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Non-Traditionally Shaped Vessel Stability Standards

Project Summary

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Non-Traditionally Shaped Vessel Stability Standards

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EXECUTIVE SUMMARY

As directed by the USCG Research and Development Center (RDC), Gibbs and Cox Inc., along with MiNO Marine LLC., has performed an in-depth study on the stability evaluation of non-traditional hull forms and vessels in the offshore energy, oil, and gas industries. The study was organized around four main tasks:

- Task 1: Literature Review
- Task 2: Develop Analysis Methodology
- Task 3: Verify Analysis Methodology
- Task 4: Technical Report

This study includes a comprehensive review of the current state of non-traditional vessel stability evaluation techniques while also proposing a five-step procedure to address identified deficiencies. Deficiencies addressed directly by the study include definition of non-traditional hull forms, identification of critical axes, and application of current wind overturning moment estimations in stability software, such as General Hydrostatics (GHS). However, when studying dynamic response in waves, wind force estimation, and free twist righting arm calculations, it becomes clear that the existing body of knowledge does not currently support the development of comprehensive stability criteria that address the failure modes of all non-traditional vessels. As each are unique, different criteria should be considered. This report contains the details of the study and includes recommendations and conclusions that will guide a path forward to the eventual development of improved non-traditional vessel stability criteria.

The key takeaways are:

- Specific deficiencies have been identified in the existing stability rules. Resolutions have been recommended where possible.
- Not all non-traditional hull forms are similar (i.e., Liftboats and Jack-Ups are quite different from column-stabilized Mobile Offshore Drilling Units and Wind Turbine Installation Vessels). Given these differences, there is not likely a “one-size-fits-all” set of criteria that can be applied to address non-traditional hull form stability. Multiple revised criteria should capture the unique issues of each vessel type.
- Identification of critical axis¹ is important to understanding and evaluating non-traditional hull form stability, and a procedure for identification has been developed. Free twist righting arm methods seem appropriate but require further validation and standardization.
- Non-traditional hull forms are highly susceptible to wind heeling and care must be taken to estimate wind heeling moment. Wind tunnel tests and computational fluid dynamic simulations offer promise but are not widely accessible and accepted by USCG. The building block approach is the standard approach, but it lacks best practices to ensure consistent results among different practitioners using different software tools. Building upon the results from SNAME OC-8 Panel, further study is needed to ensure wind heeling moments are applied correctly to these vessel types.
- The existing stability criteria do not explicitly address the dynamic response to waves. The body of knowledge of non-traditional hull form failure modes when subject to the combined effects of wind and waves is not complete. This is reflected in the stability criteria which lack explicit specification of design wave heights and periods. While this report contains an analysis of the behavior of one

¹ See Section 4.4 for definition.



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typical Liftboat example and a potential assessment method, much more analysis is required to develop a robust criterion that addresses the wave dynamics of non-traditional hull forms.

- A roadmap has been developed to address how the recommendations could be implemented with the ultimate goal of updating the CFR for Liftboat stability evaluation.



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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ACV	Air Cushion Vehicle
AHTS	Anchor Handling Tug Supply
ABS	American Bureau of Shipping
API	American Petroleum Institute
CCW	Counterclockwise
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CG	Center of Gravity
CG-ENG	United States Coast Guard Office of Design and Engineering Standards
DNV	Det Norske Veritas
DOF	Degree of Freedom
DSV	Dive Support Vessel
GHS	General HydroStatics
GM	Metacentric Height
GMt	Transverse Metacentric Height
HMMT	Applied Heeling Moment
IACS	International Association of Classification Societies
ICLL	International Conventions on Load Lines
IMO	International Maritime Organization
ITTC	International Towing Tank Conference
JONSWAP	Joint North Sea Wave Project
KG	Distance Between Keel and Center of Gravity
LCG	Longitudinal Center of Gravity
LT	Long Tons
MODU	Mobile Offshore Drilling Unit
MOU	Mobile Offshore Unit
MSC	United States Coast Guard Maritime Safety Center
NTH	Non-Traditional Hull form
OTC	Offshore Technology Conference
PSV	Platform Supply Vessel
RMS	Root Mean Square
SES	Surface Effect Ship
SEMI	Semi-Submersible
SNAME	Society of Naval Architects and Marine Engineers
SWATH	Small Waterplane Area Twin Hull
TUG	Tugboat
US	United States
USCG	United States Coast Guard
WTIV	Wind Turbine Installation Vessel



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1 INTRODUCTION

This document summarizes work performed by Gibbs & Cox Inc. (G&C) along with its subcontractor, MiNO Marine LLC. (MiNO) is under the OASIS Pool 3 Contract Number GS00Q14OADU420. The topic of the Task Order is Non-Traditionally Shaped Vessel Stability Standards.

1.1 Background

In 2022, The USCG Research and Development Center (RDC) issued an award to G&C to conduct a study investigating issues surrounding stability evaluation of non-traditionally shaped vessels. The underlying need for this study is summarized as follows:

- Commercial vessel stability regulations may not provide adequate safety factors for non-traditionally shaped vessels, for example Liftboats, Jack-Up Units, Mobile Offshore Drilling Units (MODU), Wind Turbine Installation Vessels (WTIV), and other vessels with unusual geometry.
- Current shape factors provided in the Title 46 of the Code of Federal Regulations (CFR) may underestimate or overestimate the wind load contribution of some vessel structures (see Section 3.3 for a detailed discussion on wind load estimation).
- These factors have presented issues and confusion with companies, class societies, and the Coast Guard, including the Coast Guard Office of Design and Engineering Standards (CG-ENG).
- CG-ENG has been directed to identify stability failure modes, risk control options, and consider updating or revising current Liftboat, Jack-Up Unit, WTIV, etc. stability regulations.

1.2 Project Objective

The overall objective of this study was to develop a generalized set of stability criteria that is applicable to all types of Liftboats, Jack-Ups, and WTIVs and can achieve a minimum level of safety for these non-traditionally shaped vessels.

1.3 Project Scope

The study was organized around four tasks:

- Task 1: Literature Review
- Task 2: Develop Analysis Methodology
- Task 3: Verify Analysis Methodology
- Task 4: Technical Report

Task 1 involved compiling the numerous sources of information on this topic and a review of the state of practice in the industry. The Task 2 purpose was to address the identified shortcomings of existing methods and develop an alternative stability methodology. Task 3 tested this new methodology on generic examples of non-traditional vessel types. Finally, Task 4 generated the summary documentation found in this report.



1.4 Project Team

The USCG RDC, CG-ENG, G&C and MiNO formed the team for this effort. MiNO Marine is a leading naval architecture firm for the design and operations of Liftboat vessels. When combined with the offshore oil and gas experience of G&C’s Houston and New Orleans offices, the project team represented a well-qualified group of highly experienced engineers with an extensive record on this topic.

2 DEFINITION OF STATE OF THE ART AND STATE OF PRACTICE

Non-Traditional Hull forms (NTH) and similar vessels have been around for decades². Methods to analyze their unique stability characteristics have been under development since the first vessels were introduced into service. To develop a better methodology for stability evaluation, it is first necessary to understand the current state of the art and state of practice. Thus, an in-depth literature review was performed to develop an understanding of the problem. The goals of the literature review were:

- Identify state of the art/practice for non-traditional hull form stability
- Identify state of the art/practice for wind loads on offshore structures
- Identify relevant and accurate methods for vessel stability
- Identify deficiencies in existing stability rules

The results of the literature review are documented in the spreadsheet entitled “Literature Search Reference Summary” [1], as well as in Appendix A. This spreadsheet contains a consolidated, annotated, and ranked list of relevant sources surveyed during the review. More than 110 references are documented.

2.1 Literature Review Methodology and Organization

The sources documented in the literature review, Appendix A, are organized into the following “tiers” to further help organize the vast amount of information:

Table 1. Literature review tiers.

Tier	Description
1	Sources listed in the original USCG Statement of Work for this project
2	Additional sources provided by the USCG post-award
3	References of interest cited by Tier 1 and Tier 2 references
4	Additional references collected through the literature search effort
5	References pertaining to marine accidents of non-traditional vessels

The tiers assigned to each reference are not necessarily indicative of their relevance or importance; however, Tier 1 and 2 references are given deference owing to the USCG’s presumed vetting of these references as relevant to their purpose in initiating this study.

² Although the terms “hull form” and “vessel” could be considered synonyms, the authors assume an important distinction between them for this report. Strictly speaking “hull form” does not include topsides or superstructure features whereas “vessel” represents the entire ship both above and below the maindeck.

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Each reference has been ranked on a scale of 1 to 4 according to the rubric shown in Table 2 while considering relevancy, comprehensiveness, and originality. Half scores are given based on judgment. For example, a reference that may be decades old but addresses the same issues may be given a 1.5 rank.

Table 2. Literature reference ranking.

Ranking	Description
1	Primary contemporary source directly related to the problems at hand. Directly addresses at least one of the challenges identified.
2	Primary source than contributes to understanding of the problems at hand, or that has some wisdom that lends itself to solving the problems at hand either by analogy or similarity to other vessel types or represents a historical effort similar to this one.
3	Supporting source that contains background and/or historical information that helps flesh out an understanding of the problems at hand and provides lessons learned. Also includes accident reports that further our understanding of failure modes, met ocean conditions, or operational aspects pertaining to stability.
4	Supporting source that contains rules, regulations, standards, criteria, useful data, or other information that may be useful.

Filters embedded in the spreadsheet allow the reader to focus on subsets of the references corresponding to the topic or keyword of interest, subsets by date of publication, or any of the other fields recorded in the spreadsheet.

In parallel with the literature review, the team documented the results of surveying commercially available stability software. These results were also tabulated in a spreadsheet according to provider, software name, general description, and methodology employed.

2.2 Literature Review Results

Having compiled the references into a useful spreadsheet, as shown in Appendix A, the project team performed a deep dive into the information. The results have been organized in accordance with the goals established in Section 2.

2.2.1 State of the Art/Practice for Non-Traditional Hull form Stability

Non-traditional hull forms in the offshore energy, oil and gas industries are typically characterized by hull shapes that may be asymmetrical or have low length-to-beam (L/B) ratios when compared to traditional ship-shaped hull forms. However, there is no concise, published definition, and some rules of thumb are deceiving. For example, using a L/B ratio threshold of 1.5 or lower to identify the need to consider all heel axes would preclude WTIVs from being considered. Yet, WTIVs are one type of non-traditional hull form where non-traditional stability analyses are required. [2] [3] Typical non-traditional hull forms include Liftboats, Jack-Up units, WTIVs, and semi-submersibles.

Current stability criteria in CFR 46 Subchapter S [18] are derived from traditional hull form criteria that have been implemented since the 1940's. The criteria appear to have been tailored over the years for various hull forms and operating environments. See Section 2.2.4 for more on the existing stability criteria.

Current practice recognizes the unique characteristics of non-traditional hull forms when it comes to computing righting arms. Free twist and least energy path methods, such as those described in [4] and [5]



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among other sources, are recognized as appropriate methods by classification societies, designers, and software providers for computing righting arms of non-traditional hull forms.

In understanding the state of practice in non-traditional hull form stability evaluation, it is helpful to recognize the capabilities of the tools used for evaluating stability. With respect to righting arm calculations, most, if not all, stability analysis software surveyed incorporate fixed or free trim righting arm calculations. Four products – GHS, HECSTAB, PIAS, and NAPA – incorporate free twist by varying names. One additional product, Wolfson’s HST, incorporates a yaw, trim, pitch equilibrium solver designed for asymmetric hulls (sailing yachts), but the software is untested for other types of hull forms.

Virtually all the software products incorporate some form of projected area, user input, or building block method for computing wind forces and moments and they all appear based on the standard empirical approach using shape and height coefficients. Further, it seems that only wind tunnel tests and Computational Fluid Dynamics (CFD) methods are capable of capturing overturning moments due to lift. [6]

CFR regulatory requirements still require fixed trim or free trim righting arm calculations using traditional methods and are silent on other righting arm calculation algorithms; although, the American Bureau of Shipping (ABS) [4] [5] does implement free twist methods in their evaluations. The literature results demonstrate that a few practitioners besides ABS implement free twist methods, but such use is not widespread. However, it does appear that the use of these methods is increasing. Practitioners have been using multi-axis methods along with fixed trim or free trim solvers for over a decade. The next step appears to be widespread adoption of free twist-like methods and there are at least three commercial stability software packages that have enabling features.

2.2.2 State of the Art/Practice for Wind Loads on Offshore Structures

With respect to wind force and moment calculations, the prevalent approach is the projected area strip method, such as that used by the US Navy [7], or the building block approach currently codified in virtually all MODU regulations such as CFR 46 Subchapter I-A, IMO MODU Code, and ABS MOU Rules. This is the conventional approach using shape and height coefficients. This method does not explicitly account for lift generated overturning moment and there are variations in implementation of the building block method. Some approaches implement multi-axis capabilities, some include shielding/shadowing, and others include the effect of exposed undersides of structures and increased exposed area of the hull as it emerges.

There are differences in stability criteria requirements in computing the wind heeling arm as a function of heel with some criteria requiring a constant heeling arm and others using a function where the heeling arm decreases or increases with heel angle.

For high value vessels and platforms, wind tunnel tests and/or CFD simulations are used for wind overturning moment predictions, but there are variations in how the model (physical or digital) is allowed to respond (heel) during the test or simulation. There exist standards, such as [8] [9] [10] that address wind tunnel tests and CFD simulations. That said, current CFR regulations and Marine Safety Center guidance requires final wind load estimates to use the empirical building block method, or model test results or CFD results that are as conservative as building block results [11].



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2.2.3 Relevant and Accurate Methods for Vessel Stability

Identification of accurate methods cannot be completed without fully validating the approach developed in Task 2. That said, there are several relevant candidate methods that will likely improve the accuracy of stability evaluation for non-traditional hull forms.

The “methods”, though, must be considered on component basis in that the available methods solve a specific part of an overall stability evaluation.

These can be subdivided as follows:

Methods for Computing Generalized Righting Arms in Calm Water:

- Fixed Trim – The trim is held constant while the heel is varied when solving for vessel righting arms.
- Free Trim – At each angle of heel a vessel’s righting arm is calculated assuming the vessel is permitted to trim free until the trimming moment is zero.
- Free Twist – Allows heeling axis to vary as the vessel heels. There are multiple methods for calculating the heeling axis variation, which are further discussed in Section 3.4.1. (i.e., the inclination axis is altered from an axis in the vessel's center plane).

Methods for Determining Critical Axis:

- Path of minimal energy build-up.
- Direct numerical simulation of capsizing using 6 DOF CFD simulation.

Methods for Computing Wind Moments:

- Building Block Method.
- CFD 6 DOF with wind lift.
- Wind Tunnel limited DOF with uplift.

Methods for Computing Wave Effects:

- Modified beam wind with roll criteria with wave height correlated to wind speed – a prominent example is the IMO Severe Wind and Roll Criteria.
- Modified righting arm calculations using hogging or sagging wave surface profiles.
- Use of current seakeeping tools for prediction of rollback angle for use in modified beam wind with roll criteria.

2.2.4 Deficiencies in Existing Stability Rules

Several deficiencies in the existing stability rules have been identified through review of relevant literature and through MiNO Marine’s specific experience designing and supporting operations of non-traditional vessels. Table 3 summarize the deficiencies.

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Table 3. Summary of deficiencies in stability rules.

Deficiency	Comments
Extrapolation	Conventional stability criteria (in general) have been empirically derived based on experience with a specific data set of conventional ships. Applying them to types and conditions outside the data set introduces uncertainty in their applicability.
Critical Axis	No standard, widely accepted definition. Definition absent in current governing criteria. Ambiguity exists in statements requiring evaluation of wind “in any horizontal direction” with no further guidance.
Range of Stability	Current limits for MODU while based on MODU tests and studies may not be appropriate given the method used to determine RoS.
Righting Arm Solver	Fixed trim and free trim righting arm solvers do not adequately capture the minimum righting capabilities of non-traditional hull forms.
Wind	Inconsistent application of wind heeling moment versus heel angle. Lack of accounting for lift. CFR language specifically requires “projected lateral area” (46 CFR Subchapter S 170.170). Hurricane wind speed predictions have improved, perhaps requiring wind speed updates. Inconsistent application of the building block approach.
Waves	No explicit accounting for waves in current governing criteria. Only still water characteristics are used to assess transverse stability. No generally accepted methods for dealing with wave action and other dynamic phenomenon other than requiring safety factors in the energy balance approach. Current Title 46 CFR 170.170 weather criteria do not account for wave/dynamics.
Non-traditional	No clearly defined criteria available to indicate whether a vessel should/must be treated as non-traditional (e.g., some Liftboats and WTIVs are not obvious).
Policy	Certain waivers are granted to deviate from ICLL requirements for domestic vessels, e.g., bow height/reserve buoyancy waiver. USCG criteria may be less stringent than other standards. Current language in the CFR explicitly only accepts fixed trim and free trim righting arm calculations.
Downflooding Angle	The definition of downflooding angle in the CFR does not envision heel axes other than the ship’s centerline. (Reference 46 CFR 174.035)
Free Surface Correction	The CFR relies on traditional free surface correction which is a simplification of the transverse shift in CG of liquids. There is no guidance on dealing with free surfaces for oblique heeling axes.
GMt	Requirements for GM must be more general than GMt. GMt is poorly defined without a defined transverse axis of inclination.
Secondary Effects	No accounting for effects such as additional heeling moment due to leg bending (static or dynamic). See the presentation by David Bourg, MiNO Marine presented to the SNAME Gulf Section in August of 2012 [24].

2.2.5 Survey of Failure Modes

A tabulation of accidents and other incidents was made to determine if any patterns are present in the failure modes of non-traditional vessels. National Transportation Safety Board (NTSB), USCG, and ABS reports were reviewed along with online articles to establish common failure modes. The results showed that five common failure modes exist, which were:



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- Excessive wind
- Excessive waves
- Progressive flooding
- Flooding from structural failures
- Operational issues (forecast data, towlines, failure to follow procedures)

Table 4 summarizes the details of the tabulation.



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Table 4. NTH failure mode summary.

Type	Operator	Name	Distance Offshore	General Area	Date	Intact or Damage	Failure Description	Weather	Waves (ft)	Wind
Liftboat	SEACOR	POWER	7 mi	Gulf of Mexico	4/13/2021	I	Excessive wind and wave, capsize	Un-named Weather	2 to 4	80 kts
Cargo Ship	TOTE Services	SS EL FARO	40 nm	South Atlantic	10/1/2015	I	Downflooding, Engine Failure, Capsize	Hurricane Joaquin		104 kts
MODU/Jack-Up	Rowan Companies Inc.	ROWAN GORILLA I	500 nm	North Atlantic	12/15/1998	D	Hull Fractures, Downflooding, Capsize	Un-named Weather	50	60 mph +
Liftboat	Montco Offshore	M/V CHRISTIE		Gulf of Mexico	3/30/1993	I	Unexpected Capsize	Un-named Weather	5 to 7	15-20 kts
Liftboat	Chevron USA (charter)	M/V AVCO V	8 mi	Gulf of Mexico	7/31/1989	I	Water on Deck, Shifted Cargo, Capsize	Hurricane Chantal	15	30 kts
Liftboat		MV TITAN		Gulf of Mexico	6/29/1989	D	Mode Changing, Flooded Leg, Capsize	---		
Semi-Sub	ODECO/MOBIL	OCEAN RANGER	166 nm	East of St. John's, NF	2/15/1982	I	Flooding of Chain Lockers, Excessive List, Capsize	Un-named Weather	50 plus max	90-100 kt
MODU/Jack-Up	Dan-Tex Int'l	DAN PRINCE	300 mi	Gulf of Alaska	10/22/1980	D	Hull Fractures, Downflooding, Capsize	Un-named Weather	60 ft	75 kts
MODU/Jack-Up		OCEAN EXPRESS		Gulf of Mexico	4/15/1976	D	Leaking, Tug Engine Failure, Broken Towline, Capsize	Un-named Weather	25	



3 ANALYSIS METHODOLOGY DEVELOPMENT

To address the challenges and deficiencies addressed in Section 2, detailed studies were performed to identify procedures and practices that can improve future evaluation analyses.

3.1 Identification of Non-Traditional Vessels

To analyze the stability of non-traditional vessels, it is first necessary to define what makes them non-traditional. This study has resulted in a set of criteria that can be used to identify non-traditional vessels from the offshore energy and oil & gas industries. These criteria are identified in Table 5³. Note that if any of these criteria are met, the vessel should be subjected to enhanced scrutiny and put through the analysis procedure set forth in Section 3.4. Many of these criteria discuss “non-zero critical axes” – a non-zero critical axis is a heeling axis that is not the zero (or conventional “long”) axis of a ship. Due to unique hull shapes, non-traditional vessels frequently have heeling axes other than zero that may present reduced stability compared to the typical longitudinal heel axis.

3.1.1 Non-Traditional Hull Features

The following key characteristics of NTH have been identified:

3.1.1.1 Multiple Hulls and/or Columns

Since traditional stability analysis is based on ship-shaped monohulls, the presence of multiple hulls and/or columns (such as in a typical column-stabilized MODU) are a clear indication that a hull is non-traditional. Hulls with columns and pontoons are highly likely to exhibit significant changes in waterplane properties suddenly when heeling. For example, with a column-stabilized MODU in transit condition, the pontoons are above the waterline, but with very low freeboard at each pontoon. Given a small angle of heel, the waterplane area can be greatly reduced in the direction of heel when one pontoon becomes submerged. This raises the chances of non-zero critical axes and/or twisting behavior when heeling.

3.1.1.2 Significant Fore/Aft Asymmetry

If the hull’s distribution of volume is significantly asymmetric about the 90-degree axis (i.e. the traditional pitching axis), there is a high potential for non-zero critical axes. For example, if a hull is in the shape of an equilateral triangle such as a typical Jack-Up rig, the hull is significantly asymmetrical about the 90-degree axis. This presents a significant chance that there is a non-zero critical axis.

3.1.1.3 Low Length-to-Beam Ratio

A traditional hull form is slender, wherein it is significantly longer than it is wide. This drives traditional hulls to a longitudinal (typical) zero-degree critical axis, and traditional stability analysis is based on this assumption. The “squarer” a hull form becomes, the more the chance of non-zero critical axes increase.

³ The authors acknowledge the possibility of adding additional criteria as needed. This proposed list represents an attempt to capture the essence of these unique vessel types.



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3.1.1.4 High Beam-to-Draft Ratio

Traditional hull forms typically have low beam to draft ratios. If a hull form has a high beam-to-draft ratio, it is more likely that the waterplane properties exhibit significant changes at small angles of heel due to bilge or keel emersion, which can dramatically affect stability. In traditional hull forms, the waterplane properties do not change significantly at small angles of heel.

3.1.1.5 High Beam-to-Freeboard Ratio (low freeboard)

Similar to the beam-to-draft ratio, low freeboard can result in significant changes to the waterplane properties at small angles of heel due to deck immersion. If for example, a small heel angle immerses the deck edge, the waterplane area and shape can change drastically. This can result in more non-linearity in the righting arm characteristics. Typical intact stability criteria do not include deck edge immersion criteria, relying more on downflooding points or angle of vanishing stability as significant points of interest on a righting arm curve.

3.1.1.6 Non-Ship-Shaped Waterplane

Like other characteristics described above, the waterplane shape has significant impact on the critical axis for stability analysis. For example, a perfectly circular waterplane has the same moment of inertia about all axes. Similarly, a triangular waterplane area exhibits symmetry about three axes as opposed to the traditional single axis waterplane symmetry. These indicate high chances of non-zero critical axes.

3.1.1.7 Waterplane Asymmetry in Evaluated Loading Conditions

Traditional stability analysis assumes zero or small initial angle of heel. In this case, the righting arms and metacentric height calculation are based on these waterplane characteristics. If an otherwise traditional hull form is designed to operate in a way the waterplane is asymmetrical in operational conditions, such as a sailboat heeled over when under sail, and these waterplane characteristics are not considered, this may not be properly accounted for in typical stability criteria.

3.1.1.8 Wind Sensitivity – Windage compared to Displacement

When surveying vessels that are widely considered non-traditional, it becomes apparent that many exhibit high “windage” or features above the waterline that are subject to wind forcing. Liftboats, Jack-Ups, MODU Semis, and WTIVs all exhibit this feature. When a vessel has significant windage, the heeling arms due to wind are higher compared to traditional vessels. This can have significant effect on the stability of the vessel, with reduced range of stability and righting energy over that range. To evaluate the wind sensitivity of a vessel, the projected wind area is multiplied by the heeling arm (the distance between the centroid of the above-waterplane projected area and the centroid of the below-waterline projected area) and is then divided by the volumetric displacement. This gives a metric of wind area vs vessel size.

3.1.2 Evaluation Limits

For each of the characteristics listed in Section 3.1.1, a limit must be established to determine if it is non-traditional. For some of the criteria, they are binary, i.e. the features are either present or they are not. For others where ratios are used, a limiting ratio has been identified based on a survey of vessel types, including vessels widely considered traditional and non-traditional. This survey resulted in the limit values provided in Table 5 below:



Non-Traditionally Shaped Vessel Stability Standards

Table 5. Non-traditional vessel criteria.

Criteria	Limit
1. Multiple hulls and/or columns	Yes
2. Significant fore-aft hull volume asymmetry	Yes
3. Low length-to-beam ratio	<2.5
4. High beam-to-draft ratio	>10
5. High beam-to-freeboard ratio	>10
6. Non-ship-shaped hull	Yes
7. Significant waterplane asymmetry in evaluation load conditions	Yes
8. Sensitivity to Wind - windage to displacement.	>5

A table showing the criteria applied for the example non-traditional hull forms (see Section 4.1) used in the study is provided in Table 6. Characteristics that fall outside the limits shown above are displayed in red. Note that if one feature is flagged, the vessel is considered *potentially* non-traditional and should be subject to non-traditional stability analysis.

For comparison purposes, other vessel types with large windage are presented in Table 6. The drillship is assumed to be the *Valaris DS-4*. The container ship is a typical 10,000 Twenty-foot Equivalent Unit (TEU). The cruise ship is the *Carnival Magic*. These were selected to test the criteria because of the unique capabilities and/or their large windage areas. As can be seen, none of them are considered to be non-traditional.⁴

Table 6. Non-traditional vessel criteria results.

CRITERIA	LIFTBOAT	JACK-UP	MODU Semi in Transit	WTIV	Drillship	Container Ship	Cruise Ship
1. Multiple hulls and/or columns	No	No	Yes	No	No	No	No
2. Significant fore-aft hull volume asymmetry	Yes	Yes	No	No	No	No	No
3. Low length-to-beam ratio	1.6	0.9	1.4	2.9	5.5	7.2	8.2
4. High beam-to-draft ratio	10.5	13.7	7.8	7.5	3.5	3.0	4.6
5. High beam-to-freeboard ratio	26.2	27.9	70.0	11.3	6.0	3.0	2.3
6. Non-ship-shaped hull	No	Yes	Yes	No	No	No	No
7. Significant waterplane asymmetry	Yes	Yes	Yes	No	No	No	No
8. Sensitivity to Wind	7.7	22.1	6.5	14.8	2.1	1.7	2.8

3.1.3 Scale of “Non-Traditionality”

As shown in Table 6, some vessels fall under many of the criteria limits assigned to non-traditional vessels. For example, the Liftboat, Jack-Up, and MODU each fall under at least 6, while the WTIV only falls under one. When assessing hull forms, it is important to consider that some may be more non-traditional than others. This does not remove them from consideration, but rather serves to provide the naval architect performing the stability analysis with a better picture of the potential areas of concern.

⁴ The authors acknowledge that the limit values proposed are a starting point for consideration. Establishing exact values would require extensive tabulation and review of hundreds of vessels.



3.2 Stability Evaluation Criteria for Non-Traditional Hull forms

As discussed in the IMO Second Generation Stability Rules [12], capsize in wind and waves is a complex process involving multiple, nonlinear interactions between hydrostatic, wave forcing, inertial and hydrodynamic forces. As generally accepted in industry, it is impractical to expect practicing naval architects to analyze the full range of these effects for every vessel through model tests, computational fluid dynamics or time domain simulations. Stability rules are, therefore, formulated to provide simplified metrics, such that a vessel, proven to be safe when compared against these metrics, will be safe in the complex dynamic operating environment in which it is expected to operate. For these metrics to be useful, evaluation of vessels relative to them must be feasible using tools and human resources normally at the disposal of a working naval architect. For the purposes of this study, the complexity and expense of such tools and resources are ordered in as follows from most to least acceptable:

1. Hydrostatics computations, including wind forcing, large angle roll effects and compartment damage
2. Linear seakeeping computations
3. Nonlinear seakeeping computations
4. Time-domain simulations
5. Physical model tests

Level 1 is expected to be available to all working naval architects to satisfy classification and regulatory requirements. Level 2 is expected to be available to naval architects working with non-traditional hull forms, for which existing regulatory and classification rules are applicable, but care must be taken to ensure that the design does not violate the underlying assumptions of such rules and for establishing safe operating envelopes. Levels 3 through 5 are required for designs which fall outside of the existing regulatory and classification framework for the non-traditional vessels addressed in this study.

One guiding principle of this study has been to formulate recommendations with as low a resource demand as possible, relative to the above list. To that end, rules which can be assessed using purely hydrostatic analysis (Level 1) are preferred. Where necessary, it is accepted that access to Level 2 resources is required. Rules requiring access to Level 3 through 5 resources have been avoided as they can become prohibitively expensive on commercial projects.

Rules that require access to static or linear tools (Levels 1 and 2 above), incorporate simplified approximations of the complex physics of vessel dynamics, so their validity must be assessed against evaluations using more sophisticated tools, such as time domain simulations or model tests. The simplified estimates must be used with margins and multiplicative factors to represent the uncertainties inherent in the simplified approximations, so simulations and/or model tests are also used to establish these factors.

3.2.1 Stability in Waves

Current regulations for non-traditional hull forms fall within the categories of Mobile Offshore Units (MOU), Mobile Offshore Drilling Units, and Liftboats. Within MOU and MODU are rules specific to self-elevating units and column-stabilized units. Such regulations are domestic as codified in the CFR and international as codified in the IMO regulations and other various IACS member Class rules, such as ABS MOU rules.

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The methods and metrics used to evaluate stability are based on traditional righting arm, GM, residual righting energy, range of stability, and other metrics such as angles of downflooding, among others. Distinction is made between Unrestricted and Restricted service where Unrestricted service generally requires assessment assuming overturning due to a 100-knot severe storm wind. Restricted service reduces that wind speed to 60 knots or 70 knots depending on the rule set.

Criteria requiring residual righting energy greater than some specified threshold presumably have sufficient margin to take wind gusts and wave effects into account. However, there is no specific wave height and period specification or any obvious way to correlate the margins on assessment metrics to a specified design wave.

Chopra [13] makes a case for the application of the IMO Weather Criteria (beam winds combined with rolling) to offshore work vessels recognizing that current stability requirements do not account for waves explicitly but that offshore work vessels spend vast amounts of time in harsh conditions and perhaps in a dynamic positioning mode. The offshore work vessels Chopra considered included an AHTS, TUG, PSV, and DSV, and preliminary analysis indicated that the weather criteria would limit their allowable KG curves, potentially significantly. Nonetheless, the philosophy of adopting an existing, and simple approach to account for wind and waves is attractive.

The US Navy has long required the Beam Winds and Rolling criteria when evaluating surface vessels. The criteria contained in DDS-079 and now DPC-010/079 [7] are essentially the same energy balance criteria as those contained in the IMO Intact Stability Code [14] Weather Criteria and the deadship vulnerability Level 1 check of the second generation intact stability criteria [12]. Figure 8-1 extracted from DPC-010/079 and duplicated in Figure 1 illustrates the form of the righting arm checks.

There have been some changes to the US Navy requirements over time. Currently, the US Navy assumes a roll back angle of 25 deg for conventional ships but reduces the roll back angle to 15 deg for hovercraft. The older DDS-079 allowed for the roll back angle for advanced craft (ACV, SES, SWATH) to be determined by model tests or best available data.

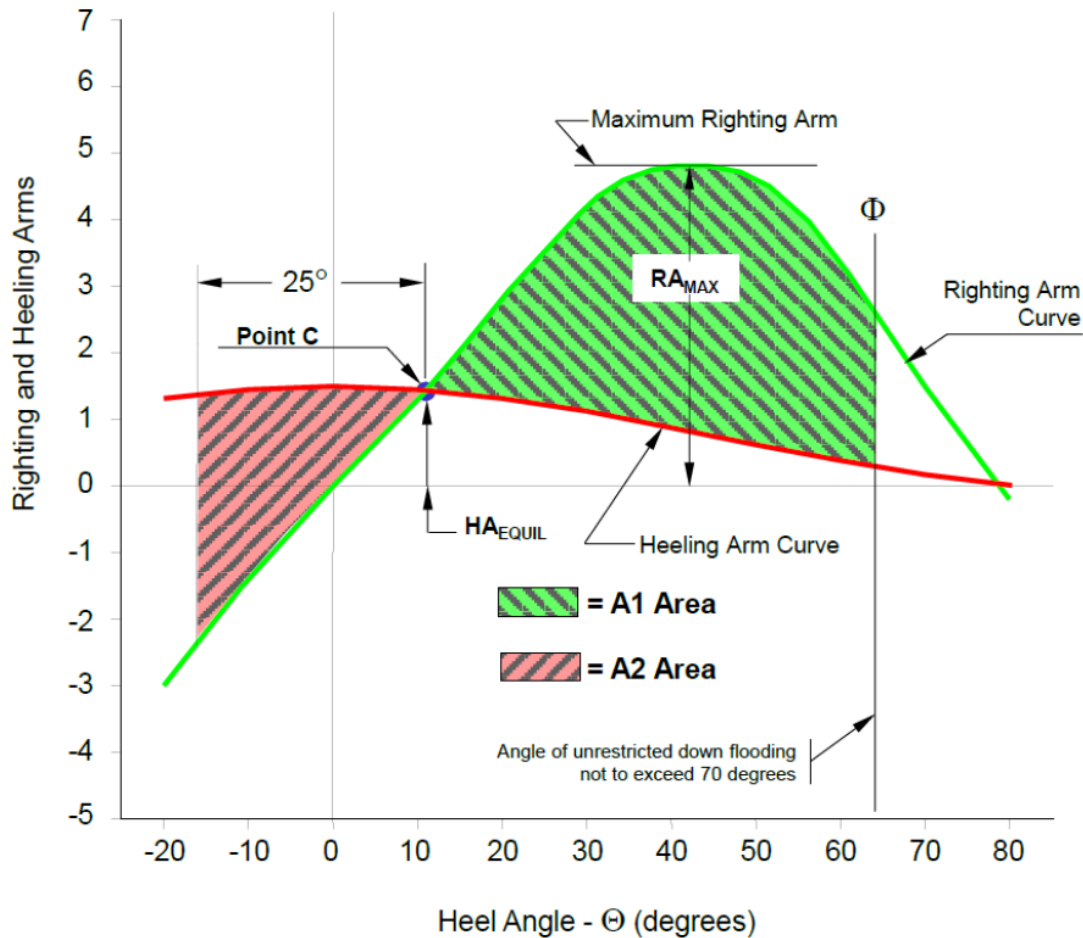


Figure 1. DPC-010/079 Figure 8-1 – Intact Stability – Effect of adverse wind and rolling.

The IMO 2008 Intact Stability Code [14], Section 2.3 – Severe Wind and Rolling Criterion (weather criterion) uses an empirical formula to calculate the roll back angle which is a function of the ship's roll damping characteristics and wave steepness. However, the various factors that go into the IMO roll back angle calculation are applicable for commercial ships that fall within specific proportions, as outlined in Section 3.1. These factors are inappropriate for non-traditional hull forms.

The Navy implementation applies a steady wind overturning moment and uses an area ratio margin to account for gusts and wave action. The IMO weather criteria assume a steady wind with a gust factor applied to the wind overturning moment, but then does not include a residual area margin. It states only that residual righting energy be greater than or equal to the overturning energy.

Of the failure modes presented in the IMO Second Generation Intact Stability Criteria [12], it seems that the weather criteria applied to the ship in the deadship condition shows the most promise for non-traditional hull forms. Semi-Submersibles, Jack-Up drilling rigs, and Liftboats spend their time being moored on location, towed at relatively slow speeds, or sailing under their own power at slow speeds. Froude numbers are estimated for smaller Liftboats traveling at 6 knots maximum speed at only 0.13 to 0.18. Larger semi-submersibles and Jack-Ups under tow are more likely in the Froude number range from 0.09 to 0.15. Larger, faster wind turbine installation ships are in the Froude number range from 0.16 to 0.21. These Froude

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number ranges are generally calm water speeds as such vessels under tow or under their own power reduce speed in severe weather.

As it turns out, the IMO MSC.1/Circ.1200 [19] guidelines specifically allow for model tests to determine the relevant characteristics of a candidate vessel to apply the weather criteria. Parameters that can be determined through testing include overturning lever, roll back angle, and others. This, like the Navy implementation, opens the door for a potential adoption of the weather criteria, or “beam winds and rolling criteria” to disambiguate the criteria from the US Coast Guard’s Weather Criteria in 46 CFR §170.170, which is a simplified minimum GM requirement.

It is not unprecedented to adapt the IMO weather criteria to other vessel types. The recently new fishing vessel requirements promulgated in 46 CFR §28.575 are essentially the IMO weather criteria with minor adjustments made for application to fishing vessels. This is an area recommended for future research as discussed further in Section 6.2.

That said, it would be reasonable to apply the beam wind and rolling criteria to our four validation models as an initial test on how restrictive, if governing at all, such a criterion would be. To that end, the US Navy version and IMO versions of the severe wind and roll criteria were tested with modified roll back angles against example non-traditional vessels. These were tested about all axes and with appropriate wind speeds as governed by current CFR requirements, taking into account the restricted service nature of some of the non-traditional hull forms. This proved challenging, as the vessels did not pass criteria and exhibited indications of capsize when applying the (reduced) roll back angles and required wind speeds. Thus, further study was initiated.

A series of time domain simulations were computed for a Liftboat in regular and irregular waves. The Liftboat was selected based on preliminary analyses that showed the Liftboat is most susceptible to the effects of waves. The goal of this task was to provide data for such stability evaluations, and to guide the establishment of appropriate margins and factors. The procedure and results of this analysis are included in Section 5.

3.3 Wind Forcing Considerations

Three methods for estimating wind force currently exist: CFD analysis, wind tunnel testing, and the building block method. CFD analysis and wind tunnel testing are less accessible and not widely available to all designers. Further, they present challenges with validation and regulatory acceptance of results as well as efficiency, timing and schedule, potential hardware and licensing costs, facility costs, and quality control and assurance. Recent research by ABS [16] and SNAME [10] has been studying and developing best practices for all three available methods.

The building block method is the most accessible method for predicting wind forces and moments, which studies show is also the most conservative [6]. Therefore, the U.S. Coast Guard still requires this method’s use. ABS and the SNAME OC-8 panel recognize this fact but also point out that there is wide dispersion in results by different practitioners using the same method. The building block method requires experience and judgment in its application particularly in the level of detail modeled, the application of shape factors, the assumptions on clustering, and the handling of shielding. Such opportunity for making different judgment calls highlights the need for best practices and the understanding of why there is dispersion in the results generate by different practitioners.



3.3.1 ABS' Perspective

In the OTC paper titled “A Class Perspective for Wind Load Assessment” (2019) [16], the authors (all ABS employees) present reasonable best practice recommendations based on ABS’s decades of experience applying the building block approach to a wide variety of non-traditional vessels. While their perspective is valuable, their internal best practices are not widely available outside of ABS. This paper provides the industry a look inside ABS and their application of the building block method that may be used as a guide for others, but it is not applicable enough across the industry to be used directly.

MiNO reached out to ABS during this effort and learned that ABS has an internal, though licensable, software application, called ABS Wind [16], that implements the building block method in accordance with Class and Coast Guard rules and regulations. This program may not be widely available or known, though it has been in existence in some form since the 1970’s. Reference [17] is the ABS Wind User Guide that was provided, and it includes some best practice recommendations that can be applied to any software tool or approach (e.g., spreadsheet calculations) and are consistent with the recommendations in [16].

Key takeaways from the ABS paper are:

- The Class rules and building block method have been used, refined, and calibrated over 50 years of application to a wide variety of vessels.
- The building block method has proven to be quick and suitably conservative.
- The conservative aspect of the method stems from the method ignoring the effects of lift as the vessel heels over.
- Attention should be given to the relative effects of different components of a vessel in order to ensure their contribution to wind force and overturning moment are captured accurately.
- Modeling details for visual accuracy will overpredict wind force and overturning moment owing to multiple duplicated projected areas.
- Models should be developed to capture the effect of wind accurately and certain simplification deviating from visual realism are required.

Some specific modeling guidelines in the ABS paper include:

- Units with columns or legs should not include shielding on the columns or legs.
- Under deck structures that get exposed when the unit heels should be modeled carefully as they affect not only projected sail area, but also underwater lateral resistance as they become submerged.
- Deck structures should be clustered (grouped as one) to avoid duplicative projected areas.
- Isolated components – houses, structures, cranes, etc. – should be modeled individually with proper shape coefficients.
- Small, isolated structures with projected areas less than 1/100th of the total projected area can be ignored.
- Open truss structures can be approximated by taking 30% of the projected area of front and back sides.
- Thrusters should be included for their contribution to lateral resistance.
- Cantilever helipads and semi-submersible decks should be modeled using a shape factor of 1.5 for the outer girders, 1.0 for the deck surface, and 1.3 for the underdeck surface.



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These recommendations are consistent with CFR requirements and example of which is shown in the following excerpt from 46 CFR §174.055:

“(c) When calculating “A” in the equation described in paragraph (b) of this section -

- (1) The projected area of each column or leg; if the unit has columns or legs, must not include shielding allowances;
- (2) Each area exposed as a result of heel must be included;
- (3) The projected area of a cluster of deck houses may be used instead of the projected area of each individual deck house in the cluster; and
- (4) The projected area of open truss work may be calculated by taking 30% of the projected areas of both the front and back sides of the open truss work rather than by determining the projected area of each structural member of the truss work.”

ABS asserts that these practices are suitable and conservative since they ignore the effects of shielding and lift (when heeled over). Note that there is some dissent on the conservativeness of ignoring lift.

There remains opportunity to exercise judgement when attempting to determine what clusters of deck structures may be treated as a block and the extents of shielding the proximity may offer. There is not specific guidance on this in the ABS paper and it remains an open topic of research.

3.3.2 DNV Perspective

In a similar manner to ABS, another Classification Society, Det Norske Veritas (DNV) was also engaged via meetings and email exchanges. DNV uses a commercial software code called NAPA to evaluate stability of NTH. Their standard method of evaluation is to use the free trim approach. However, they do recommend free twist for some spot checks, for instance on triangular shaped Jack-Ups. For applications to MODUs, they noted there is no clear definition of “critical axis” in their rules. Most designers apply the following approach which they normally accept:

- Intact stability is simply calculated for all inclination axes in steps, for example 15 degrees.
- Damage stability is checked for the axis that gives zero trim (pure heel) in equilibrium after damage.

When asked about their thoughts on the specific application of a stability criterion that includes the explicit effect of wave overturning, DNV said it had not been discussed and intuitively it sounds difficult to implement correctly.

Regarding wind loading, DNV was asked about which published standards/best practices do they follow. Their response at least from a stability point of view was they have no specific recommendation to standards to be applied. There is no recommendation or reference in the MODU code either. The default approach of establishing the wind heeling moments in the MODU Code are by building block calculations. Wind tunnel testing is only listed as an alternative approach. Further when they are doing stability approval, DNV will perform manual spot-checks of the test results.



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As for CFD simulations, they are not listed as an option to establish overturning moment neither in the MODU code nor their offshore standard. It may however be possible to use CFD under the equivalence provisions in MODU Code Reg 1.5 subject to acceptance by the regulatory bodies.

3.3.3 SNAME OC-8 Perspective

Hodapp et. al. summarizes the status and major findings of the SNAME OC-8 Activities in their OTC paper [15]. The paper discusses all three methods mentioned earlier in this memo and states that each has their advantages and disadvantages. None of the three methods is without modeling errors and uncertainty nor the opportunity for the practitioner to apply judgment in either modeling simplifications, scaling, materials, or software used, and other aspects of performing CFD analysis, building scale models, or performing simplified empirical calculations. Wind tunnel testing remains the “gold standard” but is out of reach of most projects due to cost and time constraints.

Hodapp et al. states that their most significant find from their comparative studies was the “close agreement and remarkably low variability” of wind tunnel and CFD results compared to conventional building block results. But, while there is variability in the building block approach results depending on the practitioner, the approach remains more conservative. CFD and wind tunnel tests can capture the lift effects that have been reported to be one of the major reasons why the building block method tends to be conservative when predicting overturning moment.

They further describe the need for best practices, not only with wind tunnel and CFD methods, but also the empirical approach and have set up a subcommittee to do so. Planned activities include development of best practices for the building block approach; however, at the time of this writing, the authors were unaware of the publication of such best practices.

3.3.4 MiNO Marine Experience

The MiNO experience implementing the building block approach for a variety of vessels is consistent with that reported by ABS and SNAME. They use a program developed by the author (David Bourg) called Wind that was originally developed for Friede and Goldman for use in Jack-Up drill rig design. It implements the standard and rules published in the ABS guidelines and the CFR. However, it allows for detailed control of shielding.

46 CFR §174.055 states that “the projected area of each column or leg, if the unit has columns or legs, must not include shielding allowances” but that “the projected area of a cluster of deckhouses may be used instead of the projected area of each individual deck house in the cluster.” The first statement makes it clear that shielding should not be applied to the legs of a Liftboat or the columns of a Semi-Submersible. The term cluster in the second statement is less clear as mentioned earlier.

It is well established in fluid dynamics that clusters can have beneficial or adverse effects, i.e., clusters of structures in aggregate may present less drag owing to perhaps their aggregate shape, or shielding of surface areas, or their geometry could interact with the fluid in such a way that drag is greater on the cluster than it would be if each component were treated separately. For example, *Fluid-Dynamic Drag* (Hoerner) [22] discusses interference drag on sets of objects. It is established that two bodies placed within close proximity of another can present a combined drag greater than the sum of individual drag components. This may be the intent captured by the 1.1 shape factor for clustered deckhouses.



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It is further established that “in the case of two bodies placed one behind the other, the drag of the second one is usually smaller than in free flow, because of the reduced dynamic pressure within the wake of the first body.” As the distance between the bodies increases, the drag of the second body gradually approaches the value that would be established during free flow conditions. Establishing the extent of these interactions for different common industrial shapes would be of great benefit to the standardization of the building block method.

With that in mind, when Bourg developed his Wind program, a method was contrived to define a “shadow” region behind each object wherein any object within that shadow region could have a portion of its projected area shielded and thus excluded from the total projected area.

The screen shots below, Figure 2 and Figure 3, illustrate the parameters that define the shadow region.

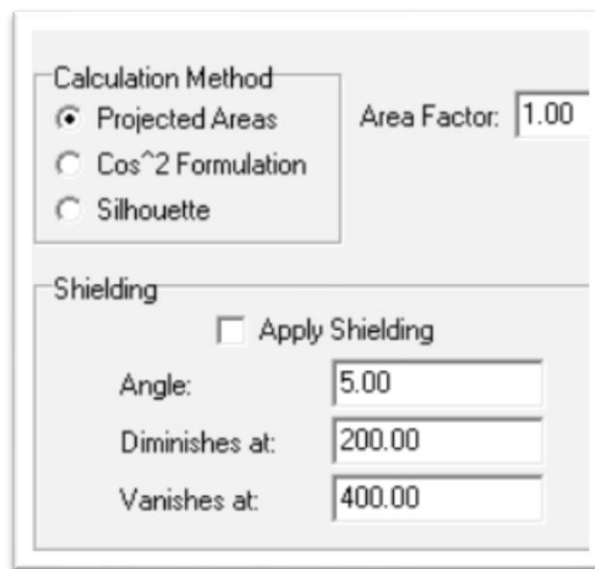


Figure 2. Example input screen for MiNO WIND software.

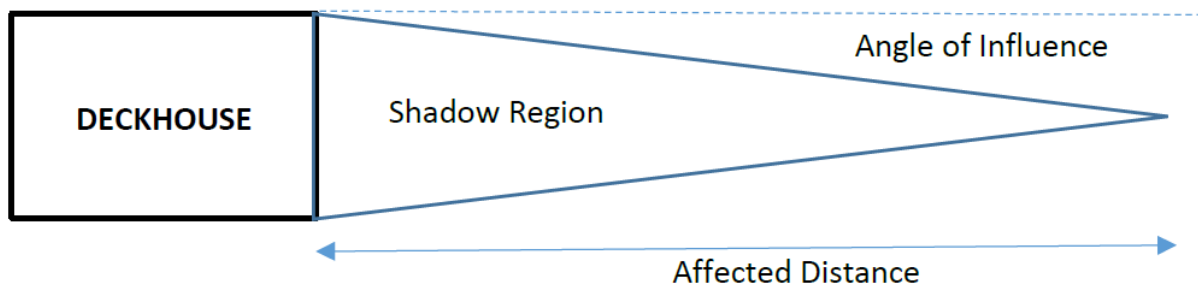


Figure 3. Shadow region geometry.

The parameters defining the shadow region are angle defining the separation zone, a distance defining how far behind the shielding effect starts to diminish, and a distance beyond which shielding is cut-off essentially truncating the shadow region.

Non-Traditionally Shaped Vessel Stability Standards

While this approach has been used with success and was originally calibrated against wind tunnel tests for a Jack-Up drill rig, it does provide opportunities for judgment and thus variability in results. Further research and calibration in this area is recommended.

Bourg's Wind program also attempted to capture another deficiency with the current rule governing the building block approach. Specifically, this relates to shape factors.

The CFR, ABS MODU Code, and IMO MODU Code address shape factors with relative consistency. The suggested values in each are included in the tables below. However, they are insufficient for some unique shapes. As an example, for large diameter Liftboat legs with small double racks, it is erroneous to apply the shape factor for a cylinder, and it would be overly conservative to use any of the higher shape factors shown in the tables. MiNO performed a CFD study to derive more accurate shape factors for such legs. It was determined that the maximum drag coefficient where the flow is perpendicular to the racks is 0.97 while the minimum where the flow is parallel to the racks is 0.65. See 3.3.4.1 for more details.

With these results, the Wind program allows for user defined shape factors, that while not published in the rules, have been accepted by Class. The authors recommend that the rules include specific allowance for and guidelines for deriving unique shape factors.

Table 7. IMO MODU shape coefficients.

Table 3-1 – Values of the coefficient C_s

Shape	C_s
Spherical	0.4
Cylindrical	0.5
Large flat surface (hull, deckhouse, smooth under-deck areas)	1.0
Drilling derrick	1.25
Wires	1.2
Exposed beams and girders under deck	1.3
Small parts	1.4
Isolated shapes (crane, beam, etc.)	1.5
Clustered deckhouses or similar structures	1.1

Table 8. ABS MODU shape coefficients.

TABLE 1 Values of C_s (2013)	
Shapes or combinations of shapes which do not readily fall into the specified categories will be subject to special consideration.	
Spherical	0.4
Cylindrical shapes (all sizes)	0.5
Hull (surface type)	1.0
Deck house	1.0
Isolated Structural shapes (cranes, angles, channels, beams, etc.	1.5
Wires	1.2
Under deck areas (smooth surfaces)	1.0
Under deck areas (exposed beams and girders)	1.3
Small parts	1.4
Rig derrick (each face)	1.25



Non-Traditionally Shaped Vessel Stability Standards

A few inconsistencies were noted in height coefficients published in various rule sets. The IMO and ABS rules are consistent at all height bands. But, the CFR Table §174.055(a) has a few inconsistent values that may be the result of typos or other clerical translations. The authors suggest defaulting to the values published by ABS and IMO. The suggested values in each are included in the tables below for reference.

Table 9. IMO MODU height coefficients.

Table 3-2 – Values of the coefficient C_H

Height above sea level (metres)	C_H
0–15.3	1.00
15.3–30.5	1.10
30.5–46.0	1.20
46.0–61.0	1.30
61.0–76.0	1.37
76.0–91.5	1.43
91.5–106.5	1.48
106.5–122.0	1.52
122.0–137.0	1.56
137.0–152.5	1.60
152.5–167.5	1.63
167.5–183.0	1.67
183.0–198.0	1.70
198.0–213.5	1.72
213.5–228.5	1.75
228.5–244.0	1.77
244.0–259.0	1.79
above 259	1.80

Table 10. ABS MODU height coefficients.

TABLE 2
Values of C_h

The height, h , in m (ft), is the vertical distance from the design water surface to the center of area, A , defined in 3-1-3/1.3.3.

Height (Meters)	Height (Feet)	C_h
0–15.3	0–50	1.00
15.3–30.5	50–100	1.10
30.5–46.0	100–150	1.20
46.0–61.0	150–200	1.30
61.0–76.0	200–250	1.37
76.0–91.5	250–300	1.43
91.5–106.5	300–350	1.48
106.5–122.0	350–400	1.52
122.0–137.0	400–450	1.56
137.0–152.5	450–500	1.60
152.5–167.5	500–550	1.63
167.5–183.0	550–600	1.67
183.0–198.0	600–650	1.70
198.0–213.5	650–700	1.72
213.5–228.5	700–750	1.75
228.5–244.0	750–800	1.77
244.0–259.0	800–850	1.79
259.0 and above	850 and above	1.80



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3.3.4.1 Shape Factor for Large Cylindrical Legs with Racks

Traditionally, Liftboat legs of the cylindrical, pipe, type use drag coefficients ranging from 0.62 to 0.65 for clean legs. Liftboat legs do not have marine growth buildup since they jack up and down frequently and the clearance between the outer surface of the leg and inner surface of the towers, which fully surround the legs, is tight effectively scraping potential marine growth off the legs. Thus, marine growth on the legs is never an issue and drag coefficients reflect that. Some account of the coatings/grease on the legs may be made by some practitioners.

In spite of the widely accepted practice of using drag coefficients of 0.62 to 0.65 for Liftboat legs, and recognizing that typical jack-up drilling unit leg chord drag coefficients are ill-suited for this application, MiNO Marine undertook a 2D CFD analysis in 2010 aimed at determining appropriate drag coefficients for the L/B Robert legs, a 335 Class vessel being designed by MiNO and built for Montco Offshore, considering flow at various angles with respect to the rack axis.

The legs on the L/B Robert are large circular cylinders 114" (9.5 ft, or nearly 3m) in diameter. The double racks (180 deg opposed) are relatively small by comparison. The racks stand off the outer surface 7.25" to the tops of the teeth. This geometry is different from typical MODU chords in that the tube diameters here are quite large with respect to the racks and the drag coefficients recommended (SNAME 5-5A [25], ISO 19905-1 [26], and ABS MODU rules) for split chords are inappropriate for large diameter Liftboat legs. The results of this study are shown in Figure 4.

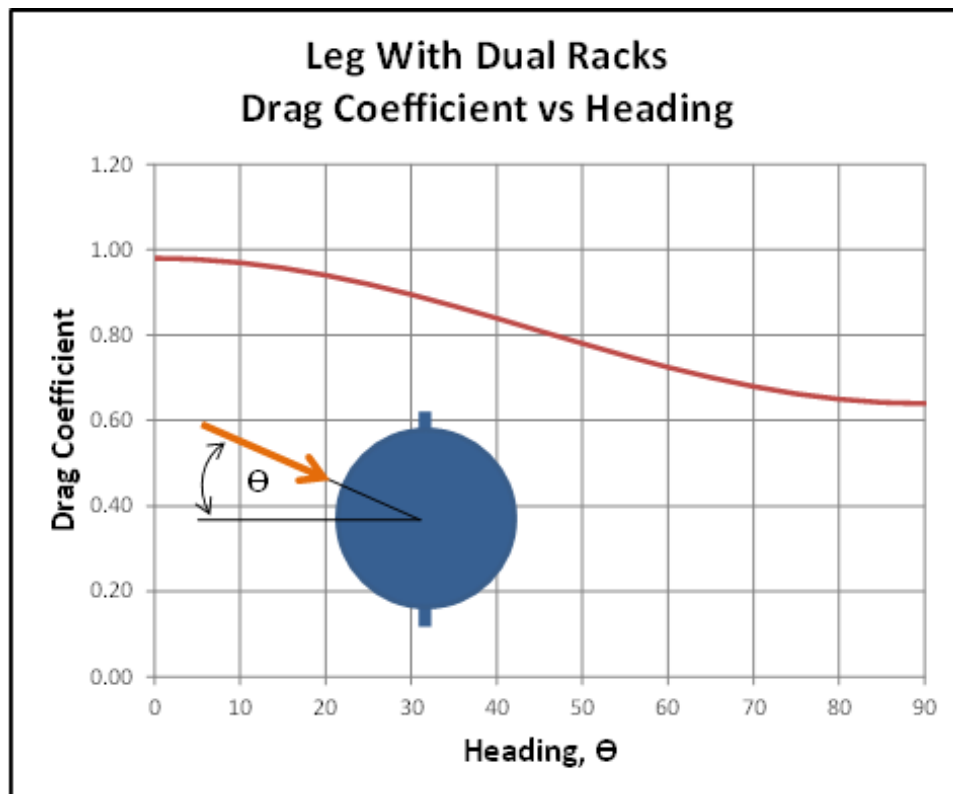


Figure 4. Double-rack cylindrical leg drag coefficients.

These drag coefficients are applicable for Reynold's numbers greater than 1×10^6 . The maximum drag coefficient where the flow is perpendicular to the racks is 0.97 while the minimum where the flow is parallel



Non-Traditionally Shaped Vessel Stability Standards

to the racks is 0.65. MiNO assumed the drag coefficients varied as a cosine curve between these two heading extremes. This shape is very similar to the piece-wise linear curve illustrated in SNAME 5-5A and the ABS MODU Rules; however, the cosine shape is slightly more conservative over the range of headings between the two previously mentioned extremes.

These drag coefficients have been accepted by ABS for the classing of MiNO's 335 and 300 Class liftboats. That said, it would be interesting to perform more comprehensive CFD studies, using the latest SNAME CFD recommended practices, considering various proportions for cylindrical legs and rack since these proportions vary by designer.

3.3.5 Defining Wind Heeling Moments in GHS

Based upon the software survey results and the project team's experience, GHS was chosen as the stability tool to test and evaluate the proposed methodology. In GHS, the definition of the applied heeling moment (HMMT) becomes important to the VARY AXIS command as the wind heeling moment varies as the axis is varied throughout the righting arm calculation. Alternatively, when running a free to trim righting arm, the heeling moment will remain in the direction of the original defined axis.

Multiple options are available for applying a wind heeling moment:

- Define a Heeling Moment Curve
- Develop heeling moments using building block methods outside of GHS
- Define longitudinal and transverse profiles
- Interpolates with cosine per ABS conversation
- Define Shapes in GHS and apply /BAND method to HMMT command
- Follow recommended methodology

Note, none of the options listed include a lifting force that may be created as the vessel experiences changes in heel, trim, or yaw.

GHS Option 1 - Define a Heeling Moment Curve

A heeling moment would be developed using the building block methodology outside of GHS.

GHS Option 2 - Define Shapes and Apply / BAND

Sail area parts and components are modeled as 3d objects within GHS. The /BAND option is used to create a total wind heeling moment from the combination of objects, shape factors, height coefficients, and shielding definitions that are implemented between parts and components.

The command HMMT WIND /BAND is issued.

Per Creative Systems, the Band Method “projects the lateral plane of all components of each Part onto a common set of horizontal bands. This has the advantage of accounting for the shielding when one component is masked by another. The contributions from individual Parts in the model can either be added without regard to shielding between them or they can be combined into a common set of bands which assumes inter-component shielding regardless of Part divisions.”

The method has its limitations, however. GHS treats shielding as a binary function – the user can leave shielding on (as is the default in the band method) or turn shielding off for specific components of the wind



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model. There is no functionality to address when one object occluded by another is sufficiently downwind that shielding should NOT be made. This is the feature included in the MiNO WIND program discussed in Section 3.3.4

While shielding is not handled perfectly, the = Band Method is useful and necessary for best capturing the wind heeling moments for non-traditional hull forms.

The Shape Factor for each part is defined in the geometry file.

The Height Coefficient for a discretized section of a part is defined per ABS or IMO MODU Rules using a macro that allows the wind pressure to be defined as a function of height above water. An example of this is included in the GHS User Information Index – Wind heeling for Drilling Units [20].

GHS Emergent Features

Very recently, (in August of 2023), GHS released the HMMT WIND /PANEL method for better handling shielding between sail components. The timing of the release precluded an in-depth study of applicability and functionality, but the available literature from GHS suggests it may better handle shielding. This methodology should be studied and investigated as a replacement for the /BAND methodology.

3.3.6 Recommended Procedure for Application of Wind Heeling Moments

It is recommended that the following procedures be used in applying wind heeling moments in GHS:

- Ensure that the modeling of above-deck shapes is done with simplified components – blocks and cylinders.
- Group geometry components together as necessary. When components are separate on the deck of a boat but in close proximity, it is usually prudent to model them as one component.
- Use shape coefficients appropriate for each component – where unique shapes are used (such as Liftboat legs with racks), conduct research necessary to select an appropriate shape coefficient.
- Use appropriate height coefficients.
- Use the HMMT /BAND command.

3.4 Procedure for Non-Traditional Stability Evaluation

As discussed in detail above, understanding the critical axes of a non-traditional hull form is essential to evaluating the stability of the vessel. The critical axes, however, are not necessarily apparent when reviewing a vessel's hull form and characteristics. This necessitates a procedure for finding the critical axis for stability evaluation. The following procedure has been developed and validated (further details of validation are provided later in this report) to identify critical axes and to evaluate a stability criterion about those axes:

1. Identify that the vessel is non-traditional using the criteria established in Section 3.1.1
2. Using a fixed trim righting arm solver, for each heel axis azimuth from 0 to 360 in 15 deg increments, compute the residual range of stability and residual righting energy over that range then record the results. Examine the results and identify weak axes, i.e., those with lowest energy and range of stability. These are candidate critical axes.

Non-Traditionally Shaped Vessel Stability Standards

3. Identify the applicable stability criteria and wind heeling moment calculation (if used). Using a fixed trim righting arm solver, run righting arm analyses for each heel axis azimuth from 0 to 360 in 15 deg increments. Examine the results and identify what axes are critical, paying special attention to the candidate critical axes identified in Step 2.
4. Using a free trim righting arm solver, evaluate the applicable stability criteria for each identified critical axis, ensuring the righting arm curves are developed correctly. Examine the free trim righting arm results looking for anomalies such as fading stability or trim/heel instability.
5. If fading stability and trim/heel instability is identified, use a free twist approach for further evaluation.

In this procedure, there are only two points where the user can stop the analysis. The first is after Step 1. If a vessel is not identified as non-traditional, there is no need to proceed through the rest of the analysis. It is important that for every vessel, Steps 2 and 3 should be followed.

Step 3 was not developed to serve as an all-around stability check but could function as one if all righting arms are valid. The reason Step 3 is implemented is two-fold:

- To account for wind forces – Step 2 captures the geometry of the hull only as it is run without a wind heeling moment. When wind heeling is part of the stability criteria, Step 3 captures the effects of wind heeling.
- To account for “weighting” of stability criteria – Since stability criteria are developed specific to vessel type, the various criteria assign “weighting” or importance numerically. Step 3 allows the user to evaluate the vessel considering the effects of the intentional weighting.

Steps 2 and 3 are not intended to produce useful stability results that could be used as a pass/fail, but rather to help the user understand the characteristics of the vessel. For example, a vessel may have weak energy and weak range at different axes in Step 2, but the criteria may “weight” one characteristic more than another, which would help down select from weak axis to critical axis for further analysis.

The second point in the analysis where the user can stop the procedure is between Steps 4 and 5, and only if the righting arms developed in Step 4 are deemed acceptable. It is not uncommon to stop after Step 4. For example, runs through this new procedure, see Section 4.3.

Figure 5 illustrates this new procedure as a series of concentric rings. Each step is represented by a ring. The user starts at the outer ring and continues inward until the resulting down selection step is satisfied.



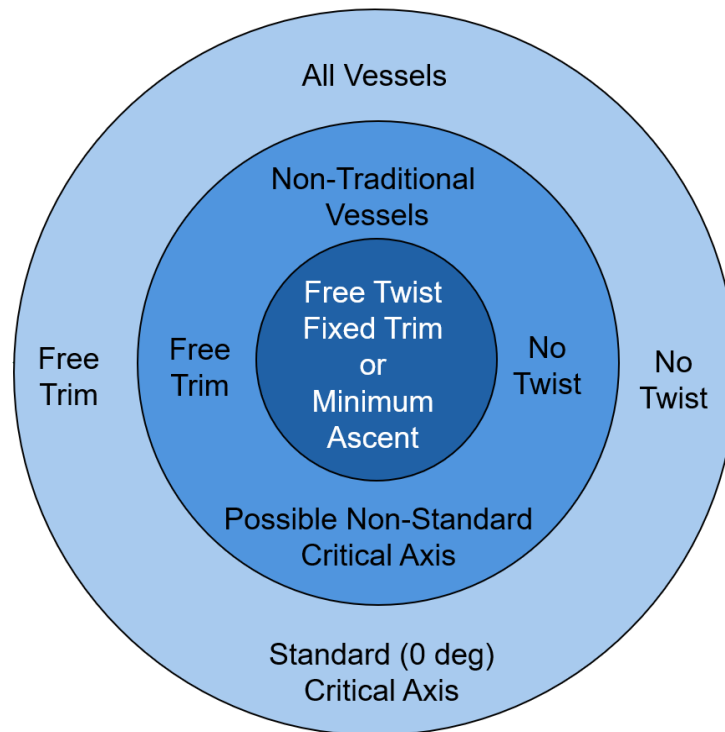


Figure 5. Formulation down select options.

Note that Step 5 relies on different methods for evaluating righting arms. The basic types of righting arm evaluation are described in Section 2.2.3. To calculate Free Twist Righting Arms, however, there are multiple options available. These options are discussed below.

3.4.1 Free Twist Righting Arms

Creative Systems, Inc (makers of GHS) provide the following guidance on generating free twist righting arms [20] (excerpts below):

“The least-stability righting-moment curve might be produced when the axis about which heel takes place is varied as heel progresses.

If the axis is allowed to vary as heel increases, a method is needed for selecting a new axis at each heel increment. This method might be:

1. minimum ascent (least slope of the residual righting moment vs. heel);
2. minimum GM (least slope of the absolute righting moment curve);
3. zero trim (the axis where the heel is the same as the total inclination).”

Each of these three methodologies have been studied at length and each can provide useful results for developing righting arms that capture the “twist” (change in heeling axis) as the righting arm calculation progresses. In discussions with Creative Systems and through internal testing and evaluation, the zero-trim method has been identified as the best method for evaluating free twist righting arms for any given hull forms. The minimum ascent and minimum GM methods may be studied for use in any particular case, but

care should be taken when evaluating the results to ensure that there is no numerical instability in the results. Indications of this could be multiple significant “jumps” in heeling axis, righting arm, or any combination of result. Care should be taken if using methods other than the zero-trim method.

4 ANALYSIS METHODOLOGY VERIFICATION

To demonstrate that the potential methodology is valid, it was tested on four representative vessel examples. These vessels are defined in Section 4.1.

4.1 Example Vessels

Four example vessel models were developed as representatives of the required NTH categories:

- Gulf of Mexico Liftboat
- Jack-Up Drilling Rig
- Column-Stabilized Mobile Offshore Drilling Unit
- Wind Turbine Installation Vessel

For each example, a hull form was developed in Rhino 3D and the *AttachGHSdata* command was used to generate GHS stations and develop the GHS part/component hierarchy. Each hull form is described in detail in the following sections. The coordinate system used in the GHS modeling for the Jack-Up, MODU SEMI, and WTIV was right-handed with +Z pointing upwards. The origin was set at the baseline and Aft Perpendicular with +X pointing forwards. When varying the heeling axis, the axis is rotated counterclockwise about the Z axis. For the Liftboat, the origin was set at the FP with +X pointing aft.

4.1.1 Liftboat

The Liftboat model is based on a 235-class Liftboat designed by MiNO Marine. Hull particulars were taken directly from the specification sheet provided by MiNO Marine and the hull shape simplified. No propellers, stern skegs, or rudders were modeled for expediency and simplicity. In departure from the reference vessel, the pads are considered as free-flooding, i.e. open on the bottom. Therefore, the pads are not considered as part of the waterplane area or buoyancy of the hull. Liftboats are designed with pads that are open, flooded, or buoyant, so this assumption follows a common Liftboat design decision, but not the assumption followed on the reference vessel. In another departure from the 235-class reference specification sheet, the design draft was selected to be 8 ft.

The Liftboat superstructure was likewise modeled according to the reference specification sheet, with the accommodation block being simplified down to a silhouette of that shown on the specification sheet. A generic cargo crane silhouette was modeled; this was not based on the crane shown on the specification sheet, as cranes are diverse, vendor-dependent equipment. A representative cargo block was modeled that occupied the available space and breadth beneath the crane will still permitting a sight line from the accommodation block. The reference design does not feature a helipad, but one was added for analysis as this is commonly found in Gulf of Mexico Liftboats. Additionally, the helipad adds significant topside windage.

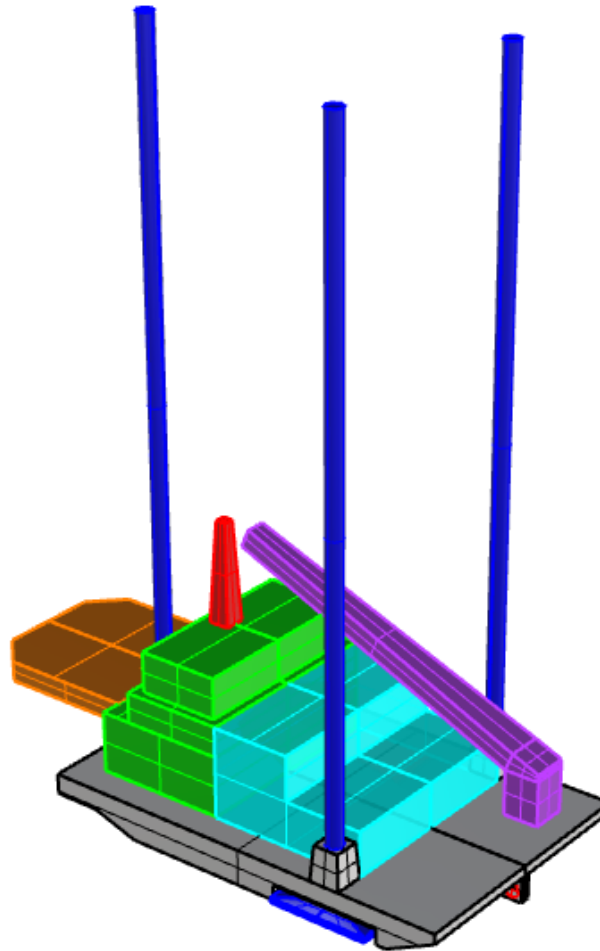


Figure 6. Liftboat rhino model.

Table 11. Liftboat principal characteristics.

Characteristic	Dimension
Hull Length	137 ft
Beam	86 ft
Depth	11.5 ft
Design Draft	8.0 ft
Leg Length	235 ft
KG	40.9 ft

4.1.2 Jack-Up Rig

The Jack-Up Model is based primarily on the information shown in the paper “The Use of Energy Build-up to Identify the Most Critical Heeling Axis Direction for Stability Calculations for Floating Offshore Structures” by Joost van Santen, published 2009 [2]. The hull principal dimensions come from this reference, with the only departures from the paper coming in a beam reduction to order to chamfer the hull corners, in line with industry practice. Additionally, a design draft of 15.4 ft was selected after the reference hull draft of 16 ft was found to provide too little freeboard.



Non-Traditionally Shaped Vessel Stability Standards

The topside of the Jack-Up is based primarily on the Hercules 267 Jack-Up and a similar Maersk Jack-Up, both of which are representative of Gulf of Mexico-styled Jack-Up rigs (Hercules 267 in particular was selected because it is an American-flagged, ABS-Classed Jack-Up). The accommodation block, helipad, derrick, and derrick were all modeled as silhouettes of the structures shown on the Hercules and the Maersk Jack-Ups. Similarly, the leg length of the Jack-Up comes from the Hercules, which had a leg length of 370 ft according to the ABS Class Record. The legs on the Hercules, and indeed on most Jack-Ups, are lattice-structured. The spud cans are not considered as buoyant in this analysis and are therefore not modeled. The leg wells (where the legs pass through the hull) are triangular, rather than circular as in the reference models.

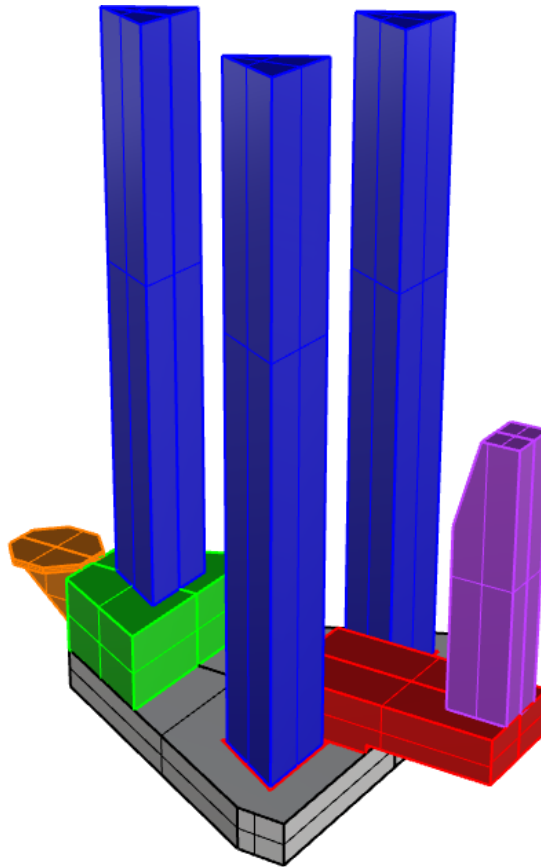


Figure 7. Jack-up rig example.

Table 12. Jack-up principal characteristics.

Characteristic	Dimension
Hull Length	190.6 ft
Beam	210.6 ft
Depth	23 ft
Design Draft	15.4 ft
Leg Length	371 ft
KG	58 ft



Non-Traditionally Shaped Vessel Stability Standards

4.1.3 Wind Turbine Installation Vessel

The wind farm installation vessel model is primarily based on the Fred Olsen vessel *Brave Tern*. This vessel was used to install the Block Island Wind Farm, the first deep water offshore wind farm in the US. The hull particulars come primarily from the *Brave Tern* spec sheet, simplified to blocks in the same way as the Liftboat and the Jack-Up examples. The topside accommodation block, helipad, primary crane, and legs were also modeled as silhouettes of the equipment shown on the *Brave Tern* spec sheet. The crane is modeled as solid. The pads are modeled as non-buoyant to remain consistent with the assumptions in the other models. The model also features a representative cargo load; the cargo load includes four wind turbine towers.

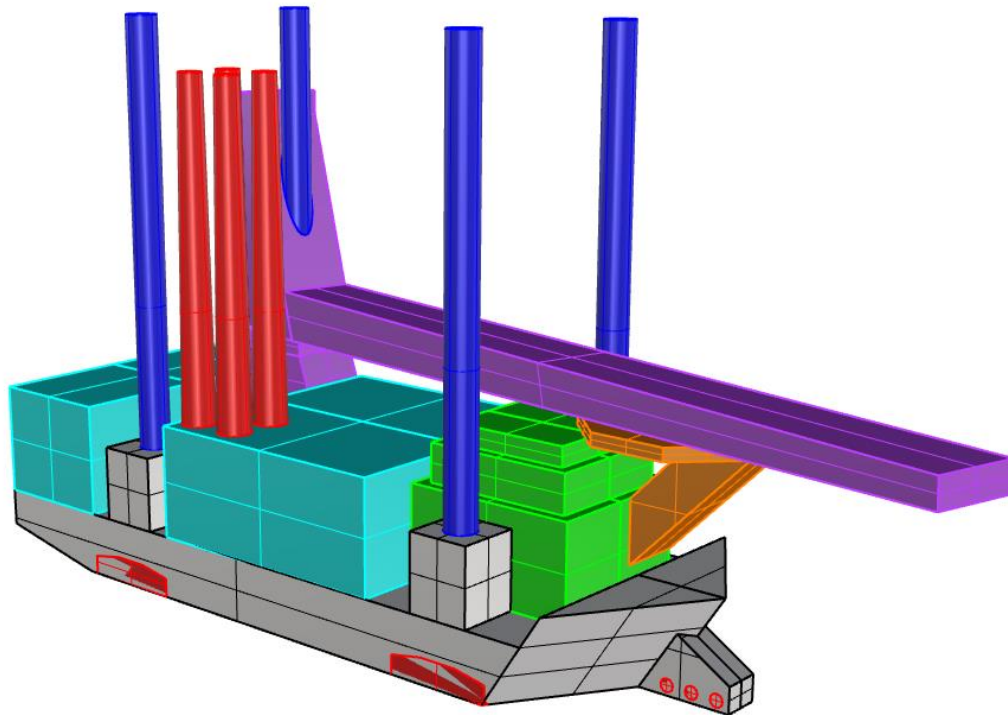


Figure 8. WTIV example.

Table 13. WTIV principal dimensions.

Characteristic	Dimension
Hull Length	426.5 ft
Beam	147.6 ft
Depth	32.8 ft
Design Draft	19.6 ft
Leg Length	295 ft
KG	75 ft



4.1.4 MODU Semi-Submersible

Like the Jack-Up Model, the hull shape of the MODU SEMI was provided by the 2009 van Santen paper [2]. Topside equipment was modeled on a variety of North-Sea Styled drilling rigs, including the Seadrill *West Eclipse* and other MODU SEMIs. The distinction between North-Sea styled rigs and American rigs is important; North Sea rigs typically consist of a single, enclosed (i.e., plate-and-girder constructed) deck with four columns extending to two pontoons. American rigs, by contrast, usually do not have an integrated deck and instead consist of a very large, latticed superstructure with 6 to 8 columns connecting to the pontoons. These “Texas Deck” style rigs are typically heavily cross-braced between the legs and the lattice superstructure, which results in significantly different wind profiles than those seen on North-Sea-styled drilling rigs.

The topside equipment on the MODU SEMI model consists of three accommodation blocks, a drilling derrick, a helipad, and two cranes; the size and shape of these are derived from typical industry vessels like the *West Eclipse*. The drilling derrick was modeled as a solid block.

Based on the pontoon geometry, the transit draft was selected at 29.5 ft.

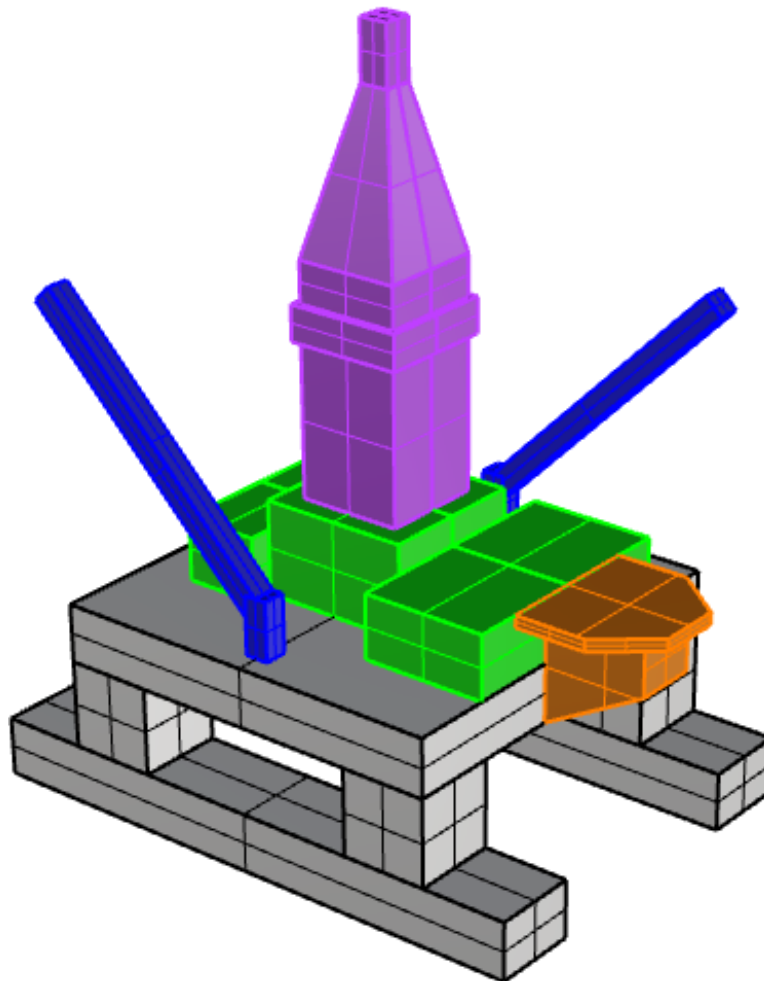


Figure 9. MODU SEMI example.

Table 14. MODU SEMI principal dimensions.

Characteristic	Dimension
Hull Length	328 ft
Beam	229.7 ft
Depth	114.8 ft
Design Draft	29.5 ft
KG	141.1 ft

4.2 NTH Stability Evaluation Criteria

4.2.1 Existing Stability Criteria

There is more work to be done in developing specific criterion that addresses waves for non-traditional hull forms. The procedure for analysis outlined in Section 3.4, however, can be demonstrated. For this, a stability criterion is required. The current applicable CFR stability criteria is used to verify the procedure for analysis. Currently, the four hull forms selected for analysis fall under current 46 CFR Subchapter S [18] requirements as detailed below. To develop the evaluation procedure, these hulls were first benchmarked against the stability criteria listed in Table 15.

Table 15. Example hull stability criteria.

Hull form	CFR Stability Criteria
Liftboat	46 CFR § 174.255 – Liftboats - Restricted Service
Jack-Up	46 CFR § 174.045 – MODU Intact Stability Requirements
MODU SEMI	46 CFR § 174.045 – MODU Intact Stability Requirements
WTIV	46 CFR § 174.045 – MODU Intact Stability Requirements

4.2.1.1 46 CFR § 174.255 – Liftboats - Unrestricted Service

The Liftboat hull form was modeled after a typical Gulf of Mexico Liftboat designed for restricted service. Restricted Service is defined in 46 CFR § 125.160:

“Restricted service means service in areas within 12 hours of a harbor of safe refuge or in areas where a Liftboat may be jacked up to meet the 100-knot-wind severe-storm criteria of § 174.255(c) of this chapter.”

The CFR stability criteria applied to these Liftboats is described in 46 CFR § 174.255, which is duplicated below:

“This section applies to each Liftboat unable to comply with § 174.250 and limited to restricted service as defined by § 125.160 of this chapter.

(a) *Intact stability.*

- (1) Each Liftboat must be shown by design calculations to meet, under each condition of loading and operation afloat, the following requirements:



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- (i) Those imposed by § 174.045, given a “K” value of at least 1.4.
 - (ii) A range of positive stability of at least 10 degrees extending from the angle of the first intercept of the curves of righting moment and wind heeling moment, either to the angle of the second intercept of those curves or to the angle of heel at which downflooding would occur, whichever angle is less.
 - (iii) A residual righting energy of at least 0.003 meter-radians (5 foot-degrees) between the angle of the first intercept of the curves of righting moment and wind heeling moment, either to the angle of the second intercept of those curves or to the angle of heel at which downflooding would occur, whichever angle is less.
- (2) For this section, each wind heeling moment must be calculated as prescribed by § 174.055 of this part using winds of 60 knots for normal conditions of operation afloat and of 70 knots for severe-storm conditions of operation afloat.
- (3) For paragraph (a)(1) of this section, the initial metacentric height must be at least 300 millimeters (1 foot) for each leg position encountered while afloat including the full range of leg positions encountered while jacking.”

4.2.1.2 46 CFR § 174.045 – MODU Intact Stability Requirements

“Each unit must be designed so that the wind heeling moments (Hm) and righting moments calculated for each of its normal operating conditions and severe storm conditions, when plotted on GRAPH 174.045, define areas that satisfy the equation:

$\text{Area}(A) \geq (K) \times (\text{Area}(B))$, where

- (1) $K = 1.4$ except that if the unit is a column-stabilized unit $K = 1.3$;
 - (2) Area (A) is the area on GRAPH 174.045 under the righting moment curve between 0 and the second intercept angle or the angle of heel at which downflooding would occur, whichever angle is less; and
 - (3) Area (B) is the area on GRAPH 174.045 under the wind heeling moment curve between 0 and the second intercept angle or the angle of heel at which downflooding of the unit would occur whichever angle is less.
- (b) Each righting moment on graph § 174.045 must be positive for all angles greater than 0 and less than the second intercept angle.
- (c) For the purposes of this section, openings fitted with the weathertight closing appliances specified in § 174.100(b) are not considered as openings through which downflooding could occur if they can be rapidly closed and would not be submerged below the units' waterline prior to the first intercept angle, except that ventilation intakes and outlets for machinery spaces, crew spaces, and other spaces where ventilation is normally required are considered as openings through which downflooding could occur regardless of location.
- (d) Each unit must be designed so that it can be changed from each of its normal operating conditions to a severe storm condition within a minimum period of time consistent with the operating manual required in § 109.121 of this chapter.”



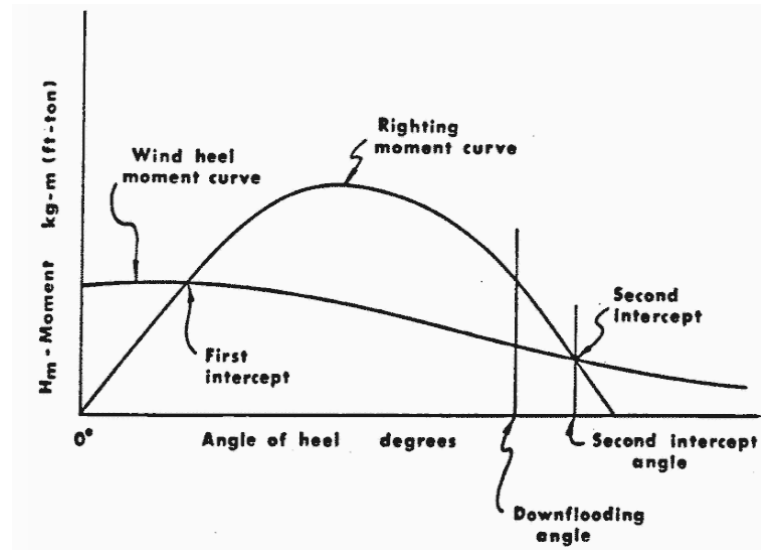


Figure 10. 46 CFR Graph 174.045.

4.2.2 Updated Approach to Existing Stability Criteria

There has been significant discussion on the application of Range of Stability (RoS) criteria on non-zero heeling axes, specifically the application of 46 CFR § 174.255 (1) (ii), requiring “A range of positive stability of at least 10 degrees extending from the angle of the first intercept of the curves of righting moment and wind heeling moment, either to the angle of the second intercept of those curves or to the angle of heel at which downflooding would occur, whichever angle is less.”

MiNO Marine wrote a technical memo on the subject in 2016 [21] detailing why this criterion applied about non-zero heeling axes is not an appropriate applications, providing detailed technical references supporting this argument.

4.3 Example NTH Stability Evaluations

Each of the four example hull forms detailed in Section 4.1 has been analyzed using the procedure outlined in 3.4. A few key notes on the application of this procedure:

- Step 1 has been skipped as this is covered in Table 6.
- For Step 3, the relevant criteria have been used as outlined in Table 15.

Non-Traditionally Shaped Vessel Stability Standards

4.3.1 Liftboat

4.3.1.1 Liftboat GHS Model

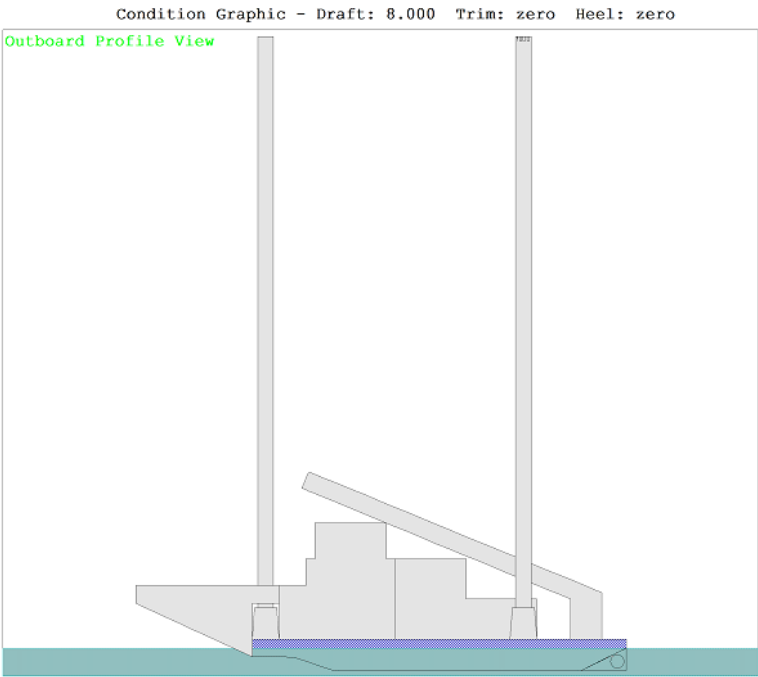


Figure 11. Liftboat GHS model.

HEAVY DRAFT						
WEIGHT and DISPLACEMENT and WATERPLANE STATUS						
Baseline draft: 8.000						
Trim: zero, Heel: zero						
Part		Weight(LT)	LCG	TCG	VCG	
WEIGHT		2,119.81	68.23a	0.00	40.90	
	SpGr	Displ(LT)	LCB	TCB	VCB	
HULL	1.025	2,119.81	68.23a	0.00	4.43	
Righting Arms:			0.00	0.00		
Part	SpGr	WPA	LCF	TCF	BML	BMT
Total Waterplane	1.025	11754	68.77a	0.00	246.8	97.52
		LT/Inch		Ft-LT/Deg	GML	GMT
		27.98		7783.24	210.3	61.06
Distances in FEET.						

4.3.1.2 Liftboat Step 2 Evaluation

The range of stability and righting energy within that range were calculated for each critical axis. This range of stability is calculated from equilibrium to the angle of vanishing stability or angle of downflooding, whichever comes first. The results are shown in Table 16.



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Table 16. Liftboat Step 2 data.

Axis	Range (deg)	Energy (ft-deg)		Axis	Range (deg)	Energy (ft-deg)
0	14.64	65.79		180	14.64	65.79
15	13.35	62.77		195	17.21	83.52
30	11.34	64.79		210	21.78	118.94
45	9.78	71.62		225	27.37	169.2
60	8.97	80.4		240	29.78	219.61
75	8.75	89.41		255	31.43	256.87
90	9.12	99.3		270	32	271.29
105	8.75	89.41		285	31.43	256.87
120	8.97	80.4		300	29.78	219.61
135	9.78	71.62		315	29.78	219.61
150	11.34	64.79		330	27.37	169.19
165	13.35	62.77		345	21.78	118.94

As shown, the potential weak axes are 0, 75, and 105 degrees. Note that there are downflooding points near the aft end of the Liftboat off centerline, which explains the difference between the 0 to 165 degree range and the 180 to 345 degree range.

The righting energy data generated in Step 2 was plotted as a carpet plot ignoring downflooding points. This shows the weak axis purely based on the hull geometry in Figure 12.

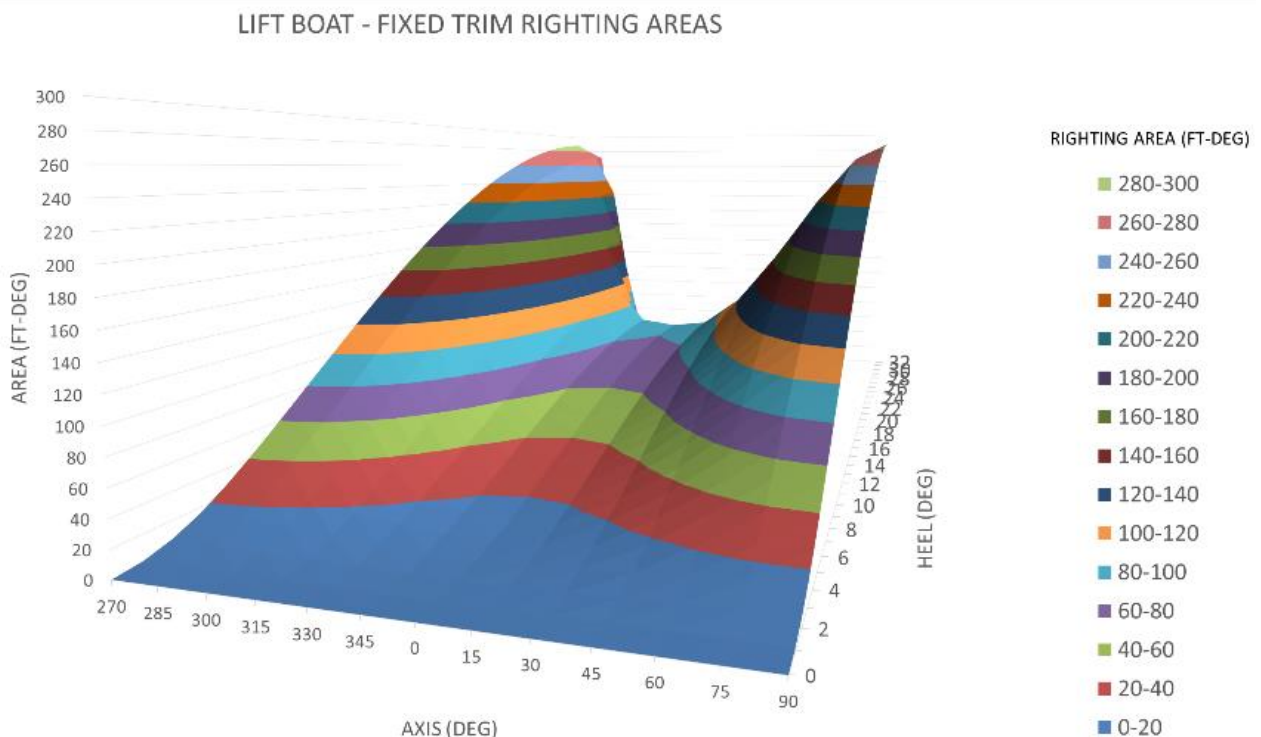


Figure 12. Liftboat righting energy.



Non-Traditionally Shaped Vessel Stability Standards

It is clear from reviewing the carpet plot that the axis with the least righting energy is the 0-degree axis.

4.3.1.3 Liftboat Step 3 Evaluation

To assess Step 3 of the procedure, the Liftboat was analyzed using the 46 CFR § 174.255 requirements for restricted service Liftboats. The criteria are expressed in GHS using the following limits:

LIM	46 CFR 174.255	Min/Max
(1)	Abs Ratio from abs 0 deg to RAzero or Flood	> 1.400
(2)	Angle from Equilibrium to RAzero or Flood	> 10.00 deg
(3)	Abs Righting Arm at abs 0.1 deg to RAzero	> 0.03 Ft
(4)	Area from Equilibrium to RAzero or Flood	> 5.00 Ft-deg
(5)	GM Upright	> 1.00 Ft

These criteria are evaluated for the full range of angles. The results are shown in Table 17 below:

Table 17. Liftboat Step 3 results.

AXIS	LIMITS					AXIS	LIMITS				
	1	2	3	4	5		1	2	3	4	5
	>1.4	>10	>0.03	>5	>1		>1.4	>10	>0.03	>5	>1
0	2.218	12.52	0.11	36.94	61.06	180	2.265	12.52	0.11	37.55	62.93
15	2.11	11.94	0.12	34.86	66	195	2.181	12.58	0.12	38.07	66
30	2.177	11.21	0.13	35.42	76.19	210	2.244	12.44	0.14	40.9	76.18
45	2.437	10.33	0.17	38.61	96.6	225	2.487	12.03	0.17	46.69	96.55
60	2.952	9.03	0.23	43.35	131.95	240	3.02	12	0.24	55.44	131.96
75	3.907	7.48	0.32	49.28	180.57	255	3.994	11	0.32	69.36	180.57
90	5.646	9	0.37	74.99	209.48	270	5.601	12	0.37	107.81	209.48
105	3.879	7.47	0.32	49.17	180.57	285	3.942	11	0.32	69.11	180.57
120	2.913	9.02	0.23	43.1	131.98	300	2.946	12	0.24	54.86	131.96
135	2.403	10.31	0.17	38.32	96.58	315	2.404	11.99	0.17	45.72	96.61
150	2.172	11.19	0.13	35.42	76.17	330	2.157	12.4	0.14	39.72	76.17
165	2.134	11.93	0.12	35.19	66	345	2.107	12.55	0.12	37.03	66.01

When reviewing the table above, it is important to note that the color plots are only relative to the other data in each column. Red does not necessarily indicate that the criteria is failing, it is intended to show the weakest axis for each criterion. In this case, however, it is clear that Limit 2 is failing from 60-120 degrees, with the worst-case results found at 75 and 105 degrees. Thus, 75 and 105 degrees are selected as the critical axis for analysis.

Note that, as discussed in Section 4.2.2, the applicability of the Range of Stability criteria at non-zero critical axes have been recently revisited. It is generally accepted that the RoS criteria is not applicable outside of the traditional (zero-degree) critical axis. This changes the outcome of Step 3 for the Liftboat. If the RoS criteria (limit 2) is ignored, the critical axes are 15 and 165, i.e. very close to the zero-degree traditional axis.

4.3.1.4 Liftboat Step 4 Evaluation

In accordance with the procedure, the critical axes identified in Step 3 are run through the stability criteria and their righting arms are to be examined. It is useful for the purposes of this report to include the zero-degree axis to show how the results change when considering critical axes. Therefore, the righting arms and stability criteria pass/fail status are included below:



Non-Traditionally Shaped Vessel Stability Standards

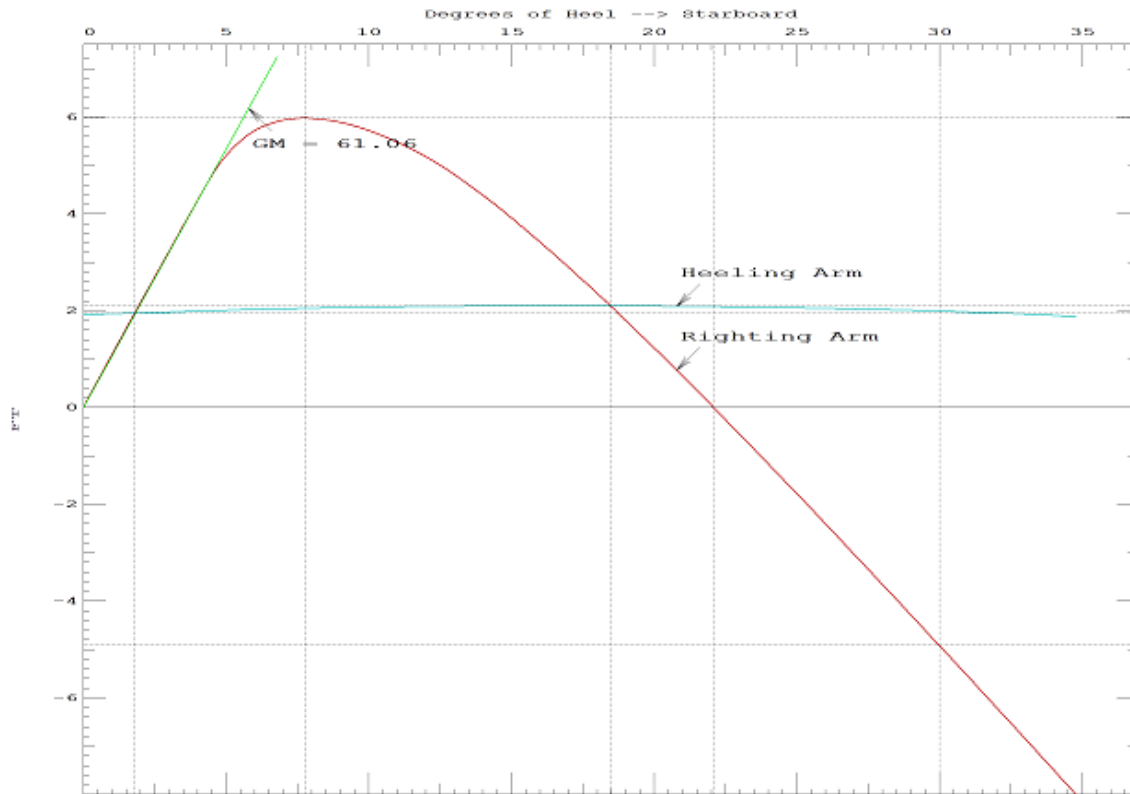


Figure 13. Liftboat righting arm 0-degree axis.

LIM	46 CFR 174.255	Min/Max	Attained
(1)	Abs Ratio from abs 0 deg to RAzero or Flood	> 1.400	2.218 P
(2)	Angle from Equilibrium to RAzero or Flood	> 10.00 deg	12.52 P
(3)	Abs Righting Arm at abs 0.1 deg to RAzero	> 0.03 Ft	0.11 P
(4)	Res. Area from Equilibrium to RAzero or Flood	> 5.00 Ft-deg	36.94 P
(5)	GM Upright	> 1.00 Ft	61.06 P

The righting arms at the zero-degree axis result in passing the stability criteria and do not exhibit any trim/heel instability, fading stability, or oscillations. Thus, this righting arm is deemed acceptable and represents an accurate representation of the vessel behavior at the zero-degree axis.



Non-Traditionally Shaped Vessel Stability Standards

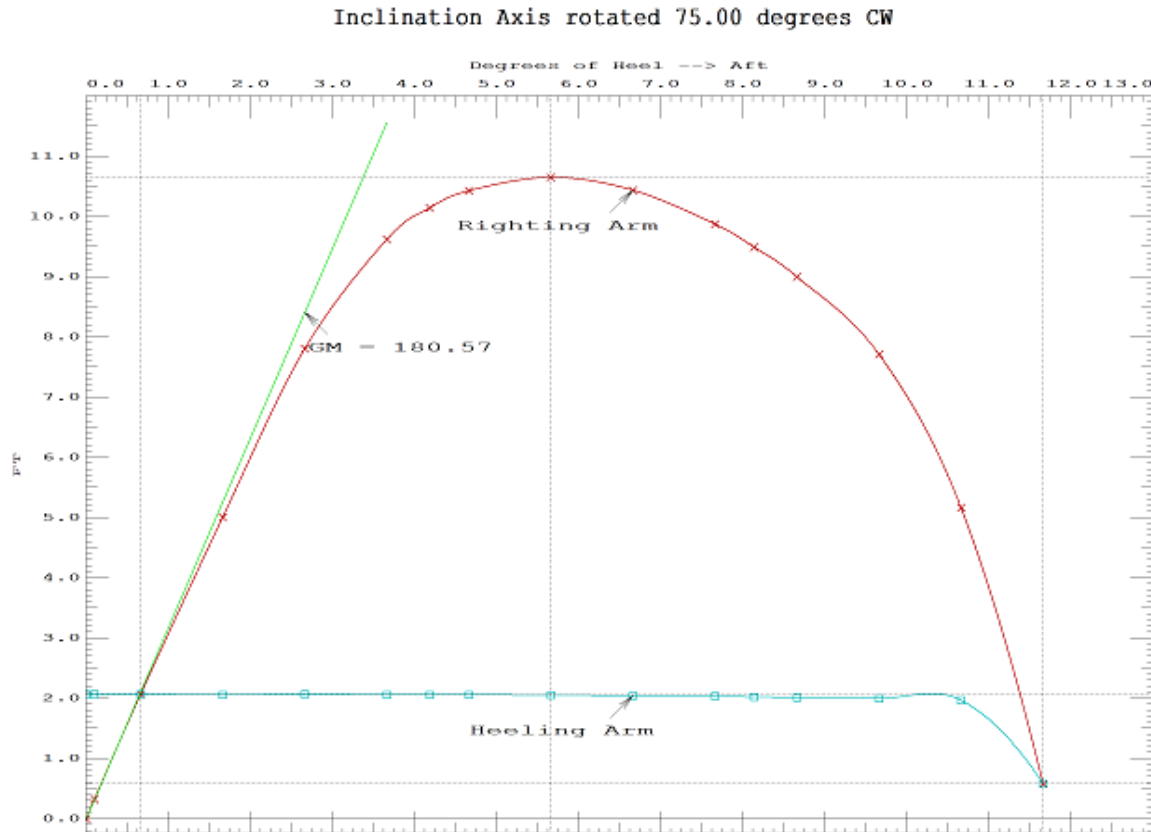


Figure 14. Liftboat righting arm 75-degree axis

LIM	46 CFR 174.255	Min/Max	Attained
(1)	Abs Ratio from abs 0 deg to RAzero or Flood	> 1.400	3.879 P
(2)	Angle from Equilibrium to RAzero or Flood	> 10.00 deg	7.47 F
(3)	Abs Righting Arm at abs 0.1 deg to RAzero	> 0.03 Ft	0.32 P
(4)	Res. Area from Equilibrium to RAzero or Flood	> 5.00 Ft-deg	49.17 P
(5)	GM Upright	> 1.00 Ft	180.57 P

The righting arms at the 75-degree axis result in failing the stability criteria and do not exhibit any trim/heel instability, fading stability, or oscillations. Thus, this righting arm is deemed acceptable and represents an accurate representation of the vessel behavior at the 75-degree axis. Note that if only the zero-degree axis was considered, the vessel would pass stability in this condition. When considering the 75-degree critical axis, the vessel does not pass the stability criteria.



Non-Traditionally Shaped Vessel Stability Standards

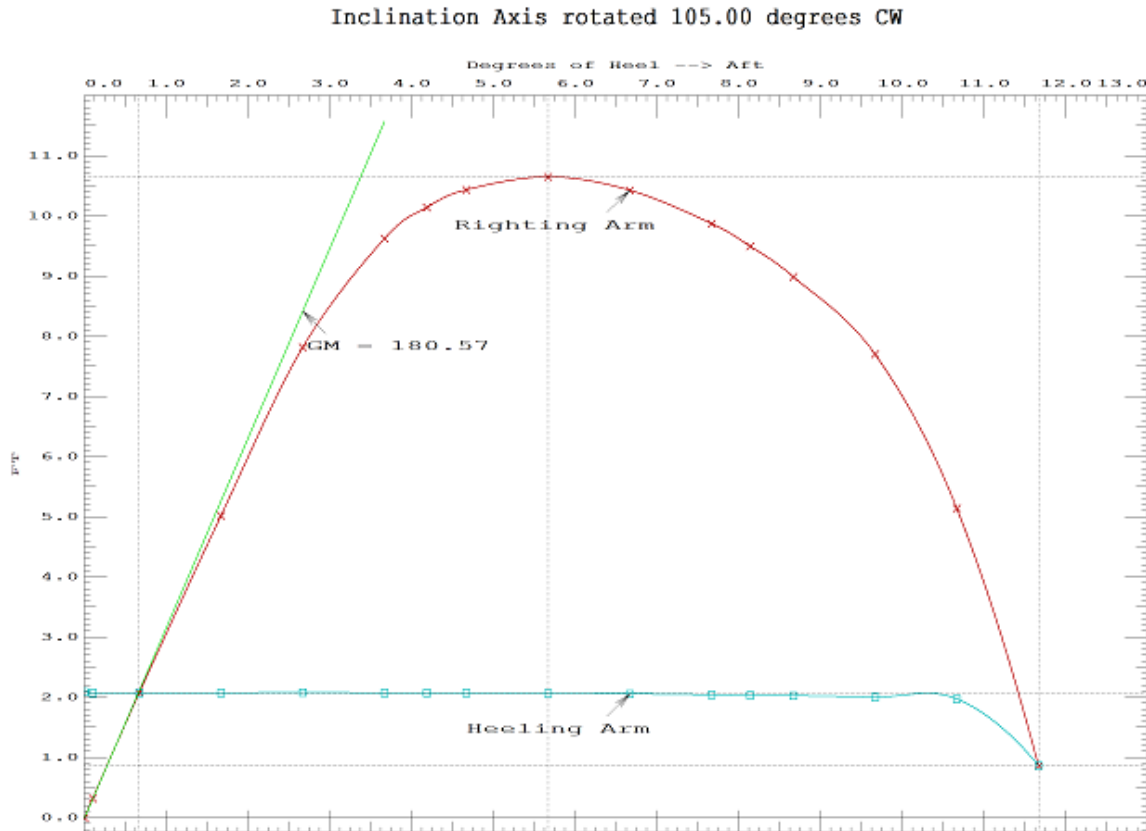


Figure 15. Liftboat righting arm 105-degree axis.

LIM	46 CFR 174.255	Min/Max	Attained
(1)	Abs Ratio from abs 0 deg to RAzero or Flood	> 1.400	3.879 P
(2)	Angle from Equilibrium to RAzero or Flood	> 10.00 deg	7.47 F
(3)	Abs Righting Arm at abs 0.1 deg to RAzero	> 0.03 Ft	0.32 P
(4)	Res. Area from Equilibrium to RAzero or Flood	> 5.00 Ft-deg	49.17 P
(5)	GM Upright	> 1.00 Ft	180.57 P

The righting arms at the 105-degree axis result in failing the stability criteria and do not exhibit any trim/heel instability, fading stability, or oscillations. Thus, this righting arm is deemed acceptable and represents an accurate representation of the vessel behavior at the 105-degree axis. Note that if only the zero-degree axis was considered, the vessel would pass stability in this condition. When considering the 105-degree critical axis, the vessel does not pass the stability criteria.



4.3.2 Jack-Up

4.3.2.1 Jack-Up GHS Model and Loading Condition

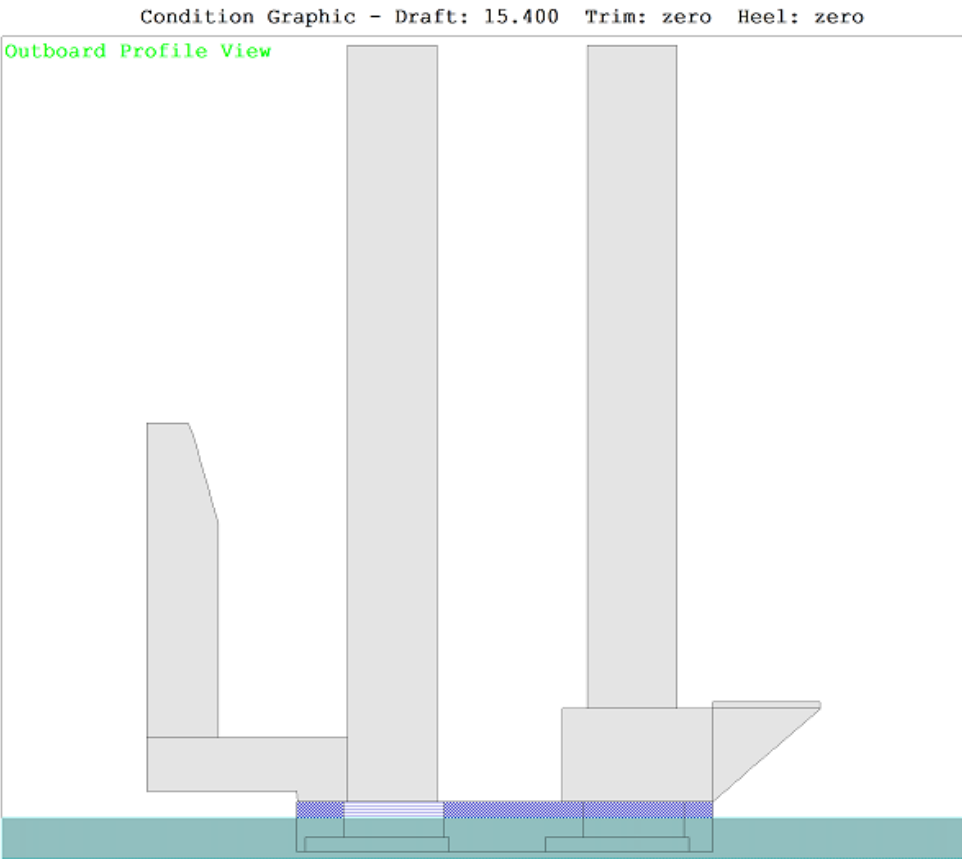


Figure 16. Jack-up GHS model.

WEIGHT and DISPLACEMENT and WATERPLANE STATUS						
Baseline draft: 15.400						
Trim: zero, Heel: zero						
Part		Weight(LT)	LCG	TCG	VCG	
WEIGHT		8,876.22	75.13f	0.00	58.00	
	SpGr	Displ(LT)	LCB	TCB	VCB	
HULL	1.025	8,876.22	75.13f	0.00	8.30	
	Righting Arms:		0.00	0.00		
Part	SpGr	WPA	LCF	TCF	BML	BMT
Total Waterplane	1.025	22919	74.92f	0.00	184.6	169.31
		LT/Inch		Ft-LT/Deg	GML	GMT
		54.56		20896.84	134.9	119.61
Distances in FEET.						

4.3.2.2 Jack-Up Step 2 Evaluation

The range of stability and righting energy within that range were calculated for each critical axis. This range of stability is calculated from equilibrium to the angle of vanishing stability or angle of downflooding, whichever comes first. The results are shown in Table 18.



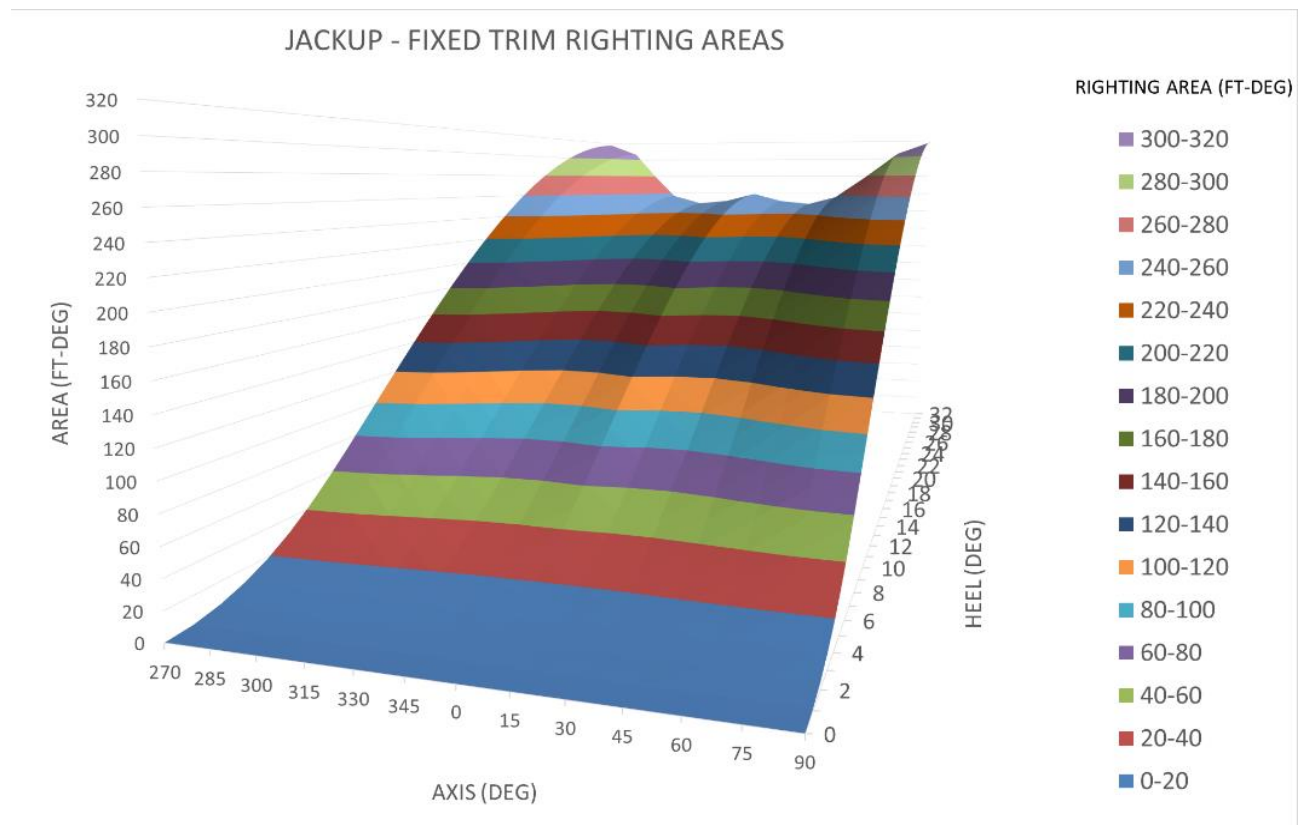
Non-Traditionally Shaped Vessel Stability Standards

Table 18. Jack-up Step 2 results.

Axis (deg)	Range (deg)	Energy (ft-deg)		Axis (deg)	Range (deg)	Energy (ft-deg)
0	30.65	259.8		180	30.65	259.8
15	30.65	251.66		195	31.15	274.47
30	30.59	248.69		210	31.64	287.11
45	30.66	257.15		225	31.65	288.35
60	31.34	280.57		240	31.37	282.17
75	32.27	306.61		255	31.65	288.35
90	32.71	318.4		270	31.37	282.17
105	32.27	306.61		285	29.15	278.3
120	31.34	280.57		300	31.37	282.17
135	30.67	257.57		315	31.65	288.35
150	30.59	248.69		330	31.64	287.11
165	30.65	251.66		345	31.15	274.47

As shown, the potential weak axes are 30, 150, and 285 degrees.

The righting energy data generated in Step 2 was plotted as a carpet plot ignoring downflooding points. This shows the weak axis purely based on the hull geometry in Figure 17.



Non-Traditionally Shaped Vessel Stability Standards

It is clear from reviewing the carpet plot that the axes with the least righting energy are the 30- and 150-degree axes.

4.3.2.3 Jack-Up Step 3 Evaluation

In order to assess Step 3 of the procedure, the Liftboat was analyzed using the 46 CFR § 174.045 requirements for MODUs. The criteria are expressed in GHS using the following limits:

LIM	46 CFR 174.045	Min/Max
(1) Abs Ratio from abs 0 deg to RAzero or Flood	>	1.400
(2) Abs Righting Arm at abs 0.1 deg to RAzero	>	0.03 Ft
(3) GM Upright	>	0.17 Ft

These criteria are evaluated for the full range of angles. The results are shown in Table 19 below:

Table 19. Jack-up Step 3 results.

AXIS	LIMITS			AXIS	LIMITS		
	1	2	3		1	2	3
	>1.4	>0.03	>0.17		>1.4	>0.03	>0.17
0	1.35	0.21	119.61	180	1.35	0.21	119.77
15	1.195	0.21	120.67	195	1.271	0.21	120.67
30	1.149	0.22	123.2	210	1.275	0.22	123.2
45	1.205	0.22	126.82	225	1.311	0.22	126.82
60	1.387	0.23	130.7	240	1.409	0.23	130.69
75	1.379	0.23	133.67	255	1.294	0.23	133.67
90	1.466	0.24	134.79	270	1.272	0.24	134.79
105	1.379	0.23	133.67	285	1.294	0.23	133.67
120	1.387	0.23	130.69	300	1.409	0.23	130.69
135	1.205	0.22	126.84	315	1.31	0.22	126.84
150	1.149	0.22	123.2	330	1.275	0.22	123.2
165	1.195	0.21	120.67	345	1.271	0.21	120.67

When reviewing Table 19, it is important to note that the color plots are only relative to the other data in each column. Red does not necessarily indicate that the criteria is failing; instead, it is intended to show the weakest axis for each criterion. In this case, however, there are a few important considerations. Limit 1 (the righting energy ratio limit) fails for nearly all angles, only passing the criteria at 90-, 240-, and 300-degree axes. This indicates that there are stability problems to address assuming all righting arms are correct. When reviewing all other axes, the worst-case results for Limit 1 are at the 30- and 150-degree axes. Thus, 30- and 150-degrees are selected as the critical axes for analysis.

4.3.2.4 Jack-Up Step 4 Evaluation

In accordance with the procedure, the critical axes identified in Step 3 are run through the stability criteria and their righting arms are to be examined. It is useful for the purposes of this report to include the zero-degree axis to show how the results change when considering critical axes. Therefore, the righting arms and stability criteria pass/fail status are included below:



Non-Traditionally Shaped Vessel Stability Standards

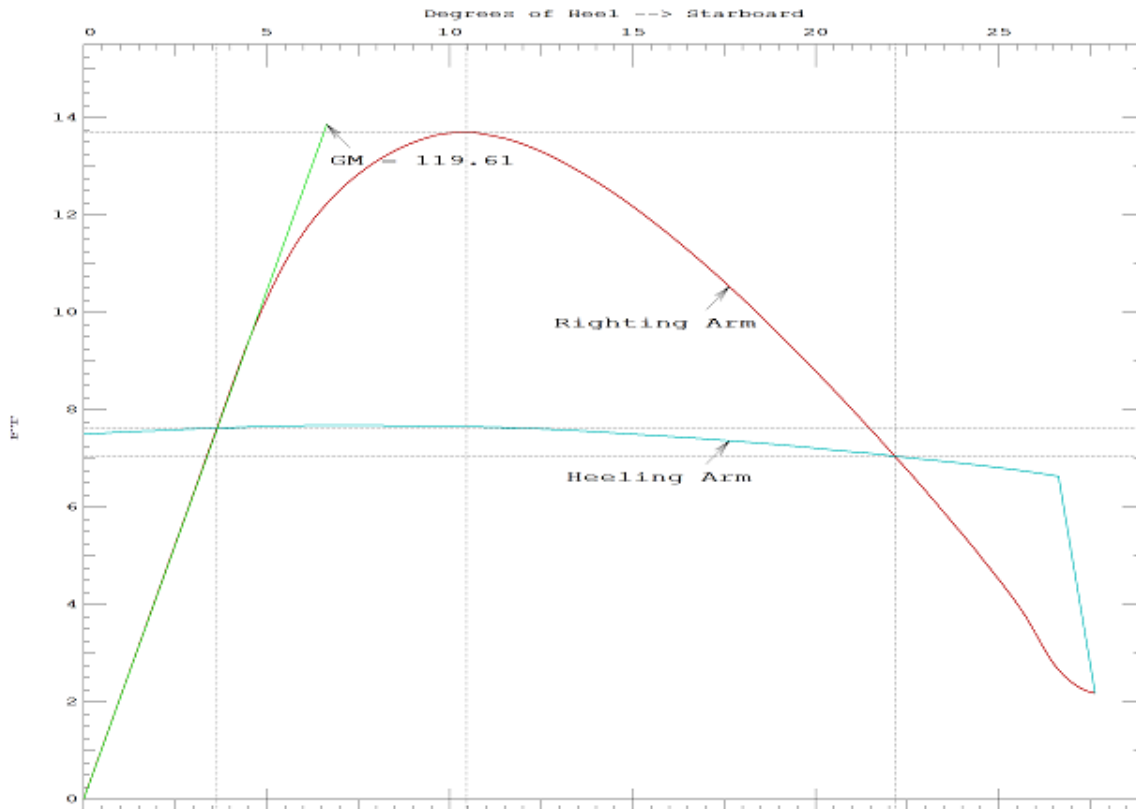


Figure 18. Jack-up righting arm 0-degree axis.

LIM	46 CFR 174.045	Min/Max	Attained
(1)	Abs Ratio from abs 0 deg to RAzero or Flood	> 1.400	1.350 F
(2)	Abs Righting Arm at abs 0.1 deg to RAzero	> 0.03 Ft	0.21 P
(3)	GM Upright	> 0.17 Ft	119.61 P

The righting arms at the zero-degree axis result in failure of the stability criteria, but do not exhibit any trim/heel instability, fading stability, or oscillations. Thus, this righting arm is deemed acceptable and represents an accurate representation of the vessel behavior at the zero-degree axis. Note that the criteria is triggered by the angle of second intercept (RAzero) limit, not the flood height limit.



Non-Traditionally Shaped Vessel Stability Standards

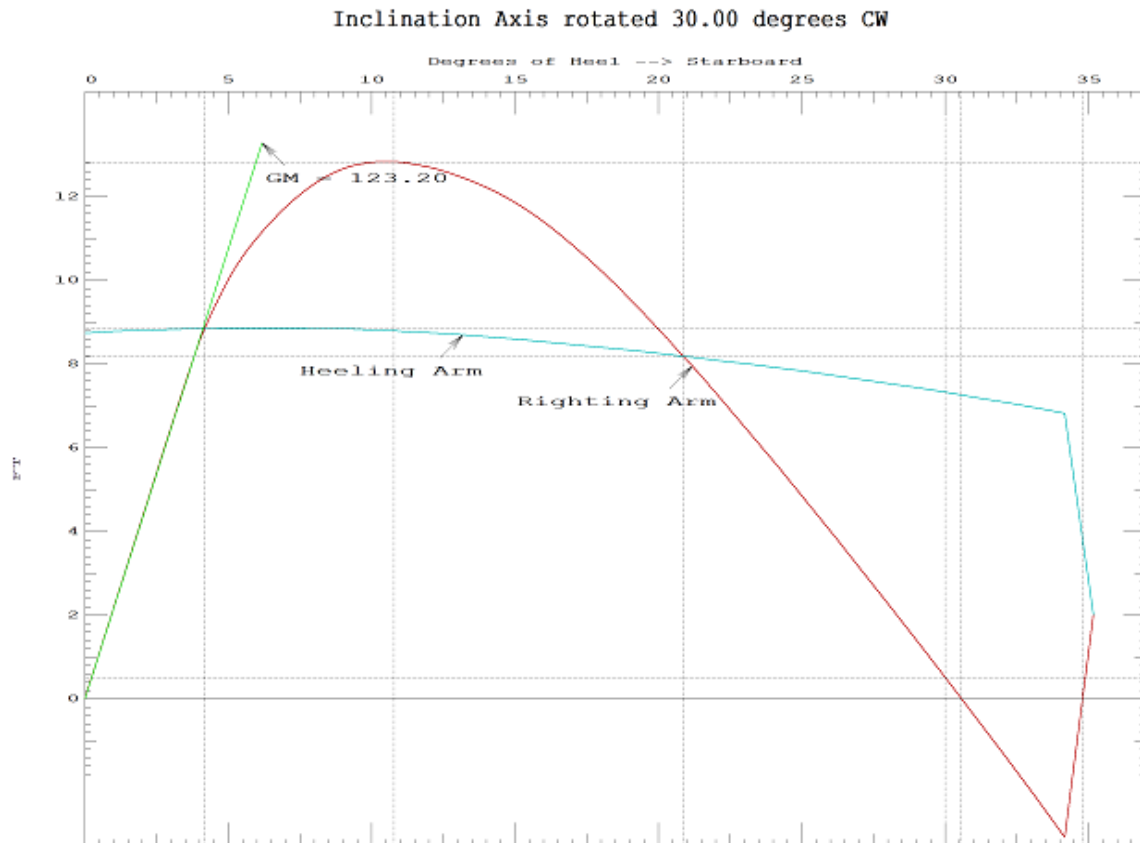


Figure 19. Jack-up righting arm 30-degree axis.

LIM	46 CFR 174.045	Min/Max	Attained
(1) Abs Ratio from abs 0 deg to RAzero or Flood	>	1.400	1.149 F
(2) Abs Righting Arm at abs 0.1 deg to RAzero	>	0.03 Ft	0.22 P
(3) GM Upright	>	0.17 Ft	123.20 P

The righting arms at the 30-degree axis result in failing the stability criteria and do not exhibit any trim/heel instability, fading stability, or oscillations. Thus, this righting arm is deemed acceptable and represents an accurate representation of the vessel behavior at the 30-degree axis. Note that the criteria is triggered by the angle of second intercept (RAzero) limit, not the flood height limit.



Non-Traditionally Shaped Vessel Stability Standards

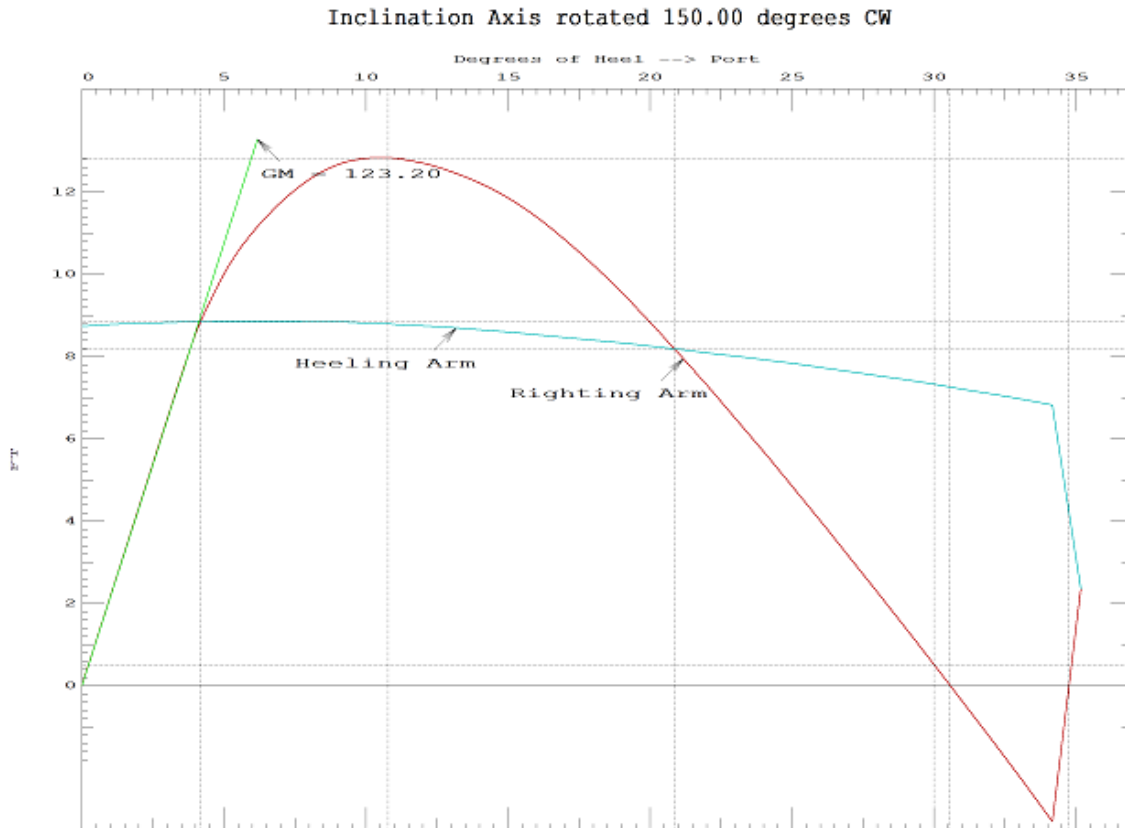


Figure 20. Jack-up righting arm 150-degree axis.

LIM	46 CFR 174.045	Min/Max	Attained
(1)	Abs Ratio from abs 0 deg to RAzero or Flood	> 1.400	1.149 F
(2)	Abs Righting Arm at abs 0.1 deg to RAzero	> 0.03 Ft	0.22 P
(3)	GM Upright	> 0.17 Ft	123.20 P

The righting arms at the 150-degree axis result in failing the stability criteria and do not exhibit any trim/heel instability, fading stability, or oscillations. Thus, this righting arm is deemed acceptable and represents an accurate representation of the vessel behavior at the 150-degree axis. Note that the criteria is triggered by the angle of second intercept (RAzero) limit, not the flood height limit.



Non-Traditionally Shaped Vessel Stability Standards

4.3.3 MODU SEMI

4.3.3.1 MODU SEMI GHS Model and Loading Condition

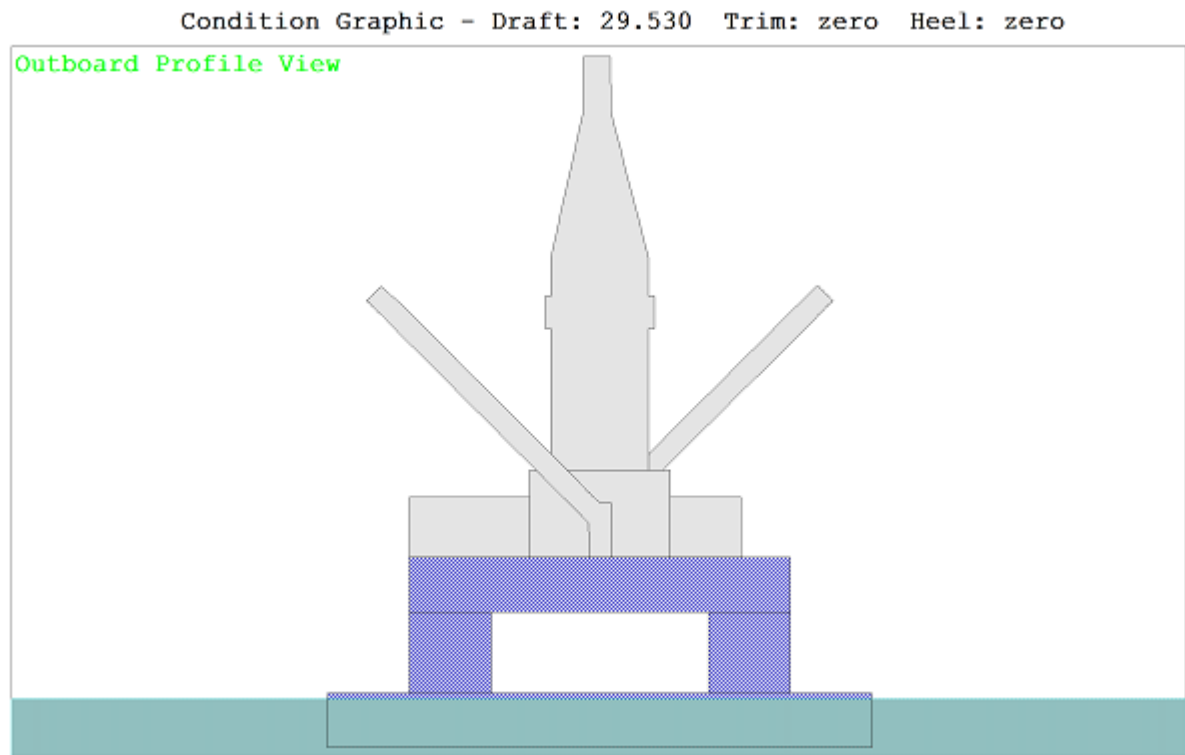


Figure 21. MODU SEMI GHS model.

WEIGHT and DISPLACEMENT and WATERPLANE STATUS						
Baseline draft: 29.530						
Trim: zero, Heel: zero						
Part		Weight(LT)	LCG	TCG	VCG	
WEIGHT		27,239.76	164.04 f	0.00	141.08	
HULL	SpGr	Displ(LT)	LCB	TCB	VCB	
	1.025	27,239.76	164.04 f	0.00	14.76	
Righting Arms:			0.00	0.00		
Part	SpGr	WPA	LCF	TCF	BML	BMT
Total Waterplane	1.025	32291	164.04 f	0.00	303.8	282.49
		LT/Inch		Ft-LT/Deg	GML	GMT
		76.87		84367.48	177.4	156.18
Distances in FEET.						

4.3.3.2 MODU SEMI Step 2 Evaluation

The range of stability and righting energy within that range were calculated for each critical axis. This range of stability is calculated from equilibrium to the angle of vanishing stability or angle of downflooding, whichever comes first. The results are shown in Table 20.



Non-Traditionally Shaped Vessel Stability Standards

Table 20. MODU SEMI Step 2 results.

Axis (deg)	Range (deg)	Energy (ft-deg)		Axis (deg)	Range (deg)	Energy (ft-deg)
0	42.93	523.76		180	42.93	523.76
15	42.16	454.16		195	42.16	454.13
30	35.64	286.42		210	35.64	286.41
45	34.04	236.7		225	34.05	236.72
60	35.71	277.58		240	35.71	277.54
75	39.82	335.69		255	39.82	335.74
90	40.49	356.97		270	40.49	357.09
105	39.82	335.69		285	39.82	335.74
120	35.71	277.58		300	35.71	277.54
135	34.04	236.7		315	34.05	236.72
150	35.64	286.42		330	35.64	286.41
165	42.16	454.16		345	42.16	454.13

As shown, the potential weak axes are 45, 135, 225, and 315 degrees. The righting energy data generated in Step 2 was plotted as a carpet plot ignoring downflooding points. This shows the weak axis purely based on the hull geometry in Figure 22.

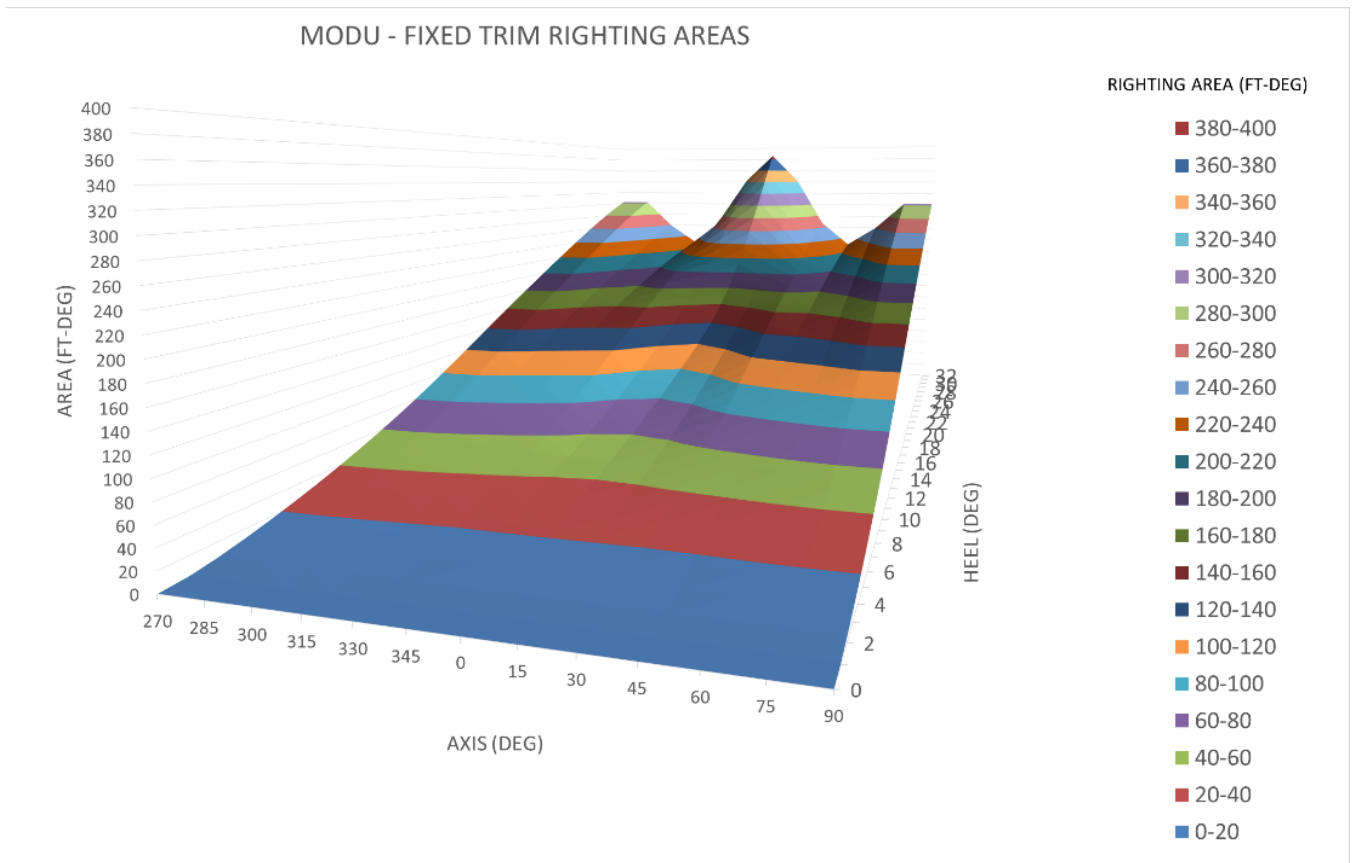


Figure 22. MODU SEMI righting energy.



Non-Traditionally Shaped Vessel Stability Standards

It is clear from reviewing the carpet plot that the axes with the least righting energy are the 45- and 315-degree axes.

4.3.3.3 MODU SEMI Step 3 Evaluation

In order to assess Step 3 of the procedure, the Liftboat was analyzed using the 46 CFR § 174.045 requirements for MODUs. The criteria are expressed in GHS using the following limits:

LIM	46 CFR 174.045	Min/Max
(1)	Abs Ratio from abs 0 deg to RAzero or Flood	> 1.400
(2)	Abs Righting Arm at abs 0.1 deg to RAzero	> 0.03 Ft
(3)	GM Upright	> 0.17 Ft

Note that 46 CFR 174.045 allows for a reduced Area Ratio Limit (from 1.4 to 1.3) for column-stabilized MODU SEMI. Since this vessel is being evaluated in the transit, condition however, the limit has been kept at 1.4. This also follows the other test vessels being analyzed. These criteria are evaluated for the full range of angles. The results are shown in Table 21 below:

Table 21. MODU SEMI Step 3 results.

AXIS	LIMITS				AXIS	LIMITS		
	1	2	3			1	2	3
	>1.4	>0.03	>0.17			>1.4	>0.03	>0.17
0	4.69	0.27	156.18		180	4.685	0.27	156.19
15	3.386	0.27	157.46		195	3.325	0.27	157.46
30	2.971	0.28	161.02		210	2.892	0.28	161.02
45	2.906	0.29	166.13		225	2.831	0.29	166.13
60	2.976	0.3	171.55		240	2.906	0.3	171.55
75	3.33	0.31	175.84		255	3.264	0.31	175.84
90	4.462	0.31	177.47		270	4.372	0.31	177.46
105	3.339	0.31	175.85		285	3.269	0.31	175.85
120	2.842	0.3	171.55		300	2.794	0.3	171.56
135	2.692	0.29	166.13		315	2.634	0.29	166.13
150	2.814	0.28	161.02		330	2.755	0.28	161.02
165	3.309	0.27	157.46		345	3.264	0.27	157.46

When reviewing the table above, it is important to note that the color plots are only relative to the other data in each column. Red does not necessarily indicate that the criteria is failing, it is intended to show the weakest axis for each criterion. For this hull, Limit 1 is by far the most conservative, with even the worst-case results being orders of magnitude above the limits. When reviewing the limit 1 results, it becomes clear that the critical axes are the 225- and 315-degree axes. the 45- and 135-degree axes are similar.

4.3.3.4 MODU SEMI Step 4 Evaluation

In accordance with the procedure, the critical axes identified in Step 3 are run through the stability criteria and their righting arms are to be examined. It is useful for the purposes of this report to include the zero-degree axis to show how the results change when considering critical axes. Therefore, the righting arms and stability criteria pass/fail status are included below:



Non-Traditionally Shaped Vessel Stability Standards

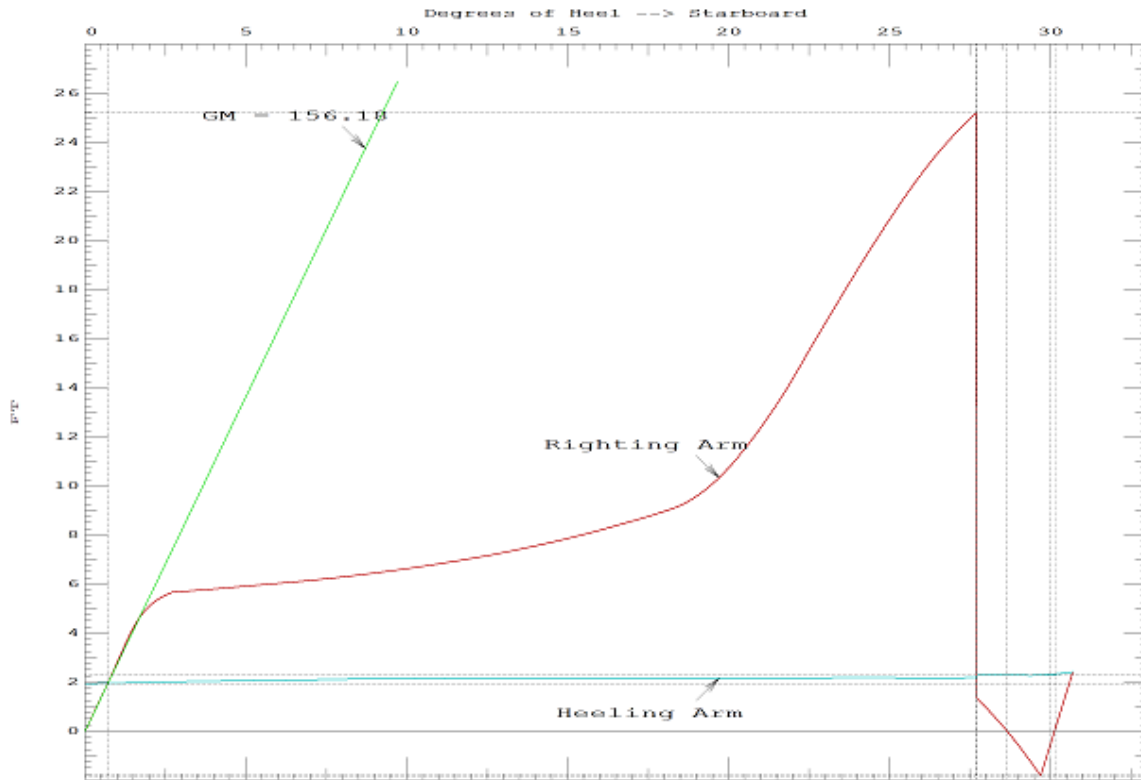


Figure 23. MODU SEMI righting arm 0-degree axis.

LIM	46 CFR 174.045	Min/Max	Attained
(1) Abs Ratio from abs 0 deg to RAZero or Flood	>	1.400	4.690 P
(2) Abs Righting Arm at abs 0.1 deg to RAZero	>	0.03 Ft	0.27 P
(3) GM Upright	>	0.17 Ft	156.18 P

The righting arms at the zero-degree axis result in passing the stability criteria, but the graph exhibits sudden changes past 27.5 degrees of heel. Thus, this righting arm must be further inspected.



Non-Traditionally Shaped Vessel Stability Standards

Table 22. MODU SEMI righting arm data 0-degree axis

RESIDUAL RIGHTING ARMS vs HEEL ANGLE							
LCG = 164.04f TCG = 0.00 VCG = 141.08							
Origin Depth	Degrees of Trim	Heel	Displacement Weight(LT)	Residual Arms in Trim	in Heel	Res. Flood Pt Area	Height
29.530	0.00	0.00	27,240	0.00	-1.916	0.00	91.30 (2)
29.530	0.00	0.10s	27,240	0.00	-1.644	-0.18	91.14 (1)
29.528	0.00	0.71s	27,240	0.00	0.000	-0.68	90.17 (1)
29.522	0.00	1.71s	27,242	0.00	2.685	0.66	88.56 (1)
30.032	0.00	2.71s	27,240	0.00	3.655	3.94	86.39 (2)
30.851	0.00	3.71s	27,240	0.00	3.733	7.72	83.88 (2)
31.661	0.00	4.71s	27,240	0.00	3.822	11.50	81.35 (2)
32.476	0.01a	5.71s	27,240	0.01a	3.916	15.37	78.78 (2)
33.238	0.00f	6.71s	27,240	0.01f	4.024	19.34	76.20 (1)
34.032	0.00	7.71s	27,240	0.00	4.144	23.42	73.60 (1)
34.788	0.00f	8.71s	27,239	0.01f	4.282	27.63	70.96 (1)
35.547	0.01f	9.71s	27,240	0.01f	4.437	31.99	68.31 (1)
36.310	0.00	10.71s	27,240	0.00	4.611	36.52	65.64 (2)
37.033	0.01f	11.71s	27,240	0.01f	4.812	41.23	62.94 (1)
37.774	0.00	12.71s	27,240	0.00	5.044	46.15	60.24 (2)
38.506	0.01a	13.71s	27,242	0.01a	5.300	51.32	57.50 (2)
39.180	0.01f	14.71s	27,242	0.01f	5.590	56.77	54.75 (1)
39.881	0.00	15.71s	27,238	0.00	5.924	62.52	52.00 (2)
40.576	0.01a	16.71s	27,240	0.01a	6.279	68.63	49.21 (2)
41.218	0.01f	17.71s	27,242	0.01f	6.671	75.10	46.41 (1)
41.873	0.00	18.71s	27,240	0.00	7.160	82.02	43.63 (2)
42.369	0.00f	19.71s	27,240	0.01f	8.163	89.68	40.93 (1)
42.761	0.00	20.71s	27,240	0.00	9.679	98.60	38.35 (2)
43.031	0.00f	21.71s	27,247	0.01f	11.577	109.23	35.83 (1)
43.202	0.00	22.71s	27,240	0.00	13.795	121.91	33.42 (2)
43.217	0.01a	23.71s	27,241	0.01a	15.995	136.81	31.14 (2)
43.019	0.01f	24.71s	27,244	0.00	18.090	153.86	29.01 (1)
42.687	0.00	25.71s	27,242	0.00	20.022	172.93	27.04 (2)
42.176	0.01a	26.71s	27,240	0.00	21.703	193.79	25.21 (2)
41.438	0.00f	27.71s	27,240	0.00	23.056	216.17	23.56 (1)
-38.708	23.55f	27.72s	27,240	0.00	-0.937	216.30	-3.32 (1)
-43.611	24.87f	28.71s	27,237	0.00	-2.350	214.70	-6.52 (1)
-49.560	26.53f	29.71s	27,241	0.00	-4.095	211.47	-10.11 (1)
-227.777	90.00f	30.71s	27,247	1432.02a	0.000	211.47	-26.49 (1)
Distances in FEET.			Specific Gravity = 1.025.				Area in Ft-Deg.

After reviewing the graphical data in Figure 23, there is trim instability at 27.71 degrees of heel, with the trim jumping from 0 to 23.55 deg forward between 27.71 degrees and 27.72 degrees. This means that for this axis, the designer must conduct a free twist righting arm analysis to satisfy Step 5 of the procedure. This is contained in Section 4.3.3.5 below. Before proceeding to Step 5, however, the other critical axes must be checked using the free-trim, fixed-twist righting arm analysis from Step 4.



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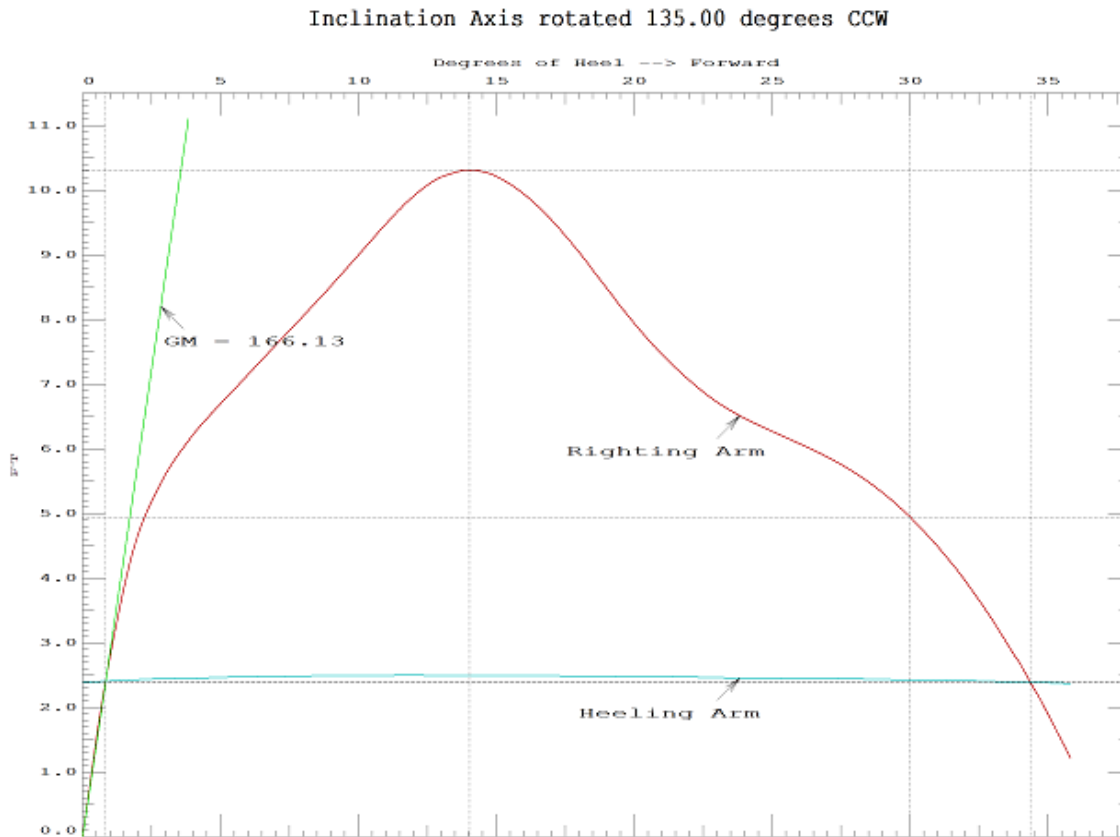


Figure 24. MODU SEMI righting arm 225-degree axis.

LIM	46 CFR 174.045	Min/Max	Attained
(1)	Abs Ratio from abs 0 deg to RZero or Flood	> 1.400	2.831 P
(2)	Abs Righting Arm at abs 0.1 deg to RZero	> 0.03 Ft	0.29 P
(3)	GM Upright	> 0.17 Ft	166.13 P

The righting arms at the 225-degree axis (GHS displays this as 135 degrees CCW) result in passing the stability criteria and do not exhibit any trim/heel instability, fading stability, or oscillations. The unique shape of the righting arm curve is due to the vessel geometry. At transit draft, the MODU SEMI is operating with both pontoon decks above the waterline. As the heels, the waterplane changes drastically when one pontoon deck becomes submerged, and again when the buoyant cross deck structure is submerged. Thus, this righting arm is deemed acceptable and represents an accurate representation of the vessel behavior at the 30-degree axis. Note that the criterion is triggered by the downflooding height limit, not the second intercept, but they occur almost simultaneously.



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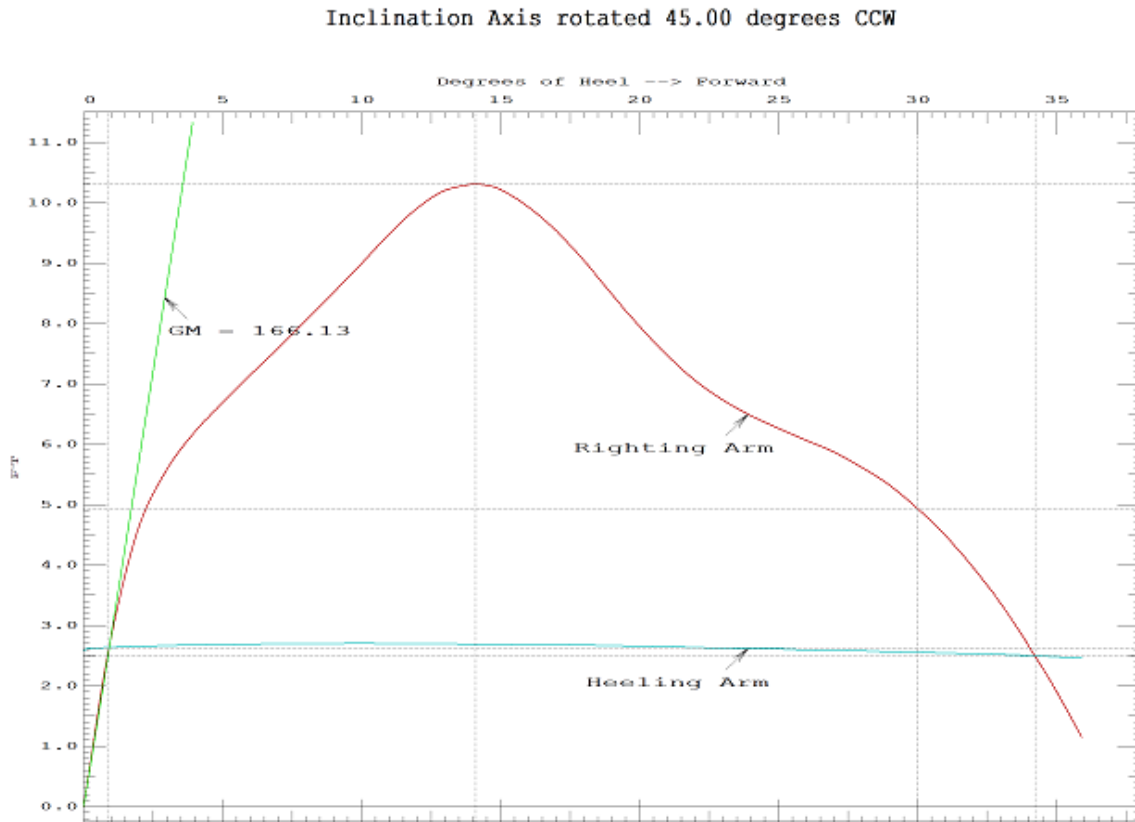


Figure 25. MODU SEMI righting arm 315-degree axis.

LIM	46 CFR 174.045	Min/Max	Attained
(1)	Abs Ratio from abs 0 deg to RAZero or Flood	> 1.400	2.634 P
(2)	Abs Righting Arm at abs 0.1 deg to RAZero	> 0.03 Ft	0.29 P
(3)	GM Upright	> 0.17 Ft	166.13 P

The righting arms at the 315-degree axis (GHS displays this as 45 degrees CCW) result in passing the stability criteria and do not exhibit any trim/heel instability, fading stability, or oscillations. The unique shape of the righting arm curve is due to the vessel geometry. At transit draft, the MODU SEMI is operating with both pontoon decks above the waterline. As the heels, the waterplane changes drastically when one pontoon deck becomes submerged, and again when the buoyant cross deck structure is submerged. Thus, this righting arm is deemed acceptable and represents an accurate representation of the vessel behavior at the 30-degree axis. Note that the criterion is triggered by the downflooding height limit, not the second intercept, but they occur almost simultaneously.

4.3.3.5 MODU SEMI Step 5 Evaluation

Since the righting arms at the zero-degree axis exhibited some unusual features, including trim instability, the procedure requires that free twist righting arms be run for evaluation. As discussed above, the preferred method for this is the zero-trim free twist calculation approach and this has been developed using the `VARY AXIS:ZEROTRIM` command in GHS. The righting arm results are shown in Figure 26 below:



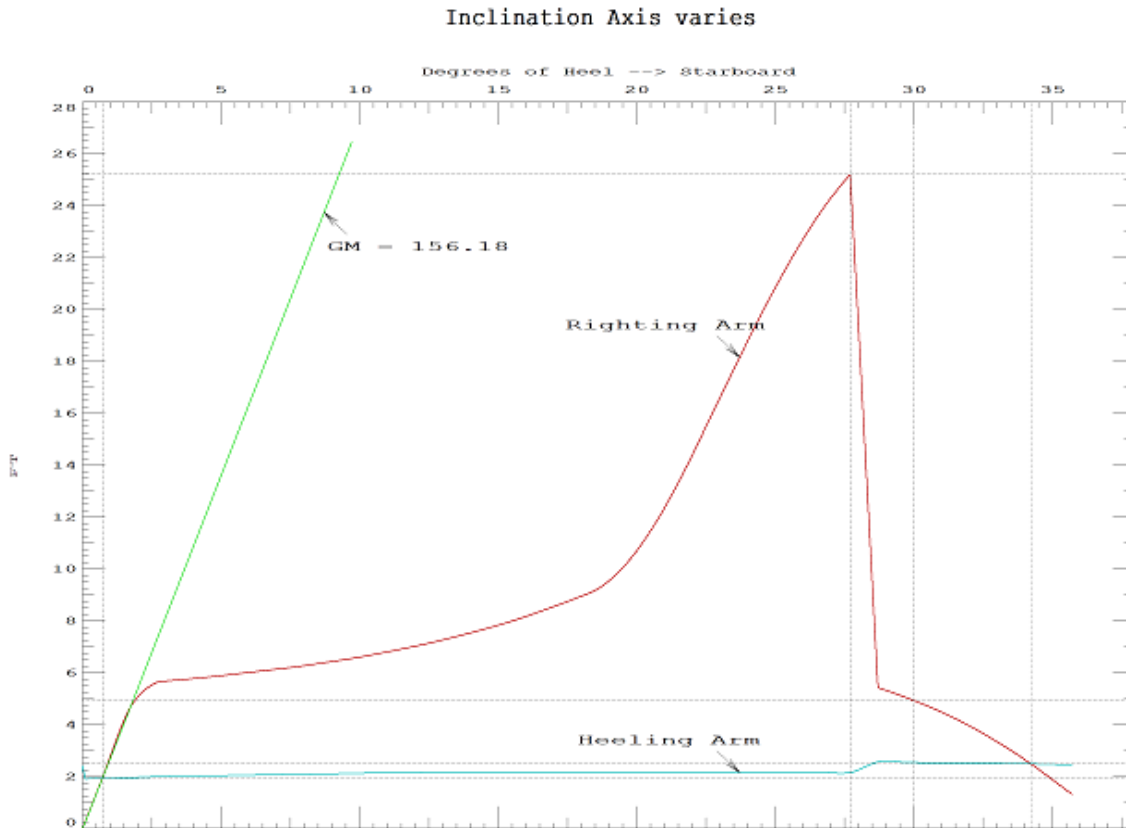


Figure 26. MODU SEMI free twist righting arm 0-degrees.

The righting arm curve shares a shape with the free-trim righting arm curve in Figure 23, sharing a peak and subsequent sharp decline at approximately 27.5-degree heel angle. Since the axis is not shown on the righting arm plot, it is necessary to inspect the numerical data, duplicated below in FIX.

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Table 23. MODU semi free twist righting arm data 0-degree axis.

Axis varied to maintain zero trim							
Degrees of		Heel	Displacement Weight(LT)	Residual Arms		Res. Area	Flood Pt Height
Axis	Trim			in Trim	in Heel		
33.75	0.00	0.00	27,240	0.00	-2.425	0.00	91.30 (1)
-0.06	0.00	0.10s	27,240	0.00	-1.644	-0.20	91.14 (1)
-0.00	0.00	0.71s	27,240	0.00	0.000	-0.71	90.17 (1)
-0.01	0.00	1.71s	27,240	0.00	2.686	0.71	88.56 (1)
0.00	0.00	2.71s	27,240	0.00	3.655	4.00	86.39 (1)
0.05	0.00	3.71s	27,240	0.00	3.733	7.79	83.88 (2)
-0.02	0.00	4.71s	27,240	0.00	3.821	11.57	81.35 (1)
0.01	0.00	5.71s	27,240	0.00	3.915	15.44	78.79 (2)
0.01	0.00	6.71s	27,240	0.00	4.024	19.41	76.20 (2)
0.00	0.00	7.71s	27,240	0.00	4.144	23.49	73.60 (2)
0.00	0.00	8.71s	27,240	0.00	4.281	27.70	70.97 (2)
0.00	0.00	9.71s	27,240	0.00	4.437	32.06	68.32 (2)
0.00	0.00	10.71s	27,240	0.00	4.611	36.59	65.64 (2)
0.00	0.00	11.71s	27,240	0.00	4.812	41.30	62.95 (2)
0.00	0.00	12.71s	27,240	0.00	5.044	46.22	60.24 (2)
0.00	0.00	13.71s	27,240	0.00	5.306	51.40	57.51 (2)
0.00	0.00	14.71s	27,240	0.00	5.596	56.85	54.76 (2)
0.00	0.00	15.71s	27,240	0.00	5.920	62.60	52.00 (2)
0.00	0.00	16.71s	27,240	0.00	6.280	68.70	49.22 (2)
0.00	0.00	17.71s	27,240	0.00	6.679	75.18	46.43 (2)
-0.02	0.00	18.71s	27,241	0.01f	7.156	82.10	43.61 (1)
0.00	0.00	19.71s	27,240	0.00	8.163	89.76	40.94 (2)
0.00	0.00	20.71s	27,240	0.00	9.680	98.68	38.35 (2)
0.00	0.00	21.71s	27,240	0.00	11.599	109.32	35.85 (2)
0.00	0.00	22.71s	27,240	0.00	13.796	122.02	33.42 (2)
0.00	0.00	23.71s	27,240	0.00	15.999	136.92	31.15 (2)
-0.10	0.00	24.71s	27,240	0.01f	18.095	153.97	28.95 (1)
-0.04	0.00f	25.71s	27,240	0.00	20.025	173.04	27.01 (1)
-0.02	0.01f	26.71s	27,240	0.00	21.703	193.90	25.19 (1)
-0.00	0.03a	27.71s	27,242	0.01a	23.054	216.28	23.52 (2)
-46.17	0.01p	28.71f	27,239	0.00	2.855	229.23	11.22 (1)
-45.92	0.00	29.71f	27,240	0.00	2.505	231.91	9.07 (1)
-45.65	0.00	30.71f	27,240	0.00	2.086	234.21	6.95 (1)
-45.38	0.00	31.71f	27,240	0.00	1.588	236.05	4.85 (1)
-45.10	0.00	32.71f	27,240	0.00	1.015	237.35	2.77 (1)
-44.83	0.00	33.71s	27,240	0.00	0.364	238.04	0.71 (1)
-44.74	0.00	34.05s	27,240	0.00	0.124	238.12	-0.00 (1)
-44.69	0.00	34.23s	27,240	0.00	0.001	238.13	-0.35 (1)
-44.57	0.00	34.71s	27,240	0.00	-0.357	238.05	-1.34 (1)
-44.30	0.00	35.71s	27,240	0.00	-1.156	237.30	-3.37 (1)

Distances in FEET.

Specific Gravity = 1.025.

Area in Ft-Deg.

In reviewing the numerical righting arm data in Table 23, the axis “jumps” from zero degrees to 46 degrees at 27.7 degrees of heel and remains in the 44 to 46-degree range past that. This righting arm data is not necessarily valid, though, due to the sudden jump in axis, but since that axis matches the critical axis check produced in Steps 2 and 3 and evaluated in Step 4, it drives to user to proceed with the 45-degree axis checks in Step 4. Figure 27 shows these two righting arms plotted on the same graph.



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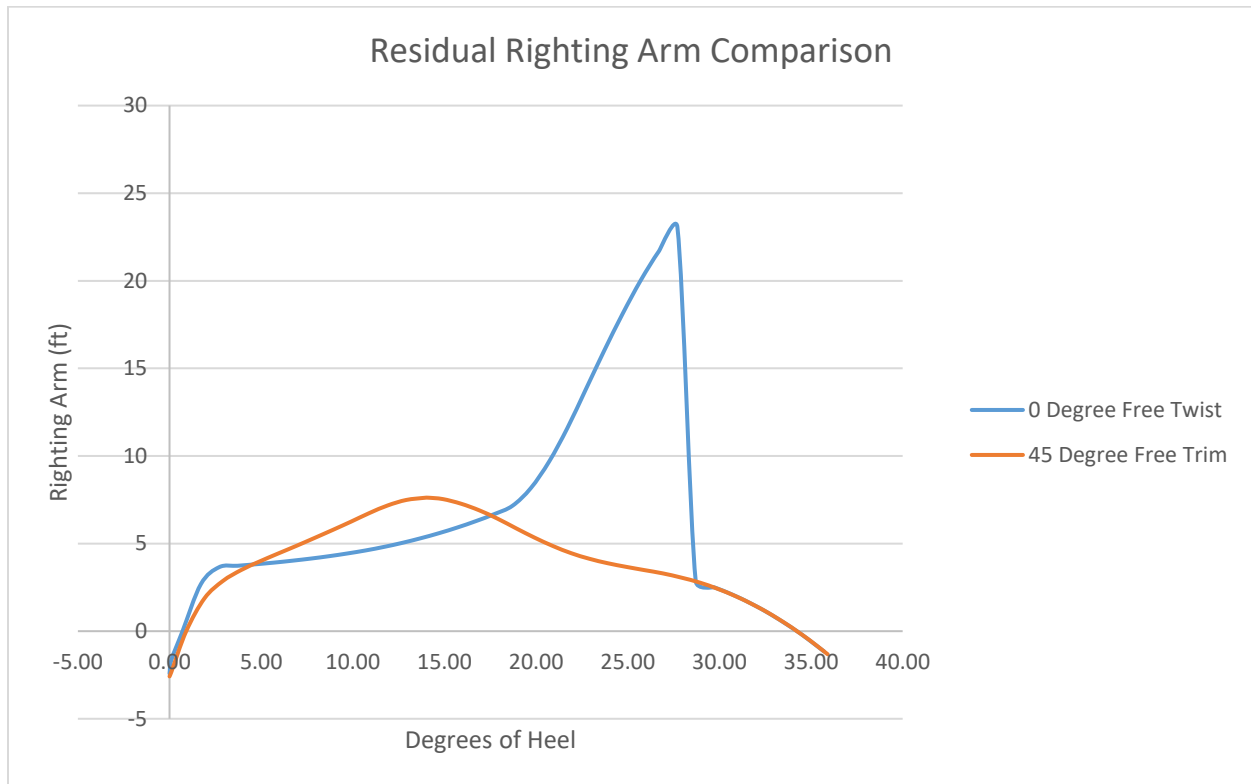


Figure 27. MODU SEMI residual righting arm comparison.

Figure 27 shows residual righting arms (righting arm minus heeling arm) and gives a general idea of the shape of the curve. At approximately 28 degrees, the curves converge as the axis jumps to 45 degrees. Since there is axis instability in the free twist curve, it is prudent to disregard this result, as long as excluding this data remains conservative. To ensure this, the free twist stability check is compared to the 45-degree free trim stability check in Table 24:

Table 24. MODU SEMI Stability Limit Comparison - 45 deg free trim vs zero deg free twist.

Limit No.	Criterion	45-Deg Free Trim	0-Deg Free Twist
1	Abs Ratio from Abs 0 deg to Razero or Flood > 1.4	2.831	4.199
2	Abs righting arm at Abs 0.1 deg to Razero > 0.03	0.29	0.27
3	GM upright > 0.17	166.13	156.18

Reviewing the data – while limits 2 and 3 present worst-case results in the free twist method, they are orders of magnitude above the required limits for each criterion. The governing criterion is evaluated via limit 1 and the 45-degree righting arm results are clearly conservative. Thus, with the available righting arm data, the 45-degree data should be considered limiting for this vessel’s stability.

It is important to note, however, that the trim instability shown in the free trim righting arm curves translated directly to an axis instability in the free twist righting arm curves. While it seemingly “found” the right axis in this case, the immediate jump gives cause for further study. Similar issues were uncovered when this righting arm was run using the minimum ascent method in GHS as well. Through discussions with Creative Systems, Inc. (makers of GHS), it is understood that there is no way to “look under the hood”



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to further understand how the solver is arriving at these twist angles and righting arms to validate this. Since there is no way to validate this with GHS alone, a validation study of free twist methods is recommended. This recommendation is further discussed in Section 6.3.

4.3.4 WTIV

4.3.4.1 WTIV GHS Model and Loading Condition

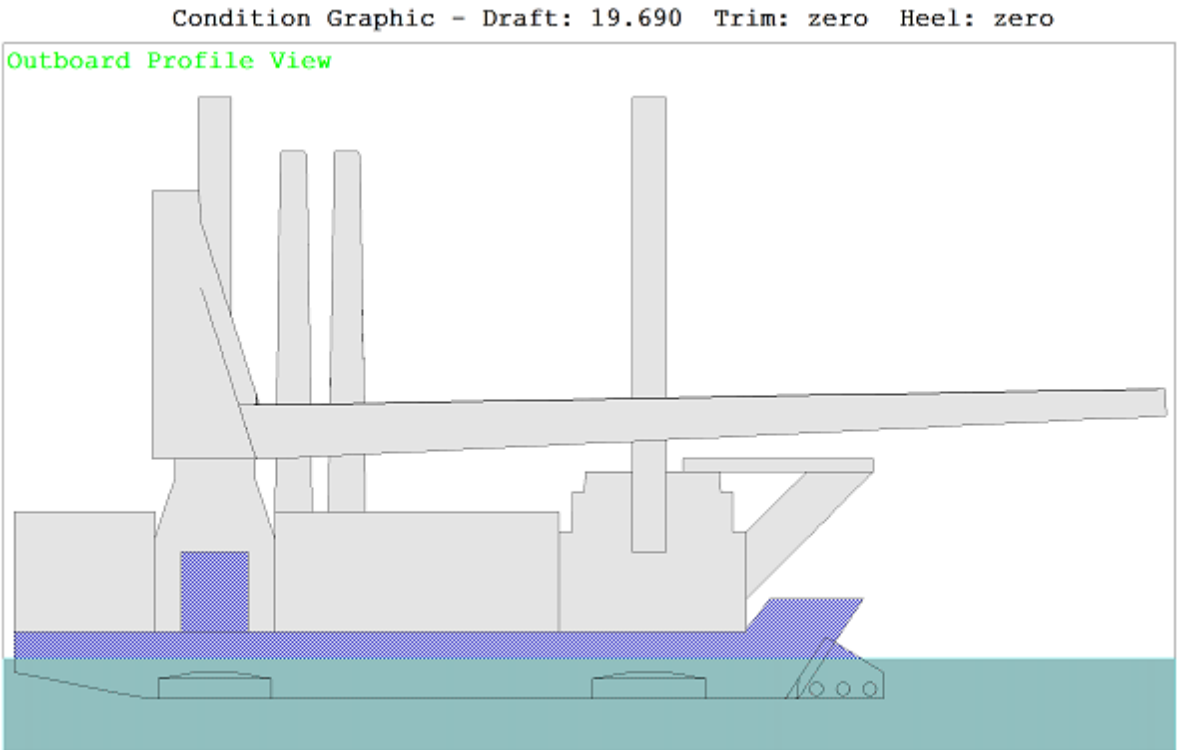


Figure 28. WTIV GHS model.

WEIGHT and DISPLACEMENT and WATERPLANE STATUS						
Baseline draft: 19.690						
Trim: zero, Heel: zero						
Part		Weight(LT)	LCG	TCG	VCG	
WEIGHT		26,061.01	196.44 f	0.00	75.00	
	SpGr	Displ(LT)	LCB	TCB	VCB	
HULL	1.025	26,061.01	196.44 f	0.00	10.74	
	Righting Arms:		0.00	0.00		
Part	SpGr	WPA	LCF	TCF	BML	BMT
Total Waterplane	1.025	55620	188.85 f	0.00	732.5	106.34
		LT/Inch	Ft-LT/Deg		GML	GMT
		132.41	303965.47		668.2	42.08
Distances in FEET.						

4.3.4.2 WTIV Step 2 Evaluation

The range of stability and righting energy within that range were calculated for each critical axis. This range of stability is calculated from equilibrium to the angle of vanishing stability or angle of downflooding, whichever comes first. The results are shown in Table 25.



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Table 25. WTIV Step 2 results.

Axis	Range	Energy		Axis	Range	Energy
0	16.97	88.61		180	16.97	88.61
15	29.51	279.36		195	12.09	96.2
30	44.11	778.73		210	9.97	154.16
45	52.03	1407.4		225	9.09	226.4
60	57.44	2008.8		240	9.02	312.63
75	59.93	2420.8		255	9.64	417.92
90	60.78	2570.7		270	11	542.45
105	59.93	2420.8		285	9.64	417.92
120	57.44	2008.8		300	9.02	312.63
135	52	1407.4		315	9.09	226.4
150	44.11	778.73		330	9.97	154.16
165	29.51	279.36		345	12.09	96.2

At first glance, the results seem to indicate that the 240- and 300- degree axes are worst-case axes, but in reviewing the hull form, this does not seem accurate. Upon further inspection, it is clear that the downflooding points (which are biased towards the forward end of the vessel limit the range of stability about axes near 90/180, and this stands to reason with a hull with a higher L/B ratio such as the WTIV. Given the increased length, the downflooding points are farther from the axis, which results in reduced range of stability. The righting energy is only measured across the range of stability, so it is similarly affected. To confirm that the downflooding points are skewing the results, Step 2 was re-run without considering downflooding points. The results are provided in Table 26.

Table 26. WTIV Step 2 Results - No downflooding.

Axis	Range	Energy		Axis	Range	Energy
0	28.92	136.77		180	29	136.77
15	35.15	294.51		195	36.35	318.46
30	44.11	778.73		210	45.91	865.29
45	52.03	1407.4		225	54.09	1581
60	57.44	2008.8		240	59	2247.8
75	59.93	2420.8		255	61.47	2695.8
90	60.78	2570.7		270	62.25	2858.2
105	59.93	2420.8		285	61.47	2695.8
120	57.44	2008.8		300	59	2247.8
135	52.03	1407.4		315	54.09	1581
150	44.11	778.73		330	45.91	865.29
165	35.15	294.51		345	36.35	318.46

Table 26 confirms that when not considering downflooding points, the weakest axis is clearly the 0-degree conventional axis. The discrepancy with downflooding points highlights the importance of understanding the results of Step 1. Reviewing the WTIV column in Table 6, the L/B ratio on the WTIV is much higher



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than the other 3 hulls studied in this analysis, so the user must keep that in mind when going through the procedure.

The righting energy data generated in Step 2 was plotted as a carpet plot ignoring downflooding points. This shows the weak axis purely based on the hull geometry in Figure 29.

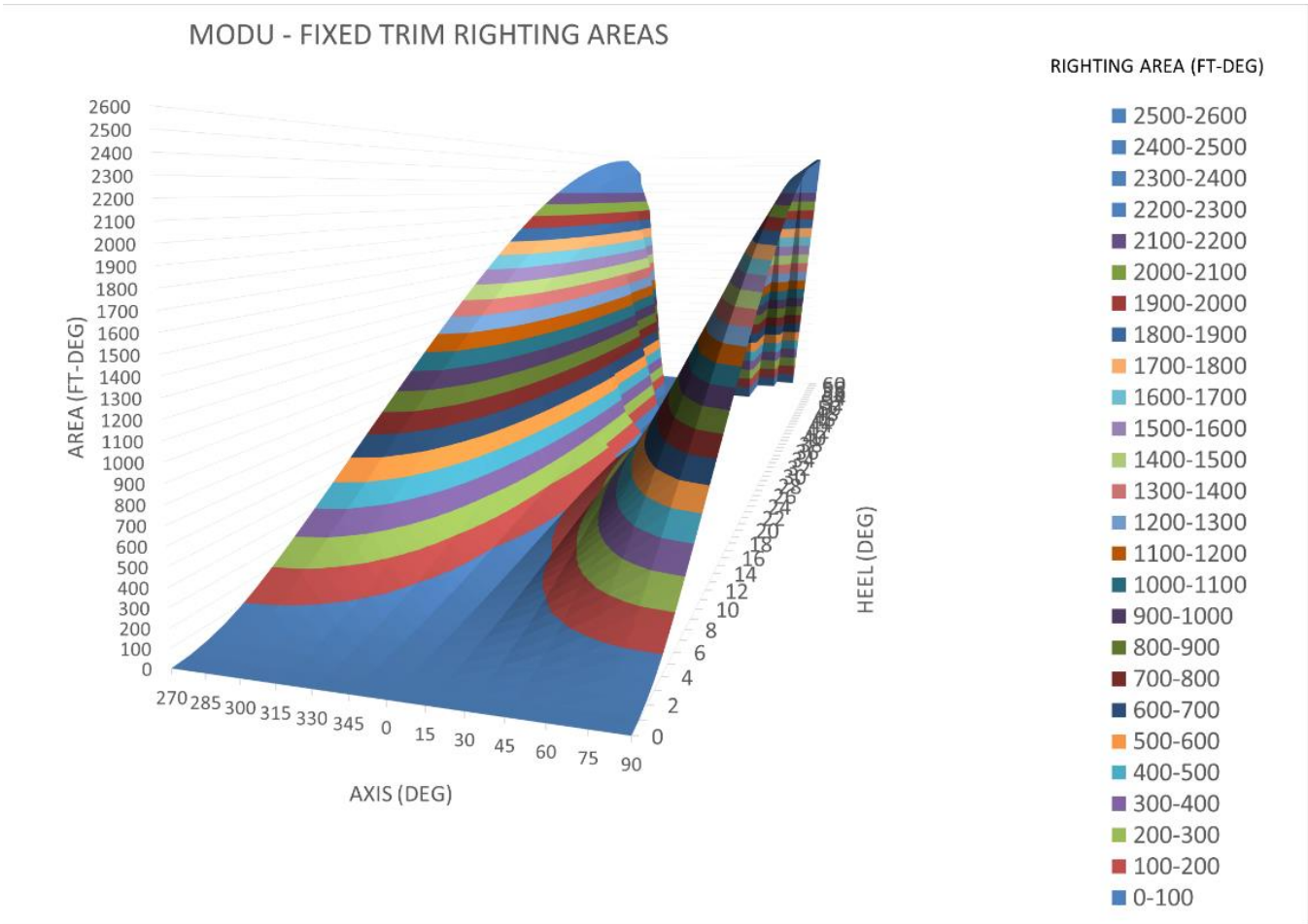


Figure 29. WTIV righting energy.

It is clear from reviewing the carpet plot that the axis with the least righting energy is the 0-degree conventional axis. Also note the extreme slope on the edge of the “valley” is different than the other 3 hull forms. This further confirms the selection of the 0-degree axis as the only weak axis.

4.3.4.3 WTIV Step 3 Evaluation

To assess Step 3 of the procedure, the Liftboat was analyzed using the 46 CFR § 174.045 requirements for MODUs. The criteria are expressed in GHS using the following limits:

LIM	46 CFR 174.045	Min/Max
(1)	Abs Ratio from abs 0 deg to RAzero or Flood	> 1.400
(2)	Abs Righting Arm at abs 0.1 deg to RAzero	> 0.03 Ft
(3)	GM Upright	> 0.17 Ft



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These criteria are evaluated for the full range of angles. The results are shown in Table 27 below:

Table 27. WTIV Step 3 results.

AXIS	LIMITS			AXIS	LIMITS		
	1	2	3		1	2	3
	>1.4	>0.03	>0.17		>1.4	>0.03	>0.17
0	2.795	0.07	42.08	180	2.871	0.07	42.4
15	2.929	0.08	45.12	195	3.004	0.08	45.14
30	3.163	0.1	55.44	210	3.243	0.1	55.37
45	3.784	0.14	79.76	225	3.861	0.14	79.77
60	5.273	0.25	142.52	240	5.275	0.25	142.51
75	9.342	0.59	336.01	255	9.036	0.59	336.07
90	22.204	1.17	668.31	270	26.011	1.17	668.2
105	11.395	0.59	336	285	10.264	0.59	336.06
120	5.894	0.25	142.52	300	5.614	0.25	142.55
135	4.033	0.14	79.75	315	3.895	0.14	79.76
150	3.244	0.1	55.36	330	3.193	0.1	55.37
165	2.909	0.08	45.23	345	2.826	0.08	45.24

When reviewing the table above, it is important to note that the color plots are only relative to the other data in each column. Red does not necessarily indicate that the criteria is failing, it is intended to show the weakest axis for each criterion. For this hull, Limit 1 is the most conservative, but in a departure from the other 3 hull forms evaluated in this analysis, the results for limit 2 are much closer to the trigger point. This would be more important if the limit 2 results were worse at different axes than the limit 1 results, but it is clear from the analysis via all 3 limits that the zero-degree axis is the critical axis for evaluation.

4.3.4.4 WTIV Step 4 Evaluation

In accordance with the procedure, the zero-degree critical axis identified in Step 3 is run through the stability criteria and their righting arms are to be examined.



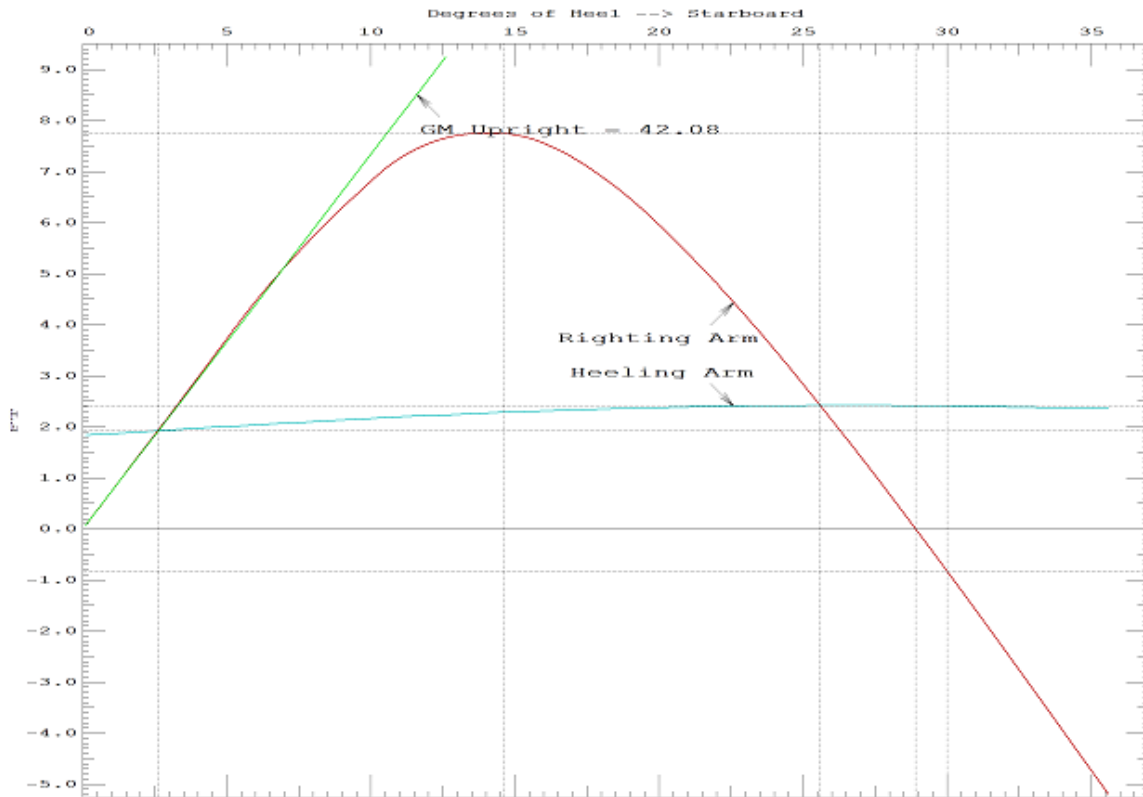


Figure 30. WTIV righting arm 0-degree axis.

LIM	46 CFR 174.045	Min/Max	Attained
(1)	Abs Ratio from abs 2.589 deg to RAzero or Fld	> 1.400	2.795 P
(2)	Abs Righting Arm at abs 0.1 deg to RAzero	> 0.03 Ft	0.07 P
(3)	GM Upright	> 0.17 Ft	42.08 P

The righting arms at the zero-degree axis result in passing the stability criteria and do not exhibit any trim/heel instability, fading stability, or oscillations. Thus, this righting arm is deemed acceptable and represents an accurate representation of the vessel behavior at the zero-degree axis. Since the zero-degree axis is the only critical axis identified in Steps 2 and 3, this vessel passes the stability criteria.

5 TIME DOMAIN SIMULATIONS OF A LIFTBOAT

To address the wave dynamics problem highlighted in Section 3.2, a time-domain simulation analysis was performed to provide a better understanding of the dynamics of non-traditional hull forms and to attempt to apply this knowledge to updating the stability criteria. A typical Liftboat was selected for this study, because this is a vessel type which is commonly used throughout the world, there have been a number of serious stability incidents involving this type of vessel, and this type of vessel exhibits many hydrostatic and hydrodynamic characteristics which are not handled well by conventional ship stability rules (see Section 3.1).

5.1 Simulation Model

5.1.1 Vessel Particulars

The simulation model for the time-domain simulations was based upon the Liftboat discussed in Section 4.1.1, at a draft of 8 ft (2.44m). The estimated weights and inertia characteristics were taken from typical data for a Liftboat of this size in transit, supplied by MiNO Marine. The load condition is presented in Table 28.

Table 28. Liftboat simulated load condition.

Parameter	Value
Draft	8 ft
Mass	2152.0 LT
LCG	69.0 ft
KG	40.0 ft
Roll Gradus	69.0 ft
Pitch Gyradius	75.0 ft
Yaw Gyradius	43.0 ft

5.1.2 Modeling Details

The time-domain simulations were carried out using OrcaFlex v11.2, a multi-body time-domain simulator commonly used in the offshore industry to model the complex nonlinear dynamics of offshore structures. The most common fundamental objects in OrcaFlex simulation models are vessels, lines and buoys, which are acted upon by external environmental forces and are coupled in a variety of ways. Vessels are typically defined by structural mass and inertia, hydrostatic stiffness, wave loading, added mass and wave damping, wind and current forces, and other user-defined loading. Vessel wave forces and added mass and wave radiation damping are typically defined by hydrodynamic terms in a manner consistent with linear radiation-diffraction models (i.e., frequency-dependent but linear with respect to wave and motion amplitude at each frequency). Similarly, hydrostatic stiffness terms are assumed to be constant, consistent with linear seakeeping models. Floating and submerged buoys share many of the same types of properties as vessels (e.g., mass and inertia, hydrostatic and hydrodynamic loads). Individual buoys have simpler definitions of hydrostatics and hydrodynamic properties than vessels. For example, buoyancy forces are based on percent submergence and added mass are based on Morison equation coefficients rather than the full volumetric computations inherent in a 3D boundary-element computation. They do, however, offer the advantage of computing forces based on instantaneous submergence of the body, rather than assuming infinitesimal perturbations about the mean waterline, as is the case for vessels.

Provided that the submerged body and waterplane do not fundamentally alter their shape as a vessel responds to wave forcing, the linearized hydrostatics and seakeeping behavior defined above provides adequate fidelity for the vessel motions. In the case of the Liftboat, however, the freeboard and draft are low enough that the waterplane area is fundamentally changed at relatively low roll and pitch angles, due to the deck submergence and keel emergence (see Section 3.1). As noted above, OrcaFlex buoy models represent the varying hydrostatics according to their instantaneous submergence, so, to model the hydrostatic effects of deck submergence and keel emergence the Liftboat hull volume was represented by an array of vertical



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buoys. During the simulations the buoyancy of each buoy was computed from its instantaneous submergence, relative to the mean water line, thus providing the correct time-varying hydrostatic stiffness.

The wave forces and added mass and radiation damping for the hull were computed in OrcaFlex's associated radiation-diffraction code, OrcaWave. The entire hull, including spud pads and skeg, were modeled in these computations, in order to capture their influence on the hydrodynamic terms. In principle, the hydrodynamic forces on the hull could have been treated similarly to the hydrostatic terms, by assigning wave forcing, added mass and damping coefficients to each buoy, thus capturing the time-accurate effects of buoy emergence and submergence. However, assigning hydrodynamic properties to the buoys requires detailed knowledge of the frequency- and spatially-dependent hydrodynamic characteristics of each point on the hull. Since the hull hydrodynamic forcing is dominated by the periods of time in which the hull is at low roll and pitch angles, floating near its mean waterline, use of the 3D boundary-element computed hydrodynamic terms, computed in the still-water floating condition, provides a better estimate of the hydrodynamic forcing mechanisms than a set of Morison Equation coefficients estimated for the full array of individual buoys. The trade-off of this approach is that the hydrodynamic forcing is poorly modeled for periods of time when the hull is at large roll, pitch, or heave displacements relative to the free surface. In those conditions, the system dynamics are increasingly dominated by hydrostatic and inertia forces, however, so it was decided that errors in wave forcing at large roll and pitch angles are of less concern than their accurate representation when the hull is near its mean position.

The mesh for the OrcaWave computations is shown in Figure 31. The coordinate system used in the Orcaflex modeling was right-handed with +Z pointing upwards. The origin was set at the waterline amidships with +X pointing forwards towards the skeg. The relative wind/wave direction followed a counterclockwise rotation (i.e., 90 deg is beam winds/seas from the starboard side).

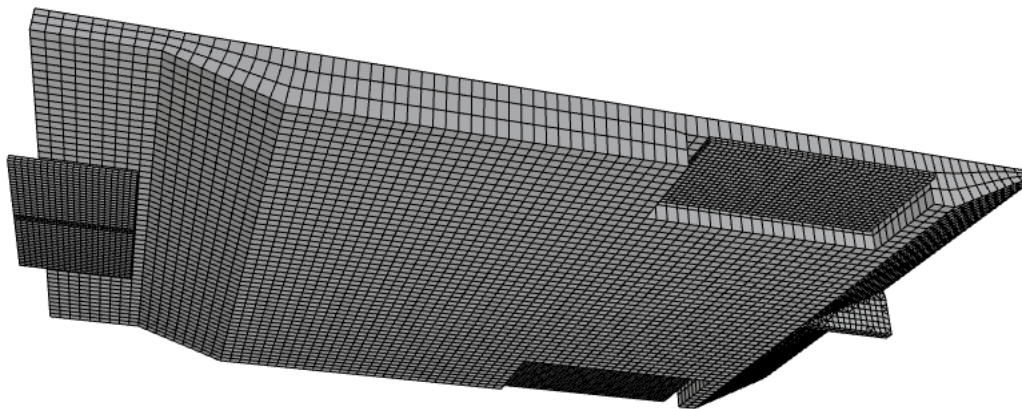


Figure 31. Mesh for OrcaWave computations.

The OrcaWave hull model, including the hull outline and the buoys used to represent the hull volume, is shown in Figure 32, shows the three mooring lines used to maintain the vessel's position during the simulations (one longitudinal and two transverse). These mooring lines were modeled as long, massless springs, with low stiffness. The stiffness was the minimum required to maintain the nominal yaw angle within approximately 5 deg. The mooring system was designed to maintain vessel position and heading in the horizontal plane, while influencing the buoyancy-dependent responses (heave, roll, pitch) as little as possible.



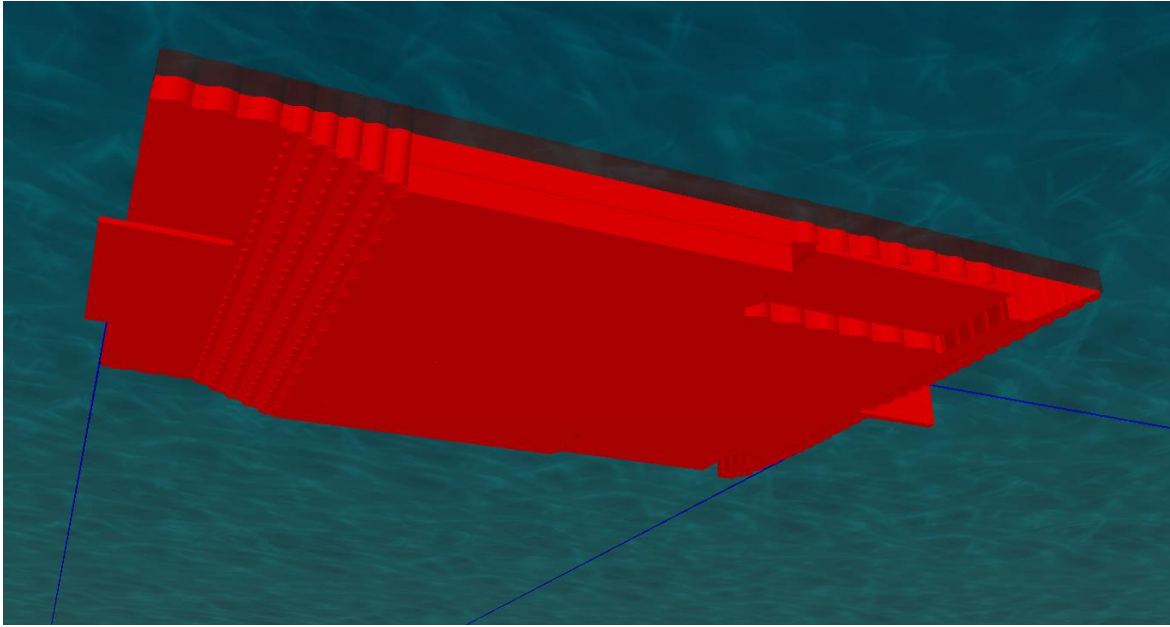


Figure 32. OrcaFlex simulation model.

Wind forces were modeled by wind moments, computed according to the methods of Section 3.3.5, applied to the vessel. Here, the moments were then normalized into coefficients, in the form:

$$C_m = \frac{Moment}{AZ_{ref} \cdot V_{wind}^2}, \text{ where}$$

AZ_{ref} is a reference area times center of pressure height and
 V_{wind} is the wind speed at 10m height

Separate coefficients were used for roll and pitch moments, and the coefficients varied with wind heading. Applying the wind heeling moments as pure moments, rather than horizontal forces at the center of pressure, minimized the transverse forces on the mooring lines, allowing minimum line stiffness.

5.2 Hydrostatic Validation

In order to establish the required resolution of the buoy representation of the hull hydrostatics the righting moments of the hull about the roll and pitch axes were computed from the 3D surface model of the hull, using the 3D modeling software Rhino's Orca3D plugin. The corresponding righting moment curves for the OrcaFlex model were computed from the static moments required to fix the buoy representation of the hull at the same roll and pitch angles as computed in Orca3D. The hydrostatic righting moments of the two models, in roll, are compared in Figure 33.

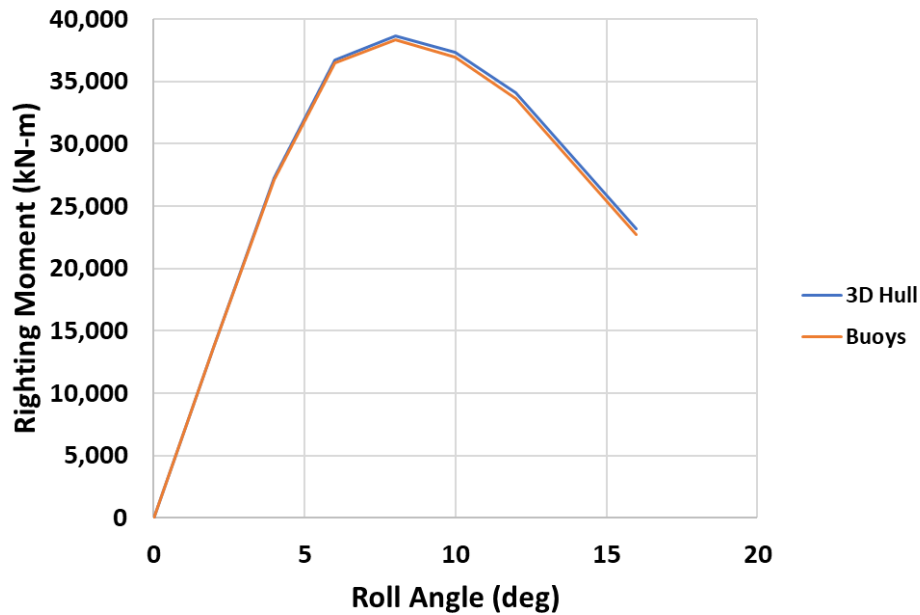


Figure 33. Liftboat roll righting moment for hull and buoy representation.

The righting moments in the solid model and buoy representation agreed to within 2% at angles from 0 to 16 deg. Similar agreement was found in the heave displacement, at varying roll and pitch angles, and pitch moment at varying pitch angle.

5.3 Roll and Pitch Damping

Liftboats in transit often have natural roll and pitch periods close to the modal periods of the sea states in which they operate. Accurate representations of the roll and pitch damping in simulations are, therefore, critical to the applicability of both linear seakeeping and time-domain simulation methods for evaluating safety. Linear seakeeping codes, such as OrcaWave, compute only the non-viscous, wave radiation part of the motion damping. Viscous damping can be represented in the OrcaFlex model by viscous Morison equation drag elements, but this method requires knowledge of the appropriate drag coefficients and center of effort locations for the viscous elements. In this study, a brief review of available literature on the roll damping of barge-like hull forms was undertaken. The estimation methodologies provided a range of viscous damping values, from which a representative value of 7.5% critical was derived. This value was used for both roll and pitch, using the appropriate stiffness and inertia values to define critical damping about each axis.

Heave is heavily damped by wave radiation, so the base simulation model included no additional damping to account for viscous effects in heave (although sensitivity to this parameter was studied, as discussed in Section 5.5

5.4 Initial Regular Wave Simulations

As discussed in Section 3.2.1 stability in severe weather conditions has been represented by several criteria in the stability rules. The simplest representation is to consider the static equilibrium between righting moment and wind heeling moment (e.g., 46 CFR §170.170). More sophisticated treatments recognize that



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capsize and large-angle rolling are energy-based phenomena, involving equilibria between righting and heeling potential energy (e.g., 46 CFR § 174.045). The weather criterion in the IMO 2008 Intact Stability Code [14] includes the effects of the potential energy stored in roll to windward prior to roll to leeward under the action of wind forcing.

This energy exchange is illustrated in Figure 34, where the potential energy in the rollback is the area A2 and the potential energy developed during the roll to leeward is the area A1. The additional kinetic energy accumulated through wind and wave forcing during the rolling event are accounted for in the factor by which area A1 must exceed A2 to satisfy the criterion.

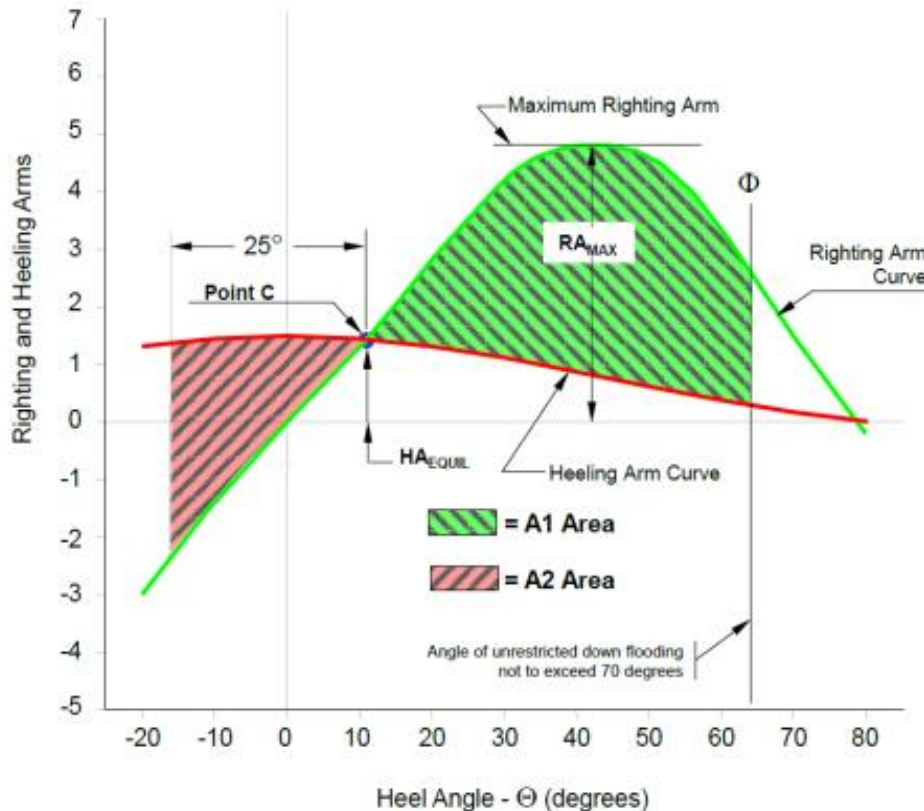


Figure 34. Potential rolling energy in IMO weather criterion.

At the initiation of this simulation study, the IMO Weather Criterion appeared to offer the best promise of a weather criterion that captured the dynamics of rolling under the action of wind and wave forcing, while being computable using static Level 1 resources (see Section 3.2). As noted in Section 3.2.1, the standard roll angles to windward (roll-back angles) required in [14] are beyond the stability range of typical Liftboats. MSC Circular 1200 [19] provides an alternative route to establishing physically realistic roll-back angles, through model testing.

An initial set of simulations in regular waves was carried out to assess the fundamental seakeeping behavior of the Liftboat and to evaluate whether regular wave simulations could be used to establish a characteristic roll-back angle for evaluating stability according to [14]. The intent was to follow the guidance and methodology of regular wave model tests in [19]. Consistent with the guidance of [19], the regular wave



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simulations concentrated on waves with frequencies ranging from 0.8 to 1.2 times the natural roll frequency of the vessel, 0.58 rad/s. (10.9 sec period).

It quickly became evident that, consistent with the findings in Section 3.2.1, stability on a typical Liftboat is too low to use regular wave simulations in this manner. In beam seas the vessel capsized in wave heights between 2.0m, and 2.5m, depending on wave period, whereas the regular wave heights required in [19], for the 10.9 second natural roll period of the Liftboat, exceeds 12m.

5.5 Irregular Sea Simulations

Given that the regular wave simulations demonstrated that the MSC Circular 1200 approach could not be used to establish roll-back angles sufficient to satisfy the requirements of [14], it was decided that a more feasible approach was to consider dynamic responses in the actual sea states encountered by Liftboats during transit, taking into account their restricted service classification notations.

Following the advice of MiNO, a matrix of simulations in irregular seas was carried out, in wave heights ranging from 2 ft to 8 ft (0.61m to 2.44m), with modal periods of 6, 9 and 12 seconds. Simulations were computed in wave headings of 0, 45, 90, 135 and 180 deg (following, stern quartering, beam, bow quartering and head seas, respectively).

All sea states were modeled as Bretschneider spectra. The wind was modeled as a constant wind speed of 70 knots. Sensitivity checks were also run with variations in wave spectral peak factor (g), wind gustiness and heave damping, to check sensitivity to these parameters. The maximum vessel roll and pitch responses were found to be somewhat sensitive to these factors, particularly wind gustiness, but they did not affect the boundaries between capsize and non-capsize sea states.

The irregular sea simulation matrix was not intended as a comprehensive statistical analysis of lifetime extreme events, but instead a targeted mapping of the boundary between capsize and non-capsize time histories to find characteristic leading indicators of capsize. It is recognized that the final quantitative formulation of the non-traditional hull form stability rule will require a more complete statistical sample of vessel characteristics and environmental conditions, to ensure that the safe boundaries of the parameter spaces are adequately resolved.

To simplify and generalize the salient physics leading to capsize, several modeling simplifications were incorporated in the simulation models:

- Wind and waves were collinear, for conservatism and to reduce the complexity of the environment parameter space.
- Waves were long-crested, for conservatism and to reduce the complexity of the environment parameter space.
- Wind speed was assumed to be constant, i.e., representative of wind speed averaged over a gust of similar time scale to vessel roll response period.
- Studies focused on loss of stability in intact hulls, rather than downflooding, to generalize the conclusions. It is presumed that ultimately the rule will be formulated with reference to the lesser of the minimum downflooding angle and the maximum allowable intact stability angle, like other criteria currently in use.
- Buoyancy in deck structures and water on deck were not modeled.



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The irregular sea simulations were analyzed to find characteristic wave and/or vessel dynamics to use as leading indicators of capsize events. The analyzed metrics included:

- Roll-back angle prior to capsize
- Statistics of deck submergence prior to capsize
- Statistics of roll angle prior to capsize
- Characteristics of wave groups preceding capsize

5.5.1 Roll-back Angle

As noted above, the computation of roll-back angles by the accepted methodology of MSC Circular 1200 leads to higher waves than expected during Liftboat transit. Nevertheless, the physical plausibility of the potential-kinetic energy transfer during the transition from roll-back to capsize (see Figure 34) made rollback angle an attractive candidate as an indicative metric for capsize susceptibility.

Irregular sea simulations in 45, 90 and 135 deg wave headings were analyzed to find the maximum roll angles to windward and to leeward. These results are summarized in Table 29.

Table 29. Maximum roll angles and roll-back angles in irregular sea simulations.

Max Δ Roll to Windward @ 45 Degree Heading				Max Δ Roll to Windward @ 90 Degree Heading				Max Δ Roll to Windward @ 135 Degree Heading			
Wave Ht (ft)/ Tp (s)	6	9	12	Wave Ht (ft)/ Tp (s)	6	9	12	Wave Ht (ft)/ Tp (s)	6	9	12
2	0.2	0.9	1.4	2	0.4	1.4	2.1	2	0.2	0.9	1.6
4	0.3	1.7	2.8	4	0.8	2.6	4.2	4	0.3	1.8	3.2
6	0.5	2.1	4.4	6	0.9	3.1	5.6	6	0.5	2.2	6.2
8	0.8	1.7	3.2	8	1.9	2.4	2.3	8	0.8	7.8	3.2
Max Roll to Leeward @ 45 Degree Heading				Max Roll to Leeward @ 90 Degree Heading				Max Roll to Leeward @ 135 Degree Heading			
Wave Ht (ft)/ Tp (s)	6	9	12	Wave Ht (ft)/ Tp (s)	6	9	12	Wave Ht (ft)/ Tp (s)	6	9	12
2	-1.7	-2.4	-2.9	2	-2.6	-3.5	-4.3	2	-1.8	-2.5	-3.1
4	-2.0	-3.5	-4.6	4	-3.1	-4.9	-6.9	4	-2.0	-3.6	-5.1
6	-2.3	-4.4	-	6	-3.9	-6.4	-	6	-2.4	-4.5	-
8	-2.7	-	-	8	-6.2	-	-	8	-2.8	-14.3	-

Simulations highlighted in yellow in Table 29 are capsize events (180 deg of roll). Simulations highlighted in beige are events in which capsize did not occur during the simulation, but the vessel motions were extreme enough to be considered stability failures in an operational sense. The maximum roll angle to windward in Table 29 is presented as *Max Δ Roll*, the difference between the maximum roll to windward and the mean roll angle. The maximum roll to leeward is presented as *Max Roll*, the maximum roll to leeward, relative to zero roll angle. *Max Δ Roll* to windward is thus equivalent to the roll-back angle, during which rolling potential energy is built up. *Max Roll* to leeward is equivalent to the maximum absolute roll angle in conventional hydrostatics terminology. For simulations in which no capsize occurred, Table 29 lists the maximum roll angle to windward and to leeward in the simulation. For simulations in which capsize occurred, *Max Δ Roll* in Table 29 is the roll-back angle to windward immediately prior to capsize and *Max Roll* to leeward is not relevant. The definitions of *Max Δ Roll* and *Max Roll*, in capsize and non-capsize events, are illustrated in Figure 35.



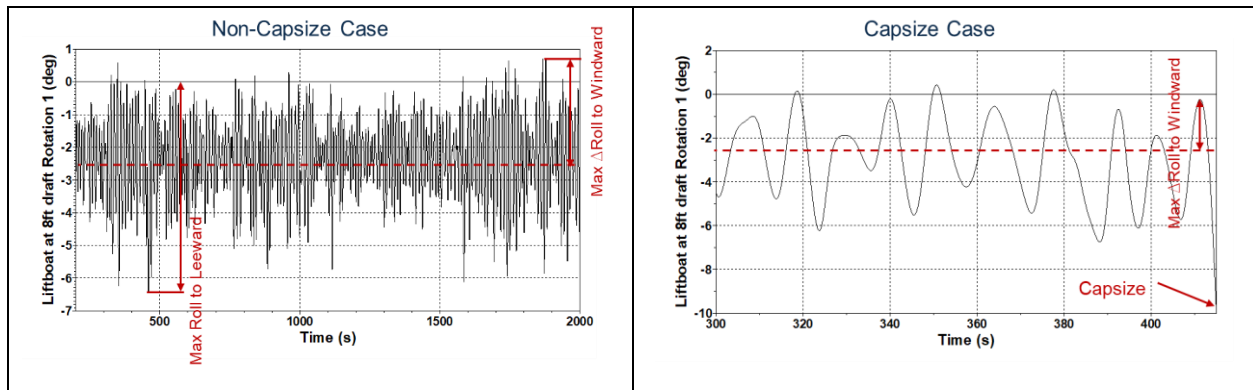


Figure 35. Definitions of *MaxDRoll* and *Max Roll*.

If roll-back angle were the governing metric for capsizing susceptibility, there should be a clear boundary between the maximum roll angle to windward in the non-capsizing cases and the roll-back angle in the capsizing events. While there is a clear trend in Table 29 towards increasing roll-back angles in capsizing conditions, the boundary between safe and unsafe conditions is not distinct or unambiguous. Roll-back angle, by itself, is therefore not considered a robust metric for impending capsizing.

This recognition indicates that the final formulation for the wind/wave criterion in the non-traditional hull form stability rule will likely require the use of a combination of static Level 1 and dynamic Level 2 resources (see Section 3.2).

On the topic of rarity, these results show frequent large amplitude motion ending in capsizing events. Based upon this repeated observed behavior demonstrated in Table 29, the Liftboat's extreme response in these small to moderate sea states is deemed not to be rare. Rather, a likely outcome given the conditions.

5.5.2 Deck Submergence Prior to Capsizing

Simulations of capsizes typically show that capsizing is preceded by a sequence of severe deck submergence events, leading to a loss of stability. The statistics of deck vertical motion and submergence were, therefore, considered promising metrics as leading indicators of capsizing. To study the validity of these metrics, irregular sea simulations in beam seas (90 deg wave heading) were analyzed to derive the statistics of vertical motions at points on the deck. The metrics studied comprised:

- Average Z value of 3 points along the leeward deck edge, relative to the still waterline
- Average Z value of 3 points along the leeward deck edge, plus 3 points along the deck centerline, relative to the still waterline
- Average Z value of 3 points along the leeward deck edge, relative to the local wave elevation
- Average Z value of 3 points along the leeward deck edge, plus 3 points along the deck centerline, relative to the local wave elevation

Figure 36 shows a snapshot from a simulation and illustrates the positions of the six analyzed deck submergence points.

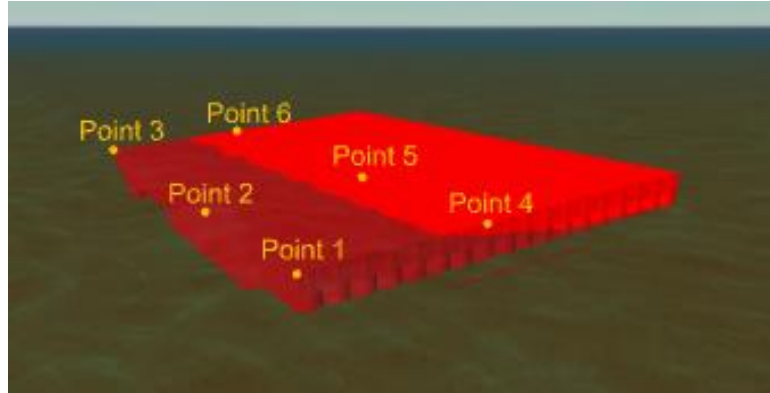


Figure 36. OrcaFlex simulation model with deck submergence points.

For each simulation, the time histories of the vertical positions of the 6 deck submergence points, relative to the still water line and to their local wave elevations, were derived from the simulation data. The average values of the 3 or 6 deck points, as appropriate, were computed at each instant of time, and the statistics of these averages computed over the simulation time history. For simulations without capsize the statistics were computed over the entire time history, and for simulations with capsize the statistics were computed for the time period up to 20 seconds prior to capsize. The 20 second time gap was imposed to eliminate the wave group prior to capsize, thus analyzing the portion of the simulation more characteristic of the statistically stationary behavior of the vessel. The results of the deck submergence study, in significant wave heights of 4, 6 and 8 ft, are summarized in Table 30. Table 30 presents the root-mean square (RMS) values of the deck submergence, averaged over 3 or 6 points, as described above.

Table 30. RMS value of deck submergence in beam seas, $H_s = 4$ ft, 6 ft, 8 ft.

Hs (ft)	Tp = 6				Tp = 9				Tp = 12			
	Absolute Z (ft)		Relative Z (ft)		Absolute Z (ft)		Relative Z (ft)		Absolute Z (ft)		Relative Z (ft)	
	Avg(3)	Avg(6)	Avg(3)	Avg(6)	Avg(3)	Avg(6)	Avg(3)	Avg(6)	Avg(3)	Avg(6)	Avg(3)	Avg(6)
4									0.79	0.79	1.08	0.49
6	0.79	0.85	1.67	0.69	1.18	1.18	1.61	0.69	1.25	1.28	1.57	0.72
8	1.05	1.12	2.20	0.89	1.71	1.71	2.10	0.89	1.61	1.71	1.90	0.89

The capsize events are highlighted in yellow. In Table 30, *Absolute Z* refers to vertical position, relative to the still waterline, and *Relative Z* refers to vertical position relative to the local wave elevation. *Avg(3)* and *Avg(6)* refer to averages taken over the 3 deck edge points or the entire group of 6 deck points.

As shown in Table 30, the deck edge submergence does not define a clear boundary between capsize and non-capsizing events, with considerable overlap between submergence statistics in capsize and non-capsizing conditions. It is not, therefore, a sufficiently robust leading indicator of capsize.

5.5.3 Roll Angle Prior to Capsizing

During the analysis of the wave group regular wave simulations reported in Section 5.6, it became evident that despite the nonlinearities discussed in Section 5.1, linear frequency-domain computations provide reliable estimates of the RMS roll motions in regular wave time-domain simulations. It follows that RMS roll motions in irregular seas should be well-estimated from RMS values computed using frequency-domain roll motion RAOs. In this case, extreme roll angles should be reliably predicted from Rayleigh probability distributions based on roll RMS values calculated by:

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$$Roll_{max} = Roll_{mean} + \sqrt{2 \ln(n)} Roll_{RMS}$$

where n is the number of waves in the time history, given by $n = \frac{T_D}{T_z}$, where T_D is the simulation duration time and T_z is the roll zero-crossing period. $Roll_{RMS}$ and T_z are computed from the statistical properties of the computed roll responses using standard frequency-domain analysis techniques. For this analysis T_D is assumed to be 1800 sec, consistent with the time-domain simulations. The extreme roll angles, computed for the same simulations as reported in Table 30, are presented in Table 31. The extreme angles include the mean roll angles due to wind loading.

Table 31. RMS and extreme value of roll angle in beam seas, $H_s = 4$ ft, 6 ft, 8 ft.

Hs (ft)	Tp = 6 Roll		Tp = 9 Roll		Tp = 12 Roll	
	RMS	Extreme	RMS	Extreme	RMS	Extreme
4					1.08	5.69
6	0.31	3.27	1.19	6.10	1.62	7.42
8	0.41	3.61	1.59	7.38	2.15	9.14

The extreme roll angles are shown overlaid on the Liftboat calm water righting moment curve in Figure 37. Here, the righting moment curve of Figure 33 is interpolated to the frequency-domain maximum roll angles of Table 31 with the interpolated righting moments overlaid on the righting moment curve.

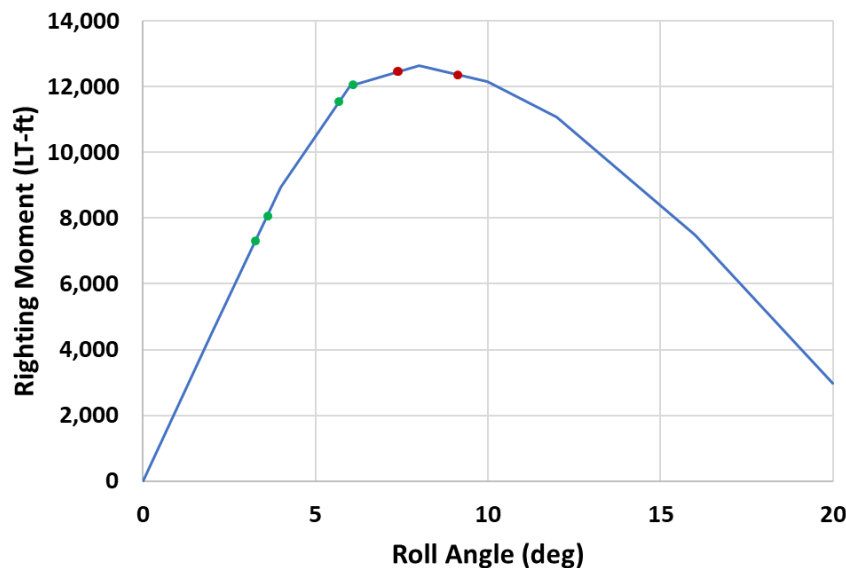


Figure 37. Righting moment at extreme roll angles computed from frequency-domain results.

The highlighted points in red are conditions in which the time domain simulations computed capsizes, and those in green are from non-capsize conditions. In the capsize conditions, the maximum roll angle is near the peak of the righting moment curve. This is considered a physically plausible result, providing a useful metric for stability safety. It is noted that the boundaries between capsize and non-capsize conditions are applicable to this vessel in beam seas only. It is also noted that using the computed extreme roll angles involves several assumptions, including the adequacy of linear seakeeping analysis to provide valid roll RAOs and the adherence of the response statistics to Rayleigh probability distribution.



For these reasons, extreme angles computed with frequency-domain methods are not currently considered as robust or well-linked to the physics of capsize events as the metrics discussed in Section 5.6, but they are far simpler to compute. They should, therefore, continue to be considered as a possible leading indicator for capsize with appropriate safety factors.

5.6 Wave Group Regular Wave Simulations

The highest waves in a seaway typically form groups with properties like regular wave trains with periods near the sea state mean wave period and heights dependent on the joint probabilities of wave period and wave envelope amplitude [27]. Time-domain simulations indicated that the characteristics of the wave group immediately preceding capsize are critical to the onset of the capsize event. Wave groups with deep troughs and periods near the vessel roll period force oscillatory behavior leading to high roll angles and capsize.

To study the characteristics of wave groups the irregular sea simulations were analyzed to extract:

- Average zero-crossing periods in wave groups
- Average trough depth in wave groups
- Maximum trough depth (i.e., maximum trough wave elevation) in wave groups

From the wave group time histories, the following statistics were derived:

- Minimum average trough depth in wave time history
- Average trough depth in wave group with average zero-crossing period closest to the Liftboat roll period
- Average zero-crossing period in wave group with minimum average trough depth

The above three metrics were derived to assess the sensitivity of capsize to the depth of the troughs in the wave group and the average period of waves in the groups. Based upon the observed vessel responses in the simulations wave groups were defined by group of three waves, defined by down-crossings of the wave elevation through the mean waterline. Group average zero-crossing period and trough depth were computed at each wave trough, utilizing a moving average over the previous two troughs and the trough itself.

Figure 38 shows a typical wave time history, in this case for an 8 ft significant wave height sea state with 9 second modal period. Capsize occurred at 465 seconds. The wave troughs and group average trough depth at each trough are highlighted.

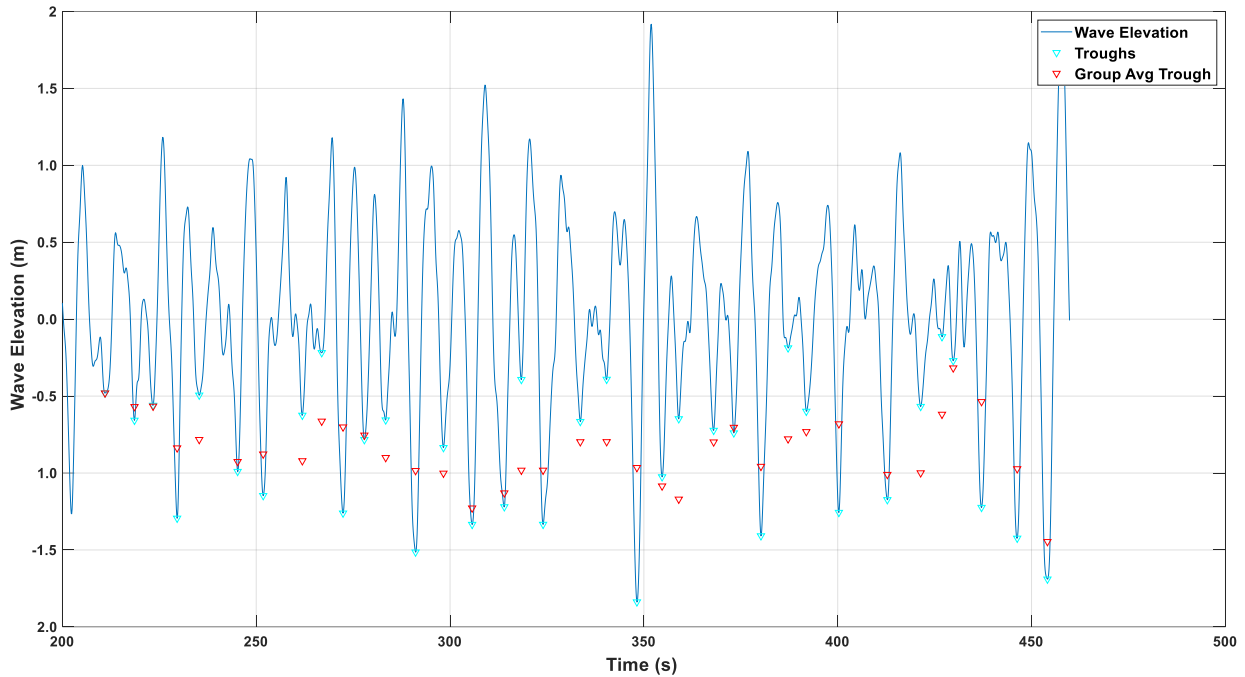


Figure 38. Wave elevation and trough time history in $H_s = 8\text{ft}$, $T_p = 9\text{s}$.

Figure 39 shows the computed average wave period and average trough depth in the wave groups of the time history in Figure 38.

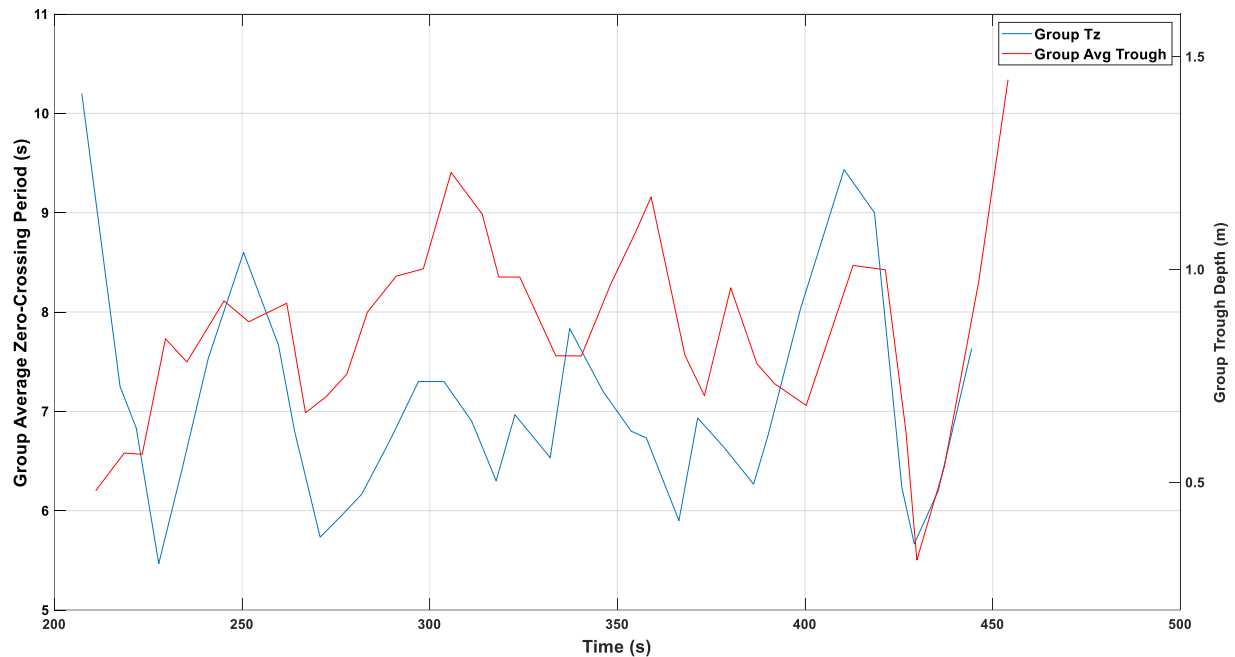


Figure 39. Average wave group period and trough depth, in $H_s = 2.44\text{m}$ $T_p = 9\text{s}$.

The wave group statistics in beam seas (wave heading 90 deg) are summarized in Table 32.



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Table 32. Wave group statistics in irregular beam seas.

Hs (ft)	Mean Period (s)	Min Trough Group Depth (ft)	Tz (s)	Min T-Roll Group Depth (ft)	Tz (s)	Group Prior to Capsize Depth (ft)	Tz (s)
Tp = 6.0s							
4	4.81						
6	4.81	-4.23	5.37	-1.93	7.70		
8	4.81	-5.64	5.37	-2.57	7.70		
Tp = 9.0s							
4	7.03						
6	7.03	-3.94	8.00	-1.83	10.97		
8	7.03	-4.74	7.63	-1.58	10.20	-4.74	7.63
Tp = 12.0s							
4	9.31	-2.69	11.30	-1.53	10.93		
6	9.31	-4.04	11.77	-1.98	10.90	-4.04	11.77
8	9.31	-5.09	9.33	-3.62	10.97	-5.09	9.33

Capsize conditions are highlighted in yellow. For non-capsize conditions Table 32 lists the average trough depths and the periods of the wave group with the minimum average trough depth and the wave group with period closest to the roll natural period. For capsize conditions Table 32 lists the above two metrics, and additionally lists the average trough depth and period of the wave group immediately preceding capsize. As can be seen in Table 32, in capsize conditions the wave group preceding capsize is, in all cases, the wave group with minimum average trough depth. The wave group with period closest to the vessel roll period is a less reliable leading indicator of capsize.

For wave groups to provide a useful leading indicator of capsize, wave group characteristics must be causally related to vessel responses. The most easily computed correlation is vessel response in regular waves with height and period defined by the wave group characteristics. A sequence of regular wave trains was defined by the 14 unique wave height-period pairs in Table 32, and the Liftboat responses were simulated in these regular waves, in beam seas. The wave heights in the regular waves were defined as twice the trough depths listed in Table 32. The regular wave responses are presented in Table 33.



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Table 33. Regular wave responses in regular waves characterized by wave groups.

H (ft)	T (s)	Frequency Domain				Time Domain			
		Roll RAO (deg/ft)	Roll Amp (deg)	Roll Mean (deg)	Max Roll (deg)	Roll RAO (deg/ft)	Roll Amp (deg)	Roll Mean (deg)	Max Roll (deg)
8.08	11.77	1.58	6.37	2.25	8.62	Capsize			
5.38	11.30	1.75	4.70	2.25	6.95	1.68	4.53	2.87	7.41
3.67	10.97	1.76	3.23	2.25	5.48	1.79	3.28	2.49	5.77
7.23	10.97	1.76	6.38	2.25	8.63	Capsize			
3.06	10.93	1.77	2.70	2.25	4.95	1.80	3.05	2.39	5.45
3.96	10.90	1.76	3.48	2.25	5.73	1.71	3.39	2.50	5.89
3.15	10.20	1.41	2.22	2.25	4.47	1.35	2.12	2.34	4.47
10.17	9.33	0.95	4.84	2.25	7.09	Capsize			
7.88	8.00	0.53	2.09	2.25	4.34	0.52	2.07	3.99	6.06
3.86	7.70	0.47	0.90	2.25	3.15	0.45	0.86	2.26	3.12
5.15	7.70	0.47	1.20	2.25	3.45	0.43	1.10	2.38	3.48
9.49	7.63	0.45	2.15	2.25	4.40	0.50	2.38	5.08	7.46
8.46	5.37	0.13	0.56	2.25	2.81	0.13	0.55	2.30	2.85
11.27	5.37	0.13	0.75	2.25	3.00	0.14	0.76	2.30	3.07

Table 33 lists the regular waves defined by the wave height-period pairs in Table 32, the roll responses computed from the frequency-domain OrcaWave computations (see Section 5.1), and the roll responses in the regular wave time-domain simulations. For the frequency-domain computations the maximum roll angle was computed by

$$Roll_{max} = Roll_{mean} + Roll_{RAO} \cdot \frac{Wave_{Height}}{2}$$

For the time-domain computations the maximum roll angle was computed equivalently:

$$Roll_{max} = Roll_{mean} + \frac{Roll_{RMS}}{Wave_{RMS}} \cdot \frac{Wave_{Height}}{2}$$

Excessive roll angles computed in the frequency domain, considered to be stability failures, are highlighted in red.

With some exceptions, the roll RAOs and maximum roll angles computed in the frequency and time domains agree reasonably well, giving confidence that frequency-domain methods can be used to predict stability failure conditions.

Figure 40 shows the maximum roll angles from Table 33 overlaid on the Liftboat righting moment plot in Figure 33. In this plot, the righting moment curve of Figure 33 is interpolated to the frequency-domain maximum roll angles of Table 33 with the interpolated righting moments overlaid on the full righting moment curve. Green, orange, and red highlighting is used to distinguish wave conditions that might be considered safe, marginal, and unsafe, respectively.



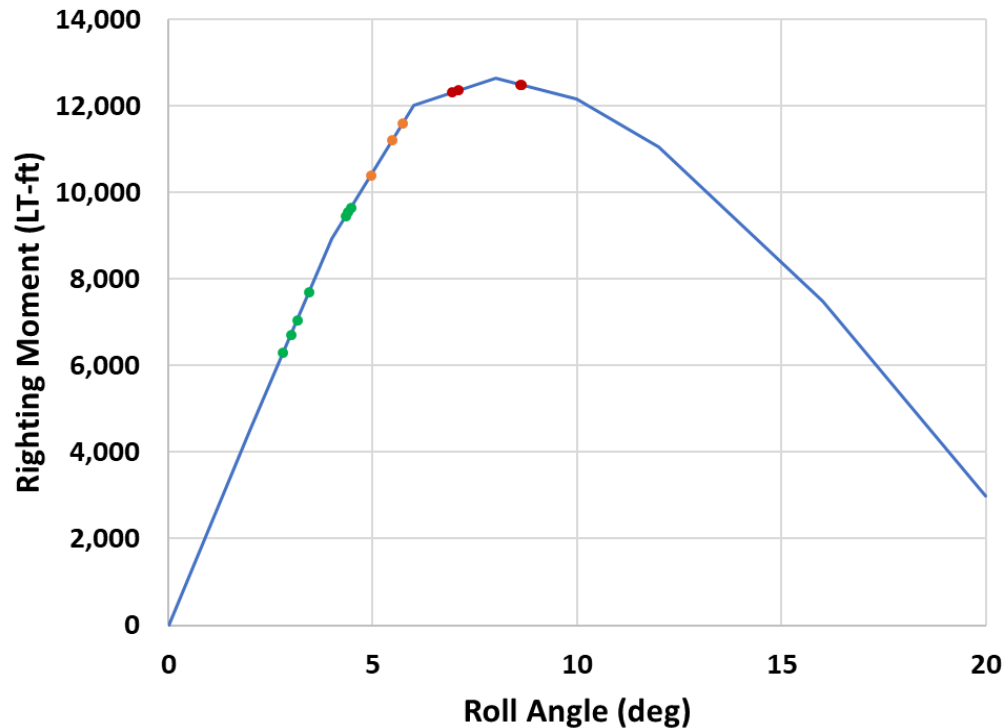


Figure 40. Righting moment at maximum computed roll angle.

Consistent with the findings of Section 5.5.3, in the unsafe conditions, the maximum roll angle is near the peak of the righting moment curve. This is considered a physically plausible result, providing a useful metric for stability safety. It is noted that the specific boundaries between safe and unsafe roll angles are applicable to this vessel in beam seas only. Further study would be required to establish appropriate boundaries and safety margins for the entire range of non-traditional hull forms and wave headings.

5.7 Potential Path for Using Extreme Roll Angle and Wave Groups for Stability Analysis

The procedures outlined in Sections 5.5.3 and 5.6 provide a framework for possible approaches to evaluating non-traditional hulled vessels, using a combination of widely-available static and dynamic naval architecture tools.

Both processes follow the same first five steps:

1. Develop mesh of hull for 3D radiation-diffraction seakeeping computations, following industry-standard procedures.
2. Run radiation-diffraction code for headings from 0 to 180 deg wave heading (or 0 to 360 if vessel is port-starboard asymmetric), taking care to incorporate appropriate viscous damping terms for heave, roll and pitch.
3. Compute righting moment about the weakest righting moment axis.
4. Compute dynamic rotation RAOs about weakest righting moment axis from radiation-diffraction results.
5. Compute steady heel angle from wind overturning moment.



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The extreme roll angle methodology then follows the following three steps:

1. Compute spectral moments of roll:

$$m_0 = \int S(\omega) \cdot Roll_{RAO}(\omega)^2 d\omega$$
$$m_2 = \int S(\omega) \cdot Roll_{RAO}(\omega)^2 \cdot \omega^2 d\omega$$

where *Roll* is rotation about the weakest righting moment axis

2. Compute $Roll_{RMS}$, T_z , $Roll_{max}$ from spectral moments:

$$Roll_{RMS} = \sqrt{m_0}$$

$$T_z = 2\pi \sqrt{\frac{m_0}{m_2}}$$

$$Roll_{max} = Roll_{mean} + \sqrt{2 \ln \left(\frac{T_D}{T_z} \right)} Roll_{RMS}$$

3. Compare maximum roll angle to righting moment curve. Maximum roll angle must be less than roll angle at maximum righting moment minus appropriate angle margin.

The wave group roll angle methodology follows the alternative steps:

1. Compute characteristic wave groups in sea states of interest:
 - a. Periods = sea state mean wave period, plus or minus appropriate margin
 - b. Wave heights = heights derived from joint probabilities of wave envelope amplitude and group periods, assuming appropriate standard sea state definition (e.g., Bretschneider or JONSWAP) spectral plus height margin
2. For each characteristic wave group, compute maximum roll angle by

$$Roll_{max} = Roll_{mean} + Roll_{RAO} \cdot \frac{Wave_{Height}}{2}$$

where *Roll* is rotation about the weakest righting moment axis

3. Compare maximum roll angle to righting moment curve. Maximum roll angle must be less than roll angle at maximum righting moment minus appropriate angle margin.

6 RECOMMENDATIONS

Through the investigation and analysis contained in this report, the currently available body of knowledge is not sufficient to fully address the unique stability issues associated with these non-traditional vessels. These gaps were identified both in the literature review and in the further studies conducted to test various



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methodologies. This conclusion indicates that there is more research to be done before a new stability criterion can be developed with sufficient confidence. Specific areas of further study are recommended below:

6.1 Wind Force Estimation

Building upon the SNAME OC-8 effort and results, more fundamental offshore research with wind tunnel testing or CFD simulations should be performed to establish best practices for shape coefficients, clustering, and shielding estimation. For example, how close must deckhouse components be to consider them acting as one component? The study should focus on a systematic study of windage elements unique to NTH vessels such as the tall and slender legs, leg racks, large cranes, clustered deck shapes, and elevated helipads. Parametric sweeps of different element sizes and arrangements from generic vessel configurations should be part of the test program. An agreed upon assumed atmospheric boundary layer should be modeled.

Confidence in the wind force estimation will be gained both at the element level and the overall combined effect on the vessel. This will address the issue of lift and the overall assumption of conservatism identified in this report. This new dataset will help to benchmark the sensitive and critical inputs used in the wind force and overturning moment estimates in stability software. A best practice memo or report should be issued to industry such that designers and software providers can incorporate the dataset into their design and analysis efforts. This would be a substantial compliment tailored to the offshore needs much in the same manner as traditional reference texts from civil and aerospace engineering.

6.2 Wave Dynamics

The time domain simulations described in Section 5 studied several potential metrics for predicting susceptibility to dynamic stability failures, using simplified industry-standard methods. Two metrics appeared to hold promise: Roll statistics prior to capsize and roll behavior in regular waves characteristic of the most severe wave group in a sea state. It is proposed that evaluation of these metrics can be accomplished using hydrostatic and linear seakeeping methodologies. Modeling the full complexity of stability failure phenomena exceeds the capabilities of such tools. However, simulations with a typical Liftboat in beam seas showed that they can potentially be used to estimate safe stability ranges, provided that the boundaries between safe and unsafe dynamic roll angles can be established.

The scope of this investigation was limited to one example Liftboat hull, in typical Liftboat transit sea conditions, focusing on beam seas. The final quantitative formulation of the non-traditional hull form stability rule will require a more complete statistical sample of vessel characteristics and environmental conditions, to ensure that the safe boundaries of the vessel and environmental parameter spaces are adequately resolved. Research should also address the correlation of wave overturning energy with design wave characteristics, to be used for operational guidance.

It is recommended that simulations and analyses similar to those reported in Section 5 be carried out on all of the representative NTH vessels discussed in Section 3.1, at a sufficient number of wave headings to adequately define heading sensitivity of the capsize/no capsize boundary. For each hull form, a minimum of two representative designs should be analyzed to derive sensitivity to the most critical design parameter variations. In addition, modeling of the structural properties of the legs should be performed to capture the static and dynamic effects of leg deflection on the vessel. This type of structural response is presently being performed for offshore wind turbine towers on floating platforms.



The simulation studies should also be supported by a systematic series of model tests, of representative vessels in selected critical conditions, to provide hydrodynamic nonlinear response data for improved simulation models and to validate the simulations for acceptance by regulatory bodies and industry. Once accomplished, this large numerical and empirical dataset should be utilized to perform verification and validation on the proposed metrics. If found to be acceptable, they would then form the basis of an updated stability rule.

6.3 Righting Arm Analysis Refinement

As discussed in Section 3.4.1 and demonstrated in Section 4.3.3.5, there are multiple methodologies available for free twist righting arm analysis, each with its own strengths and weaknesses. This study focused on the methodologies and software capabilities of GHS, but as identified in Section 2.2.1, there are plenty of other available software options for stability analysis. Each software option likely has its own approach to free twist righting arms.

To ensure that twist behavior is accurately captured, the various capabilities of each software must be evaluated and the results from each compared. The results should be benchmarked using advanced analysis methods to ensure that the results are as suitable representation of the real-world vessel behavior.

Once the software's have been verified and validated, it will be important to perform a benchmark study on the various methods for evaluating free twist righting arm curves and which is most appropriate. In addition, the software should allow an engineer to “look under the hood” to ensure that the results are valid and reflect the real-world vessel behavior. Software providers should provide examples or detailed references to designers so that full comprehension on this complicated topic is achieved.

6.4 Path Forward

The above recommendations should be considered as critical elements of a larger multi-year effort to provide an update to how the stability of NTH vessels is evaluated. A flowchart has been developed to depict how these would be incorporated specifically for the needs of Liftboats. As shown in Figure 41, five areas of effort are needed to resolve the issues identified in this report. They are:

- Task 1: Project Planning
- Task 2: Improved Wind Force Estimation
- Task 3: Dynamic Response in Waves
- Task 4: Improved Righting Arm Calculations
- Task 5: Revised Subchapter I and L.

Task 1 is vital to the success of the future effort as it will identify and set the requirements of the work packages to be performed. By understanding the end goal and documenting what is ultimately needed, a comprehensive plan can be developed for project execution needs.

As discussed in Section 6.1, Task 2 is focused on addressing the knowledge gap surrounding wind load estimation. Here, a combination of CFD and wind tunnel testing should be used to benchmark standard inputs for block method calculations. This effort is similar to that of OC-8, except that it will focus on design features unique to Liftboats. This task's product is a summary report documenting all relevant



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findings and conclusions. Best practices and design recommendations associated with using the block method should be addressed.

Task 3 addresses the knowledge gap associated with the response of Liftboats in waves. Its goal is to provide the needed analytical and experimental datasets that will be used as the basis of evaluation for Task 5. Namely, the wave group prediction method discussed in Section 5.7. A limited seakeeping model test campaign is suggested to provide an independent dataset which captures nonlinear effects that simulations lack. At least two Liftboat classes should be tested to provide adequate coverage across class size and different topside configurations. Further if practical, the influence of a known wind force should be included in the design of the experiment. In conjunction with the model testing, time domain simulations similar to the Orcaflex ones discussed in this report should be made for prediction purposes. The empirical dataset will then be used to calibrate the analytical simulation predictions in a “model of the model” activity. This calibrated analytical model will then be used to perform a systematic sweep in the time domain of all relevant variables which affect Liftboat responses in waves. This includes:

- Multiple Liftboat Designs
- Multiple Liftboat Load Conditions
- Multiple Liftboat Leg Configurations
- Operating Environments
- Extreme Environments

The final element to Task 3 will be the simulation of match runs in the frequency domain. A summary report will be developed to document all the results and findings of Task 3.

Task 4 will improve the righting arm estimates as discussed in Section 6.3. Emphasis will be placed on resolving the issues associated with free twist methods by virtue of benchmarking the different methods. By working with software providers and known example cases, the goal is to arrive at a consensus for how to standardize free twist. A set of new righting arms for the conditions tested in Task 3 shall be made. All findings will be documented in a best practices report and used later in Task 5.

Task 5 is where the updated stability criteria for Liftboat will be generated. It starts by utilizing the results from Task 3, 4 and implementing the proposed stability methodology for wave groups. Assuming good correlation is observed, an updated stability rule will be derived from these results. Emphasis will be placed on the setting of adequate safety margins and performance limits to ensure the safety of the crew and vessel. In addition, IMO Guidelines on the Second Generation Intact Stability Criteria [12] Level 2 Criteria should be applied to the dataset and reviewed for applicability. The final element of Task 5 will be a verification, validation, and possibly accreditation activity. Using all the documented references, an independent group of subject matter experts including class societies will review the overall effort and make a recommendation to the Client on how to proceed.

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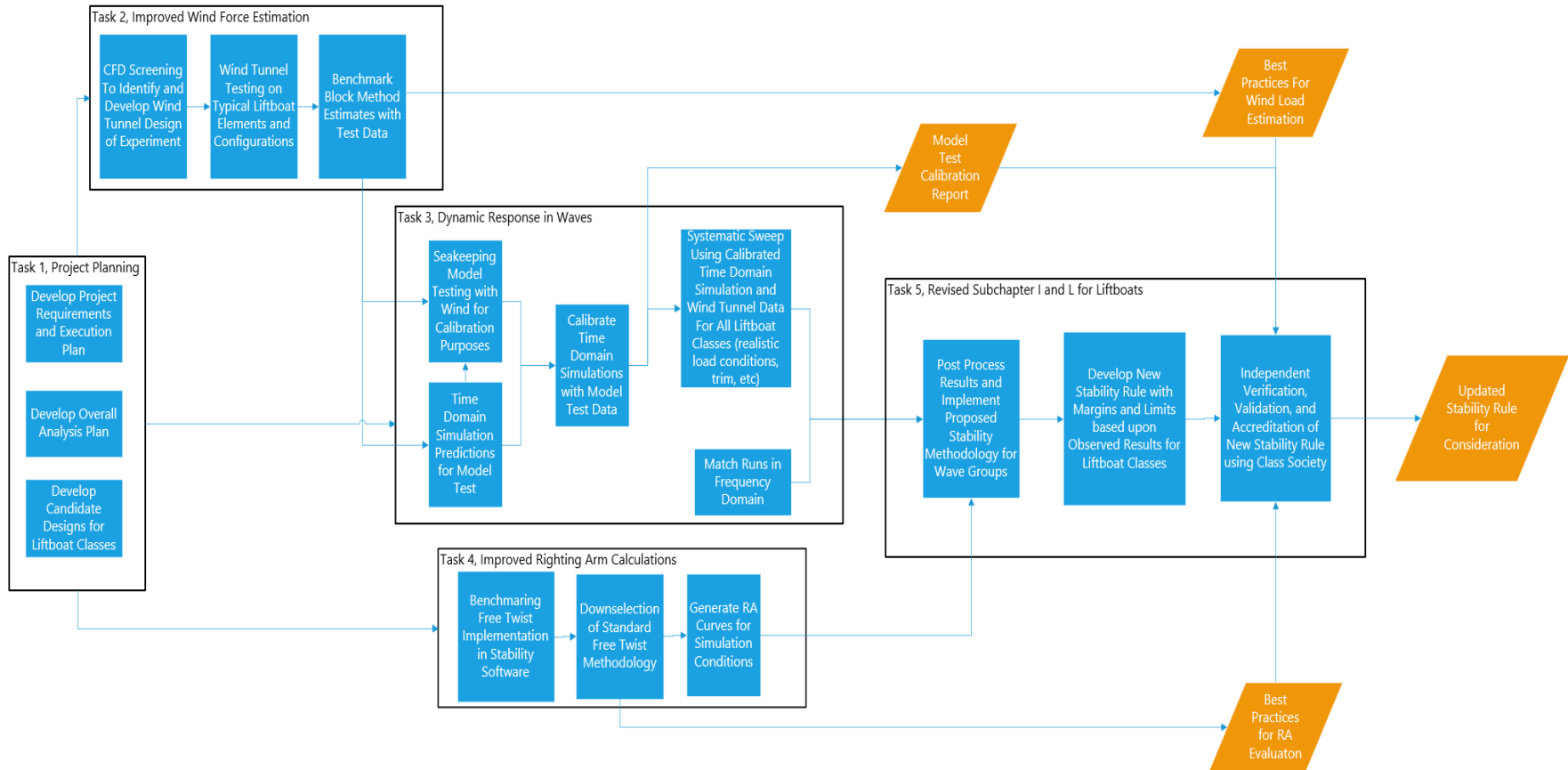


Figure 41. Proposed path to updating liftboat stability rule.



7 CONCLUSIONS

As discussed extensively in this report, the key takeaways from this study:

- Specific deficiencies have been identified in the existing stability rules. Resolution has been recommended where possible.
- Not all non-traditional hull forms are similar. i.e., Liftboats and Jack-Ups are quite different from column-stabilized MODUs and WITVs. Given these differences, there is not likely a “one-size-fits-all” set of criteria that can be applied to address non-traditional hull form stability. Multiple revised criteria should capture the unique issues of each vessel type.
- Identification of critical axis is important to understanding and evaluating non-traditional hull form stability, and a procedure for identification has been developed. Free twist righting arm methods seem appropriate but require further validation and standardization.
- Non-traditional hull forms are highly susceptible to wind heeling and care must be taken to estimate wind heeling moment. Wind tunnel tests and CFD simulations offer promise but are not widely accessible and accepted by USCG. The building block approach is the standard approach, but it lacks best practices to ensure consistent results among different practitioners using different software tools. Building upon the results from SNAME OC-8 Panel, further study is needed to ensure wind heeling moments are applied correctly.
- The existing stability criteria do not explicitly address the dynamic response to waves. The body of knowledge of non-traditional hull form failure modes when subject to the combined effects of wind and waves is not complete. This is reflected in the stability criteria which lack explicit specification of design wave heights and periods. While this report contains an analysis of the behavior of one typical Liftboat example and a potential assessment method, much more analysis is required to develop a robust criterion that addresses the wave dynamics of non-traditional hull forms.
- A roadmap has been developed to address how the recommendations could be implemented with the goal of updating the CFR for Liftboat stability evaluation.



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APPENDIX A. LITERATURE SEARCH REFERENCE SUMMARY

Rank	Title	Year	Source	Author
1	Review of Issues Associated With the Stability of Semi-Submersibles.	2007	Health and Safety Executive for the United Kingdom.	BMT Fluid Mechanics Limited
1	Orthogonal Tipping in Conventional Offshore Stability Evaluations.	2006	Proceedings of the 9th International Conference on Stability of Ships and Ocean Vehicles.	Breuer, J. A., & Sjolund, K.-G.
1	Steepest Descent Method - Resolving an Old Problem.	2009	10th International Conference on Stability of Ships and Ocean Vehicles, 87-100	Breuer, J. A., & Sjolund, K.-G.
1	The use of energy build up to identify the most critical heeling axis direction for stability calculations for floating offshore	2009	10th International Conference on Stability	van Santen, J.
1	Problems met in stability calculations of offshore rigs and how to deal with them.	2013	Proceedings of the 13th International Ship Stability Workshop, 1-9.	van Santen, J.
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1.5	Stability of Jack-Ups in Transit: Phase II Final Summary Report.	2006	Health and Safety Executive for the United Kingdom.	BMT Fluid Mechanics Limited
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1	Orthogonal Tipping in Conventional Offshore Stability Evaluations	2006	Proceedings of the 9th International Conference on Stability of Ships and Ocean Vehicles	A. Breuer and K.G. Sjolund
2	The Future of Jack-Up Stability Learning from Our Past	2003	9th International Conference on the Jack-Up Platform; City University, London	A. Breuer and R. Bowie
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3	NTSB Safety Recommendation - M79-102 - OCEAN EXPRESS	1979	Letter from NTSB to Admiral T. B. Hayward, USCG	James B. King
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3	Preliminary Report - Marine - DCA21MM024	2022	NTSB - DCA21MM024	National Transportation Safety Board
3	USCG MSC Post-Casualty Analysis of Liftboat SEACOR POWER, Revision 2 Comments	2022	Letter from ABS to NTSB and USCG	T. Gruber and J. Rousseau
3	USCG MSC Post-Casualty Analysis of Liftboat SEACOR POWER, Revision 4	2022	USCG MSC	USCG MSC

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