NOWDRC Agreement #103

Technical Validation of Existing U.S. Flagged Barges as a Feeder Solution for the U.S. Offshore Wind Industry:

Dynamic Barge Motions and Mooring Study Technical Report

Milestone Number 2.4 (Rev 0)

Prepared for: Mel Schultz
Program Manager,
The National Offshore Wind Research and Development Consortium, NOWRDC

and

New York State Energy Research and Development Authority

Prepared by: Melissa Hertel, Chris Hooper & Ali Mohtat (of Crowley Engineering Services)

Crowley Marine Services

Seattle, WA

Project Manager: Melissa Hertel, PE
Sr. Naval Architect

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Abstract

This report provides a description of motions and mooring analyses developed as part of the technical validation of existing U.S. flagged barges as offshore wind turbine generator (WTG) installation feeder vessels. This report includes (1) a frequency domain motion study developed for use in a weather downtime simulation, (2) a mooring analysis to evaluate the mooring arrangement tested in the *maritime navigation mission simulations* to determine environmental limits, and (3) a time domain motion analysis of the moored vessel to demonstrate that a render/recovery winch is a workable alternative to "stretchy" lines, which are likely too large to handle.

Keywords

Feeder barge, tight-line operation, wind turbine generator installation, wind turbine installation vessel, frequency domain motion analysis, mooring, time domain motion analysis.

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Acronyms and Abbreviations

CES	Crowley Engineering Services
CF	cargo feeder (prefix to identify tug or barge that is part of CFS)
CFS	cargo feeder system (including tug, barge, and support vessel, if required)
CFV	cargo feeder vessel (any vessel or assembly that deliver WTG components offshore)
CGS	Crowley Government Services
CMS	Crowley Marine Services
DNV	Det Norske Veritas (was DNV GL Det Norske Veritas / Germanischer Lloyd)
DOF	degrees of freedom
ft	feet
HMPE	high modulus polyethylene
Hs	significant wave height
IEA	International Energy Agency
kJ	kilojoules
kWh	kilowatt hours
m/s	meters per second
MW	megawatts
MWS	marine warranty survey
N	newtons
NOWRDC	The National Offshore Wind Research and Development Consortium
NREL	National Renewable Energy Laboratory
NYS	New York State
NYSERDA	New York State Energy Research and Development Authority
OCMI	Officer in Charge, Marine Inspection
OEM	original equipment manufacturer
POI	points of interest
RAO	response amplitude operator
SRAO	spectral response amplitude operator
TBD	to be determined
Tp	wave period, peak
VOI	variables of interest
W	watts
WCS	worst case scenario
WDT	weather downtime
WTIV	wind turbine installation vessel
WTG	wind turbine generator

1 Executive Summary

1.1 Overview

Wind Turbine Installation Vessels (WTIV) are high value, high day-rate equipment whose primary role is installing wind turbine generators on site. Using WTIVs to ferry equipment to the installation site may not be cost effective if that operation can be conducted by a fleet of low-cost cargo feeder vessels (CFV). This could free up the WTIVs to remain on site and continually erect wind generators.

The overall study examines WTIV feeder system feasibility using a minimally modified deck cargo barge accompanied by the appropriate tugs. The analysis includes:

- Dynamic Motions Analysis – under tow and alongside the WTIV which is covered in this report and includes:
    - Frequency Domain Motions Study that is used to develop the weather/motions files for the weather downtime study (described in Reference 6.1.3.)
    - Mooring Analysis to confirm that mooring is practical for reasonable weather limits.
    - Time Domain Motions Analysis to predict motions when vessel is moored to WTIV and determine minimum breaking strength for mooring system components.
- Maneuvering Simulation – bringing barge to standoff zone and to make "soft landing"
- WTIV/Feeder Weather Down Time (WDT) Simulation – based on motions and maneuvering

The routes studied are Salem, MA to Empire Wind and Brooklyn, NY to Empire Wind.

1.2 Summary of Findings

1.2.1 Frequency Domain Motions Study

The study is developed in support of the weather downtime simulation. Using the motions study, a two tower-section / light ballast (LtBal-2T) base case was developed with the task list and weather limits described in Section A1.2 of Reference 6.1.3. The base case assumptions include: (1) a maximum landing velocity of 0.6 m/s, (2) 20 knots on beam / 25 knots on bow wind limits, (3) 2.0 m top and base motions, (4) 2-degree feeder roll or pitch and 2 m heave limits, and (5) standard cargo acceleration limits, the number of days required to complete one delivery round trip voyage for a feeder OR to complete one installation cycle for the WTIV are:

Days Required to Deliver One WTG by Month

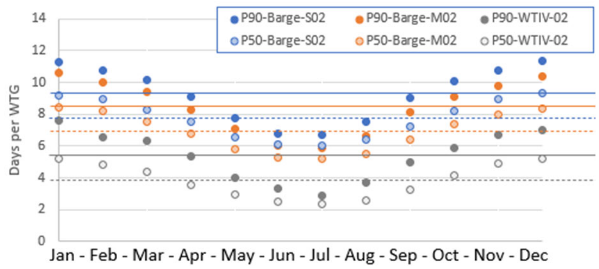


Figure 1 – Time to Install One WTG - Salem to Empire

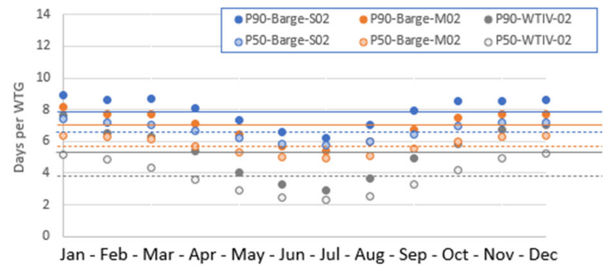


Figure 2 – Time to Install One WTG - Brooklyn to Empire

The annual average values for the year are shown with the horizontal lines.

See Reference 6.1.3 for additional findings.

1.2.2 Mooring Analysis

A mooring system with four breast and two spring lines with breaking strength of 276.1 MT (304 ST) each is satisfactory for winds up to 50 knots and 6 ft waves on the beam.

1.2.3 Time Domain Motions Analysis

The mooring system was found to be operable in unrestricted wave periods and directions for wave heights of up to 1.5 m, although substantially larger wave heights are workable if the wave periods do not align to the natural periods of the vessel mooring system. For waves predominately aligned to within +/-30 degrees of the feeder vessel centerline from bow or stern, the mooring system is operable up to wave heights around 3 m.

2 Introduction

Europe presently has a total installed offshore wind capacity of 28.3 GW. That corresponds to 5,785 grid-connected wind turbines across 12 countries.[1] There are two projects totaling 42 MW in operation in the United States with an additional 35.3 GW in various stages of development.[2] The U.S. offshore wind industry is just transitioning from the pilot stage to utility-scale commercial development.

Fixed foundation offshore wind turbines are installed in water depths of up to about 160 ft (50 m). Wind Turbine Installation Vessels (WTIVs) are self-propelled with azimuthing thrusters, a ship-shaped hull, and a jack-up system to lift the hull out of the water providing a stable foundation for a very large crane. The first Jones Act-compliant vessel, the 472-ft (144 m) *WTIV CHARYBDIS,* is currently under construction at a cost of a half billion dollars[3] with a day rate assumed to be above a quarter of a million dollars. It is highly unlikely that there will be enough WTIVs available to meet the needs of all the projects in the pipeline due to the high cost of Jones Act-compliant WTIVs.

Foreign flag WTIVs may be used to install offshore wind turbine generators (WTGs) if they do not transport any cargo within the U.S. territorial sea (46 U.S. Code § 55102). Jones-Act qualified cargo vessels are available to transport cargo, and they have day rates several orders of magnitude less than WTIVs. In theory, a cargo feeder vessel (CFV) could improve the efficiency of a WTIV by eliminating the time spent traveling to and from port. The CFV would deliver cargo to the WTIV just-in-time for it to transload the cargo, install the WTG and move to the next installation site. CFVs may also be able to operate out of ports with restrictive bridge clearance or water depth limitations, thus offering more flexibility for marshalling site selection.

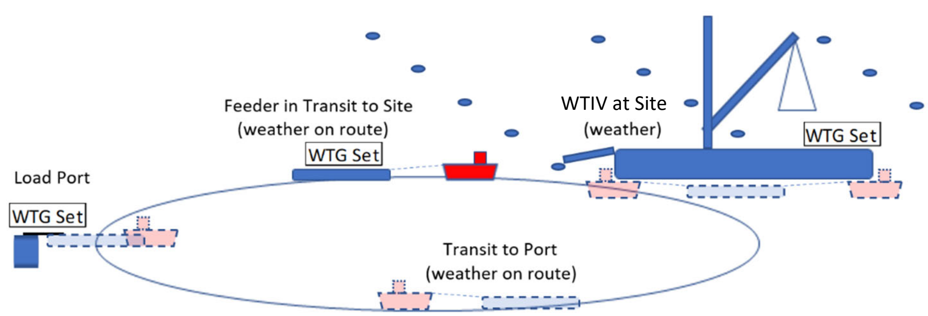


Figure 3 – WTIV with Feeder System

This study evaluates a cargo feeder system (CFS) comprised of a minimally modified deck cargo barge accompanied by the appropriate tugs in three key facets of the operation:

- Dynamic Motions Analysis – under tow and alongside the WTIV
- Maneuvering Simulation – bringing barge to standoff zone and to make "soft landing"
- WTIV/Feeder Weather Down Time (WDT) Simulation – based on motions and maneuvering

2.1 Background

Before existing U.S. flagged barges will be accepted as a cargo feeder vessel (CFV) solution, it must be demonstrated that they can safely deliver wind turbine generator (WTG) components to a wind turbine installation vessel (WTIV). The WTG components include very tall, heavy towers, heavy nacelles, and long blades which are subject to damage:

- During transit – if accelerations (x, y, z-directions) are beyond manufacturer specified limits, or
- During lift-off – if the top motions (lifting point) of a component are too large, the crane cannot hook the component and/or if the bottom motions are too great, the component might hit the barge structure or another component.

The feeder vessel or WTIV are subject to damage:

- Coming alongside – if the feeder athwartship velocity is too high and it lands hard, or
- While moored – if the feeder roll, pitch and heave are too high mooring line or fittings can fail or the cargo can hit the barge and damage it.

The motion analysis described in this report, will be used in the weather downtime study to calculate system throughput with various motion and acceleration limits.

The Marine Warranty Survey defines minimum acceleration values for design, however, the limits evaluated in this study exceed those requirements. The 455 series barge used for this study is a deck cargo barge that is strong enough to support the 15 MW reference WTG components used in this study. The sea fastenings require specific details that must be designed for each WTG component or transport frame.

The mooring and time domain motion analysis described in this report demonstrate that the feeder can be safely and securely moored to the WTIV. They will also establish environmental limits for use in the weather downtime study if the mooring system limits are more restrictive than other environmental or motions limits.

2.2 Intent

The purpose of this *dynamic motion analysis* is to predict the motions of the fully loaded barge while under tow at various sea states and headings to be used as input for the weather downtime study and to establish limiting sea states for operations. In addition, the motions study will be used to develop cargo component foundation and mooring system design loads. The intent of the time domain mooring simulation is to explore feasibility of a simple mooring system for directly mooring a feeder vessel to a wind installation vessel.

2.3 Objective

2.3.1 Motions

There have been many studies examining the barge motions and the relative motions between the WTIV and CFVs but using the dynamic motions within the weather downtime analysis of a feeder in several load configurations is rarely done. In this study, spectral response amplitude operators (SRAOs) are computed so motion/acceleration responses can be collected at vessel and cargo Points Of Interest (POI) and that data can be used to evaluate the various load configurations for overall system through-put.

2.3.2 Mooring

Various mooring and station keeping solutions have been proposed for transloading cargo between a feeder vessel carrying wind turbine components and the wind installation vessel. In this study, a simple mooring arrangement is evaluated using highly elastic lines and with HMPE lines, render-recover winches, and pneumatic mooring fenders with the goal of demonstrating basic workability of the concept.

2.4 Limits of Study

2.4.1 Mooring Analysis

The OPTIMOOR[4] model used for this study is a static analysis which only considers the main loading condition. The wave and wind conditions were derived from the operational states, resulting from the maneuvering simulations. These environmental conditions were imposed in the athwartship direction. The worst-case scenarios studied assume the environmental forces are pushing the feeder “away” from WTIV for mooring line tension forces and “toward” the WTIV for fender compression forces. The ratio of response to wave height at beam seas were assumed to be one, which is a very conservative assumption. The projected area for the wind force calculations were chosen as the largest between all loading conditions. The failure criteria for the mooring line is passing with 40% of the maximum strength. (F.S. 1.8 for max of 75%.)

2.4.2 Time Domain Mooring Analysis

Time domain mooring feasibility was determined by maximum barge motion limits and the minimum breaking strength of the mooring system components including the mooring lines and fenders. The motion limits for the barge were taken to be 2 deg in roll and pitch and 2 m in heave. The line and fender load limits were as specified by vendor data including a factor of safety of 5.

3 Discussion

3.1 Findings

3.1.1 Frequency Domain Motions Analysis

The study is developed in support of the weather downtime simulation. Some examples of weather files are shown in Section A2.3 below.

3.1.2 Mooring Study

The mooring and fender configurations that provides the best initial assessment results is the case with 4 breast and 2 spring lines that are nylon with a 276.1 MT (304 ST) breaking strength and a maximum diameter of 108 mm. This configuration is satisfactory for winds up to 50 knots and 6 ft waves on the beam.

This is an initial assessment and will be modified / optimized for the cargo operation limits during the time domain motion analysis. The line material may be changed if any limits are violated.

Four Breast Lines and Two Spring Lines, 6 ft Waves on the Beam

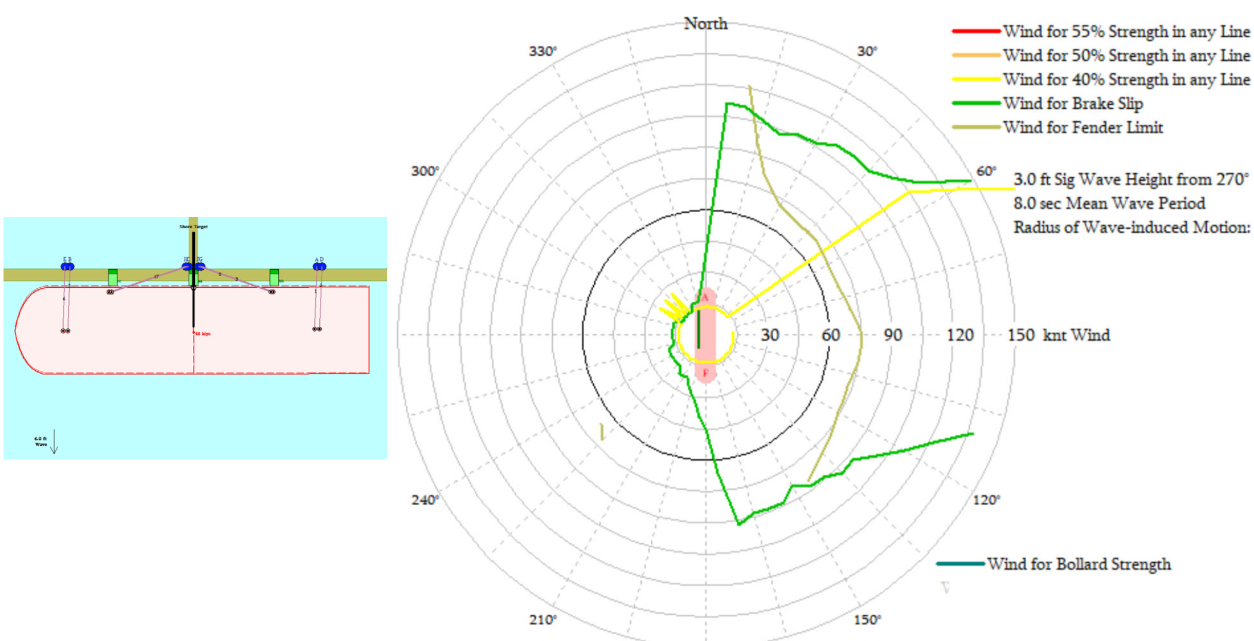


Figure 4 – Four Breast & Two Spring Lines, 6 ft Beam Waves (37% of maximum strength)

3.1.3 Time Domain Analysis

A feasibility level study was completed in the time domain to show adequate mooring line strength, fender loads, and cargo motions. An upper limit to the mooring system was identified as being around 3 m Hs for waves predominately aligned to within +/-30 degrees of the feeder vessel centerline from bow or stern. For waves outside of this direction range, vessel motions and system dynamics were found to be highly dependent on the frequency content of the wave spectrum aligned to the vessel athwart direction. First order and higher order wave forces in this direction exciting roll and yaw related resonances in the coupled greatly reduce wave height limits for cargo transfer and mooring system workability. Exact limits for the system dependent on the feeder vessel mass moments of inertia and will therefore change with cargo type and ballast. For the purposes of this study, Load Case 2 with two (2) wind turbine tower sections and relatively significant ballast (the DNV ballast case) was selected for analysis. The mooring system was found to be operable in unrestricted wave periods and directions for wave heights of up to 1.5 m, although substantially larger wave heights are workable if the wave periods do not align to the natural periods of the vessel mooring system.

3.1.4 Sea-Fastening & Foundation Loads

The DNV requirements for design accelerations in the Marine Warranty Survey and Rules for the Classification of Ships are less than one third of the maximum allowable WTG component accelerations assumed for this study. The barge's overall deck load rating is greater than the design loads. For each component, a grillage and sea fastening must be designed based on OEM specifications, however, no additional global deck strengthening is required.

3.2 Methodology

3.2.1 Frequency Domain Motion Analysis

3.2.1.1 Spectral Response Amplitude Operators (SRAOs)

For each load condition, frequency domain vessel motions were calculated using OrcaFlex[5] for a range of significant wave heights (Hs), wave periods (Tp) and wave directions (ϕ). The ITTC 2011 (Ikeda Method) was used to model viscous roll damping. The range covered in the study is:

- Wave Heights, Hs: 1.0, 1.5, 2.0, 2.5 m
- Wave Periods, Tp: 4 to 14 seconds in 0.25 second increments
- Wave Direction, ϕ: 0 to 180 degrees in 10-degree increments with respect to vessel centerline

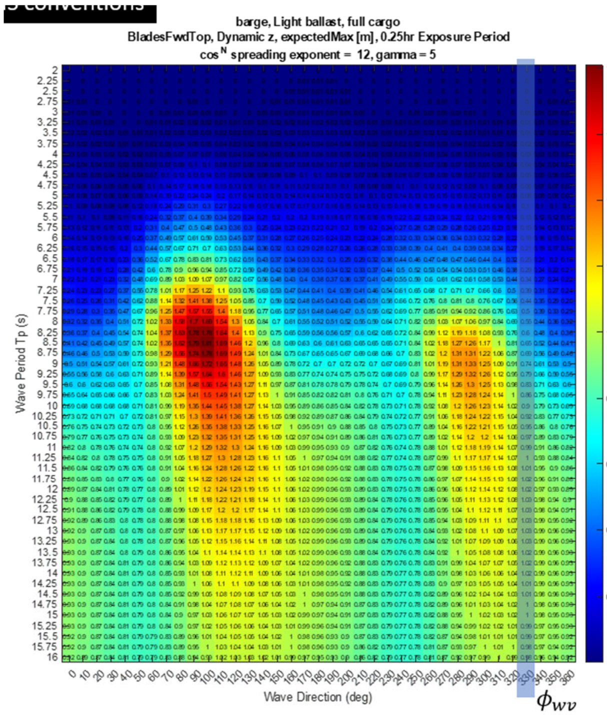


Figure 5 – Example SRAO Contours

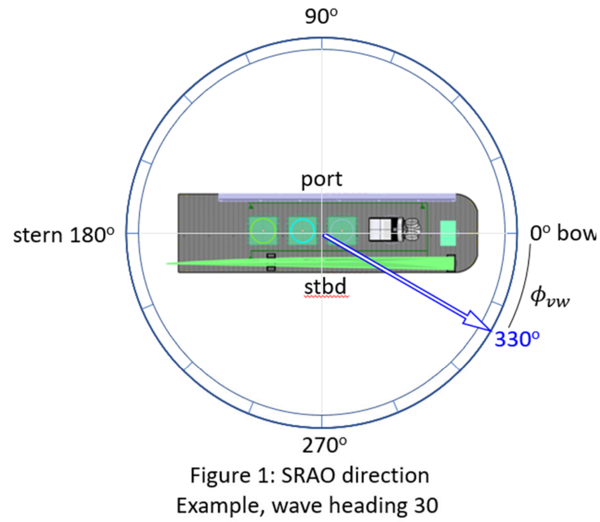


Figure 6 – Wave Direction (f) with respect to Barge Coordinates

The Hs-Tp-Phi Study was run for all load cases in both full and empty cargo conditions. The spectral response amplitude operators (SRAOs) were computed, and motion/acceleration responses were collected at vessel and cargo points of interest (POI).

The cargo points of interest include the bottom (base), the center of gravity and the Pick-up Point (top) of each cargo item. The vessel POI are at the center of gravity, longitudinal center of floatation and on the main deck at the bow, stern and sides at midships.

3.2.2 Route Planning

Routes between the load ports and the wind farm sites were selected based on normal charted traffic lanes.

- The heading on Legs 1 & 2 outbound is 100 degrees.
- The heading on Legs 3 & 4 outbound is 167 degrees.
- The heading on Legs 5 & 6 outbound is 285 degrees.

The heading from the NY Pilots Station to Way Point 6 is 120 degrees.

The routes between Salem, MA and Empire Wind, NY and between South Brooklyn, NY and Empire Wind, NY are shown in Figure 7 below.

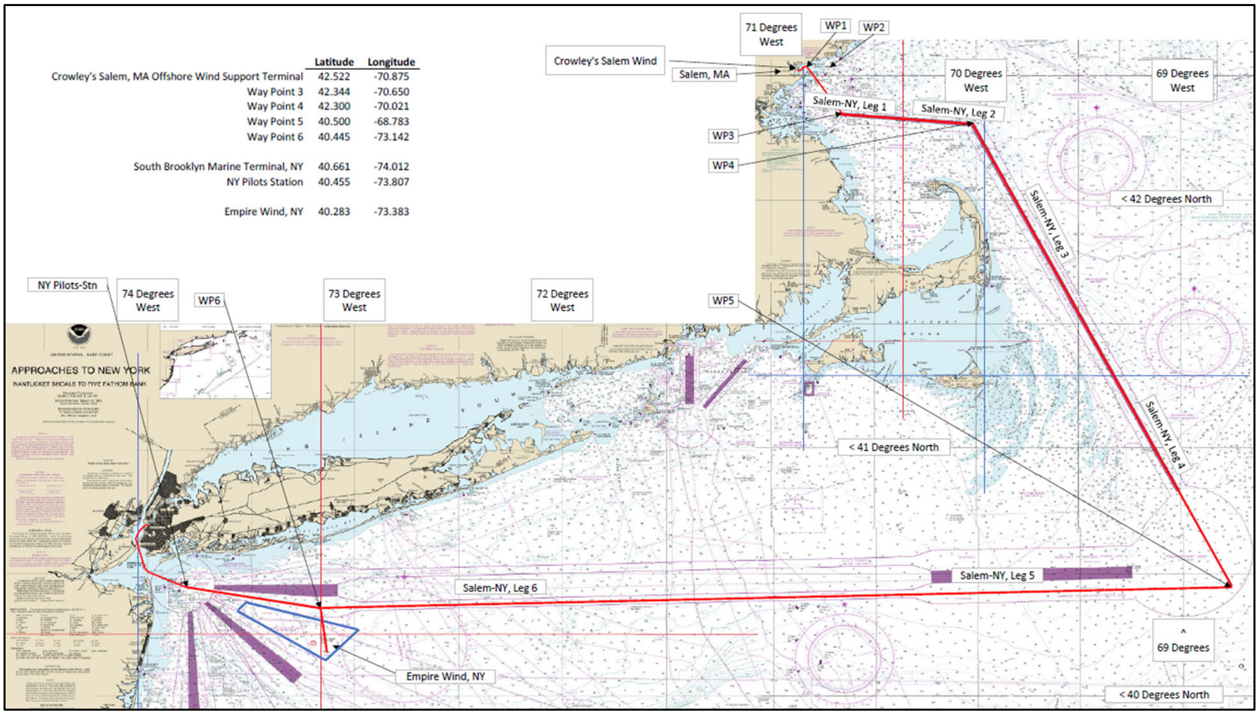


Figure 7 – Feeder Routes between Salem or South Brooklyn Load Ports and Empire Wind

The NOAA Wave Watch 3 hindcast wave data was used to create weather files at up to four (4) locations for each route. See Section A2.3 below for additional discussion about weather data.

The Weather Downtime Extraction feature of the inhouse Offshore Motions Simulator (OMS) was then used to pre-process the resulting 7-dimensional database to develop a "go / no-go" decision matrix for each activity at each hour for each of four locations. The acceleration or motion limits being evaluated are described below.

The details of the motion analysis are provided in more detail in Appendix A.

3.3 Mooring Analysis

The mooring system must hold the Feeder vessel securely to the WTIV in winds, waves, and currents from any direction. This fender and mooring analysis was performed using OPTIMOOR which is based on the Oil Companies International Marine Forum (OCIMF) recommendations and procedures. The moored vessel and "berth", which in this case in a WTIV in open water, is modeled and OPTIMOOR computes the mooring forces produced by defined wind, wave, current, and other forces and by changes in draft, trim, and tide. This software is both a planning and simulation tool to check the feasibility of mooring a vessel in various circumstances.

The assumptions for the mooring/fender analysis are as follows:

Load Condition: Barge with Fender Wall and other outfit transporting two (2) Tower sections (T1/2, T3), Nacelle and Blades with minimum ballast (Draft 27% hull depth)

Environmental Condition: Beam seas with a combination of wind speeds and directions

- Loads on Mooring Lines: Seas and wind push Feeder away from WTIV
- Loads on Fenders: Seas and wind push Feeder toward WTIV
- Failure Condition: Force on Mooring Line exceeds 40% of the maximum strength

This implies a Factor of Safety of 1.8 for a maximum line load of 75%.

As a worst-case scenario, the motion response from the beam seas is assumed to correlate (one-to-one) with the significant wave height, which means the incoming wave would result in a same amplitude in motion response. Projected wind area is kept constant as the worst-case scenario (different cases are presented in Figure 34).

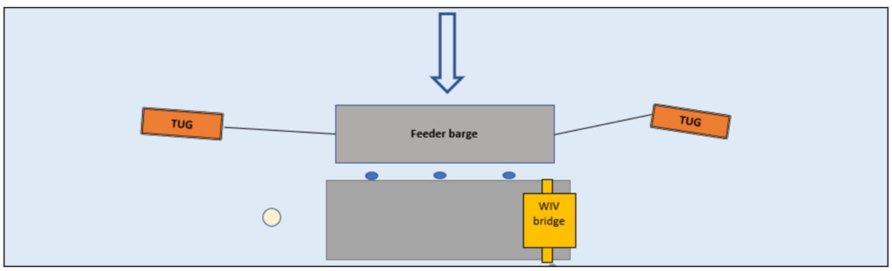


Figure 8 – Maximum Fender Loads with Wind and Waves Pushing Feeder Toward WTIV

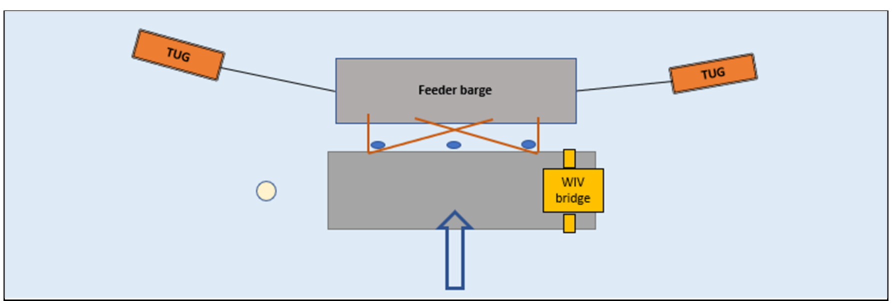


Figure 9 – Maximum Mooring Line Loads with Wind and Waves Pushing Feeder Away from WTIV

3.3.1 Load Conditions

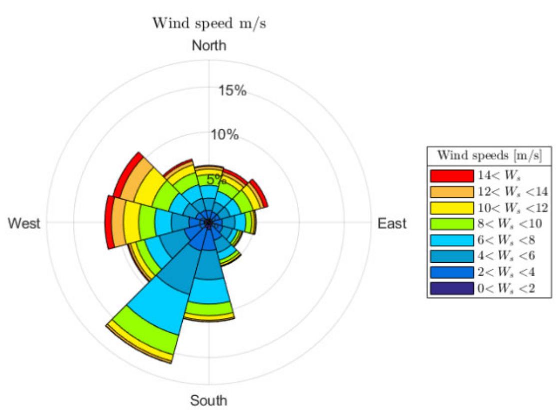
The overall study will examine four stow plan and ballast level combinations. When both the full cargo and post cargo discharge conditions are included, those four load conditions become eight and they become many more when all possible discharge combinations are included. Maritime navigation simulation is time consuming, so the main condition to test was the light ballast, three tower section case. The two sensitivity cases were the lightest and heaviest two tower section cases:

	Load Case	draft (m)	Displacement (mt)
Case 1	**Base Case (0-Lt-Disch) - 2 Tower Sections**	**1.48**	**4,848.4**
	Sensitivity (1-Lt-Disch) - 3 Tower Sections	1.59	5,227.5
	Base Case (0-Lt) - 2 Tower Sections	2.07	6,875.4
Main Load	**MAIN: Sensitivity (1-Lt) - 3 Tower Sections**	**2.17**	**7,254.5**
	Sensitivity (0-Hvy-Disch) - 2 Tower Sections	2.73	9,245.5
	Sensitivity (1-Hvy-Disch) - 3 Tower Sections	2.84	9,624.6
Case 2	**Sensitivity (0-Hvy) - 2 Tower Sections**	**3.29**	**11,272.5**
	Sensitivity (1-Hvy) - 3 Tower Sections	3.39	11,651.6

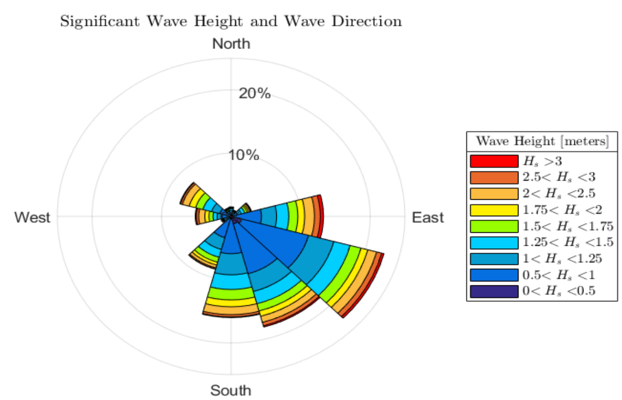
Figure 10 – Load Conditions Selected for Maritime Navigation Simulation

3.3.2 Metocean Data

For this study, the full 2D ocean wave spectra measured at the National Data Buoy Center (NDBC) Station 44025 was collected. The prevailing wave and wind cardinal direction and magnitude were determined from the measured data for the past 22 years (since 2000):



Wind from 210º dominates.



Waves from 120º dominate.

Figure 11 – Most Probable Wind and Wave Conditions

See Appendix B for more information.

3.4 Time Domain Analysis

Mooring of the feeder vessel to the WTIV has been investigated using time domain analysis. Using OrcaFlex, a general simulation software developed by Ocarina, mooring loads were studied to determine feasibility. The mooring arrangement was based on a preliminary static mooring study performed in OPTIMOOR. The mooring design was evolved beyond this study based on information from industry partners. A generalized depiction of the mooring design is presented in Figure 12. This version of the mooring design utilizes three (3) pneumatic fenders to keep the feeder vessel off the WTIV. Fender contact is maintained using render-recover constant tension mooring winches. Four breast lines and four spring lines provide some redundancy in the system. HMPE lines allow for ease of line handling. For the finalized time domain version of the mooring design, fenders are connected to the WTIV via deployable external structure on the vessel's side shell. The mooring system feasibility study was based on 1152 cases of weather conditions over a range of wave period, heights, directions based on available metocean data. Wave periods and heights were selected with reference to metocean data used in the frequency domain analysis.

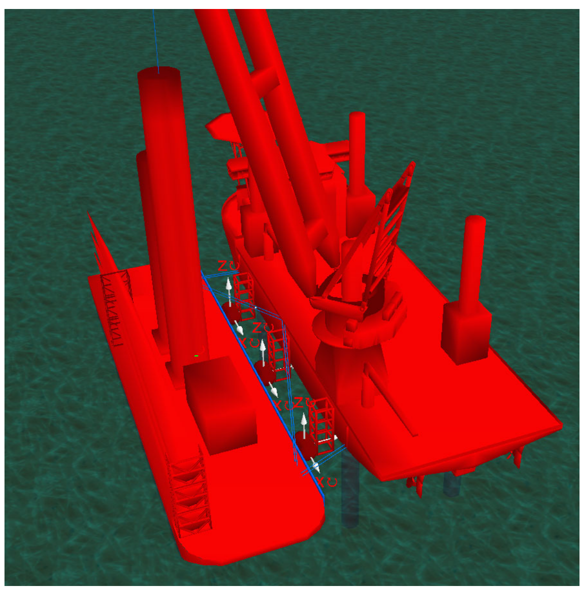
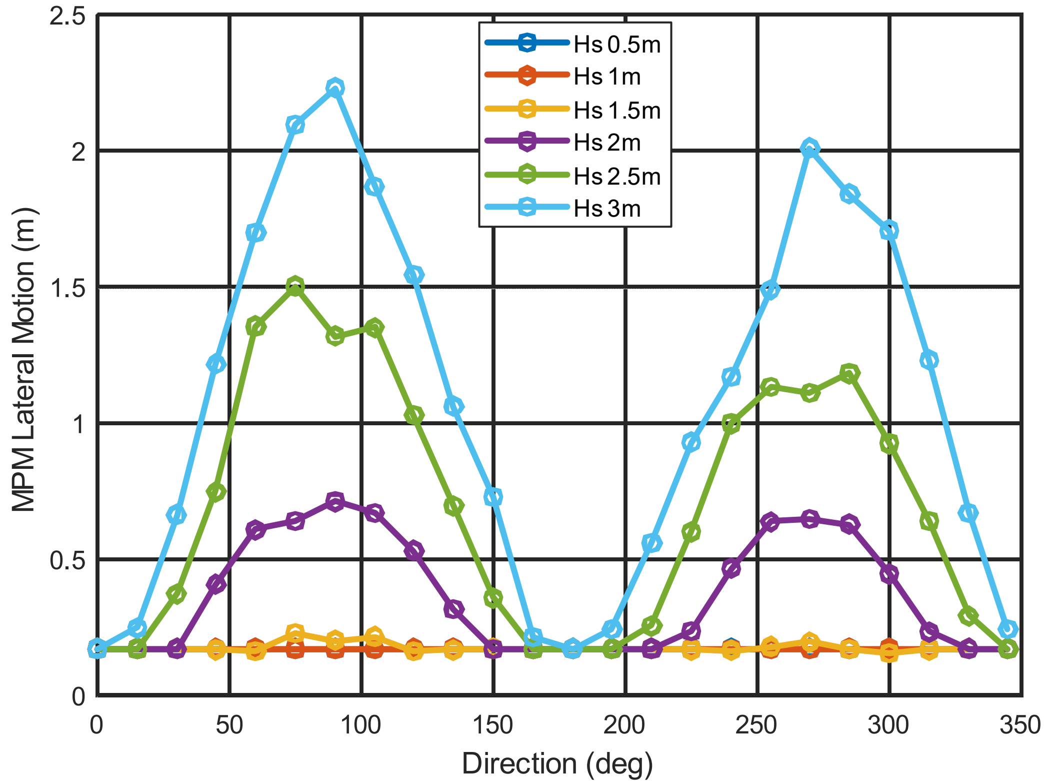


Figure 12 – Time Domain Analysis Model of Wind Feeder Barge Moored Directly to Wind Installation Vessel

The most probable maximum (MPM) lateral motion over a range of wave heights is shown in Figure 13 below.



0° aligned with vessel longitudinal direction from the bow

Figure 13 – Time Domain Analysis Lateral Motion of Feeder Vessel's Center of Gravity in Weather Various Conditions (limiting modal period over 4 – 15s) over three-hour exposure period

4 Concluding Remarks

4.1 Intersection of Findings

An initial mooring design based on high elasticity nylon lines and OPTIMOOR static mooring analysis was evolved upon review of other industry solutions and further engineering analysis using time domain simulations. A feasibility level mooring system design was analyzed and found to be workable in a range of weather conditions up to 3 m significant wave height for a limited range of wave headings as discussed in the findings section of this report.

4.2 Evaluation of Method

4.2.1 Challenges

Direct mooring of a feeder vessel to a wind turbine installation vessel is a novel concept. This approach has the benefit of reducing relative motion between the feeder and installation vessel, but the approach also brings with it many challenges. Existing WTIVs were not originally designed with this application in mind and extensive engineering is required ensure their successful operation as a ground-fixed mooring platform for feeder vessels. One of the major challenges in conducting such analysis will be determining the holding capacity of the WTIV itself as a fixed point for mooring the feeder vessel. For example, the range of acceptable mooring forces and moments on the WTIV are in part determined by the soil bearing capacity in way of the jack-up feet of the WTIV and are therefore site specific. The scope of this report is limited to the strength of the mooring system itself, not the holding capacity of the WTIV.

4.2.2 Strengths

The advantages of directly mooring a feeder vessel to a WTIV include the reduction in relative motions during cargo transloading and potentially safer operations due to reduced risk of collision (relative to a dynamic positioning system). A simple mooring solution was initially studied in OPTIMOOR using elastic nylon lines fixed on winch breaks. The advantage of this system is in its simplicity, but the disadvantage is a lack of damping and motion compensation to contend with feeder vessel motions, particularly in the roll, heave, and yaw degrees of freedom. A more expensive but also more robust system was studied in the time domain using render-recover constant tension winches and HMPE line to allow for better handling of feeder vessel motions and safer operation in larger waves. An advantage of conducting a time domain simulation beyond the initial static mooring study conducted in OPTIMOOR is the ability to more robustly model the impacts system nonlinearities and motions on the mooring system design.

5 Areas for Further Study

5.1 Mooring Analysis

Prior to performing a WTG installation project, the design should be reviewed using site specific information including, but not limited to:

- A full dynamic analysis of the mooring/fender/vessel system, to improve accuracy and eliminate overdesign of the components.
- Model system performance using 2D wind-wave input from the measured/hindcast values at the project location.
- Analyze system with WTIV foundation performance using soil interactions instead of a rigidly fixed WTIV as is assumed in this study.

5.2 Time Domain Mooring Analysis

A feasibility level design was identified for the purposes of mooring a wind turbine component feeder vessel to a wind installation vessel. The scope of this study was limited to the study of the mooring system equipment. Further study is needed to determine the site-specific mooring loads allowable on the WTIV with respect to soil holding capacity in way of the WTIV jack-up leg feet and any other considerations which might limit the allowable loads on the WTIV such as wind loads, overturning moment, allowable loads on the jack-up machinery, leg buckling. Further study of site specific metocean data for a real-world project should likewise be considered, including the effects of wind driven sea and swell on feeder vessel motions and mooring loads. The time domain modeling approach is also appropriate for studying cargo transloading including lift-off and re-hit analysis, dynamic loads on the WTIV crane, cargo handling during transfer, and cargo sea fastening release prior to lift off.

6 References

6.1 NOWDRC Agreement #103 Reports

1. Technical Validation of Existing U.S. Flagged Barges as a Feeder Solution for the U.S. Offshore Wind Industry: Barge, Cargo and WTIV Load Properties Technical Report, Milestone Number 1.3.
2. Technical Validation of Existing U.S. Flagged Barges as a Feeder Solution for the U.S. Offshore Wind Industry: Maneuvering Simulation to Indicate Operational Limits Technical Report, Milestone Number 3.4.
3. Technical Validation of Existing U.S. Flagged Barges as a Feeder Solution for the U.S. Offshore Wind Industry: Weather Downtime Based on Metocean Data & Frequency Domain Motions FINAL Technical Report, Milestone Number 4.3 and Number 5.5.

6.2 Barge Info

1. 400’ x 105’ x 26’ Deck Cargo Barge, GENERAL ARRANGEMENT, Dwg 73-03, Rev B
2. Crowley Spec Sheet: 455 Series – 400’ x 105’ x 25’
   [applicable to Barges: 455-1 (Marty J), 455-3, 455-4, 455-5, 455-6, 455-7. 455-8, 455-9]
3. 213025-833-1, Weight Estimate
4. 213025-034-01, 15 MW NREL Reference Turbine Stow Plan, Base Case – Two Tower Sections
5. 213025-034-02, 15 MW NREL Reference Turbine Stow Plan, Sens. Case 1 – Three Tower Sections
6. 213025-034-03, 15 MW NREL Reference Turbine Stow Towing & Mooring Arrangement
7. General HydroStatics (GHS) model: (21-11-29) 213025-455.gf

6.3 Tug Info

1. Crowley Spec Sheet: Ocean Class Tugs [applicable to DP1 Ocean Wind & Ocean Wave, and DP2 Ocean Sky & Ocean Sun]
2. Crowley Spec Sheet: Alert Class Tugs [applicable to Alert, Attentive & Aware which are outfitted with azimuthing drives (z-drive)/controllable pitch (CP) propellers]

6.4 Wind Turbine Generator Info

1. IEA Wind TCP Task 37, Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine Technical Report, March 2020

6.5 Fender Design Info

1. Yokohama Pneumatic Fender ISO 17357-1: 2014 PIANC: 2002, Catalog No. FDL-2019-9

6.6 Endnotes

[1] https://windeurope.org/intelligence-platform/

[2] https://www.energy.gov/eere/wind/wind-market-reports-2021-edition#offshore

[3] https://news.dominionenergy.com/2021-06-01-Dominion-Energy,-rsted-and-Eversource-Reach-Deal-on-Contract-to-Charter-Offshore-Wind-Turbine-Installation-Vessel

[4] https://www.tensiontech.com/software/optimoor

[5] https://www.orcina.com/orcaflex/

Appendix A. Feeder Vessel Motions

A.1 Frequency Domain Motion Analysis

A1.1 Load Conditions

Maximizing the performance of the feeder vessel supported WTIV installation system is critical to driving down the cost of WTG installation. There are trade-offs to each decision. For example, dividing the tower into three sections reduces the top motions of the towers which increases the weather windows available to off-load the towers, however, assembling three tower sections takes more time than assembling two. Another decision relates to ballast. A more heavily ballasted barge will tend to have less roll motions but higher cargo accelerations and will apply a higher force against the WTIV for a given landing velocity than a more lightly loaded vessel. It is important to examine all combinations throughout the delivery cycle to understand which combination offers the best system performance.

Load conditions studied include conditions with cargo loaded and discharged for the following cases:

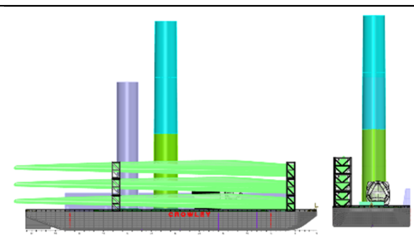
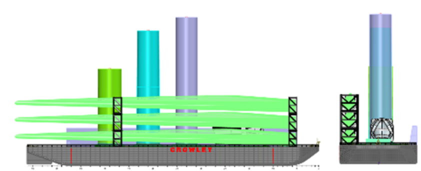
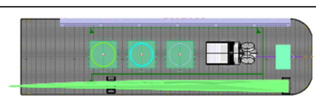
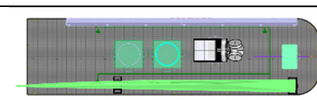
Towers / Ballast	Two Tower Sections	Three Tower Sections
		
		
Minimal Ballast	Draft = 27% of Hull Depth	Draft = 29% of Hull Depth
DNV1 (wing tks)	Draft = 43% of Hull Depth Minimum Free Surface	Draft = 45% of Hull Depth Minimum Free Surface
DNV2 (center tks)	Draft = 43% of Hull Depth Maximum Fred Surface	Draft = 45% of Hull Depth Maximum Fred Surface

Figure 14 – Cargo / Ballast Combinations

The load cases were developed to include:

- Stow plans,
- Weight estimates,
- Shear and bending moment values,
- Radius of gyration values,
- Ballast Plans for port-to-starboard and starboard-to-port cargo discharge,

- Maximum KG curves for each cargo transport and discharge step load condition, and
- Stability analysis.

Hydrostatics and other details about the load cases can be found in Figure 15 below. More information can be found in Reference 6.1.1.

Case ID	project		213025											
	vessel		Crowley 455 barge											
	project case name		0-0 BaseCase		0-1 DNV		1-0 Sensitivity		1-1 DNV		0-1 DNV2		1-1 DNV2	
	vessel name		455	455	455	455	455	455	455	455	455	455	455	455
	study		1	1	1	1	1	1	1	1	1	1	1	1
	case subindex (motions study)		1	2	3	4	5	6	7	8	9	10	11	12
	case name (motion study)		V455S01C01	V455S01C02	V455S01C03	V455S01C04	V455S01C05	V455S01C06	V455S01C07	V455S01C08	V455S01C09	V455S01C10	V455S01C11	V455S01C12
	Melissa Manuever Sim Name		-	Cdn B	Cdn C	-	Cdn A	-	-	-	-	-	-	-
	MITAGS Manuever Sim Name		-	Case 1	Case 2	-	Main Ld	-	-	-	-	-	-	-
	ballast		light	light	DNV1	DNV1	light	light	DNV1	DNV1	DNV2	DNV2	DNV2	DNV2
	turbine		15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL Re
	turbine sets		1	1	1	1	1	1	1	1	1	1	1	1
	cargo load condition		full	empty	full	empty	full	empty	full	empty	full	empty	full	empty
	tower segments		2	2	2	2	3	3	3	3	2	2	3	3
Hydrostatic Model (imperial)	draft	ft	6.8	4.859	10.80	8.967	7.14	5.221	11.14	9.312	10.785	8.954	11.123	9.299
	Displacement	LT	6767	4770	11094	9098	7140	5143	11468	9471	11079	9083	11452	9456
	VCG	ft	35.72	15.49	25.04	12.09	29.85	14.81	21.74	11.86	24.235	11.082	20.949	10.887
	VCG Corr for FSM	ft	36.55	16.67	26.56	13.95	30.64	15.90	23.21	13.64	35.18	24.46	31.55	23.74
	Radius of Gyration Kxx	ft	56.26	36.0	52.89	39.138	45.40	36.526	45.37	39.268	47.563	29.165	39.171	29.787
	Radius of Gyration Kyy	ft	113.95	118.86	97.60	95.716	113.59	120.145	97.59	97.577	97.764	95.781	97.724	97.639
	Radius of Gyration Kzz	ft	108.49	123.315	96.31	102.62	113.45	124.719	100.22	104.419	93.381	99.272	97.502	101.266

Figure 15 – Hydrostatics for Load Conditions

A1.2 Frequency Domain Modeling

For each load condition, a mesh model of the hull below the load waterline is created. The models for the two DNV load conditions are the same for each cargo configuration because the quantity of ballast is the same. The difference between the two ballast conditions is that the ballast is in the wing tanks for the DNV cases and is in the centerline tanks for the DNV2 cases.

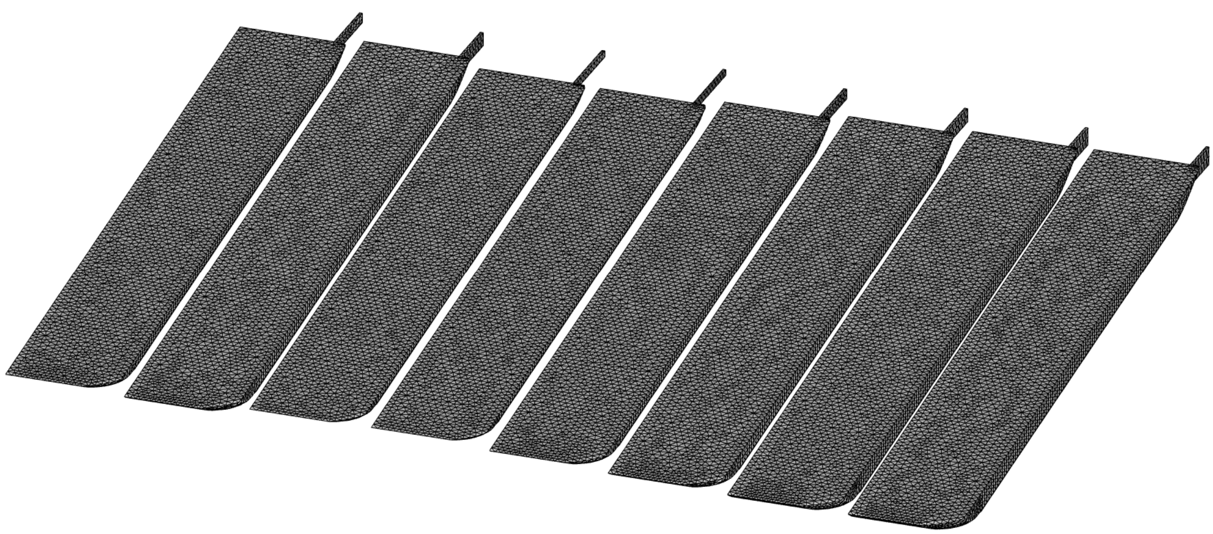


Figure 16 – Hull Mesh Models (Symmetry Assumed)

A1.3 Frequency Domain Analysis

The initial step in a frequency domain analysis is "system identification". During system identification, for each vessel load condition, the response amplitude operators (RAOs) are computed, representing a linear relation between the incoming ocean wave condition and the vessel responses for each of the six degrees of freedom (6-DoF). This frequency domain analysis was performed for all 12 load cases. Two software packages were implemented for this analysis:

- GHS-SK (Seakeeping)
- OrcaWave

Before running the frequency domain analysis, viscous roll damping and roll damping due to radiated waves must be addressed. The viscous roll damping computations were performed using ITTC 2011 (Ikeda Method) implemented in GHS seakeeping. The roll damping coefficients due to radiated waves are computed using the 3D panel code, OrcaWave. The viscous roll damping values where then applied within the OrcaWave model.

A1.4 Viscous Roll Damping

A comparison between the computed radiation and viscous roll damping, together and individually, are shown in Table 1 below.

Loading case	GHS		Orcaflex	
		damping ratio (damping sources)		
	Peak Visc. Damping (kg.m^2/s)	GHS radiation + visc.	Orcaflex radiation only	Orcaflex radiation + visc.
1	47,181,544	5%	5%	6%
2	25,994,950	11%	16%	17%
3	46,589,896	4%	2%	3%
4	33,610,284	9%	7%	8%
5	38,118,168	6%	6%	7%
6	26,684,000	10%	15%	16%
7	46,421,576	6%	3%	4%
8	34,253,868	9%	7%	8%
9	43,616,388	5%	2%	3%
10	29,945,054	9%	9%	9%
11	43,261,024	6%	3%	4%
12	30,858,576	9%	8%	9%

same loadout design, with and without cargo

light draft + small mass moment

deep draft + high mass moment

Table 1 – Comparison of Roll Damping Values

The values used for this study are shown in Table 2 below.

Load case	Critical Damping Ratio
V455S01C01	0.0506
V455S01C02	0.1075
V455S01C03	0.0446
V455S01C04	0.0878
V455S01C05	0.0624
V455S01C06	0.1046
V455S01C07	0.0552
V455S01C08	0.0866
V455S01C09	0.0508
V455S01C10	0.0918
V455S01C11	0.0604
V455S01C12	0.0906

Table 2 – Frequency Domain Analysis Critical Roll Damping Ratios

After computing the roll damping coefficients, a numerical free decay test was conducted for roll, pitch, and heave responses, the results of which are presented in Figure 17. It can be seen from this figure that only roll responses, both frequencies and amplitudes, are highly dependent on the loading conditions. To this end, the free decay roll damping curves/results were used to compute and compare the linearized decay assumption with curve fitting.

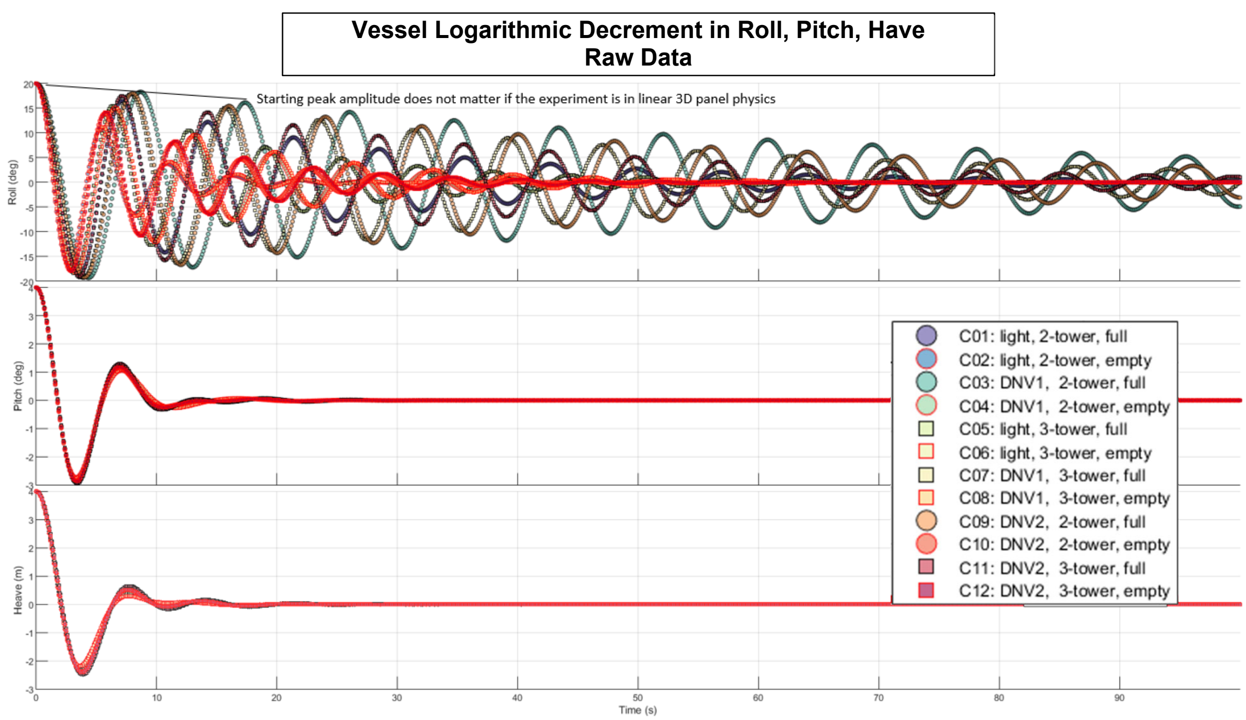


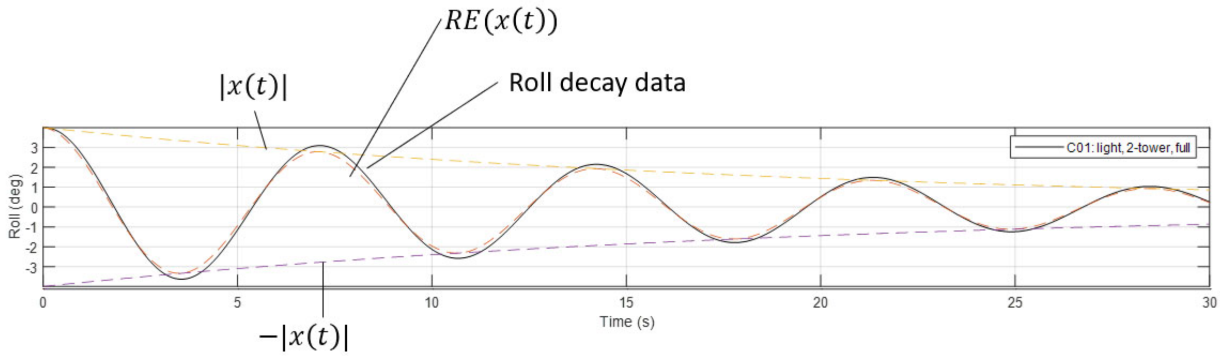
Figure 17 – Free Decay Test for Roll, Pitch, and Heave for Twelve Loading Conditions

The linearized roll damping coefficient can be computed using the free roll decay curve with the following equations:

$$\delta = \frac{1}{n}\ln\left(\frac{x(t)}{x(t+nT)}\right)$$

$$\zeta = \frac{1}{\sqrt{1+\left(\frac{2\pi}{\delta}\right)^2}}$$

$$x(t) = C_0 e^{-i\omega t\left(\zeta + i\sqrt{1-\delta}\right)} \quad \text{with } C_0 \rightarrow \text{starting amplitude}$$



The results of the linear curve fitting test, with the numerical free roll decay test, for all 12 vessel loading cases are presented in Figure 18 - Figure 20**Error! Reference source not found.**.

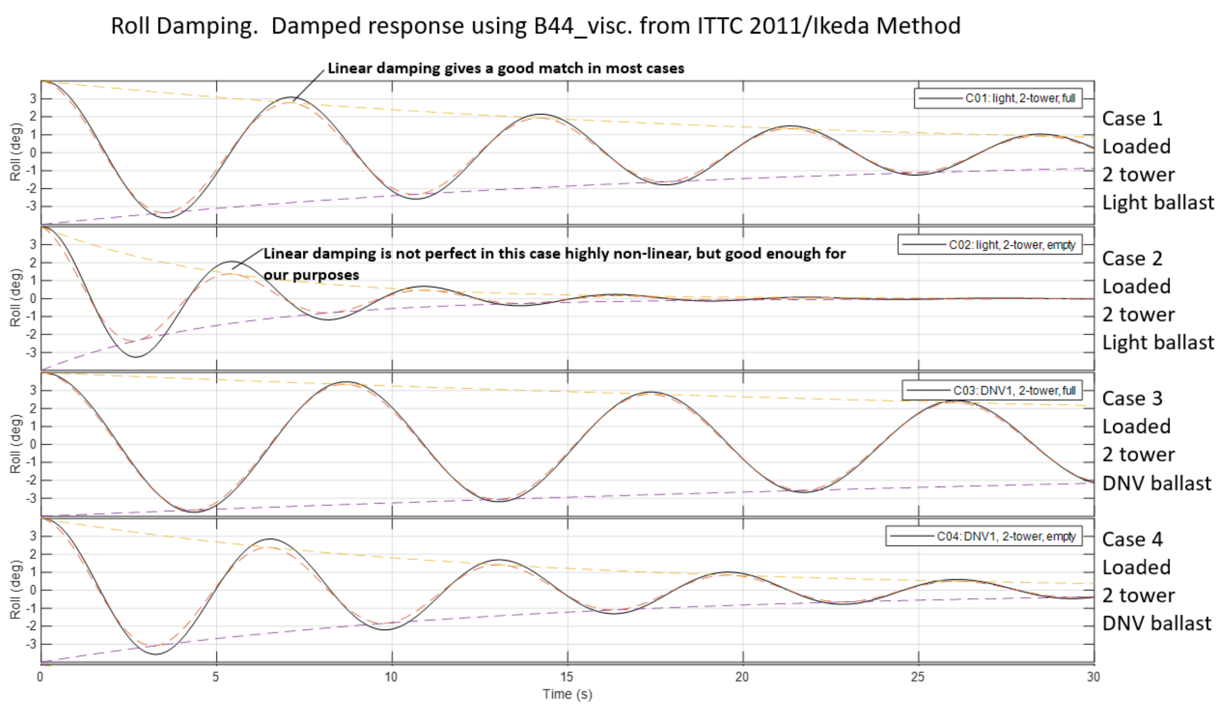


Figure 18 – Free Roll Decay assuming Linear Damping, Load Cases 1-4

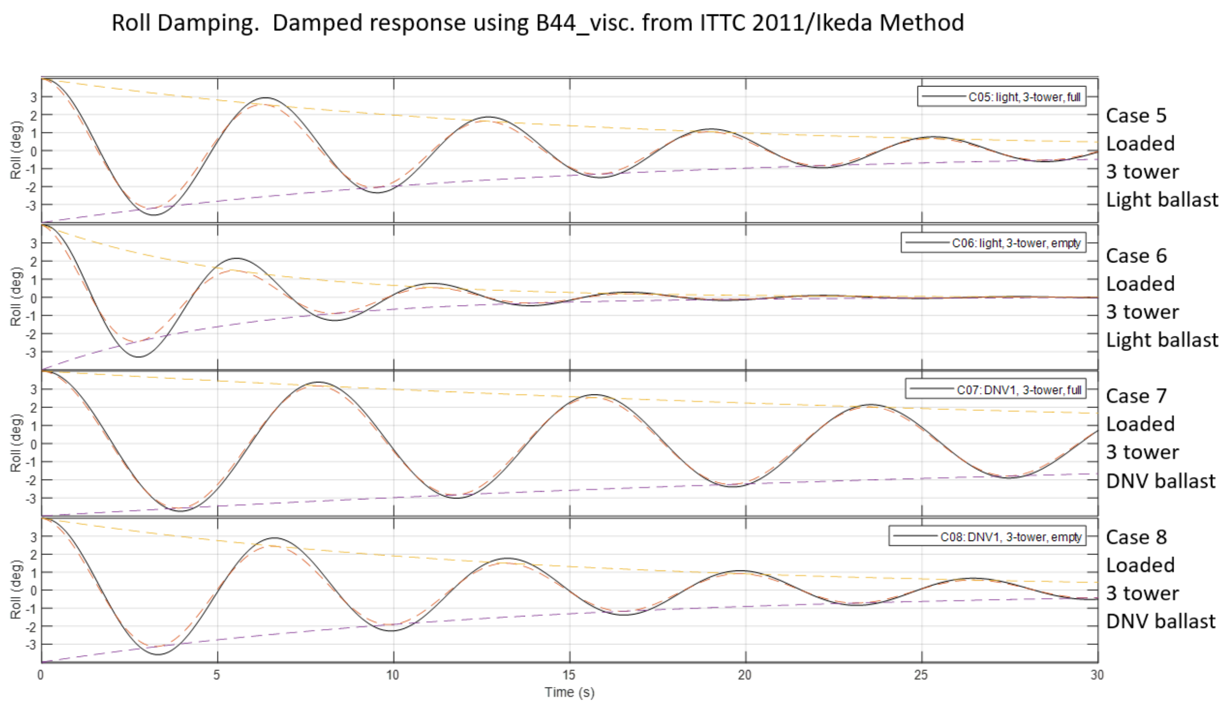


Figure 19 – Free Roll Decay assuming Linear Damping, Load Cases 5-8

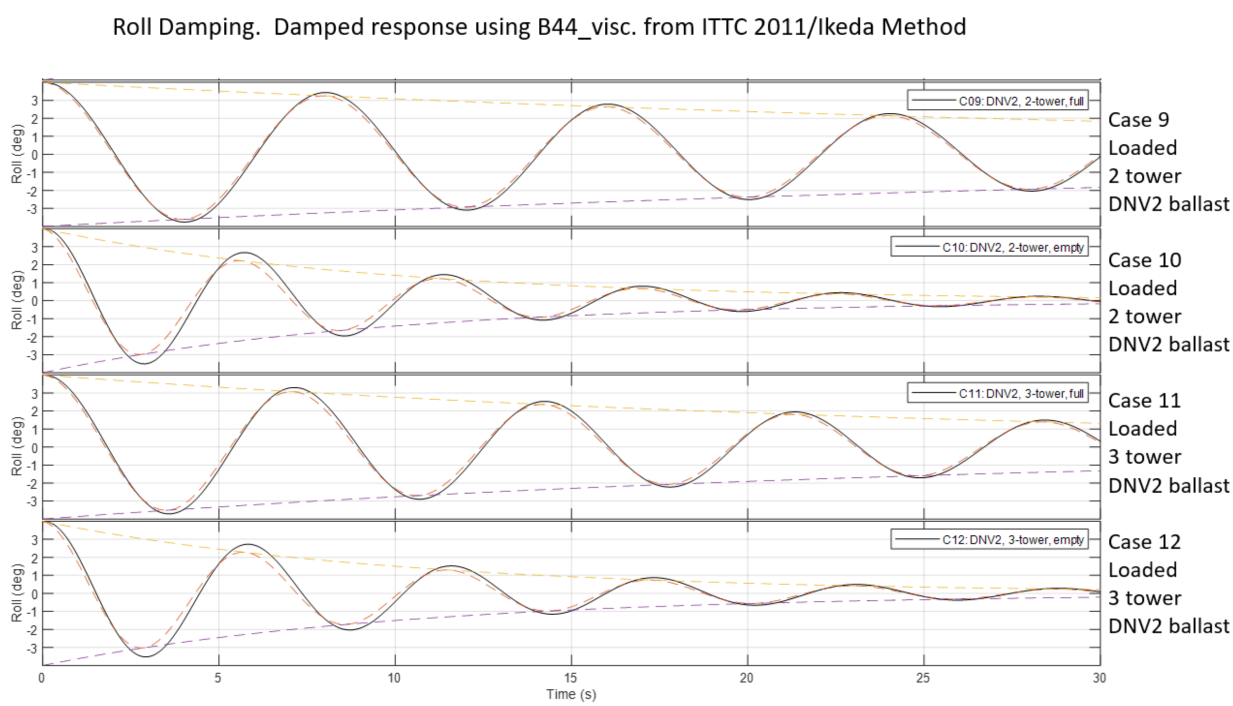


Figure 20 – Free Roll Decay assuming Linear Damping, Load Cases 9-12

A1.5 RAOs from the Frequency Domain Analysis

The Response Amplitude Operators (RAOs) were computed using the viscous roll damping coefficients with the Orca software. Some examples of the RAOs resulting for 6 DoF for the Base Case (2 Towers, Light Ballast) are presented in Figure 21 with direction and frequency, and in Figure 22, for selected directions of 0, 10, and 20 degrees of incoming waves. Also, the added mass coefficient for 6 DoF are presented in Figure 23.

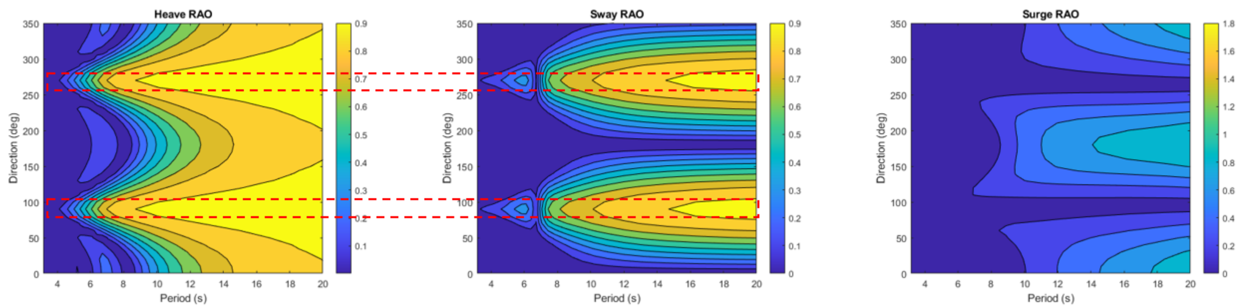
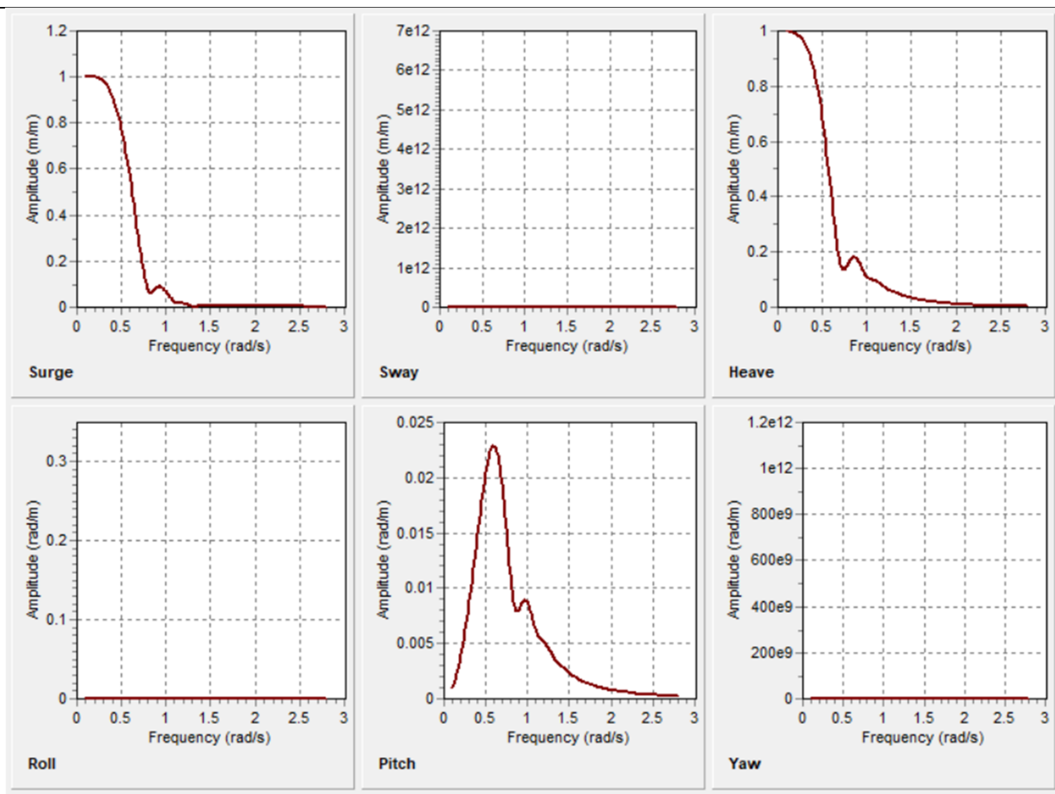


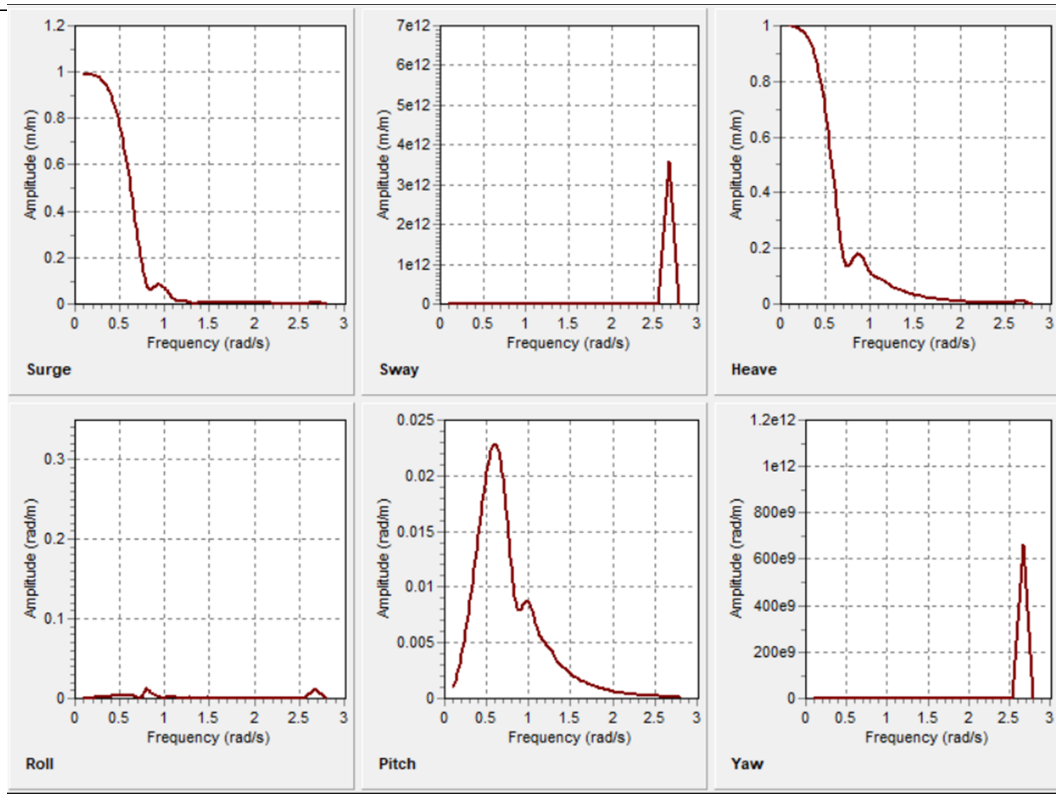
Figure 21 – RAO of the Base Case (2 Towers, Light Ballast), as a Function of Direction and Frequency

See Figure 6 for wave direction convention.

$\phi = 0$



$\phi = 10$



$\phi = 20$

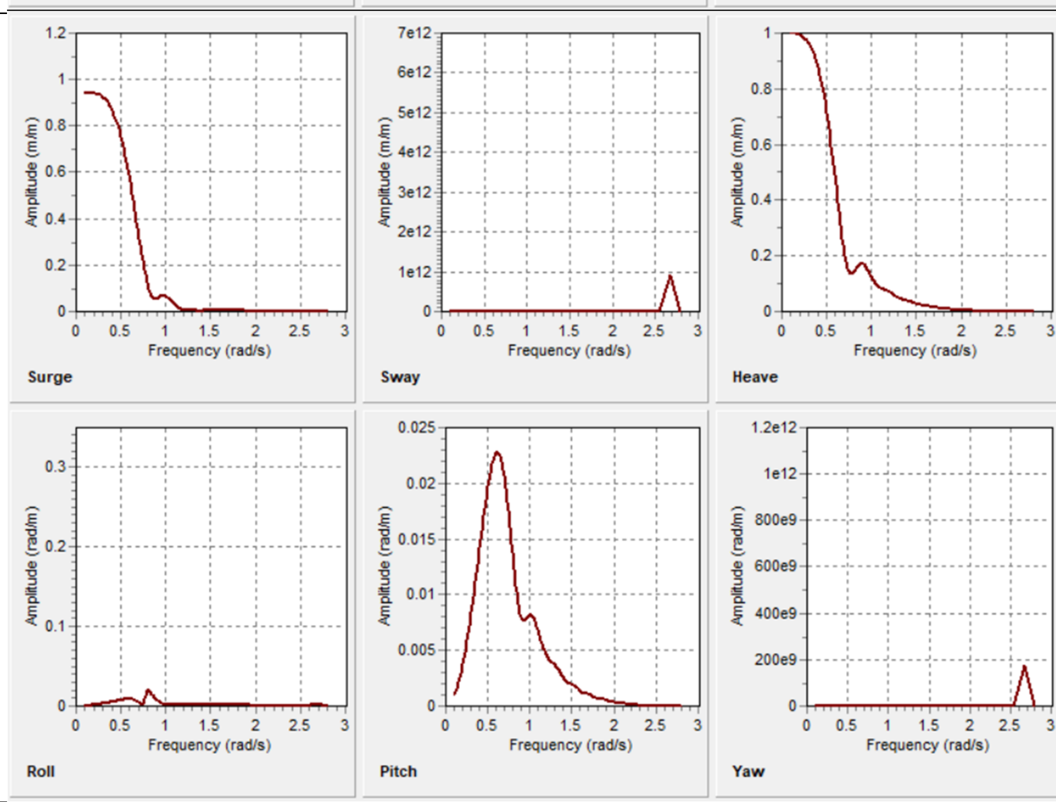


Figure 22 – RAO of the Feeder Base Case (2 Towers, Light Ballast) for three Wave Approach Directions

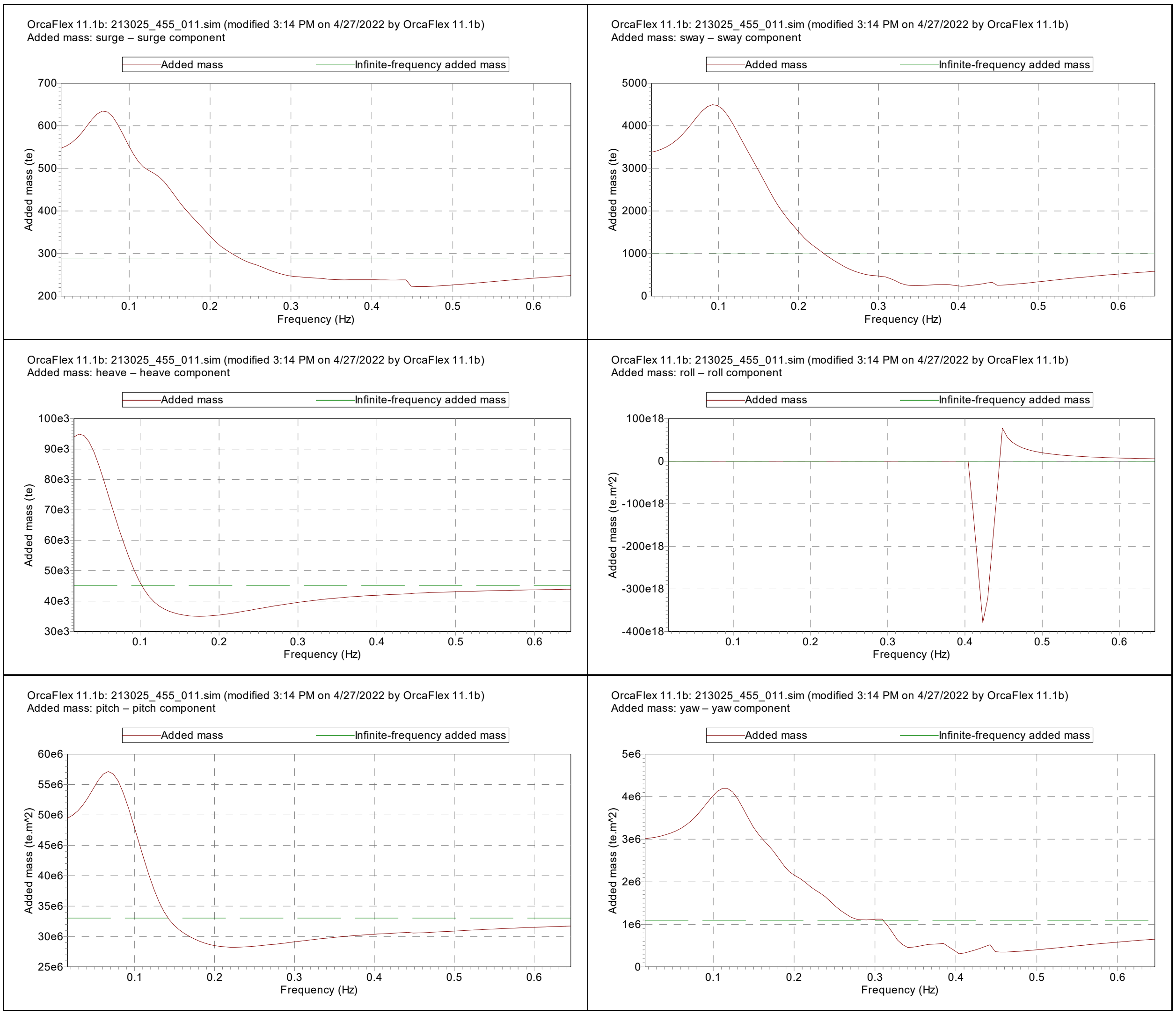


Figure 23 – Added Mass Coefficient as a Function of Frequency for 6 DoF

A.2 Hs-Tp-Phi Study

A2.1 Spectral RAOs

Using the methods described above, a comprehensive motion study was conducted using the OrcaFlex Frequency Domain Solver and the viscous damping (Ikeda method). The study is a systematic analysis of the six (6) load conditions, both with full cargo and loaded for return voyage, totaling twelve (12) different load conditions described in Section A.1.1.

The measured variables of interest (VoI) are displacement and acceleration which are measured the points of interest (POI) including:

	Displacement (m)			Acceleration at CG (g)		
	Base	CG	Top	x	y	z
Tower 1	X	X	X	X	X	X
Tower 2	X	X	X	X	X	X
Tower 3*	X	X	X	X	X	X
Nacelle	X	X	X	X	X	X
Blades, Fwd	X	X	X	X	X	X
Blades, Aft	X	X	X	X	X	X
Feeder Vessel		X		X	X	X
* If tower is divided into three (3) sections.						

Figure 24 – Variables of Interest at Points of Interest

Also, from each analysis, multiple statistical properties are computed as:

- RMS
- Most Probable Maximum
- Period
- Spectral moments m0, m1, m2, m3, m4

For each of the twelve load conditions, the motions were systematically evaluated by computing 3,116 SRAOs covering the range of four (4) significant wave heights from 1.0 to 2.5 m in 0.5 m intervals, forty one (41) peak wave periods from 4 to 14 seconds, in 0.25 sec intervals, and nineteen (19) wave directions from 0 to 180 degrees, in 10 degrees steps. In total, responses were collected at a total of 19 locations described in the Displacement portion of Figure 24.

A2.2 Hs-Tp-Phi Study Raw Data

The initial Hs-Tp-Phi study was performed on relatively coarse mesh, both in direction and peak periods, with 1 second steps in periods and 30 degrees steps in direction. The results were found to be unsatisfactory because local extrema were not clearly defined. So, the intervals were refined to the levels described in Section A.2.1. The comparison between the results of the coarse and fine mesh, for the expected maximum displacement of the top of tower 1, for a 30-minute exposure period, is presented in Figure 25.

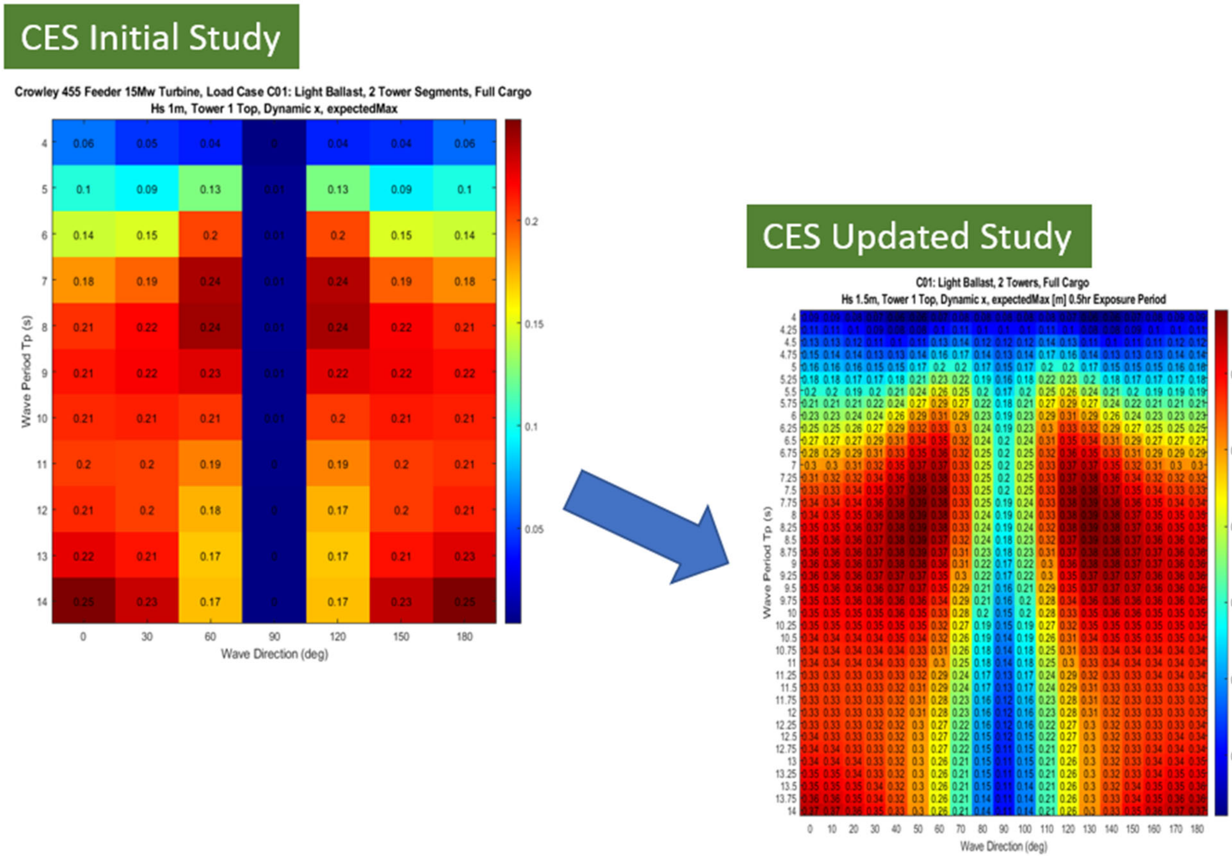


Figure 25 – Comparison between Course (7x11 points) and Fine Grid (19x41 points) for Analysis Case Grid

The database created by the Hs-Tp-Phi study, is very large, in fact, it is too large to be useful as a published document. However, this database as the basis of the weather file that will be used for the Weather Downtime (WDT) analysis to process the weather file into cargo acceleration and feeder motions limits. How this information is used is described briefly in Section A.2.3 and will be described in more detail in the Weather Downtime Report. As an example, the expected displacement motions in meters for a 30-minute exposure period in the x-, y- and z-directions for the Top of Tower 1 (which is one of eighteen points of interest) for the Light Ballast/2 Tower Segments/Full Cargo load condition (which is one of twelve loading conditions) for Hs = 1.5 m (which is one of four significant wave heights) are shown in Figure 26 through Figure 28 below:

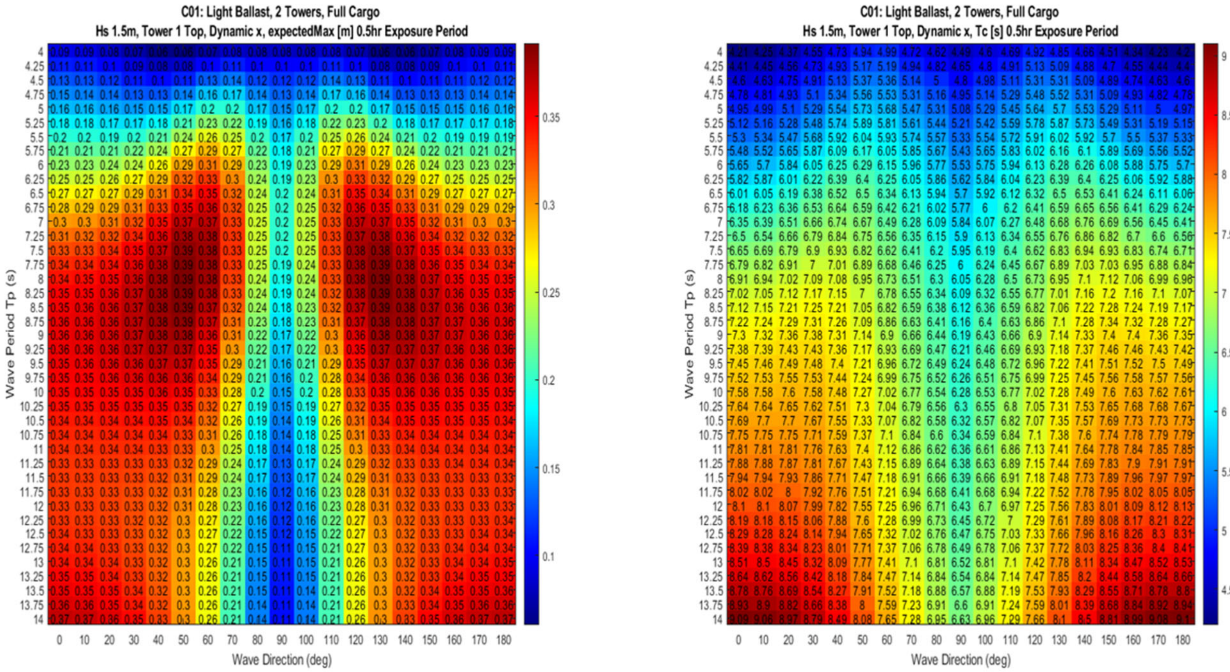


Figure 26 – Hs-Tp-Phi Sample Data for Motions in Longitudinal (x-direction)

As expected, Figure 26 shows, the most extreme longitudinal motions at the tower top occur when the vessel is in quartering seas (ϕ = 30 to 60 degrees or 120 to 150 degrees) and longitudinal motions are minimized when seas are directly on the beam and when the wave period is very small.

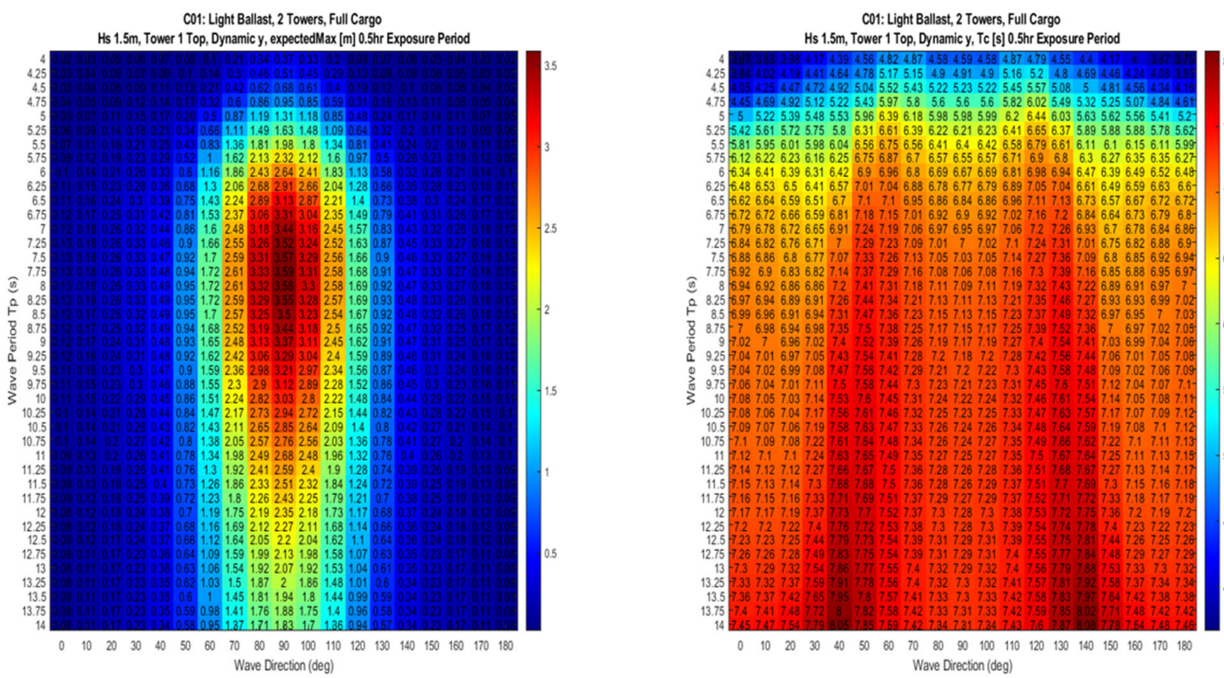


Figure 27 – Hs-Tp-Phi Sample Data for Motions in Transverse (y-direction)

Figure 27 shows, the most extreme transverse motions at the tower top occur when the vessel is in beam seas (ϕ = 90 degrees) and transverse motions are minimized when the vessel is aligned with the waves. The transverse motions are on the order of ten times the magnitude of the longitudinal motions.

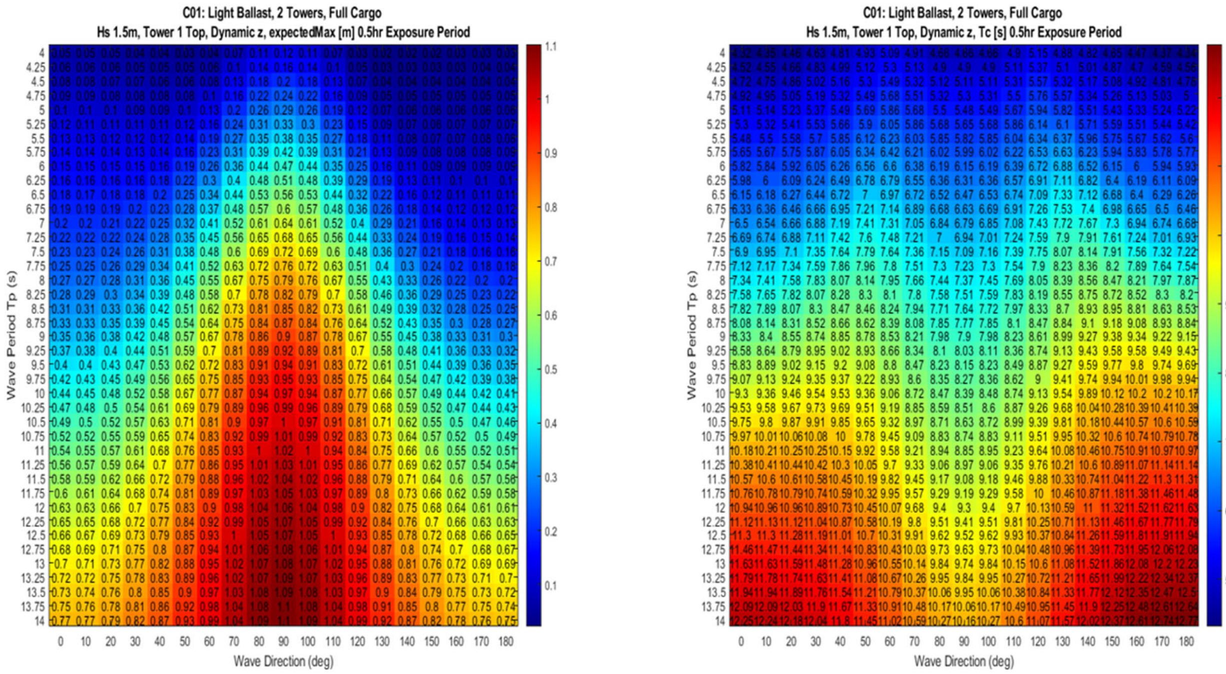


Figure 28 – Hs-Tp-Phi Sample Data for Motions in Vertical (z-direction)

Figure 28 shows, the most extreme vertical motions at the tower top occur when the vessel is in long period beam seas (Tp > 11 sec and ϕ = 90 degrees) and vertical motions are minimized when vessel is aligned with the waves, or the wave period is shorter. The transverse motions are on the order of three times the magnitude of the longitudinal motions.

Figure 29 shows the variation of longitudinal, transverse, and vertical displacement motions in meters for a 30-minute exposure period over a range of wave heights and wave directions for a given wave period. The Tower 1 Top point of interest represents a point in space for each empty cargo position and are only included for illustrative purposes. As expected, the cargo top motions increase as the overall displacement of the feeder is reduced. For this reason, consideration should be given to removing the tallest tower first.

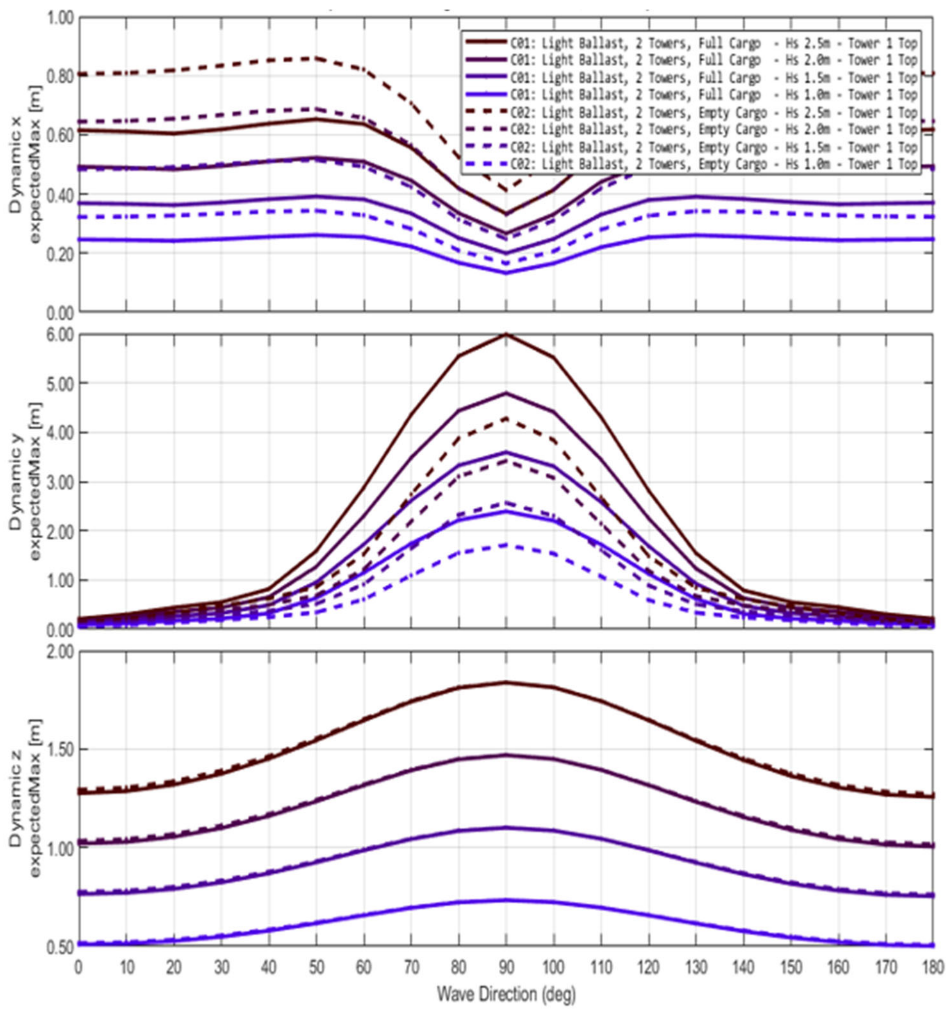


Figure 29 – Hs-Tp-Phi Sample Data for Range of Wave Heights

A2.3 Motions Limits in Weather Downtime Study

In the Weather Downtime (WDT) study, Hs-Tp-Phi database will be used to pre-process the environmental data to provide a go/no go condition based on weather conditions at each hour for a specified location. For example, if the maximum landing velocity is varied between 0.4 and 0.7 m/s in 0.1 m/s increments, the available operating time at Empire varies as follows:

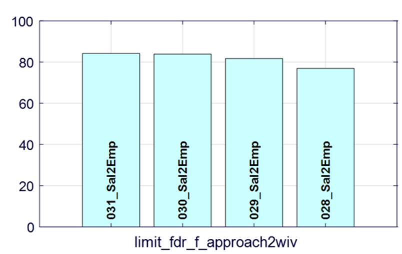


Figure 30 – Operational Availability for Landing Velocities of 0.4, 0.5, 0.6 & 0.7 m/sec

For the WDT study, the Hs-Tp-Phi database will be used in conjunction with the travel direction for the barge when pre-process the environmental data to provide a go/no go condition. For example, the route between Salem and Empire Wind is shown in Figure 31 below. The heading into the second way point (Leg 4) is 167 degrees. The heading away from the second way point (Leg 5) is 285 deg.

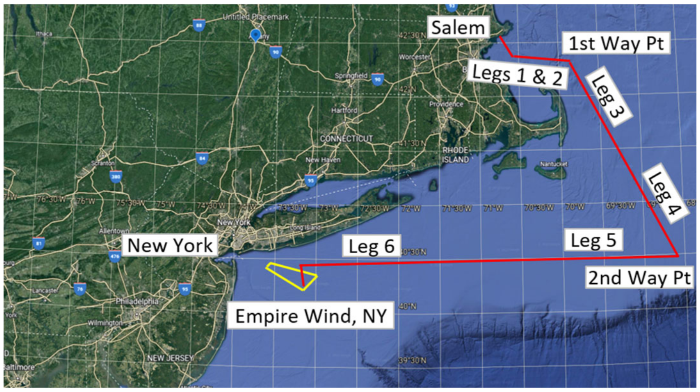


Figure 31 – Feeder Routes between Salem Load Port and Empire Wind

For example, if the cargo acceleration limits are varied between typical limits and acceleration limits that are half or double the typical limits. The available operating time at the 2nd Way Point varies as follows:

Weather Uptime Analysis, 01-Jan-1979 to 01-Jan-2010, Month Range: All Year

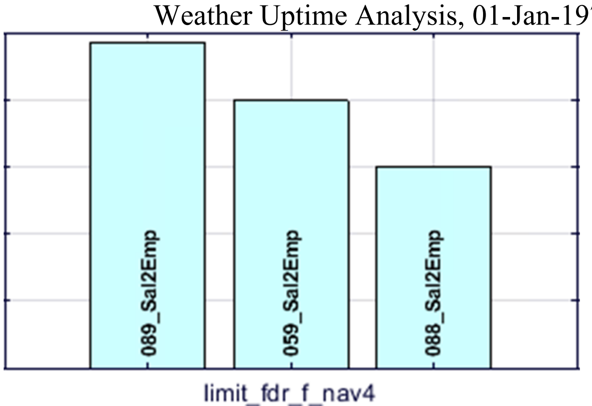


Figure 32 – Example Uptime Analysis for Cargo Accelerations, Leg 4

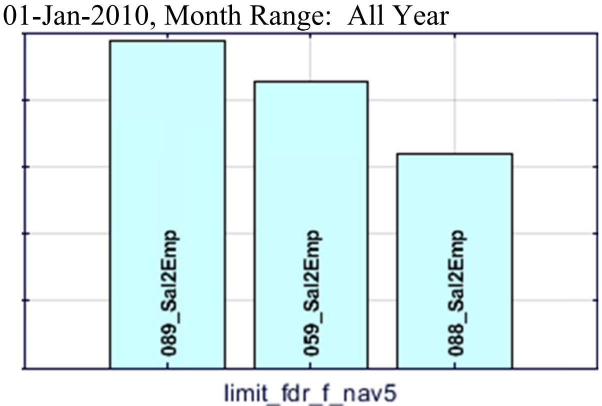


Figure 33 – Example Uptime Analysis for Cargo Accelerations, Leg 5

On Leg 4, with acceleration limits ranging from half the typical limits to twice the typical limits, the operational time varies from 96.7% to 79.8% to 60.1% and at Leg 5, the operational time varies from 97.4% to 85.3% to 64.0% as shown in Figure 32 and Figure 33 above.

Appendix B. Mooring Analysis

B.1 Mooring Arrangement

B1.1 Load Cases – Projected Wind Area

The projected wind area for the load cases:

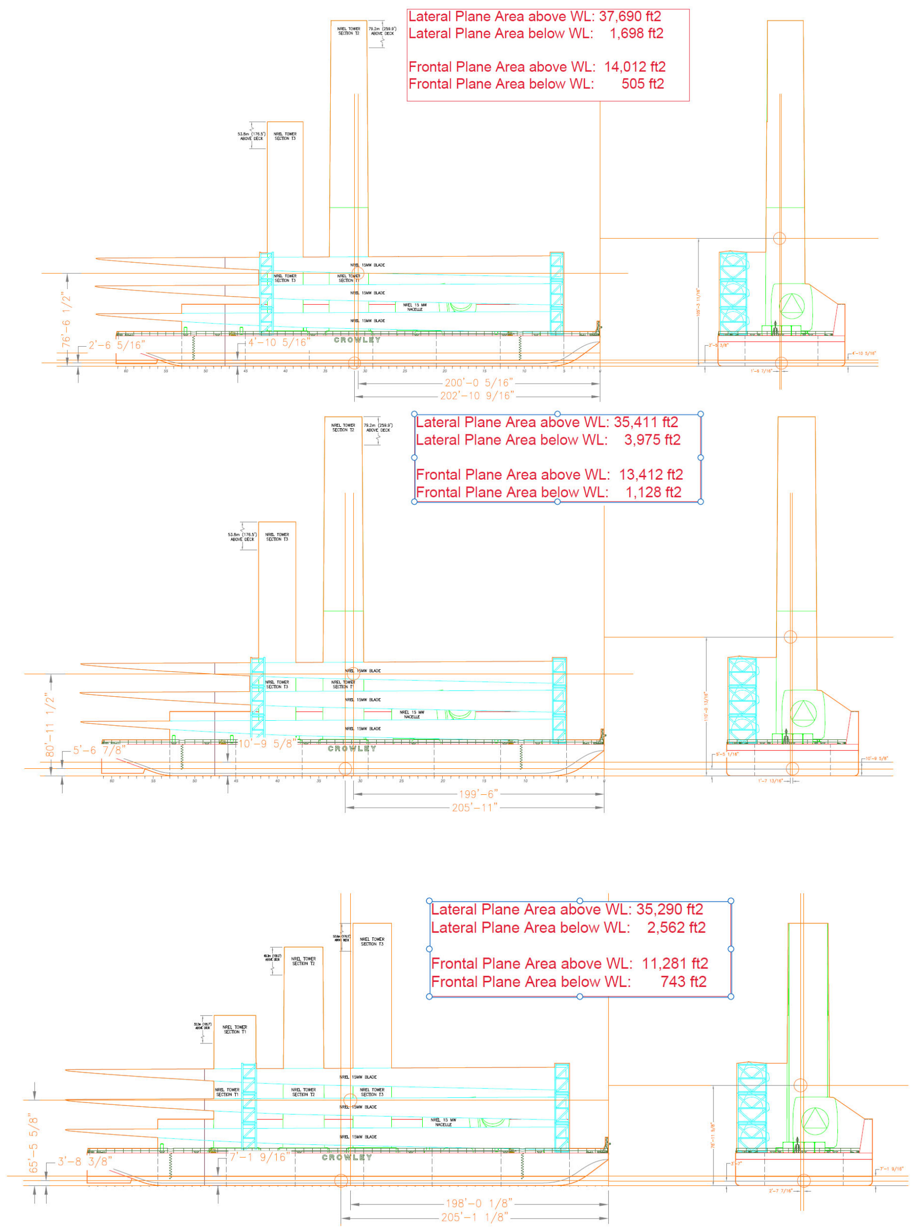


Figure 34 – Projected Wind Areas for Load Conditions

B1.2 Mooring Environment

As reported in the Maneuvering Simulation to Indicate Operational Limits Technical Report (Reference 6.1.2), the operational conditions for landing the feeder against the WTIV were evaluated by the tug captains for safety of the operation. Those limits were used as minimum requirements for the mooring system:

- Significant wave height (Hs) > 1.85 m
- Wind > 25 knots

The safety ratings as determined by the captains are shown in Figure 35 and Figure 36 below.

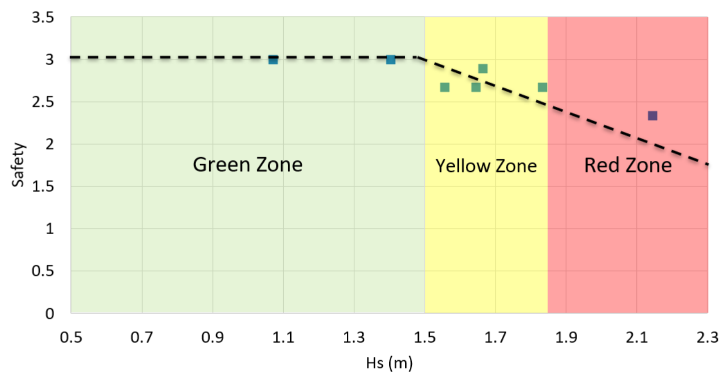


Figure 35 – Safety Levels over a range of Wave Heights

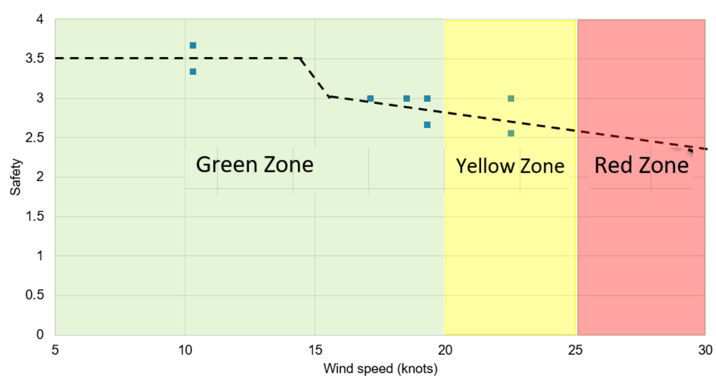


Figure 36 – Safety Levels over a range of Wind Speeds

B1.3 Configuration of Mooring Lines and Fenders

An initial assessment of the mooring line configuration was performed during the same maneuvering simulation. The ability to keep station was evaluated for two configurations:

- Only breast lines (Figure 37)
- Breast lines with spring lines (Figure 38)

All test cases had 3 fenders (described in Section B1.4.)

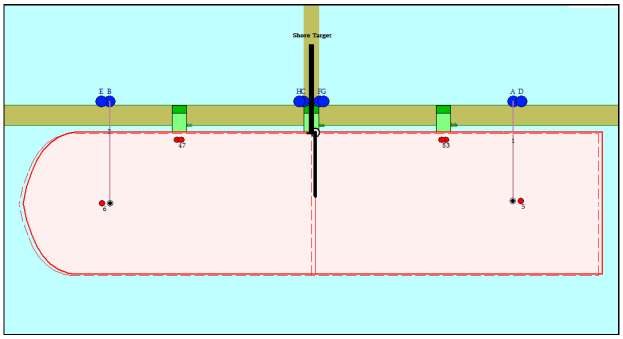


Figure 37 – Three Fenders / Breast Lines Only

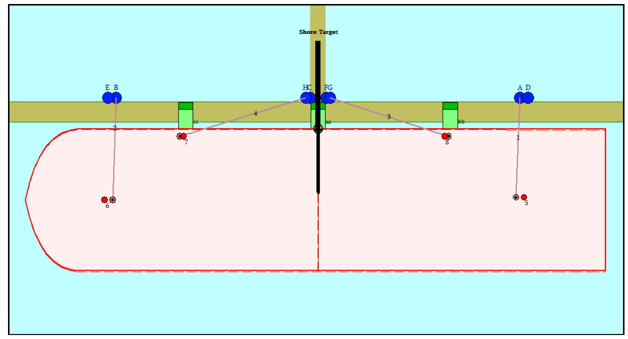


Figure 38 – Three Fenders / Breast and Spring Lines

As reported in the Maneuvering Simulation to Indicate Operational Limits Technical Report (Reference 6.1.2), spring lines are necessary to minimize the size of the watch circle.

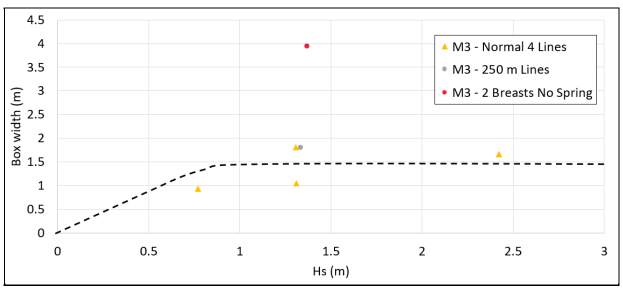


Figure 39 – Watch Circle (Box) Width for Hs

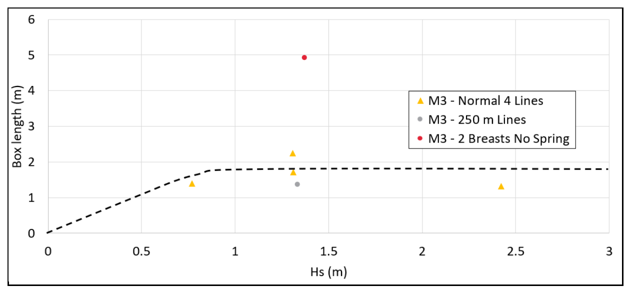


Figure 40 – Watch Circle (Box) Length for Hs

B1.4 WTIV Mooring Configuration

To minimize vertical loads on the mooring system, the mooring lines are assumed to pass through sheaves on the side of the WTIV. The sheaves are placed so that the line contact point is approximately 3 m (10 ft) above the barge deck when loaded to the post-cargo discharge draft. The sheave location is a compromise between being low enough to minimize the vertical force on the barge but high enough so that the line will not chafe on the barge deck edge.

For the OPTIMOOR model, quick release mooring hooks were located on the barge centerline. If a fender wall is used, the mooring lines would through openings in the wall to the hooks.

B1.5 Mooring Line Material

The mooring lines were assumed be high-performance, floating mooring rope with a Maximum Breaking Force of 276.1 MT (304 ST) and a maximum diameter of 108 mm.

In the maneuvering simulator (see Reference 6.1.2), the "Nylon" material was selected for its extensibility of 22%.

B1.6 WTIV Fenders

For this study, fenders were assumed to be Trelleborg pneumatic fenders with a diameter of 3300 mm and a length of 6500 mm.

Figure 41 – Trelleborg Pneumatic Fenders

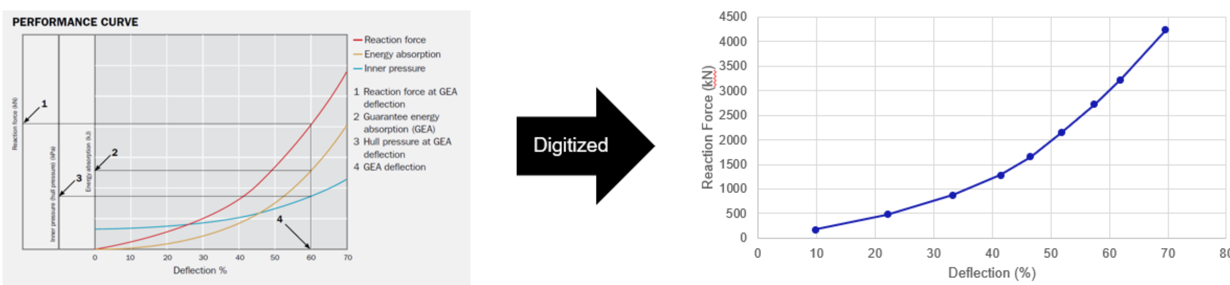


Figure 42 – Fender Material Properties and the Digitized Values

As described above, all OPTIMOOR cases were simulated with three pneumatic rubber fenders. The fender material and configuration are satisfactory for up to 50 knots of wind under 6 feet of beam waves.

B.2 Mooring Analysis Findings

The mooring and fender configurations were analyzed as follows:

B2.1 Two Breast Lines, No Waves

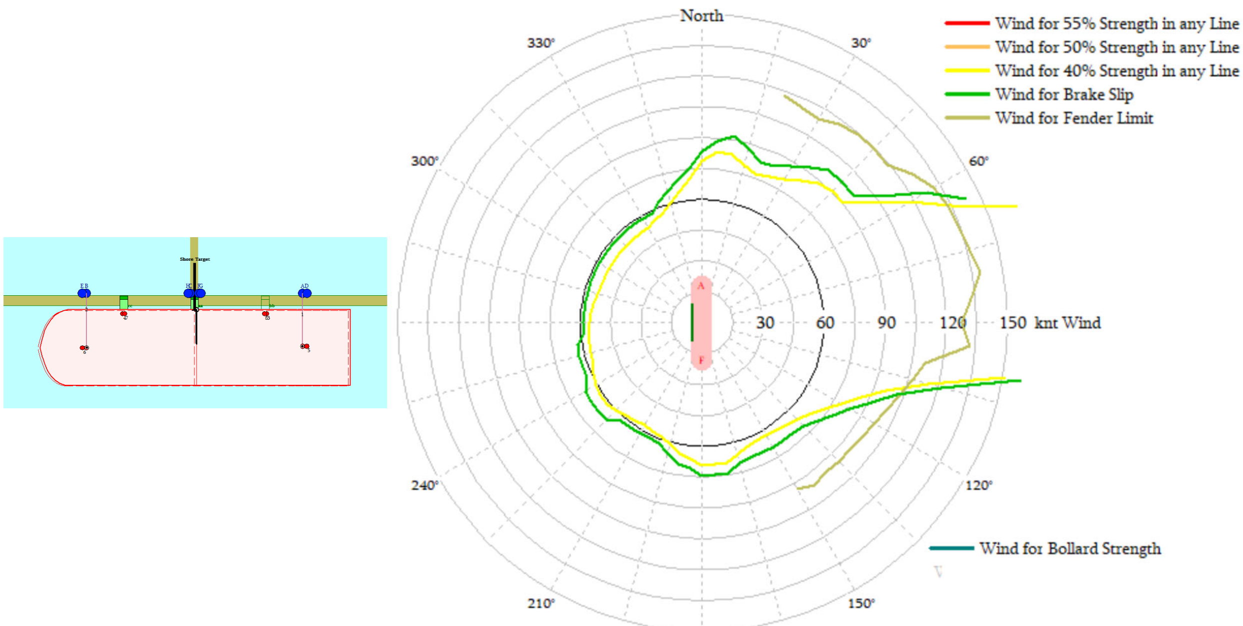


Figure 43 – Two Breast Lines, No Waves

B2.2 Two Breast Lines, 1 ft Waves on the Beam

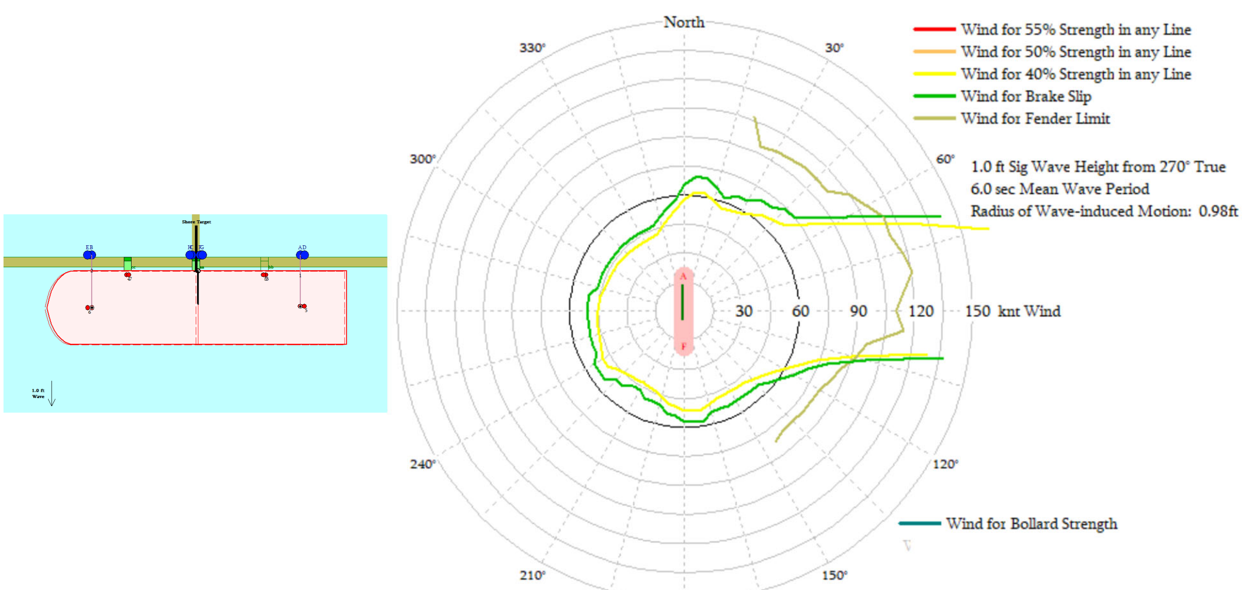


Figure 44 – Two Breast Lines, 1 ft Beam Waves (19% of maximum strength)

B2.3 Two Breast Lines, 2 ft Waves on the Beam

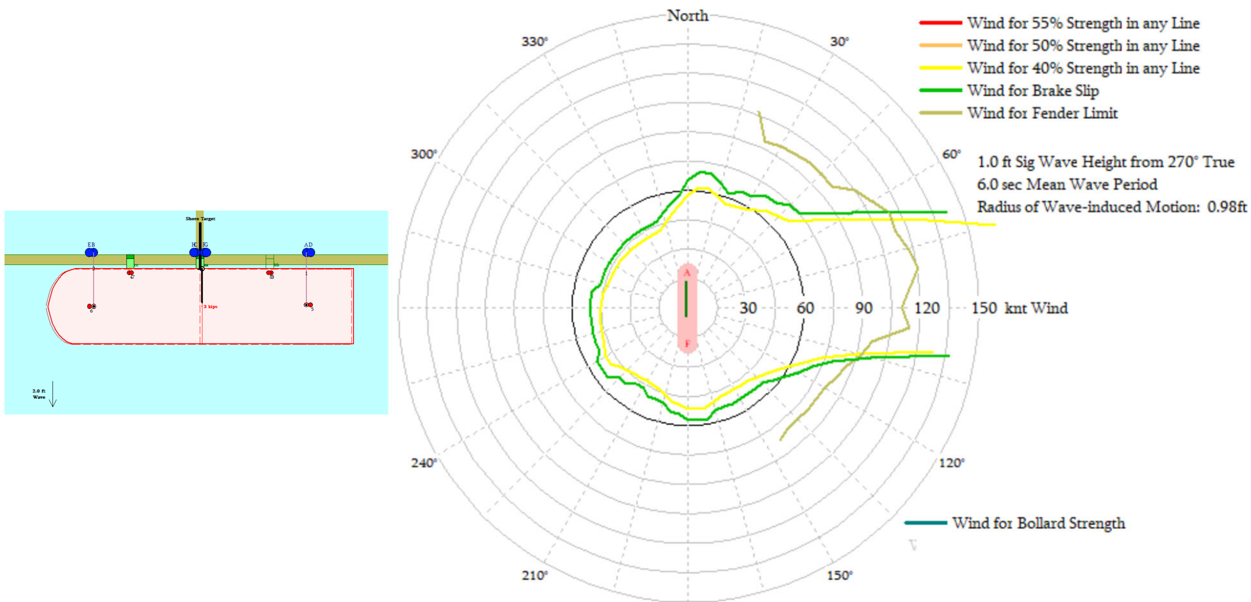


Figure 45 – Two Breast Lines, 2 ft Beam Waves (32% of maximum strength)

B2.4 Two Breast Lines, 2.6 ft Waves on the Beam

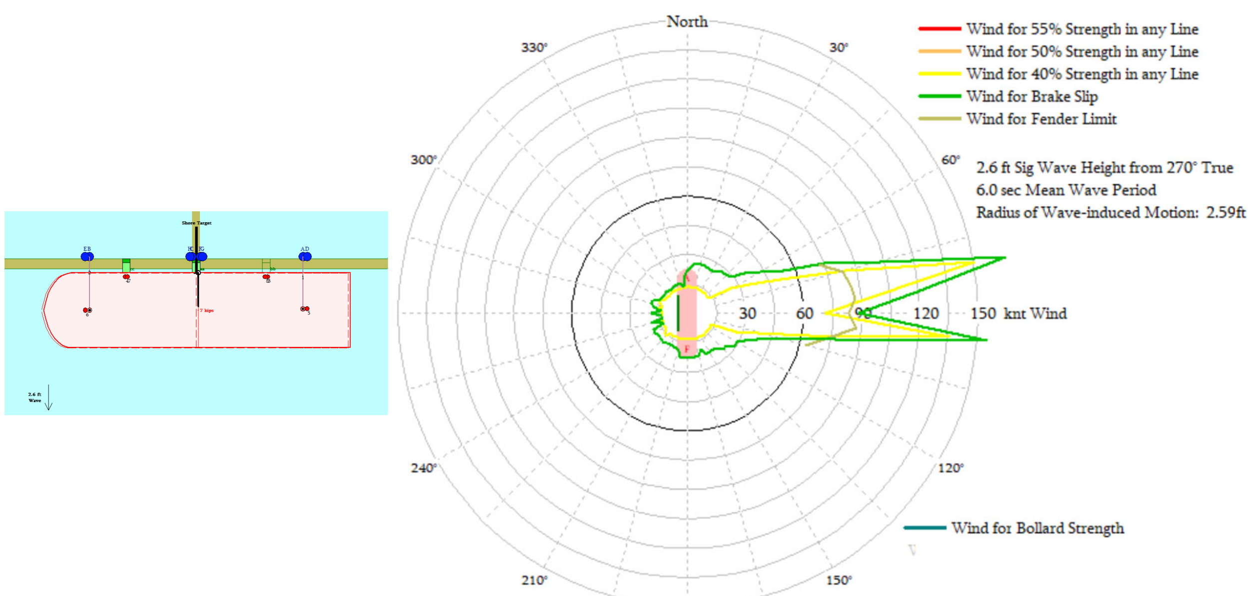


Figure 46 – Two Breast Lines, 2.6 ft Beam Waves (40% of maximum strength)

B2.5 Two Breast Lines and Two Spring Lines, No Waves

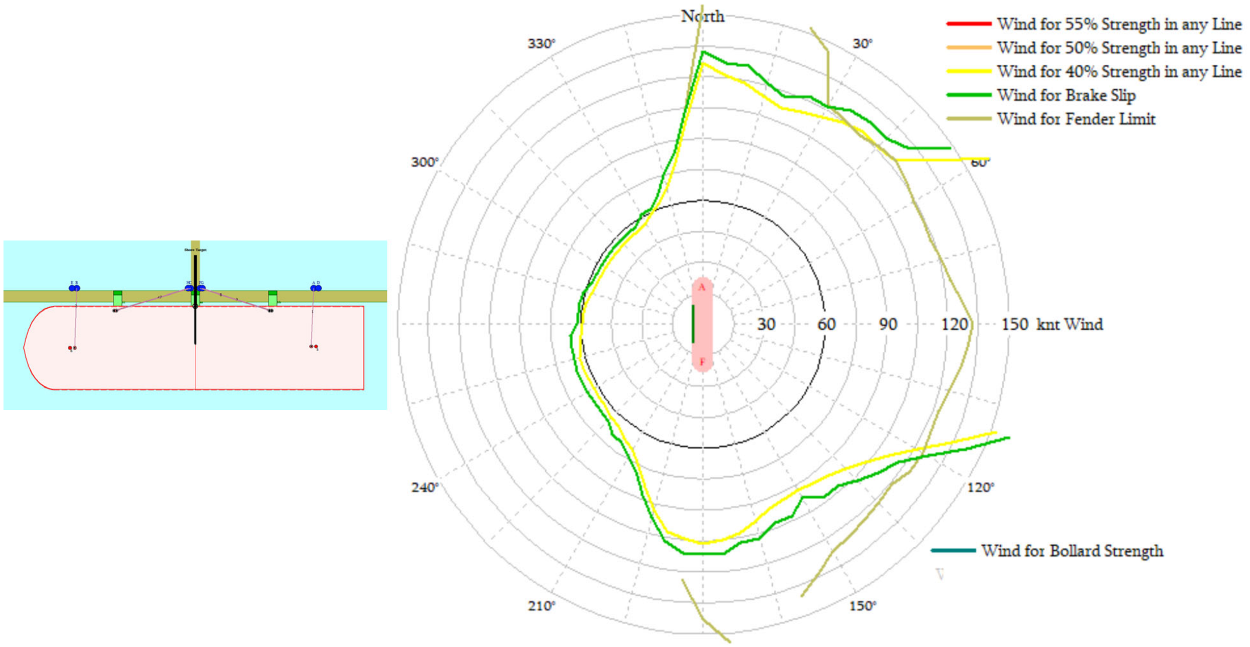


Figure 47 – Two Breast & Two Spring Lines, No Waves (5% of maximum strength)

B2.6 Two Breast Lines and Two Spring Lines, 2.6 ft Waves on the Beam

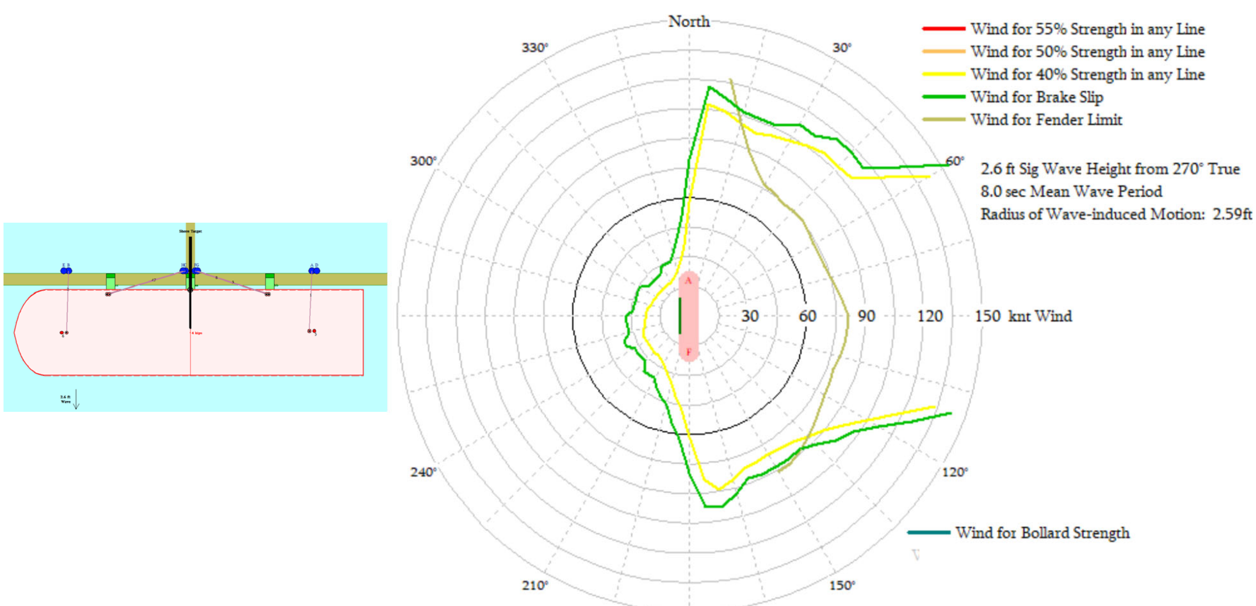


Figure 48 – Two Breast & Two Spring Lines, 2.6 ft Beam Waves (35% of maximum strength)

B2.7 Four Breast Lines and Two Spring Lines, 6 ft Waves on the Beam

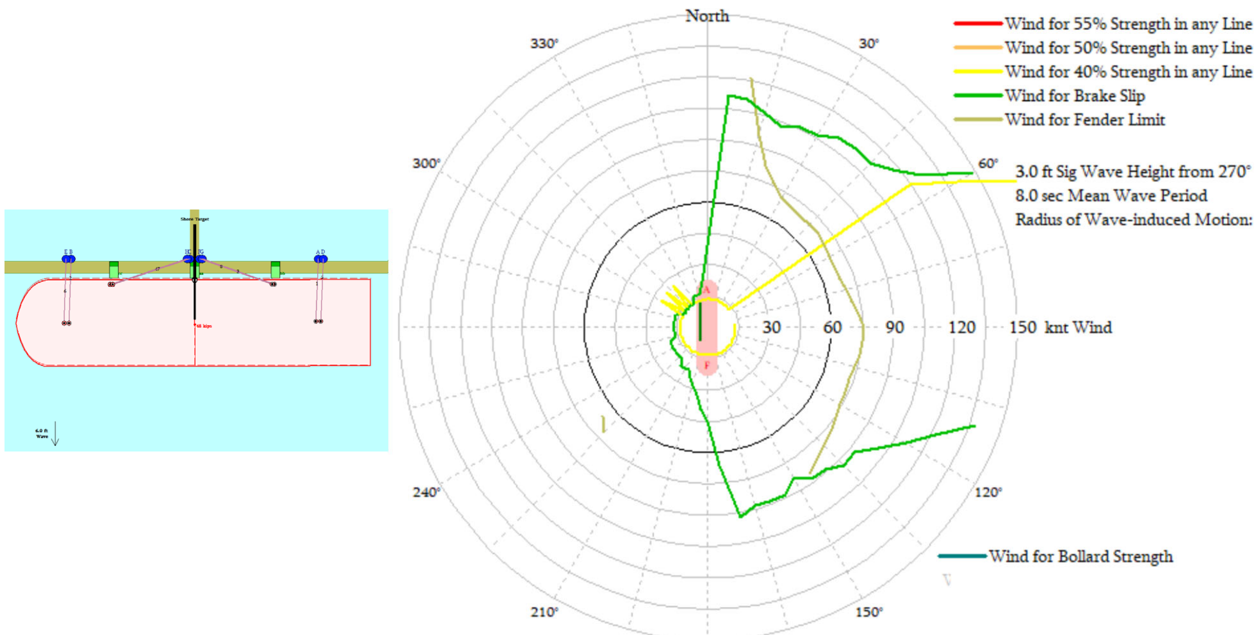


Figure 49 – Four Breast & Two Spring Lines, 6 ft Beam Waves (37% of maximum strength)

Appendix C. Time Domain Analysis

C.1 Time Domain Mooring Analysis Example Results

C1.1 Example Time History Outputs

A database of 1152 models were run over a range of modal wave period Tp, significant wave height Hs, and wave heading. Success of the mooring system over a range of environmental parameters was judged according to vessel excursions and loads on the mooring system. Various example outputs data from the time domain mooring analysis are given in the following figures:

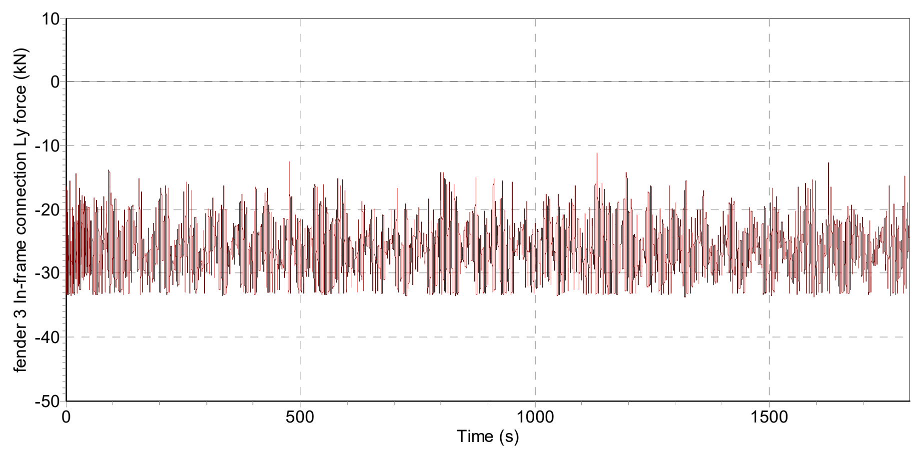


Figure 50 – Time Domain Mooring Analysis Fender Forces (Example Time History)

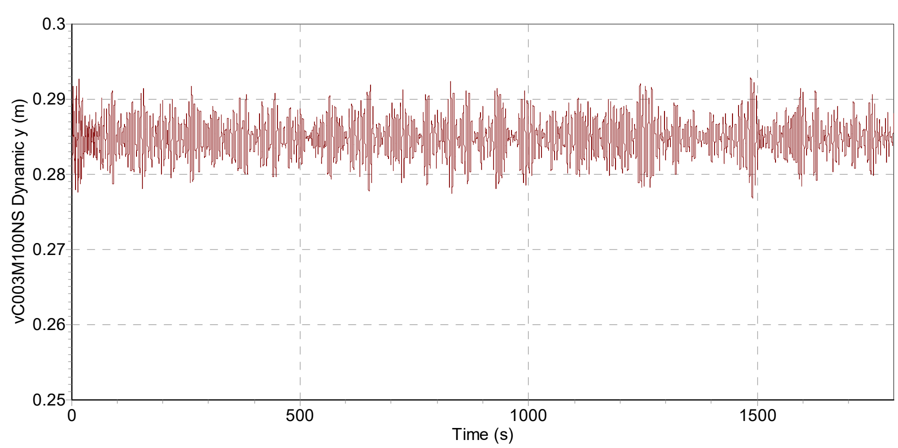


Figure 51 – Time Domain Mooring Analysis Barge y Motions (Example Time History)

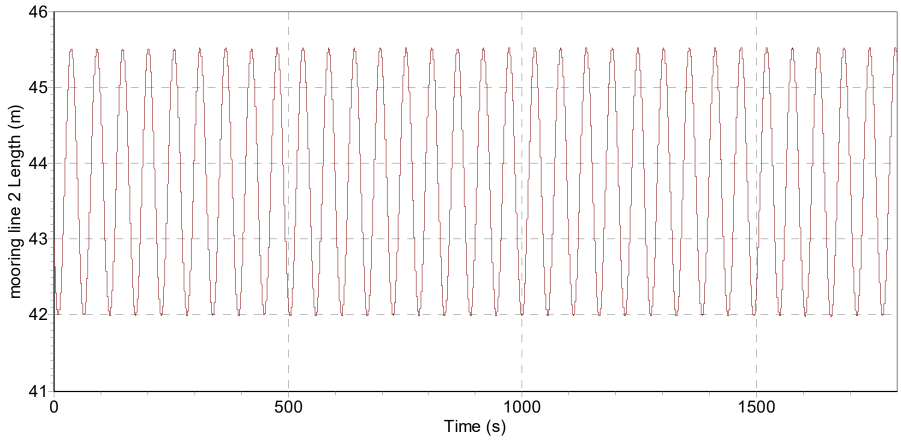


Figure 52 – Time Domain Mooring Constant Tension Winch Line Length (Example Time History)