \left(\frac{\omega}{\omega_{0k3}}\right)^2 \frac{(c_c + c_d)^2}{k_{c3} \cdot M}} \]
5.14 Analysis 4

\[ k_{c4} := 0.3 \cdot k_c \]

\[ \omega_{0k4} := \frac{k_{c4}}{\sqrt{M}} \]

\[ \text{Analysis}_{k4}(\omega) := \frac{1 + \left( \frac{\omega}{\omega_{0k4}} \right)^2 c_c^2}{\sqrt{1 - \left( \frac{\omega}{\omega_{0k4}} \right)^2 + \left( \frac{\omega}{\omega_{0k4}} \right)^2 (c_c + c_d)^2 k_{c4}^2 M}} \]

5.15 Analysis 5

\[ k_{c5} := 0.1 \cdot k_c \]

\[ \omega_{0k5} := \frac{k_{c5}}{\sqrt{M}} \]

\[ \text{Analysis}_{k5}(\omega) := \frac{1 + \left( \frac{\omega}{\omega_{0k5}} \right)^2 c_c^2}{\sqrt{1 - \left( \frac{\omega}{\omega_{0k5}} \right)^2 + \left( \frac{\omega}{\omega_{0k5}} \right)^2 (c_c + c_d)^2 k_{c5}^2 M}} \]

5.16 Variation in compensator stiffness results

![Variation in compensator stiffness results graph](image-url)
5.2 Variation in compensator damping

5.21 Analysis 1

\[ c_{c1} := 2\cdot c_c \]

\[
\text{Analysis}_{c_1}(\omega) := \\
\sqrt{1 + \left( \frac{\omega}{\omega_0} \right)^2 \frac{c_{c1}}{k_cM}} \\
\sqrt{1 - \left( \frac{\omega}{\omega_0} \right)^2} + \left( \frac{\omega}{\omega_0} \right)^2 \cdot \frac{(c_{c1} + c_d)^2}{k_cM}
\]

5.22 Analysis 2

\[ c_{c2} := 3\cdot c_c \]

\[
\text{Analysis}_{c_2}(\omega) := \\
\sqrt{1 + \left( \frac{\omega}{\omega_0} \right)^2 \frac{c_{c2}}{k_cM}} \\
\sqrt{1 - \left( \frac{\omega}{\omega_0} \right)^2} + \left( \frac{\omega}{\omega_0} \right)^2 \cdot \frac{(c_{c2} + c_d)^2}{k_cM}
\]

5.23 Analysis 3

\[ c_{c3} := 0.5\cdot c_c \]

\[
\text{Analysis}_{c_3}(\omega) := \\
\sqrt{1 + \left( \frac{\omega}{\omega_0} \right)^2 \frac{c_{c3}}{k_cM}} \\
\sqrt{1 - \left( \frac{\omega}{\omega_0} \right)^2} + \left( \frac{\omega}{\omega_0} \right)^2 \cdot \frac{(c_{c3} + c_d)^2}{k_cM}
\]
5.24 Analysis 4

c_{c4} := 0.3 \cdot c_c

Analysis_{c4}(\omega) := \sqrt{1 + \left( \frac{\omega}{\omega_0} \right)^2 \frac{c_{c4}^2}{k_c M}}
\sqrt{\left[ 1 - \left( \frac{\omega}{\omega_0} \right)^2 \right]^2 + \left( \frac{\omega}{\omega_0} \right)^2 \left( \frac{c_{c4} + c_d}{k_c M} \right)^2}

5.25 Analysis 5

c_{c5} := 0.1 \cdot c_c

Analysis_{c5}(\omega) := \sqrt{1 + \left( \frac{\omega}{\omega_0} \right)^2 \frac{c_{c5}^2}{k_c M}}
\sqrt{\left[ 1 - \left( \frac{\omega}{\omega_0} \right)^2 \right]^2 + \left( \frac{\omega}{\omega_0} \right)^2 \left( \frac{c_{c5} + c_d}{k_c M} \right)^2}

5.26 Variation in compensator damping results

Variation_c := \begin{pmatrix} 2 \cdot c_c \\ 3 \cdot c_c \\ 0.5 \cdot c_c \\ 0.3 \cdot c_c \\ 0.1 \cdot c_c \end{pmatrix}
5.3 Variation in drag damping

5.31 Analysis 1

\[ c_{d1} := 2 \cdot c_d \]

\[
\text{Analysis}_{d1}(\omega) := \left[ 1 + \left( \frac{\omega}{\omega_0} \right)^2 \frac{c_c^2}{k_c \cdot M} \right] \cdot \frac{1}{\sqrt{1 - \left( \frac{\omega}{\omega_0} \right)^2} + \left( \frac{\omega}{\omega_0} \right)^2 \left( \frac{c_c + c_{d1}}{k_c \cdot M} \right)^2}
\]

5.32 Analysis 2

\[ c_{d2} := 3 \cdot c_d \]

\[
\text{Analysis}_{d2}(\omega) := \left[ 1 + \left( \frac{\omega}{\omega_0} \right)^2 \frac{c_c^2}{k_c \cdot M} \right] \cdot \frac{1}{\sqrt{1 - \left( \frac{\omega}{\omega_0} \right)^2} + \left( \frac{\omega}{\omega_0} \right)^2 \left( \frac{c_c + c_{d2}}{k_c \cdot M} \right)^2}
\]

5.33 Analysis 3

\[ c_{d3} := 0.5 \cdot c_d \]

\[
\text{Analysis}_{d3}(\omega) := \left[ 1 + \left( \frac{\omega}{\omega_0} \right)^2 \frac{c_c^2}{k_c \cdot M} \right] \cdot \frac{1}{\sqrt{1 - \left( \frac{\omega}{\omega_0} \right)^2} + \left( \frac{\omega}{\omega_0} \right)^2 \left( \frac{c_c + c_{d3}}{k_c \cdot M} \right)^2}
\]
5.34 Analysis 4

\[ c_{d4} := 0.3 \cdot c_d \]

\[
\text{Analysis}_{d4}(\omega) := \sqrt{1 + \left( \frac{\omega}{\omega_0} \right)^2 \cdot \frac{c_c^2}{k_c \cdot M}} \cdot \left[ 1 - \left( \frac{\omega}{\omega_0} \right)^2 \right]^2 + \left( \frac{\omega}{\omega_0} \right)^2 \cdot \frac{(c_c + c_{d4})^2}{k_c \cdot M} \]

5.35 Analysis 5

\[ c_{d5} := 0.1 \cdot c_d \]

\[
\text{Analysis}_{d5}(\omega) := \sqrt{1 + \left( \frac{\omega}{\omega_0} \right)^2 \cdot \frac{c_c^2}{k_c \cdot M}} \cdot \left[ 1 - \left( \frac{\omega}{\omega_0} \right)^2 \right]^2 + \left( \frac{\omega}{\omega_0} \right)^2 \cdot \frac{(c_c + c_{d5})^2}{k_c \cdot M} \]

5.36 Variation in drag damping results

\[
\text{Variation}_{d} := \begin{pmatrix} 2 \cdot c_d \\ 3 \cdot c_d \\ 0.5 \cdot c_d \\ 0.3 \cdot c_d \\ 0.1 \cdot c_d \end{pmatrix}
\]
5.4 Variation in mass

5.41 Analysis 1

\[ M_1 := 2M \]

\[ \omega_{0M1} := \frac{k_c}{\sqrt{M_1}} \]

\[
\text{Analysis}_{M1}(\omega) := \left\lfloor \frac{1 + \left( \frac{\omega}{\omega_{0M1}} \right)^2 \frac{c_c^2}{k_cM_1}}{\sqrt{1 - \left( \frac{\omega}{\omega_{0M1}} \right)^2 + \left( \frac{\omega}{\omega_{0M1}} \right)^2 \frac{(c_c + c_d)^2}{k_cM_1}}} \right\rfloor
\]

5.42 Analysis 2

\[ M_2 := 3M \]

\[ \omega_{0M2} := \frac{k_c}{\sqrt{M_2}} \]

\[
\text{Analysis}_{M2}(\omega) := \left\lfloor \frac{1 + \left( \frac{\omega}{\omega_{0M2}} \right)^2 \frac{c_c^2}{k_cM_2}}{\sqrt{1 - \left( \frac{\omega}{\omega_{0M2}} \right)^2 + \left( \frac{\omega}{\omega_{0M2}} \right)^2 \frac{(c_c + c_d)^2}{k_cM_2}}} \right\rfloor
\]

5.43 Analysis 3

\[ M_3 := 0.5M \]

\[ \omega_{0M3} := \frac{k_c}{\sqrt{M_3}} \]

\[
\text{Analysis}_{M3}(\omega) := \left\lfloor \frac{1 + \left( \frac{\omega}{\omega_{0M3}} \right)^2 \frac{c_c^2}{k_cM_3}}{\sqrt{1 - \left( \frac{\omega}{\omega_{0M3}} \right)^2 + \left( \frac{\omega}{\omega_{0M3}} \right)^2 \frac{(c_c + c_d)^2}{k_cM_3}}} \right\rfloor
\]
### 5.44 Analysis 4

\[ M_4 := 0.3M \]

\[ \omega_{0M4} := \sqrt{\frac{k_c^{\omega}}{M_4}} \]

\[ \text{Analysis}_{M4}(\omega) := \sqrt{\frac{1 + \left(\frac{\omega}{\omega_{0M4}}\right)^2 \frac{c_c^2}{k_cM_4}}{1 - \left(\frac{\omega}{\omega_{0M4}}\right)^2} + \left(\frac{\omega}{\omega_{0M4}}\right)^2 \frac{(c_c + c_d)^2}{k_cM_4}}} \]

### 5.45 Analysis 5

\[ M_5 := 0.1M \]

\[ \omega_{0M5} := \sqrt{\frac{k_c^{\omega}}{M_5}} \]

\[ \text{Analysis}_{M5}(\omega) := \sqrt{\frac{1 + \left(\frac{\omega}{\omega_{0M5}}\right)^2 \frac{c_c^2}{k_cM_5}}{1 - \left(\frac{\omega}{\omega_{0M5}}\right)^2} + \left(\frac{\omega}{\omega_{0M5}}\right)^2 \frac{(c_c + c_d)^2}{k_cM_5}}} \]

### 5.46 Variation in mass results

![Graph showing variations in mass results](image-url)
5.5 Variations in compensator stiffness - harmonic motion model

5.51 Analysis 1

\( k_1 := 2 \cdot k_c \)

\[ \omega_{0k1} := \sqrt{\frac{k_1}{M}} \quad \text{Analysis}_{k1}(\omega) := \sqrt{1 + \left( \frac{\omega}{\omega_{0k1}} \right)^2 \cdot \frac{c_c^2}{k_c1 \cdot M}} \]

5.52 Analysis 2

\( k_2 := 3 \cdot k_c \)

\[ \omega_{0k2} := \sqrt{\frac{k_2}{M}} \quad \text{Analysis}_{k2}(\omega) := \sqrt{1 + \left( \frac{\omega}{\omega_{0k2}} \right)^2 \cdot \frac{c_c^2}{k_c2 \cdot M}} \]

5.53 Analysis 3

\( k_3 := 0.5 \cdot k_c \)

\[ \omega_{0k3} := \sqrt{\frac{k_3}{M}} \quad \text{Analysis}_{k3}(\omega) := \sqrt{1 + \left( \frac{\omega}{\omega_{0k3}} \right)^2 \cdot \frac{c_c^2}{k_c3 \cdot M}} \]
5.54 Analysis 4

\[ k_4 := 0.3 \cdot k_c \]

\[ \omega_{0k4} := \sqrt{\frac{k_c}{M}} \]

\[ \text{Analysis}_{k_c4}(\omega) := \sqrt{1 + \left( \frac{\omega}{\omega_{0k4}} \right)^2 \cdot \frac{c_c^2}{k_c4 \cdot M}} \]

\[ 1 - \left( \frac{\omega}{\omega_{0k4}} \right)^2 + \left( \frac{\omega}{\omega_{0k4}} \right)^2 \cdot \frac{(c_c + c_d)^2}{k_c4 \cdot M} \]

5.55 Analysis 5

\[ k_5 := 0.1 \cdot k_c \]

\[ \omega_{0k5} := \sqrt{\frac{k_c}{M}} \]

\[ \text{Analysis}_{k_c5}(\omega) := \sqrt{1 + \left( \frac{\omega}{\omega_{0}} \right)^2 \cdot \frac{c_c^2}{k_c5 \cdot M}} \]

\[ 1 - \left( \frac{\omega}{\omega_{0}} \right)^2 + \left( \frac{\omega}{\omega_{0}} \right)^2 \cdot \frac{(c_c + c_d)^2}{k_c5 \cdot M} \]

5.56 Variation in compensator stiffness results

![Graph showing response curves for different analyses and stiffness variations](image)

\[ \text{Variation}_{k_c} := \begin{cases} 2 \cdot k_c \\
3 \cdot k_c \\
0.5 \cdot k_c \\
0.3 \cdot k_c \\
0.1 \cdot k_c \end{cases} \]
6. Response variations for all three models

6.1 Compensator stiffness times 3

\[
\begin{align*}
\text{Res}_{\text{transfer}} & : = \begin{pmatrix} 1.24 \\ 3.52 \\ 1.74 \\ 1.38 \\ 1.24 \\ 1.16 \\ 1.12 \\ 1.09 \\ 1.07 \\ 1.06 \end{pmatrix} \\
\text{Res}_{\text{harmonic}} & : = \begin{pmatrix} 1.28 \\ 3.7 \\ 1.75 \\ 1.39 \\ 1.24 \\ 1.16 \\ 1.12 \\ 1.09 \\ 1.07 \\ 1.06 \end{pmatrix} \\
\text{Res}_{\text{2.order}} & : = \begin{pmatrix} 0.74 \\ 4.40 \\ 1.96 \\ 1.51 \\ 1.30 \\ 1.15 \\ 1.15 \\ 1.08 \\ 1.09 \\ 1.06 \end{pmatrix}
\end{align*}
\]
### 6.2 Compensator stiffness times 0.3

<table>
<thead>
<tr>
<th>Res_{0.3\text{transfer}}</th>
<th>Res_{0.3\text{harmonic}}</th>
<th>Res_{0.3\text{2order}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.16</td>
<td>0.06</td>
</tr>
<tr>
<td>0.46</td>
<td>0.28</td>
<td>0.134</td>
</tr>
<tr>
<td>0.75</td>
<td>0.44</td>
<td>0.25</td>
</tr>
<tr>
<td>0.96</td>
<td>0.69</td>
<td>0.44</td>
</tr>
<tr>
<td>1.05</td>
<td>1.02</td>
<td>0.71</td>
</tr>
<tr>
<td>1.07</td>
<td>1.47</td>
<td>1.07</td>
</tr>
<tr>
<td>1.07</td>
<td>1.85</td>
<td>1.39</td>
</tr>
<tr>
<td>1.06</td>
<td>1.99</td>
<td>1.57</td>
</tr>
<tr>
<td>1.06</td>
<td>1.91</td>
<td>1.58</td>
</tr>
<tr>
<td>1.05</td>
<td>1.78</td>
<td>1.53</td>
</tr>
</tbody>
</table>

![Graph showing the comparison of Res_{0.3\text{transfer}}, Res_{0.3\text{harmonic}}, and Res_{0.3\text{2order}} against \omega range]
7. Tension in crane hook

Crane wire stiffness

\[ k_w := k_{w_{\text{ kristin}}} \]

\[ k_w = 11176 \, \text{kN/m} \]

Static hook

\[ \text{Load}_s := M_m + M_{\text{wire}K} \]

\[ F_s := \text{Load}_s 9.81 \frac{\text{m}}{\text{s}^2} \]

Compensator stroke

\[ \text{Stroke} := \begin{pmatrix} 0 \\ 0.2 \\ 0.4 \\ 0.6 \\ 0.8 \\ 1.0 \\ 1.2 \\ 1.4 \\ 1.6 \\ 1.8 \\ 2 \end{pmatrix} \text{m} \]

Calculation of points in graph:

\[ F_0 = \text{zero} \]

\[ F_1 = \text{Static load} \]

\[ F_2 = \text{Compensation mid} \]

\[ F_3 = \text{Compensator end} \]

\[ F_4 = \text{Override of compensator} \]
\[ F_0 = F_s \]

\[ F_2 = F_1 + k_c \cdot 1m \]

\[ F_3 = F_1 + k_c \cdot 2m \]

\[ F_4 = F_1 + k_c \cdot 2m + F_s \]

\[ E_2 = E_1 + 1m \]

\[ E_3 = E_1 + 2m \]

\[ E_4 = 2E_1 + 2m \]

\[
\begin{pmatrix}
0 \\
5259 \\
6259 \\
7259 \\
12519
\end{pmatrix}
\]

\( F = \text{kN} \)

\[
\begin{pmatrix}
0 \\
1.75 \\
2.75 \\
3.75 \\
5.51
\end{pmatrix}
\]

\( E = \text{m} \)

![Graph showing force vs. elongation](image)
Appendix B

2. Order Mathematical Model
Appendix B
2. Order Mathematical Model

References:
/2/ Nielsen F.G., Lecture Notes SIN 1546 Marine Operations, NTNU 2003

1. Input

Mass compensator
\[ M_c := 6 \text{ ton} \]

Mass module (incl. added mass)
\[ M := 2135 \text{ kN} \]

Compensator stiffness
\[ k_c := 1000 \text{ kN/m} \]

Crane wire stiffness
\[ k_w := 11167 \text{ kN/m} \]

Compensator damping:
\[ c_c := 20 \text{ kN s/m} \]

Drag damping:
\[ c_d := 500 \text{ kN s/m} \]

Heave amplitude
\[ X := 1 \]

\[
\begin{bmatrix}
4 \\
6 \\
8 \\
10 \\
12 \\
14 \\
16 \\
18 \\
20 \\
22
\end{bmatrix}
\]

\[
T_p := \begin{bmatrix}
4 \\
6 \\
8 \\
10 \\
12 \\
14 \\
16 \\
18 \\
20 \\
22
\end{bmatrix}
\]

\[ \omega_{\text{range}} := \frac{2\pi}{T_p} \]

\[ \omega_{\text{range}} = \begin{bmatrix}
1.571 \\
1.047 \\
0.785 \\
0.628 \\
0.524 \\
0.449 \\
0.393 \\
0.349 \\
0.314 \\
0.286
\end{bmatrix} \]

Example 1:
\[ \omega := 1.047 \]
2. Calculation

\[
M_{\text{matrix}} := \begin{pmatrix} M_c & 0 \\ 0 & M \end{pmatrix}
\]

\[
C_{\text{matrix}} := \begin{pmatrix} c_c & 0 \\ 0 & c_d \end{pmatrix}
\]

\[
K_{\text{matrix}} := \begin{pmatrix} k_c + k_w & -k_w \\ -k_w & k_w \end{pmatrix}
\]

\[
D := M_{\text{matrix}}^{-1} \cdot K_{\text{matrix}}
\]

\[
D = \begin{pmatrix} 2.028 \times 10^3 & -1.861 \times 10^3 \\ -5.23 & 5.23 \end{pmatrix}
\]

\[
e_{\text{val}} := \text{eigenvals}(D)
\]

\[
e_{\text{val}} = \begin{pmatrix} 2032.635 \\ 0.429 \end{pmatrix}
\]

\[
\text{resonans}_{\text{val}} := \sqrt{e_{\text{val}}}
\]

\[
\text{resonans}_{\text{val}} = \begin{pmatrix} 45.085 \\ 0.655 \end{pmatrix}
\]

\[
T_1 := 1000
\]

Given

\[
\frac{d}{du} y_0(u) = y_1(u)
\]

\[
\frac{d}{du} y_1(u) = \frac{X \cdot k_c \cdot \sin(\omega \cdot u) + X \cdot c_c \cdot \omega \cdot \cos(\omega \cdot u)}{M_c} - \frac{c_c}{M_c} y_1(u) - \left( \frac{k_c + k_w}{M_c} \right) y_0(u) + \left( \frac{k_w}{M_c} \right) y_2(u) \quad y_0(0) = 0
\]

\[
\frac{d}{du} y_2(u) = y_3(u)
\]

\[
\frac{d}{du} y_3(u) = \frac{c_d}{M} y_3(u) + \left( \frac{k_w}{M} \right) y_0(u) - \left( \frac{k_w}{M} \right) y_2(u) \quad y_2(0) = 0
\]

\[
\frac{d}{du} y_1(u) = \frac{d}{du} y_2(u) = \frac{d}{du} y_3(u) = 0
\]
\[
\begin{align*}
\begin{pmatrix}
  x_1 \\
  v_1 \\
  x_2 \\
  v_2
\end{pmatrix}
:= \text{Odesolve}
\begin{pmatrix}
  y_0 \\
  y_1 \\
  y_2 \\
  y_3
\end{pmatrix}, u, T1, 1000
\end{align*}
\]
Response:

\[ \text{Response} = \text{Res} = \frac{x_2}{X} \]

\[ \text{Res} := \begin{pmatrix} 0.2 \\ 0.59 \\ 1.6 \\ 2.7 \\ 2.13 \\ 1.67 \\ 1.47 \\ 1.34 \\ 1.26 \\ 1.21 \end{pmatrix} \]

\[ \omega_{\text{range}} := \begin{pmatrix} 0.2 \\ 0.4 \\ 0.6 \\ 0.8 \\ 1 \\ 1.2 \\ 1.4 \\ 1.6 \end{pmatrix} \]

\[ \text{Res} := \begin{pmatrix} 0.2 \\ 0.4 \\ 0.6 \\ 0.8 \\ 1 \\ 1.2 \\ 1.4 \\ 1.6 \end{pmatrix} \]

\[ \text{Value peak} := \begin{pmatrix} 2.66 \\ 2.66 \\ 2.7 \\ 2.6 \end{pmatrix} \]

\[ \omega_{\text{iteration}} := \begin{pmatrix} 0.635 \\ 0.645 \\ 0.655 \\ 0.665 \\ 0.675 \end{pmatrix} \]
2.1 Varying in compensator stiffness

\[
\begin{bmatrix}
0.44 \\
1.98 \\
3.06 \\
1.85 \\
1.46 \\
1.3 \\
1.22 \\
1.17 \\
1.12 \\
1.09
\end{bmatrix}
\begin{bmatrix}
0.74 \\
4.40 \\
1.96 \\
1.51 \\
1.30 \\
1.15 \\
1.15 \\
1.08 \\
1.09 \\
1.06
\end{bmatrix}
\begin{bmatrix}
0.1 \\
0.24 \\
0.48 \\
0.95 \\
1.59 \\
1.95 \\
1.89 \\
1.66 \\
1.52 \\
1.41
\end{bmatrix}
\begin{bmatrix}
0.05 \\
0.13 \\
0.24 \\
0.44 \\
0.71 \\
1.07 \\
1.39 \\
1.56 \\
1.58 \\
1.52
\end{bmatrix}
\]

\[
\begin{bmatrix}
46.893 \\
0.89
\end{bmatrix}
\begin{bmatrix}
48.643 \\
1.052
\end{bmatrix}
\begin{bmatrix}
44.153 \\
0.473
\end{bmatrix}
\begin{bmatrix}
43.775 \\
0.369
\end{bmatrix}
\]

![Graph showing response variations with compensator stiffness]
2.2 Varying compensator damping

\[
\begin{align*}
\text{Res}_{2Cc} & := \begin{pmatrix} 0.2 \\ 0.59 \\ 1.58 \\ 2.62 \\ 2.1 \\ 1.66 \\ 1.46 \\ 1.33 \\ 1.22 \\ 1.21 \end{pmatrix} \\
\text{Res}_{3Cc} & := \begin{pmatrix} 0.2 \\ 0.59 \\ 1.62 \\ 2.75 \\ 2.15 \\ 1.68 \\ 1.42 \\ 1.34 \\ 1.26 \\ 1.21 \end{pmatrix} \\
\text{Res}_{0.5Cc} & := \begin{pmatrix} 0.2 \\ 0.59 \\ 1.62 \\ 2.75 \\ 2.15 \\ 1.68 \\ 1.47 \\ 1.3 \\ 1.23 \\ 1.16 \end{pmatrix} \\
\text{Res}_{0.3Cc} & := \begin{pmatrix} 0.2 \\ 0.59 \\ 1.62 \\ 2.75 \\ 2.15 \\ 1.65 \\ 1.42 \\ 1.3 \\ 1.23 \\ 1.16 \end{pmatrix}
\end{align*}
\]

\[
\begin{align*}
\text{Res}_{\text{val}2Cc} & := \begin{pmatrix} 45.085 \\ 0.655 \end{pmatrix} \\
\text{Res}_{\text{val}2Cc} & := \begin{pmatrix} 48.085 \\ 0.655 \end{pmatrix} \\
\text{Res}_{\text{val}0.5Cc} & := \begin{pmatrix} 45.085 \\ 0.655 \end{pmatrix} \\
\text{Res}_{\text{val}0.3Cc} & := \begin{pmatrix} 45.085 \\ 0.655 \end{pmatrix}
\end{align*}
\]
2.3 Varying drag damping

\[
\begin{align*}
\text{Res}_2\text{Cd} & := 
\begin{pmatrix}
0.18 \\
0.51 \\
0.99 \\
1.4 \\
1.46 \\
1.37 \\
1.26 \\
1.22 \\
1.16 \\
1.13
\end{pmatrix} \\
\text{Res}_3\text{Cd} & := 
\begin{pmatrix}
0.15 \\
0.41 \\
0.68 \\
0.96 \\
1.06 \\
1.07 \\
1.09 \\
1.07 \\
1.07 \\
1.04
\end{pmatrix} \\
\text{Res}_{0.5}\text{Cd} & := 
\begin{pmatrix}
0.20 \\
0.6 \\
1.92 \\
4.9 \\
2.51 \\
1.8 \\
1.52 \\
1.38 \\
1.28 \\
1.22
\end{pmatrix} \\
\text{Res}_{0.3}\text{Cd} & := 
\begin{pmatrix}
0.20 \\
0.59 \\
2.06 \\
6.7 \\
2.6 \\
1.83 \\
1.55 \\
1.34 \\
1.29 \\
1.22
\end{pmatrix}
\end{align*}
\]

\[
\begin{align*}
\text{Res}_{\text{val}2}\text{Cd} & := 
\begin{pmatrix}
45.085 \\
0.655
\end{pmatrix} \\
\text{Res}_{\text{val}2}\text{Cd} & := 
\begin{pmatrix}
48.085 \\
0.655
\end{pmatrix} \\
\text{Res}_{\text{val}0.5}\text{Cd} & := 
\begin{pmatrix}
45.085 \\
0.655
\end{pmatrix} \\
\text{Res}_{\text{val}0.3}\text{Cd} & := 
\begin{pmatrix}
45.085 \\
0.655
\end{pmatrix}
\end{align*}
\]
### 2.4 Variation in mass

Res\(_{2M}\) := 
\[
\begin{pmatrix}
0.1 \\
0.2 \\
0.51 \\
1.01 \\
2.43 \\
3.78 \\
2.72 \\
2.09 \\
1.66 \\
1.52
\end{pmatrix}
\]

Res\(_{3M}\) := 
\[
\begin{pmatrix}
0.06 \\
0.12 \\
0.3 \\
0.55 \\
1.01 \\
2.09 \\
4.25 \\
4.06 \\
2.78 \\
2.16
\end{pmatrix}
\]

Res\(_{0.5M}\) := 
\[
\begin{pmatrix}
0.43 \\
1.38 \\
1.85 \\
1.46 \\
1.27 \\
1.24 \\
1.15 \\
1.08 \\
1.08 \\
1.08
\end{pmatrix}
\]

Res\(_{0.3M}\) := 
\[
\begin{pmatrix}
0.7 \\
1.47 \\
1.39 \\
1.22 \\
1.11 \\
1.11 \\
1.07 \\
0.7 \\
1.05 \\
1.04
\end{pmatrix}
\]

Res\(_{\text{val2M}}\) := \[
\begin{pmatrix}
45.058 \\
0.463
\end{pmatrix}
\]

Res\(_{\text{val3M}}\) := \[
\begin{pmatrix}
45.049 \\
0.378
\end{pmatrix}
\]

Res\(_{\text{val0.5M}}\) := \[
\begin{pmatrix}
45.058 \\
0.856
\end{pmatrix}
\]

Res\(_{\text{val0.3M}}\) := \[
\begin{pmatrix}
45.058 \\
1.193
\end{pmatrix}
\]
2.4 Variation in compensator mass

\[
\begin{align*}
\text{Res}_2^{2Mc} & := \begin{pmatrix} 0.2 \\ 0.59 \\ 1.60 \\ 2.71 \\ 2.14 \\ 1.65 \\ 1.42 \\ 1.34 \\ 1.26 \end{pmatrix}, \\
\text{Res}_3^{3Mc} & := \begin{pmatrix} 0.20 \\ 0.59 \\ 1.59 \\ 2.72 \\ 2.15 \\ 1.68 \\ 1.42 \\ 1.34 \\ 1.26 \end{pmatrix}, \\
\text{Res}_0^{0.5Mc} & := \begin{pmatrix} 0.20 \\ 0.59 \\ 1.61 \\ 2.70 \\ 2.13 \\ 1.67 \\ 1.41 \\ 1.34 \\ 1.23 \end{pmatrix}, \\
\text{Res}_0^{0.3Mc} & := \begin{pmatrix} 0.20 \\ 0.59 \\ 1.67 \\ 2.70 \\ 2.13 \\ 1.67 \\ 1.41 \\ 1.34 \\ 1.23 \end{pmatrix}, \\
\text{Res}_{val}^{2Mc} & := \begin{pmatrix} 31.917 \\ 0.654 \end{pmatrix}, \\
\text{Res}_{val}^{3Mc} & := \begin{pmatrix} 26.091 \\ 0.653 \end{pmatrix}, \\
\text{Res}_{val}^{0.5Mc} & := \begin{pmatrix} 63.722 \\ 0.655 \end{pmatrix}, \\
\text{Res}_{val}^{0.3Mc} & := \begin{pmatrix} 78.028' \\ 0.655 \end{pmatrix},
\end{align*}
\]
2.5 New crane wire stiffness - Girassol

In this analysis a crane wire for the stiffness for 1300 meter is used.

Input crane wire:

Young modulus: \( E := 210 \text{GPa} \)

Area

\[
A_{cw} := \left( \frac{154\text{mm}}{2} \right)^2 \cdot \pi
\]

\[
A_{cw} = 0.019 \text{m}^2
\]

West Africa - Girassol Field:

\[
w_{girassol} := 1300\text{m}
\]

\[
k_{w_{girassol}} := \frac{E \cdot A_{cw}}{w_{girassol}}
\]

\[
k_{w_{girassol}} = 3009 \frac{\text{kN}}{\text{m}}
\]

\[
R_{\text{es}_{\text{valGirassol}}} := \begin{pmatrix} 25.869 \\ 0.592 \end{pmatrix}
\]

\[
R_{\text{es}_{\text{Girassol}}} := \begin{pmatrix} 0.15 \\ 0.41 \\ 0.98 \\ 2.12 \\ 2.50 \\ 1.98 \\ 1.66 \\ 1.45 \\ 1.36 \\ 1.28 \end{pmatrix}
\]
2. Fourier Analysis

Fourier analysis is used to analyse the output signal, and check if the compensator function works as expected. The analysis output should be the frequencies for the signals that the output has.

To be able to calculate the output signal, the signal has to be converted into numerical data.

\[ f(x) := x_2(x) \]

\[ N_0 := 512 \]

\[ f_s := 4 \quad \text{Sampling per second} \]

\[ k := 0 \ldots N_0 - 1 \]

\[ n_k := \frac{k}{f_s} \]

\[ v_k := f(n_k) \]

\[ t_i := 0, 0.1 \ldots 20 \]

The red lines in the graph showes sampled values
The graph shows the data that are used in the Fourier analysis

\[ \text{Spec} := \text{fft}(v) \]

\text{fft} is the MathCAD built-in for calculation the Fast Fourier Transform

\[ c_p = \frac{1}{\sqrt{N_0}} \sum_{k} v_k e^{i \left( \frac{2 \cdot \pi \cdot p}{N_0} \right) \cdot k} \]

Variables used in calculations:

\( N_0 = 512 \)

\[ \text{length}(\text{Spec}) = 257 \]

\[ \frac{1}{T_0} = 0.083 \quad \text{signal frequency} \]

\( N_0 = 2^9 \)

\( T_0 = 12.1 \quad \text{period} \)

\( f_s = 4 \quad \text{sampling frequency} \)
The peak values are located at:

\[ f_1 := 0.10156 \]
\[ f_2 := 0.16406 \]

Which corresponds to:

\[ \omega_1 := (2\pi) \cdot f_1 \quad \omega_1 = 0.638 \]
\[ \omega_2 := (2\pi) \cdot f_2 \quad \omega_2 = 1.031 \]
Appendix C

Moonpool Calculations
Appendix C
Moonpool Calculations

1. Introduction

1.1 General
This spreadsheet is used to determine characteristic forces when lifting the template through moonpool. The deployment vessel is the barge looked at in the corresponding master thesis.

References:
/1/ Sandvik, P.C, COSMAR Moonpool dynamic, SINTEF Trondheim, April 2007

1.2 Constants
Sea water density: \( \rho_{\text{sea}} := 1025 \frac{\text{kg}}{\text{m}^3} \)

1.3 Simplifications
- The vertical motion of the lifted object can be considered to be the same as the vertical motion of the moonpool structure.
- The winch speed is small compared to the wave particle motion.
- The blocking effect from the lifted object on the moonpool water is moderate.
- Cursors prevent impact into the moonpool walls. Only vertical forces parallel to the moonpool axis are considered.
- The moonpool dimensions are small compared to the ship breadth.
- Only motion of the water and object in axial direction is considered (i.e. no transverse wave models)
2. Input Data

2.1 Moonpool Main Dimensions

Length: \( L := 50 \text{m} \)

Breadth: \( B := 30 \text{m} \)

Area: \( A := L \cdot B \quad A = 1.5 \times 10^3 \cdot \text{m}^2 \)

Height (draft): \( h := 7 \text{m} \)

Rectangular geometry parameter (3.6.1.5): \( \kappa := 0.46 \)

3. Calculations

3.1 Moonpool Resonance Period - section 3, 3.6.1.5

Energy-equivalent mass:

\[
M_{\text{eq}} = \rho_{\text{sea}} A(h) \left( \int_0^h \frac{A(z)}{A(0)} \frac{\text{d}z}{h} + \frac{A(h)}{A(0)} \kappa \sqrt{A(0)} \right)
\]

Simplified equation for moonpool with constant section area:

\[
M_{\text{eq}} := \rho_{\text{sea}} A \left( h + \kappa \sqrt{A} \right) \quad M_{\text{eq}} = 3.815 \times 10^7 \text{ kg}
\]

Moonpool resonance period:

\[
T_0 = 2\pi \sqrt{\frac{M_{\text{eq}}}{\rho_{\text{sea}} g A}}
\]

Simplified equation for moonpool with constant section area:

\[
T_0 := 2\pi \sqrt{\frac{h + \kappa \sqrt{A}}{g}} \quad T_0 = 9.995 \text{ s}
\]
Appendix D

Moonpool Barge RAO’s and Motion Characteristics

(Only as .PDF document)
&insert barge.ppo

&dimen -save -dimen Meters   M-Tons
&LOCAL xfac = 1 yfac = 1 zfac = 1
&default -save
&default -fyield 248.04 -alpha 3.6111E-6 -spgravit 7.8492 -emodulus 1.9981E5 -poi_ratio 0.3 -kfac 1 1 -cmfac 0.85 0.85 -flood no -use

&set xfac = 1
&set yfac = 1
&set zfac = 1

&describe body BARGE

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*PNT0005
*PNT0006     0.000*%xfac     0.000*%yfac    10.000*%zfac
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+++ IMAGES OF INPUT DATA +++

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*PNT1008 180.000*xfac 20.000*yfac
*PNT1009 180.000*xfac 30.000*yfac
*PNT1010 180.000*xfac 30.000*yfac 10.000*zfac

Define BARGE

Define Panels

Set Piece to BARGE

Finish Up

Describe piece BARGE -diftype 3ddif -perm 1.00
## MOTION RESPONSE OPERATORS

Results are in Body System

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**Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0**

Process is Defaults: Units Are Degrees, Meters, and M-Tons Unless Specified
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### MOTION RESPONSE OPERATORS

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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## MOTION RESPONSE OPERATORS

###RESULTS

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

---

###ENCOUNTER PROCESS

- Draft = 7.0 Meters
- Trim Angle = 0.00 Deg.
- GM = 41.4 Meters
- Roll Gy. Radius = 20.4 Meters
- Pitch Gy. Radius = 48.6 Meters
- Yaw Gy. Radius = 48.6 Meters
- Heading = 15.00 Deg.
- Forward Speed = 0.00 Knots
- Linearization Based on 1/20

---

###DRAFT RESPONSE OPERATORS

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<th>Heave Wave Amplitude (meters)</th>
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### Motion Response Operators

Results are in Body System

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**MOSES**

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10 June, 2008

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* Draft = 7.0 Meters  
  Trim Angle = 0.00 Deg.  
  GMT = 41.4 Meters

* Roll Gy. Radius = 20.4 Meters  
  Pitch Gy. Radius = 48.6 Meters  
  Yaw Gy. Radius = 48.6 Meters

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  Forward Speed = 0.00 Knots  
  Linearization Based on 1/20

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+++ MOTION RESPONSE OPERATORS +++

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--- MOTION RESPONSE OPERATORS ---

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

--- MOTION RESPONSE OPERATORS ---
### Motion Response Operators

Results are in Body System

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**Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0**

---

**1.833**

---

**Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified**

---

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Results are in Body System
### Motion Response Operators

Results are in Body System

**Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0**

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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- Draft = 7.0 Meters
- Trim Angle = 0.08 Deg.
- GMT = 41.4 Meters
- Roll Gy. Radius = 20.4 Meters
- Pitch Gy. Radius = 48.6 Meters
- Yaw Gy. Radius = 48.6 Meters
- Heading = 30.00 Deg.
- Forward Speed = 0.00 Knots
- Linearization Based on 1/20
Proc. is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

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### Motion Response Operators

**Results are in Body System**

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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**Table 2:**

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**Table 3:**

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**Table 4:**

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**Table 5:**

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Trim Angle = 0.00 Deg.
GMT = 41.4 Meters
Roll Gy. Radius = 20.4 Meters
Pitch Gy. Radius = 48.6 Meters
Yaw Gy. Radius = 48.6 Meters
Heading = 45.00 Deg.
Forward Speed = 0.00 Knots
Linearization Based on 1/20

--- MOTION RESPONSE OPERATORS ---
Results are in Body System
Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0
Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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### MOTION RESPONSE OPERATORS

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified
Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Results are in Body System
* Draft = 7.0 Meters  Trim Angle = 0.00 Deg.  GMT = 41.4 Meters *
* Heading = 60.00 Deg.  Forward Speed = 0.00 Knots  Linearization Based on 1/ 20 *

*** MOTION RESPONSE OPERATORS ***

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified
### MOTION RESPONSE OPERATORS

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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Results are in Body System

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified
### Motion Response Operators

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

**Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified**

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* Heading = 90.00 Deg.  Forward Speed = 0.00 Knots  Linearization Based on 1/ 20 *

*** MOTION RESPONSE OPERATORS ***

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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66
**+MOTION RESPONSE OPERATORS++**

Results are in Body System

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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* Heading = 105.00 Deg.  Forward Speed = 0.00 Knots  Linearization Based on 1/ 20

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### E N C O U N T E R  S u r g e / W a v e  A m p l i t u d e  /---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/-/---/
Results are in Body System

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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--- M O T I O N   R E S P O N S E   O P E R A T O R S ---

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

--- M O T I O N   R E S P O N S E   O P E R A T O R S ---

Results are in Body System
Draft = 7.0 Meters  Trim Angle = 0.00 Deg.  GMT = 41.4 Meters
Heading = 105.00 Deg.  Forward Speed = 0.00 Knots  Linearization Based on 1/20

+++ MOTION RESPONSE OPERATORS +++
Results are in Body System
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Page

28

Licensee - Acergy
Rev 7.02.034
***************************************************************************************************************
*
*** MOSES
***
*
*
---------------10 June, 2008
*
*
*
*
*
*
Draft
=
7.0 Meters
Trim Angle
=
0.00 Deg.
GMT
= 41.4 Meters *
*
Roll Gy. Radius
= 20.4 Meters
Pitch Gy. Radius = 48.6 Meters
Yaw Gy. Radius
= 48.6 Meters *
*
Heading
= 120.00 Deg.
Forward Speed
= 0.00 Knots
Linearization Based on 1/ 20
*
*
*
***************************************************************************************************************

Ser254

+++ M O T I O N
R E S P O N S E
O P E R A T O R S +++
=========================================================
Results are in Body System
Of Point On Body BARGE At X =

110.0 Y =

10.0 Z =

30.0

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified
E N C O U N T E R
-------------------Frequency
Period
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5.75
5.50
5.25
5.00
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4.50
4.25
4.00
3.75
3.50

Surge /
Sway /
Heave /
Roll /
Pitch /
Yaw /
Wave Ampl.
Wave Ampl.
Wave Ampl.
Wave Ampl.
Wave Ampl.
Wave Ampl.
/--------------/ /--------------/ /--------------/ /--------------/ /--------------/ /--------------/
Ampl.
Phase
Ampl.
Phase
Ampl.
Phase
Ampl.
Phase
Ampl.
Phase
Ampl.
Phase
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0.074
0.078
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0.234
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0.198
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0.080
0.060
0.038
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0.022
0.020
0.012
0.020
0.016
0.019
0.007
0.007
0.003
0.002
0.001

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0.019
0.021
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0.013
0.004
0.004

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0.011
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0.008
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0.000
0.000

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0.409
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0.401
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0.367
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0.275
0.247
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0.035
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0.016
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-59
111
55
7
-122
139
-95


* Draft = 7.0 Meters  Trim Angle = 0.00 Deg.  GMT = 41.4 Meters
* Heading = 120.00 Deg.  Forward Speed = 0.00 Knots  Linearization Based on 1/ 20

+++ MOTION RESPONSE OPERATORS +++

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0
Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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E N C O U N T E R     Surge / Wave Ampl. / Roll / Wave Ampl. Yaw / Wave Ampl. Frequency Period / Wave Ampl. Phase / Phase / Phase / Phase / Phase / Phase / Phase / Phase / Phase / Phase / Phase
-----------------/--------/--------/--------/--------/--------/--------/--------/--------/--------/--------/--------
0.1571 40.00  0.653 -99  0.653 79  0.996 -9  0.102 81  0.101 81  0.071 -8
0.1611 39.00  0.650 -100  0.650 78  0.996 -10  0.107 80  0.107 80  0.075 -9
0.1653 38.00  0.647 -100  0.647 77  0.995 -10  0.113 80  0.112 80  0.079 -9
0.1698 37.00  0.643 -101  0.643 77  0.995 -11  0.119 79  0.118 79  0.083 -10
0.1745 36.00  0.639 -102  0.639 76  0.994 -12  0.126 79  0.125 79  0.088 -10
0.1795 35.00  0.635 -102  0.635 75  0.994 -12  0.133 78  0.132 78  0.093 -11
0.1848 34.00  0.630 -103  0.631 74  0.993 -13  0.141 77  0.140 77  0.098 -12
0.1904 33.00  0.625 -104  0.626 73  0.992 -14  0.150 76  0.148 76  0.104 -13
0.1963 32.00  0.620 -105  0.620 72  0.991 -15  0.159 76  0.158 76  0.110 -13
0.2027 31.00  0.613 -106  0.614 71  0.990 -16  0.170 75  0.168 75  0.117 -14
0.2094 30.00  0.606 -107  0.607 70  0.988 -17  0.181 74  0.179 74  0.124 -15
0.2167 29.00  0.599 -108  0.600 68  0.987 -18  0.193 72  0.191 72  0.131 -16
0.2244 28.00  0.590 -110  0.591 67  0.985 -20  0.207 71  0.205 71  0.142 -18
0.2327 27.00  0.580 -112  0.582 65  0.982 -21  0.223 70  0.220 70  0.152 -19
0.2417 26.00  0.569 -114  0.571 63  0.979 -23  0.240 68  0.236 68  0.163 -21
0.2515 25.00  0.556 -116  0.559 60  0.976 -25  0.259 66  0.255 66  0.175 -23
0.2618 24.00  0.542 -118  0.546 58  0.972 -27  0.280 64  0.276 64  0.188 -24
0.2732 23.00  0.526 -121  0.530 55  0.967 -30  0.304 62  0.299 62  0.203 -27
0.2856 22.00  0.506 -124  0.512 51  0.961 -33  0.331 59  0.325 60  0.220 -29
0.2992 21.00  0.484 -127  0.491 47  0.953 -36  0.361 56  0.354 57  0.238 -32
0.3142 20.00  0.458 -131  0.467 42  0.943 -40  0.395 53  0.387 53  0.258 -36
0.3307 19.00  0.427 -136  0.439 37  0.930 -44  0.434 49  0.425 49  0.280 -40
0.3491 18.00  0.391 -142  0.407 30  0.914 -49  0.477 44  0.467 45  0.305 -44
0.3696 17.00  0.348 -149  0.369 21  0.893 -56  0.526 39  0.515 39  0.331 -50
0.3808 16.50  0.324 -154  0.348 16  0.880 -59  0.553 36  0.541 36  0.344 -53
0.3927 16.00  0.297 -159  0.325 10  0.864 -63  0.580 32  0.569 33  0.358 -56
0.4054 15.50  0.268 -164  0.301 4  0.847 -67  0.609 28  0.599 29  0.371 -60
0.4189 15.00  0.236 -171  0.275 -3  0.826 -72  0.639 24  0.629 25  0.384 -64
0.4333 14.50  0.202 -178  0.249 -12  0.803 -77  0.669 19  0.661 21  0.396 -68
0.4488 14.00  0.166 -186  0.222 -23  0.775 -83  0.700 14  0.694 15  0.407 -73
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0.4742 13.25  0.112 -196  0.182 -44  0.726 -93  0.744 5  0.746 7  0.420 -81
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0.5027 12.50  0.077 -207  0.149 -74  0.667 -105  0.778 -6  0.799 -3  0.426 -90
### MOTION RESPONSE OPERATORS

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Results are in Body System
Draft = 7.0 Meters  Trim Angle = 0.00 Deg.  GMT = 41.4 Meters
Heading = 135.00 Deg.  Forward Speed = 0.00 Knots  Linearization Based on 1/20

+++ MOTION RESPONSE OPERATORS +++
Results are in Body System
Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0
Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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### Motion Response Operators

**Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified**

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The process is DEFAULT: Units are Degrees, Meters, and M-Tons unless specified.
**MOSES**

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10 June, 2008

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**Draft** = 7.0 Meters  
**Trim Angle** = 0.00 Deg.  
**GMT** = 41.4 Meters

**Roll Gy. Radius** = 20.4 Meters  
**Pitch Gy. Radius** = 48.6 Meters  
**Yaw Gy. Radius** = 48.6 Meters

**Heading** = 150.00 Deg.  
**Forward Speed** = 0.00 Knots  
**Linearization Based on 1/20**

---

### MOTION RESPONSE OPERATORS

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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### Motion Response Operators

Results are in Body System

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Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Results are in Body System
Draft = 7.0 Meters  Trim Angle = 0.00 Deg.  GMT = 41.4 Meters
Heading = 165.00 Deg.  Forward Speed = 0.00 Knots  Linearization Based on 1/20

+++ MOTION RESPONSE OPERATORS +++

Results are in Body System
Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0
Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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## MOTION RESPONSE OPERATORS

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

### MOTION RESPONSE OPERATORS

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### ***MOTION RESPONSE OPERATORS***

Results are in Body System

**Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified**

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### MOTION RESPONSE OPERATORS

Results are in Body System

Of Point On Body BARGE At X = 110.0  Y = 10.0  Z = 30.0

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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### Motion Statistics

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

#### Single Amplitude Motions

<table>
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<tr>
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<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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#### Single Amplitude Velocities

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#### Single Amplitude Accelerations

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### MOTION STATISTICS ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

#### Single Amplitude Motions ####

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<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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#### Single Amplitude Velocities ####

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<th>Yaw</th>
<th>Mag</th>
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#### Single Amplitude Accelerations ####

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**NOTES:**

- Draft = 7.0 Meters
- Trim Angle = 0.00 Deg.
- GMT = 41.4 Meters
- Roll Gy. Radius = 20.4 Meters
- Pitch Gy. Radius = 48.6 Meters
- Yaw Gy. Radius = 48.6 Meters
- JONSWAP Height = 1.00 Meters
- Period = 5.0 Sec.
- M. Heading = 0.0 Deg.
- S. Coef. = 200.
### MOTION STATISTICS ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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### MOTION STATISTICS ###

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#### Single Amplitude Velocities ####

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#### Single Amplitude Accelerations ####

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<th>Mag</th>
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*** M O T I O N   S T A T I S T I C S ***  

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<th>Yaw</th>
<th>Mag</th>
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Single Amplitude Velocities  

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<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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<tbody>
<tr>
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<td>0.040</td>
<td>0.003</td>
<td>0.048</td>
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Single Amplitude Accelerations  

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<th>Pitch</th>
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<th>Mag</th>
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### Single Amplitude Motions

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### Single Amplitude Velocities

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<td>0.317</td>
<td>0.017</td>
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### Single Amplitude Accelerations

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<td>0.010</td>
<td>0.145</td>
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</table>
Parameters:

- Draft = 7.0 Meters
- Roll Gy. Radius = 20.4 Meters
- JONSWAP Height = 1.00 Meters
- S. Coef. = 200.

Mooring System:

- Trim Angle = 0.00 Deg.
- Period = 10.0 Sec.
- M. Heading = 0.0 Deg.
- Roll Gy. Radius = 48.6 Meters
- Pitch Gy. Radius = 48.6 Meters
- Yaw Gy. Radius = 48.6 Meters
- Gamma = 2.0

Results:

- Maximum Responses Based on a Multiplier of 3.720
- Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

Single Amplitude Motions:

<table>
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<tr>
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<th>Mag</th>
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<tr>
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Single Amplitude Velocities:

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<tbody>
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Single Amplitude Accelerations:

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<th>Yaw</th>
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<tbody>
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### MOTION STATISTICS ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

#### Single Amplitude Motions

<table>
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<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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<tbody>
<tr>
<td>RMS</td>
<td>0.062</td>
<td>0.006</td>
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#### Single Amplitude Velocities

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#### Single Amplitude Accelerations

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### Motion Statistics ###

Results are in Body System

Of Point On Body BARGE at \( X = 110.0 \) \( Y = 10.0 \) \( Z = 30.0 \)

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

#### Single Amplitude Motions ####

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<th>Pitch</th>
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<th>Mag</th>
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#### Single Amplitude Velocities ####

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<th>Yaw</th>
<th>Mag</th>
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#### Single Amplitude Accelerations ####

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<th>Yaw</th>
<th>Mag</th>
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<td>0.129</td>
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### MOSES Statistics ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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<tbody>
<tr>
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#### Single Amplitude Velocities

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<th>Pitch</th>
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<th>Mag</th>
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#### Single Amplitude Accelerations

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### MOTION STATISTICS ###

Results are in Body System
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Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

#### Single Amplitude Motions ####

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#### Single Amplitude Velocities ####

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#### Single Amplitude Accelerations ####

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<th>Mag</th>
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### Motion Statistics ###

Results are in Body System

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Maximum Responses Based on a Multiplier of 3.720

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<th>Yaw</th>
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<tbody>
<tr>
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<td>0.133</td>
<td>0.010</td>
<td>0.204</td>
<td>0.009</td>
<td>0.148</td>
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<td>0.024</td>
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#### Single Amplitude Velocities

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<th>Mag</th>
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<tbody>
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#### Single Amplitude Accelerations

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### MOTION STATISTICS ###

Results are in Body System

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Maximum Responses Based on a Multiplier of 3.720

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#### Single Amplitude Motions ####

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<th>Yaw</th>
<th>Mag</th>
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#### Single Amplitude Velocities ####

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#### Single Amplitude Accelerations ####

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--- MOSES ---

10 June, 2008

---

Draft = 7.0 Meters
Trim Angle = 0.00 Deg.
GMT = 41.4 Meters

Roll Gy. Radius = 20.4 Meters
Pitch Gy. Radius = 48.6 Meters
Yaw Gy. Radius = 48.6 Meters

JONSWAP Height = 1.00 Meters
Period = 20.0 Sec.
M. Heading = 0.0 Deg.

S. Coef. = 200.
Gamma = 2.0

---

+++ MOTION STATISTICS +++

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Single Amplitude Motions

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<tr>
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<th>Sway</th>
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Single Amplitude Velocities

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Single Amplitude Accelerations

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#### Single Amplitude Velocities

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#### Single Amplitude Accelerations

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### MOTION STATISTICS ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

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### Single Amplitude Motions ###

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### Single Amplitude Velocities ###

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### Single Amplitude Accelerations ###

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### Motion Statistics ###

Results are in Body System

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Maximum Responses Based on a Multiplier of 3.720

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#### Single Amplitude Motions ####

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<th>Yaw</th>
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#### Single Amplitude Velocities ####

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#### Single Amplitude Accelerations ####

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### MOTION STATISTICS ###

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</table>

Single Amplitude Accelerations

<table>
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<tr>
<th></th>
<th>Surge</th>
<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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</thead>
<tbody>
<tr>
<td>Root Mean Square</td>
<td>0.023</td>
<td>0.020</td>
<td>0.044</td>
<td>0.053</td>
<td>0.064</td>
<td>0.028</td>
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<tr>
<td>Ave of 1/3 Highest</td>
<td>0.047</td>
<td>0.040</td>
<td>0.089</td>
<td>0.105</td>
<td>0.129</td>
<td>0.057</td>
<td>0.108</td>
</tr>
<tr>
<td>Ave of 1/10 Highest</td>
<td>0.060</td>
<td>0.052</td>
<td>0.113</td>
<td>0.134</td>
<td>0.164</td>
<td>0.072</td>
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<tr>
<td>Maximum</td>
<td>0.087</td>
<td>0.075</td>
<td>0.165</td>
<td>0.196</td>
<td>0.239</td>
<td>0.105</td>
<td>0.201</td>
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### Motion Statistics

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

#### Single Amplitude Motions

<table>
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<tr>
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<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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<tbody>
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#### Single Amplitude Velocities

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<th>Pitch</th>
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<th>Mag</th>
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#### Single Amplitude Accelerations

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</table>
### MOTION STATISTICS ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

**Single Amplitude Motions**

<table>
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<tr>
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<th>Yaw</th>
<th>Mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
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**Single Amplitude Velocities**

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<th>Yaw</th>
<th>Mag</th>
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<tbody>
<tr>
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<td>0.086</td>
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<td>0.069</td>
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**Single Amplitude Accelerations**

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<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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</thead>
<tbody>
<tr>
<td>RMS</td>
<td>0.017</td>
<td>0.016</td>
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<td>0.204</td>
<td>0.097</td>
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</table>

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106
**MOSES**

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10 June, 2008

---

**Draft** = 7.0 Meters  **Trim Angle** = 0.00 Deg.  **GMT** = 41.4 Meters

**Roll Gy. Radius** = 20.4 Meters  **Pitch Gy. Radius** = 48.6 Meters  **Yaw Gy. Radius** = 48.6 Meters

**JONSWAP Height** = 1.00 Meters  **Period** = 11.0 Sec.  **M. Heading** = 45.0 Deg.

**S. Coef.** = 200.

---

**MOTION STATISTICS**

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

---

### Single Amplitude Motions

<table>
<thead>
<tr>
<th></th>
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<th>Mag</th>
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<tbody>
<tr>
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<td>0.060</td>
<td>0.187</td>
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<td>0.759</td>
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### Single Amplitude Velocities

<table>
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<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
</tr>
</thead>
<tbody>
<tr>
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### Single Amplitude Accelerations

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<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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<td>0.049</td>
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<tr>
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<tr>
<td>Maximum</td>
<td>0.060</td>
<td>0.057</td>
<td>0.160</td>
<td>0.162</td>
<td>0.182</td>
<td>0.088</td>
<td>0.180</td>
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</table>
Draft = 7.0 Meters  Trim Angle = 0.00 Deg.  GMT = 41.4 Meters
JONSWAP Height = 1.00 Meters  Period = 12.0 Sec.  M. Heading = 45.0 Deg.
S. Coef. = 200.

### MOTION STATISTICS ###

Results are in Body System
Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0
Maximum Responses Based on a Multiplier of 3.720
Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

#### Single Amplitude Motions ####

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<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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<tbody>
<tr>
<td>Root Mean Square</td>
<td>0.066</td>
<td>0.070</td>
<td>0.199</td>
<td>0.154</td>
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#### Single Amplitude Velocities ####

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<th>Mag</th>
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</thead>
<tbody>
<tr>
<td>Root Mean Square</td>
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#### Single Amplitude Accelerations ####

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<th>Yaw</th>
<th>Mag</th>
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<td>0.015</td>
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<td>0.145</td>
<td>0.163</td>
<td>0.080</td>
<td>0.171</td>
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Results are in Body System

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Maximum Responses Based on a Multiplier of 3.720

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<th>Mag</th>
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<td>0.081</td>
<td>0.209</td>
<td>0.146</td>
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<td>Ave 1/3</td>
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<td>0.161</td>
<td>0.417</td>
<td>0.292</td>
<td>0.304</td>
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<td>0.473</td>
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#### Single Amplitude Velocities ####

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<td>0.144</td>
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#### Single Amplitude Accelerations ####

<table>
<thead>
<tr>
<th></th>
<th>Surge</th>
<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMMS</td>
<td>0.014</td>
<td>0.014</td>
<td>0.038</td>
<td>0.035</td>
<td>0.039</td>
<td>0.019</td>
<td>0.043</td>
</tr>
<tr>
<td>Ave 1/3</td>
<td>0.029</td>
<td>0.028</td>
<td>0.077</td>
<td>0.070</td>
<td>0.078</td>
<td>0.039</td>
<td>0.087</td>
</tr>
<tr>
<td>Ave 1/10</td>
<td>0.037</td>
<td>0.036</td>
<td>0.098</td>
<td>0.089</td>
<td>0.100</td>
<td>0.049</td>
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<tr>
<td>Maximum</td>
<td>0.053</td>
<td>0.053</td>
<td>0.142</td>
<td>0.130</td>
<td>0.145</td>
<td>0.072</td>
<td>0.161</td>
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</table>
### Motion Statistics ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

#### Single Amplitude Motions ####

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<th>Yaw</th>
<th>Mag</th>
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<tr>
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#### Single Amplitude Velocities ####

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<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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</thead>
<tbody>
<tr>
<td>RMSE</td>
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<td>0.033</td>
<td>0.084</td>
<td>0.063</td>
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<td>0.083</td>
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<td>0.160</td>
<td>0.171</td>
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<td>0.133</td>
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#### Single Amplitude Accelerations ####

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<th>Yaw</th>
<th>Mag</th>
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<tr>
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<td>0.031</td>
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<td>0.035</td>
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<td>0.051</td>
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<td>0.130</td>
<td>0.065</td>
<td>0.151</td>
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</table>
### Motion Statistics ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

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#### Single Amplitude Motions ####

<table>
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<tr>
<th>Motion</th>
<th>Surge</th>
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<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root Mean Square</td>
<td>0.001</td>
<td>0.058</td>
<td>0.025</td>
<td>0.067</td>
<td>0.003</td>
<td>0.005</td>
<td>0.063</td>
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<td>0.116</td>
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<td>0.007</td>
<td>0.011</td>
<td>0.127</td>
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<tr>
<td>Ave of 1/10 Highest</td>
<td>0.002</td>
<td>0.148</td>
<td>0.064</td>
<td>0.170</td>
<td>0.009</td>
<td>0.014</td>
<td>0.162</td>
</tr>
<tr>
<td>Maximum</td>
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<td>0.094</td>
<td>0.249</td>
<td>0.013</td>
<td>0.020</td>
<td>0.236</td>
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</table>

#### Single Amplitude Velocities ####

<table>
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<tr>
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<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
</tr>
</thead>
<tbody>
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<td>0.025</td>
<td>0.064</td>
<td>0.003</td>
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<tr>
<td>Maximum</td>
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<td>0.092</td>
<td>0.239</td>
<td>0.012</td>
<td>0.021</td>
<td>0.248</td>
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#### Single Amplitude Accelerations ####

<table>
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<tr>
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<th>Surge</th>
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<th>Mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root Mean Square</td>
<td>0.001</td>
<td>0.069</td>
<td>0.025</td>
<td>0.064</td>
<td>0.003</td>
<td>0.006</td>
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### MOTION STATISTICS ###

Results are in Body System

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Maximum Responses Based on a Multiplier of 3.720

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<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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</thead>
<tbody>
<tr>
<td>RMS</td>
<td>0.002</td>
<td>0.131</td>
<td>0.079</td>
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<td>Ave of 1/3 Highest</td>
<td>0.005</td>
<td>0.262</td>
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<td>0.294</td>
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<td>0.039</td>
<td>0.036</td>
<td>0.570</td>
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</table>

#### Single Amplitude Velocities ####

<table>
<thead>
<tr>
<th></th>
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<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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<tbody>
<tr>
<td>RMS</td>
<td>0.002</td>
<td>0.115</td>
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<td>0.182</td>
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<td>0.229</td>
<td>0.130</td>
<td>0.364</td>
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<td>0.018</td>
<td>0.264</td>
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<tr>
<td>Maximum</td>
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<td>0.427</td>
<td>0.241</td>
<td>0.676</td>
<td>0.033</td>
<td>0.034</td>
<td>0.490</td>
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#### Single Amplitude Accelerations ####

<table>
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<tr>
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<th>Yaw</th>
<th>Mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>0.002</td>
<td>0.105</td>
<td>0.055</td>
<td>0.152</td>
<td>0.007</td>
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<td>Ave of 1/3 Highest</td>
<td>0.004</td>
<td>0.210</td>
<td>0.110</td>
<td>0.304</td>
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<td>0.018</td>
<td>0.237</td>
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<td>Maximum</td>
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<td>0.390</td>
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<td>0.566</td>
<td>0.028</td>
<td>0.033</td>
<td>0.440</td>
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</table>
Draft = 7.0 Meters
Trim Angle = 0.00 Deg.
GMT = 41.4 Meters
Roll Gy. Radius = 20.4 Meters
Pitch Gy. Radius = 48.6 Meters
Yaw Gy. Radius = 48.6 Meters
JONSWAP Height = 1.00 Meters
Period = 6.0 Sec.
M. Heading = 90.0 Deg.
S. Coef. = 200.

*** MOT I O N S T A T I S T I C S ***

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---

**Single Amplitude Motions**
---

**Root Mean Square**: 0.004, 0.210, 0.155, 0.440, 0.020, 0.012, 0.261
**Ave of 1/3 Highest**: 0.009, 0.420, 0.309, 0.880, 0.040, 0.025, 0.522
**Ave of 1/10 Highest**: 0.011, 0.576, 0.395, 1.123, 0.051, 0.031, 0.665
**Maximum**: 0.016, 0.781, 0.576, 1.638, 0.074, 0.046, 0.971

---

**Single Amplitude Velocities**
---

**Root Mean Square**: 0.003, 0.166, 0.115, 0.328, 0.015, 0.010, 0.202
**Ave of 1/3 Highest**: 0.007, 0.331, 0.230, 0.656, 0.030, 0.020, 0.403
**Ave of 1/10 Highest**: 0.009, 0.422, 0.293, 0.836, 0.038, 0.026, 0.514
**Maximum**: 0.013, 0.616, 0.427, 1.220, 0.056, 0.038, 0.750

---

**Single Amplitude Accelerations**
---

**Root Mean Square**: 0.003, 0.135, 0.088, 0.250, 0.012, 0.009, 0.161
**Ave of 1/3 Highest**: 0.005, 0.269, 0.175, 0.500, 0.023, 0.018, 0.321
**Ave of 1/10 Highest**: 0.007, 0.343, 0.233, 0.637, 0.029, 0.022, 0.410
**Maximum**: 0.010, 0.501, 0.326, 0.930, 0.043, 0.033, 0.597
### MOTION STATISTICS ###

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<th>Yaw</th>
<th>Mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root Mean Square</td>
<td>0.005</td>
<td>0.239</td>
<td>0.217</td>
<td>0.596</td>
<td>0.027</td>
<td>0.014</td>
<td>0.323</td>
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#### Single Amplitude Velocities ####

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<tr>
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<th>Mag</th>
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<td>0.039</td>
<td>0.856</td>
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<th>Mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root Mean Square</td>
<td>0.003</td>
<td>0.134</td>
<td>0.104</td>
<td>0.295</td>
<td>0.013</td>
<td>0.008</td>
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<tr>
<td>Ave of 1/3 Highest</td>
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<td>0.589</td>
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<td>0.016</td>
<td>0.309</td>
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<td>0.030</td>
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### MOTION STATISTICS ###

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<th>Mag</th>
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#### Single Amplitude Velocities

<table>
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<tr>
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#### Single Amplitude Accelerations

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### Motion Statistics

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

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Single Amplitude Motions

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Single Amplitude Velocities

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Single Amplitude Accelerations

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#### Single Amplitude Accelerations

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### MOTION STATISTICS ###

---

Results are in Body System

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Maximum Responses Based on a Multiplier of 3.720

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#### Single Amplitude Velocities

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#### Single Amplitude Velocities ####

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#### Single Amplitude Accelerations ####

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### Motion Statistics ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and N-Tons Unless Specified

#### Single Amplitude Motions

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#### Single Amplitude Velocities

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#### Single Amplitude Accelerations

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**MOSES***

10 June, 2008

- Draft = 7.0 Meters
- Trim Angle = 0.00 Deg.
- GMT = 41.4 Meters
- Roll Gy. Radius = 20.4 Meters
- Pitch Gy. Radius = 48.6 Meters
- Yaw Gy. Radius = 48.6 Meters
- JONSWAP Height = 1.00 Meters
- Period = 18.0 Sec.
- H. Heading = 90.0 Deg.
- S. Coef. = 200.

---

+++ MOTION STATISTICS +++

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<th>Yaw</th>
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Single Amplitude Velocities

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Single Amplitude Accelerations

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### Motion Statistics

Results are in Body System

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Single Amplitude Velocities

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Single Amplitude Accelerations

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MOTION STATISTICS

Results are in Body System
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Maximum Responses Based on a Multiplier of 3.720
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Single Amplitude Velocities

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Single Amplitude Accelerations

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### MOTION STATISTICS ###

**Results are in Body System**

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Maximum Responses Based on a Multiplier of 3.720

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#### Single Amplitude Velocities

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#### Single Amplitude Accelerations

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#### Single Amplitude Velocities

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<td>0.203</td>
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#### Single Amplitude Accelerations

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<tr>
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<th>Heave</th>
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<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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<td>Maximum</td>
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<td>0.195</td>
<td>0.237</td>
<td>0.105</td>
<td>0.161</td>
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</table>
Draft = 7.0 Meters  Trim Angle = 0.00 Deg.  GMT = 41.4 Meters
* JONSWAP Height = 1.00 Meters  Period = 9.0 Sec.  M. Heading = 135.0 Deg.
* S. Coef. = 200.

**+++ MOTION STATISTICS+++**

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

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<th>Yaw</th>
<th>Mag</th>
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<td>0.041</td>
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<tr>
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### Single Amplitude Velocities

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<th>Yaw</th>
<th>Mag</th>
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### Single Amplitude Accelerations

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<td>RM</td>
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<td>0.162</td>
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### MOTION STATISTICS ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

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<th>Yaw</th>
<th>Mag</th>
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<td>0.148</td>
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<td>0.096</td>
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#### Single Amplitude Velocities

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<tbody>
<tr>
<td>RMS</td>
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<td>0.354</td>
<td>0.175</td>
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#### Single Amplitude Accelerations

<table>
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<td>Mag</td>
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<tr>
<td>Root Mean Square</td>
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### MOTION STATISTICS ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

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### Single Amplitude Motions ###

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<th>Yaw</th>
<th>Mag</th>
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</thead>
<tbody>
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### Single Amplitude Velocities ###

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<td>0.181</td>
<td>0.088</td>
<td>0.156</td>
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<th>Mag</th>
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<td>0.328</td>
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<th>Mag</th>
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<th>Pitch</th>
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<th>Mag</th>
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<td>0.039</td>
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<tbody>
<tr>
<td>Root Mean Square</td>
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<td>0.146</td>
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<td>0.561</td>
<td>0.315</td>
<td>0.835</td>
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#### Single Amplitude Velocities ####

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<tr>
<td>Root Mean Square</td>
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#### Single Amplitude Accelerations ####

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<th>Heave</th>
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<th>Pitch</th>
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<th>Mag</th>
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Draft = 7.0 Meters  Trim Angle = 0.00 Deg.  GMT = 41.4 Meters
JONSWAP Height = 1.00 Meters  Period = 14.0 Sec.  M. Heading = 135.0 Deg.
S. Coef. = 200.

+++ MOTION STATISTICS +++
Results are in Body System
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Maximum Responses Based on a Multiplier of 3.720
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--- Single Amplitude Motions ---

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### MOTION STATISTICS ###

Results are in Body System

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<td>Maximum</td>
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<td>0.006</td>
<td>0.013</td>
<td>0.011</td>
<td>0.063</td>
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#### Single Amplitude Velocities

<table>
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#### Single Amplitude Accelerations

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<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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<td>0.044</td>
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<td>0.060</td>
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<td>Maximum</td>
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<td>0.007</td>
<td>0.013</td>
<td>0.010</td>
<td>0.065</td>
<td>0.008</td>
<td>0.088</td>
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</table>
*** MOTION STATISTICS ***  
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<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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<tbody>
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<td>0.011</td>
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<td>0.052</td>
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### Single Amplitude Velocities  
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### Single Amplitude Accelerations  
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139
### MOTION STATISTICS ###

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#### Single Amplitude Velocities ####

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</table>
### Motion Statistics

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

**Single Amplitude Motions**

<table>
<thead>
<tr>
<th></th>
<th>Surge</th>
<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root Mean Square</td>
<td>0.061</td>
<td>0.005</td>
<td>0.045</td>
<td>0.011</td>
<td>0.126</td>
<td>0.007</td>
<td>0.076</td>
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<tr>
<td>Ave of 1/3 Highest</td>
<td>0.122</td>
<td>0.010</td>
<td>0.090</td>
<td>0.023</td>
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**Single Amplitude Velocities**

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<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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</thead>
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**Single Amplitude Accelerations**

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<th>Pitch</th>
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<tbody>
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<td>Yaw Gy. Radius</td>
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<td>JONSWAP Height</td>
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### Motion Statistics

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

#### Single Amplitude Motions

<table>
<thead>
<tr>
<th></th>
<th>Surge</th>
<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>0.058</td>
<td>0.005</td>
<td>0.074</td>
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<td>0.157</td>
<td>0.008</td>
<td>0.094</td>
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#### Single Amplitude Velocities

<table>
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<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
</tr>
</thead>
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#### Single Amplitude Accelerations

<table>
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<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
</tr>
</thead>
<tbody>
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<tr>
<td>Ave of 1/3 Highest</td>
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<td>0.035</td>
<td>0.009</td>
<td>0.094</td>
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<td>0.059</td>
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<td>Ave of 1/10 Highest</td>
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</table>
### MOTION STATISTICS ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

<table>
<thead>
<tr>
<th>Single Amplitude Motions</th>
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<td><strong>Root Mean Square</strong></td>
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</tr>
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<td>Ave of 1/10 Highest</td>
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<tr>
<td>Maximum</td>
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<tr>
<th>Single Amplitude Velocities</th>
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<tbody>
<tr>
<td><strong>Root Mean Square</strong></td>
</tr>
<tr>
<td>Surge</td>
</tr>
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<th>Single Amplitude Accelerations</th>
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</thead>
<tbody>
<tr>
<td><strong>Root Mean Square</strong></td>
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<td>Surge</td>
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<td>Ave of 1/3 Highest</td>
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<td>0.052</td>
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<td>Maximum</td>
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</table>
**Draft** = 7.0 Meters  
**Trim Angle** = 0.00 Deg.  
**GMT** = 41.4 Meters  

**Roll Gy. Radius** = 20.4 Meters  
**Pitch Gy. Radius** = 48.6 Meters  
**Yaw Gy. Radius** = 48.6 Meters  

**JONSWAP Height** = 1.00 Meters  
**Period** = 11.0 Sec.  
**M. Heading** = 180.0 Deg.  

**S. Coef.** = 200.  
**Gamma** = 2.0

---

### **MISSION STATISTICS**

---

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

---

**Single Amplitude Motions**

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<table>
<thead>
<tr>
<th></th>
<th>Surge</th>
<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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<tbody>
<tr>
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**Single Amplitude Velocities**

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<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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**Single Amplitude Accelerations**

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<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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### Motion Statistics

Results are in Body System

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Maximum Responses Based on a Multiplier of 3.720

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<tr>
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<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
<th>Mag</th>
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<tbody>
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<td>0.175</td>
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#### Single Amplitude Velocities

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<th>Roll</th>
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<th>Yaw</th>
<th>Mag</th>
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#### Single Amplitude Accelerations

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### MOTION STATISTICS ###

Results are in Body System

Of Point On Body BARGE At X = 110.0 Y = 10.0 Z = 30.0

Maximum Responses Based on a Multiplier of 3.720

Process is DEFAULT: Units Are Degrees, Meters, and M-Tons Unless Specified

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--- Motion Statistics ---

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Maximum Responses Based on a Multiplier of 3.720

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### Single Amplitude Velocities

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### Single Amplitude Accelerations

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