SCHOOL OF ENGINEERING
POSTGRADUATE

DETERMINING OPERATIONAL LIMITATIONS FOR CONDUCTING SUBSEA LIFTING FROM A DIVE SUPPORT VESSEL

ADAM BEATON (1418528)
MSc IN SUBSEA ENGINEERING
AUGUST 2018

DETERMINING OPERATIONAL LIMITATIONS FOR CONDUCTING SUBSEA LIFTING FROM A DIVE SUPPORT VESSEL

ADAM BEATON

1418528

AUGUST 2018

This report is submitted in partial fulfilment of the requirements for the Degree of Master of Science in Subsea Engineering at Robert Gordon University, Aberdeen.

DECLARATION

This thesis is submitted to The Robert Gordon University in accordance with the requirements of the degree of Master of Science in Subsea Engineering in the School of Engineering. I confirm that the material presented in this report is my own work. Where this is not the case, the source of material has been acknowledged.

Student Name ADAM BEATON

Signed 

Date 4 August 2018

ABSTRACT

Subsea lifting is the practice of deploying and recovering items from a surface crane to the seabed. The sea conditions directly influence the dynamic loads placed on the crane system. Crane operators avoid overloading the crane by stipulating seastate limits for the lifting operation. Seastate operating limits have the potential to be over or under-conservative. If over-conservative, the lifting operation is overly restricted which can result in unnecessary and costly project delays while the vessel waits for good weather. If the limits are under-conservative the lift can be at risk of a catastrophic accident.

Due to the relatively small scale of lifts on a Dive Support Vessel (DSV), operators often refer to simple guidelines for determining the seastate limits for lifting operations in lieu of a full engineering analysis.

The aim of this project was firstly to develop an accurate numerical calculation method for determining seastate operating limits for subsea lifting. The second aim was to compare commonly used simple guidelines to the accurate numerical calculation.

A numerical calculation method was developed and validated by trialling three lift scenarios to observe the effects of modifying different aspects of the lift. It was further validated by comparing the results to time-domain simulations using the software Orcaflex.

The seastate operating limits produced by the numerical calculation method were compared to simple guidelines. The simple guidelines were found to be both over and under-conservative for varying conditions and were deemed unreliable. It was concluded that the numerical calculation method should be used for all subsea lifts from a DSV.

ACKNOWLEDGEMENTS AND DEDICATION

I would like to acknowledge the assistance I have received from my Project Supervisor Mr George Kidd, my colleagues at Shelf Subsea and especially Dr. Amir Bahrami who has been incredibly generous with his help and support throughout this project.

Most of all I thank my wife Simone for enduring by my side through countless late nights and weekends for this Master's Degree.

This project is dedicated to my late father Brian Beaton.

TABLE OF CONTENTS

1.0 INTRODUCTION 13

1.1 SUBSEA LIFTING 13
1.2 DIVE SUPPORT VESSELS 14
1.3 OPERATING LIMITATIONS 14
1.3.1 DYNAMIC AMPLIFICATION FACTORS 15
1.3.2 SEASTATE LIMITS 15

2.0 AIMS AND OBJECTIVES 16

3.0 LITERATURE REVIEW 17

3.1 DET NORSKE VERITAS STANDARDS 17
3.1.1 DNVGL-ST-0377 STANDARD FOR SHIPBOARD LIFTING APPLIANCES 17
3.1.2 DNVGL-ST-0378 STANDARD FOR OFFSHORE AND PLATFORM LIFTING 17
3.1.3 DNVGL-RP-N201 LIFTING APPLIANCES USED IN SUBSEA OPERATIONS 18
3.1.4 DNVGL-RP-N103 MODELLING AND ANALYSIS OF MARINE OPERATIONS 18
3.2 DYNAMIC FORCES DURING DEEPWATER LIFTING OPERATIONS 18
3.3 DEVELOPMENT OF OPERATIONAL LIMIT DIAGRAMS FOR OFFSHORE LIFTING PROCEDURES 21
3.4 RE-EVALUATION OF DNV SIMPLIFIED FORMULA FOR CRANE TIP MOTIONS 22

4.0 LIFTING ANALYSIS METHODOLOGY 25

4.1 LIFTING PHASES 25
4.1.1 PHASE 1: PASSING THROUGH THE SPLASH ZONE 25
4.1.2 PHASE 2: LOWERING IN DEEPWATER 26
4.2 DIVE SUPPORT VESSEL 27
4.2.1 RESPONSE AMPLITUDE OPERATORS (RAO) 28
4.2.2 DSV DECK CRANE 29
4.3 SEASTATE RANGE 30
4.4 CRITERIA FOR OPERABLE SEASTATES 31
4.4.1 CRITERION A: TOTAL HOOK LOAD 31
4.4.2 CRITERION B: NO SNAP LOADS 31
4.5 CALCULATION INPUTS 32
4.6 CALCULATION OUTPUTS 32
4.7 PRESENTATION OF RESULTS 32
4.8 COMPARISON TO GUIDELINE OPERATING LIMITS 33
4.8.1 DNV-ST-0378 33
4.8.2 DNV-ST-0377 34
4.8.3 DSV CRANE LOAD CHART 34
4.9 ANALYSIS LIMITATIONS 34
4.10 CALCULATION SEQUENCE 35
4.11 TIME-DOMAIN SIMULATION 36

5.0 CALCULATION DEMONSTRATIONS 39

5.1 OBJECT 1: SUBSEA COOLING SKID 39
5.2 OBJECT 2: SUBSEA AUTOMATIC PIG LAUNCHER (SAPL) 40
5.3 OBJECT 3: EXPANSION LOOP SPOOL 41

6.0 SUMMARY OF RESULTS 43

6.1 GENERAL 43
6.2 OBJECT 1: SUBSEA COOLING SKID 43
6.2.1 NUMERICAL ANALYSIS RESULTS 43
6.2.2 TIME-DOMAIN SIMULATION RESULTS 44
6.2.3 DISCUSSION 44
6.3 OBJECT 2: SUBSEA AUTOMATIC PIG LAUNCHER (SAPL) 45
6.3.1 NUMERICAL ANALYSIS RESULTS 45

6.3.2 Time-Domain Simulation Results ... 46
6.3.3 Discussion ... 46
6.4 Object 3: Expansion Loop Spool ... 47
6.4.1 Numerical Analysis Results ... 47
6.4.2 Time-Domain Simulation Results ... 48
6.4.3 Discussion ... 48
7.0 DISCUSSION ... 50
7.1 General Validity of the Numerical Calculation Method ... 50
7.2 Orcaflex Validity Check ... 50
7.3 Numerical Calculation Method Trials ... 50
7.4 Improvements to the Numerical Calculation Method ... 51
7.4.1 Lifting Phases ... 51
7.4.2 Crane Tip Motion Formulae ... 51
7.4.3 Operating Limits Tables ... 52
7.5 Comparison of Numerical Calculation Method to Common Guidelines ... 53
7.5.1 DNV-ST-0378 ... 53
7.5.2 DNV-ST-0377 ... 53
7.5.3 Crane Curve ... 53
8.0 CONCLUSIONS ... 54
8.1 Performance of the numerical calculation method ... 54
8.2 Value of the Numerical Calculation Method ... 54
9.0 REFERENCES ... 55
APPENDIX A CRANE LOAD CHARTS 56
APPENDIX B DSV RAO DATA 60
APPENDIX C NUMERICAL CALCULATION SHEETS 62
APPENDIX D NUMERICAL CALCULATION RESULTS 84
APPENDIX E ORCAFLEX SIMULATION RESULTS 91

LIST OF FIGURES

Figure 1-1 A Typical DSV – NPP Nusantara (courtesy of Shelf Subsea) 14
Figure 3-1 Subsea Lifting Analysis Sequence proposed by T. Boe et al 19
Figure 3-2 Numerical calculation vs. software simulation (T. Boe et al) 20
Figure 3-3 Operating Limits Table (T. Boe et al) 20
Figure 3-4 DAF Contour Chart (L. Roncetti et al).. 21
Figure 3-5 OCOLD Diagram (L. Roncetti et al) 22
Figure 4-1 Dynamic Load Analysis – Lifting Phase 1: Splash Zone.................... 26
Figure 4-2 Dynamic Load Analysis – Lifting Phase 2: Deepwater Lowering 27
Figure 4-3 MMA Prestige (courtesy of Shelf Subsea)... 28
Figure 4-4 Vessel 6 Degrees of Motion (photo courtesy of Shelf Subsea)........ 29
Figure 4-5 DSV RAO's – Heave and Roll Responses 30
Figure 4-6 Crane Tip Displacement per m Hs with chosen period range 31
Figure 4-7 Example Operating Limits Table used in the analysis........................ 33
Figure 4-8 Sequence developed for Numerical Calculation 35
Figure 4-9 Orcaflex – Simulation Model of DSV Subsea Lift (Orcina)................. 37
Figure 4-10 Orcaflex – Example Results Data (Orcina)... 38
Figure 5-1 Typical Subsea Cooling Skid (Quadrant Energy)................................. 40
Figure 5-2 Subsea Automatic Pig Launcher (SAPL) (Petronas)........................... 41
Figure 5-3 Example Expansion Loop Spool (Saka Petroleum)............................. 42
Figure 7-1 Crane Tip Motions - X. Gu et al vs DNV-RP-N103................................ 52
Figure 9-1 MMA Prestige 100 t Crane Load Chart (Sheet 1) 57
Figure 9-2 MMA Prestige 100 t Crane Load Chart (Sheet 2) 58
Figure 9-3 MMA Prestige 100 t Crane Load Chart (Sheet 3) 59
Figure 9-4 Object 1: Subsea Cooling Skid – Results Chart (Lift Phase 1)......... 86
Figure 9-5 Object 1: Subsea Cooling Skid – Results Chart (Lift Phase 2)......... 86
Figure 9-6 Object 2: SAPL – Results Chart (Lift Phase 1)...................................... 88
Figure 9-7 Object 2: SAPL – Results Chart (Lift Phase 2)...................................... 88
Figure 9-8 Object 3: Expansion Loop Spool – Results Chart (Lift Phase 1) 90
Figure 9-9 Object 3: Expansion Loop Spool – Results Chart (Lift Phase 2) 90

LIST OF TABLES

Table 3-1 DNV Crane Tip Motion vs Orcaflex simulation (X. Gu et al) 23
Table 3-2 Crane Tip Motion vs. Orcaflex simulation (X. Gu et al) 24
Table 5-1 Summary of example object properties.. 39
Table 6-1 Object 1: Subsea Cooling Skid – Operating Limits Table.................... 44
Table 6-2 Object 1: Subsea Cooling Skid – Orcaflex Results 44
Table 6-3 Object 1: Subsea Cooling Skid – Comparison to Guideline Limits... 45
Table 6-4 Object 2: SAPL – Operating Limits Table... 46
Table 6-5 Object 2: SAPL – Orcaflex Results 46
Table 6-6 Object 2: SAPL – Comparison to Guideline Limits................................ 47
Table 6-7 Object 3: Expansion Loop - Operating Limits Table 48
Table 6-8 Object 3: Expansion Loop – Orcaflex Results 48
Table 6-9 Object 3: Expansion Loop Spool – Comparison to Guideline Limits49
Table 9-1 DSV Response Amplitude Operators (RAO) 61
Table 9-2 Object 1: Subsea Cooling Skid – Results Table..................................... 85
Table 9-3 Object 1: Subsea Cooling Skid – Operating Limits Table.................... 85
Table 9-4 Object 2: SAPL – Results Table.. 87
Table 9-5 Object 2: SAPL – Operating Limits Table... 87
Table 9-6 Object 3: Expansion Loop – Results Table.. 89
Table 9-7 Object 3: Expansion Loop - Operating Limits Table 90

ABREVIATIONS

AHC	Active Heave Compensation
CWC	Concrete Weight Coat
DAF	Dynamic Amplification Factor
DNV	Det Norske Veritas
DP	Dynamic Positioning
DSV	Dive Support Vessel
JONSWAP	Joint Offshore North Sea Wave Program
LOA	Length Overall
MBL	Minimum Breaking Load
MMA	Mermaid Marine Australia
OCOLD	Offshore Crane Operational Limit Diagram
PHC	Passive Heave Compensation
RAO	Response Amplitude Operator
RGU	Robert Gordon University
RP	Recommended Practice
SAPL	Subsea Automated Pig Launcher
WOW	Waiting on Weather

SYMBOLS

Latin

A_{33}	Added mass (kg)
A_P	Projected area (m^2)
A_L	Cross-sectional area of crane line (m^2)
a_{ct}	Crane tip characteristic acceleration (m/s^2)
a_w	Vertical water acceleration (m/s^2)
b	Horizontal distance from centreline to crane tip (m)
C	Correction factor for velocity
C_A	Added mass coefficient
C_{Df}	Longitudinal friction coefficient
C_{Dz}	Drag coefficient in vertical
D_C	Diameter of crane line (m)

C_s	Crane stiffness (kN/m)
EA	Stiffness of crane line (N)
F_D	Drag force (N)
F_d	Dynamic force amplitude at crane hook (N)
F_{dL}	Dynamic force amplitude at object (N)
F_{Hyd}	Total hydrodynamic force (N)
F_M	Characteristic mass force (Froude Kriloff force) (N)
F_{snap}	Snap force (N)
F_{static}	Total static force (N)
F_{Total}	Total force at crane tip (N)
F_ρ	Varying buoyancy force (N)
g	Acceleration of gravity (m/s^2)
H_{max}	Maximum wave height (m)
H_s	Significant wave height (m)
i	Complex number
K	Unit stiffness of crane line (N/m)
k	Complex wavenumber (m^{-1})
L	Length of crane line (m)
L_{Nsee}	Nominal load at see (t)
L_s	Stretched crane line length (m)
M	Mass in air (kg)
M’	Total hydrodynamic mass (kg)
m_L	Unit mass of crane line (kg/m)
N_z	Number of waves
P	Probability of H_{max} occuring
T_f	Natural period of crane line system (s)
T_H	Vessel natural period for heave (s)
T_R	Vessel natural period for roll (s)
T_P	Peak spectral period (s)
T_z	Zero up-crossing wave period (s)
T_γ	Peak period correction factor
V_R	Reference volume (m^3)
v_c	Crane line hoisting speed (m/s)
v_{ct}	Crane tip characteristic velocity (m/s)

v_{ff}	Free-fall velocity (m/s)
v_r	Characteristic velocity relative to water (m/s)
v_{snap}	Snap velocity (m/s)
v_w	Vertical water velocity (m/s)
v_x	Wavenumber for natural frequency (m^{-1})
W_{air}	Weight in air (N)
W_{sub}	Weight in water (N)
w	Unit weight of crane line in water (N/m)
w_f	Natural frequency of crane line system (s^{-1})
z	Position along crane line (m)

Greek

ε	Mass ratio
η_a	Crane tip characteristic displacement (m)
η_L	Vertical displacement of object (m)
η_{st}	Static stretched crane line length (m)
η_{Vheave}	Vessel heave response amplitude (m)
η_{Vroll}	Vessel roll response amplitude (rad)
Σ	Linear damping coefficient for object (N/s)
σ	Linear damping coefficient for crane line (N/s)
ρ	Density of seawater (kg/m^3)
ψ_{see}	Hoist load coefficient

Subscripts

Surf	Lift Phase 1: Crossing the splash zone
Sub	Lift Phase 2: Deepwater lowering

1.0 INTRODUCTION

1.1 Subsea Lifting

Subsea lifting involves the deployment and recovery of objects from a floating vessel crane to and from the seabed. In open seas, wave conditions induce vessel motions which are magnified at the extended crane tip and transferred through the crane line to the suspended object via a dynamic, non-linear relationship (Bøe 2010). Consequently, lifting objects from a floating vessel introduces the following general challenges;

1. The lifted object is subject to hydrodynamic forces as it crosses the air/water boundary, known as the 'splash zone';
2. When submerged, the geometry of the object introduces drag and added mass forces through the crane line as the object heaves within the water column;
3. The object may 'free-fall' at a slower rate than the crane tip movement which causes the crane to be momentarily slack and then suddenly tensioned resulting in significant impact loads;
4. The oscillating object can be difficult to set down on the seabed at a precise location and impact velocity;
5. The overboarded weight of the object introduces an additional heeling moment to the vessel which reduces stability.

The challenges above can be met by using heave compensation systems. These systems reduce the motion amplitude of the object by either adding spring damping between the object and the crane tip, called Passive Heave Compensation (PHC), or by controlling tension on the crane line to effectively decouple the crane tip motion from the object, called Active Heave Compensation (AHC).

The highest risks associated with subsea lifting are that of failure of the rigging or parting of the crane line and dropping objects. Dropped loads onto the deck or subsea assets can be catastrophic and life-threatening.

1.2 Dive Support Vessels

Dive Support Vessels (DSV) are a class of offshore service vessel that provide diving facilities and cranes to assist in small to medium-sized operations for the offshore energy sector. Typical operations include installation, intervention, maintenance and inspection of subsea facilities. Deck cranes are used to lift objects for deployment to the seabed and recovery to the surface.

DSVs are typically less than 100 m in overall length (LOA), with the largest dedicated DSV being the Skandi Arctic at 157 m (Dasgupta 2016). Deck cranes on a typical DSV are commonly rated between 50 to 100 t. Relative to the scale of subsea facilities they are limited in the types of objects that can be lifted without additional support from dedicated lifting barges and other vessels. **Figure *1-1*** shows a typical 80 m DSV with 50 t deck crane.

Figure 1-1 A Typical DSV – NPP Nusantara (courtesy of Shelf Subsea)

1.3 Operating Limitations

The risks of subsea lifting can be controlled by applying operating limits to the lifting activities in terms of allowable seastate conditions. A full dynamic load analysis by way of numerical calculations or simulation software is the most comprehensive method of determining the operating limits. This approach is commonplace for large-scale, critical subsea lifts.

Due to the relatively small scale of lifts from a DSV, operators often use simplified methods to determine operating limits in lieu of an engineered lift approach. These can be in the form of a de-rating factor applied to the crane chart, or a seastate limit.

The simple approaches below have the potential to be over-conservative, which unnecessarily restricts the operation and results in costly downtime while the vessel is 'waiting on weather' (WOW). Conversely, the operating limits could be under-conservative which could place the operation at risk of catastrophic failure.

The suitability of these simple lifting approaches for small DSVs is the basis of this study.

1.3.1 Dynamic Amplification Factors

A dynamic amplification factor (DAF) is applied to a static load when planning a lift to account for all possible dynamic effects. The static load is multiplied by the DAF before referencing the crane load chart for allowable boom reach and height. Alternatively, the load chart itself can be de-rated by applying the DAF to the chart values.

DAFs can be determined through sophisticated lifting analysis, or by many simplified tables, formulae and guideline values offered in industry codes and standards. DSV operators often reference these simplified values in leu of a full lifting analysis.

1.3.2 Seastate Limits

A further simplified approach for DSV operations is to specify a maximum significant wave height (Hs) for conducting a particular lift. This maximum may be determined analytically but is often simply chosen based on operator experience or a qualitative risk assessment. The Hs limitation does not consider the effect of different wave periods.

2.0 AIMS AND OBJECTIVES

The aims of this project were as follows;

1. To develop a numerical calculation method to determine seastate operating limits for subsea lifting;
2. To assess whether the numerical calculation method is of value for small-scale lifts from a DSV when compared to various simple guidelines.

The project achieved these aims with the following strategy;

1. Research current industry guidelines and methods to determine seastate operating limits for subsea lifting;
2. Develop the numerical calculation method using suitable industry standards and other sources of guidance;
3. Validate the method against time-domain simulation software;
4. Demonstrate the method by analysing a selection of lifting scenarios and outputting the operating limits;
5. Compare the results to typical operating limits provided by commonly used simple guidelines;
6. Discuss the performance and value of the calculation method for use in DSV subsea lifting applications.

3.0 LITERATURE REVIEW

A literary review was conducted on the topic of subsea lifting analysis to understand the different approaches to the task and the level of complexity and resources required to perform each method. Various industry codes and standards were also reviewed to ensure the chosen method would consider all aspects required by common industry practice.

3.1 Det Norske Veritas Standards

Det Norske Veritas / Germanischer Lloyd (DNVGL) is a classification society, with a major focus on the maritime industry. DNVGL publishes many standards and recommended practices (RP) related to subsea lifting. The following DNVGL documents have formed the basis of the numerical calculations for this project.

3.1.1 DNVGL-ST-0377 Standard for Shipboard Lifting Appliances

DNVGL-ST-0377 provides requirements for DNV certification of offshore lifting appliances. Section 5.4.6 "*Calculation of the hoist load coefficient by means of hydrodynamic analysis*" outlines the required considerations for the analysis:

- Vertical and horizontal vessel motion;
- Load-bearing structure of the crane;
- Hydrodynamic properties of floating or submerged load.

3.1.2 DNVGL-ST-0378 Standard for Offshore and Platform Lifting

DNVGL-ST-0378 includes the following pertinent guidance:

- Section 9.2.4.1 "Load charts reflecting the crane's de-rated allowable working load for various wave heights shall be presented";
- Section 9.1.1.3 "Subsea handling operation are normally to be handled as an engineered lift. However, for small cranes, the specified in 9.2.2.1 may be applied";
- Section 9.2.2.1 "… for operations up to significant wave height of 2 m, a dynamic factor of not less than 1.7 shall be applied".

3.1.3 DNVGL-RP-N201 Lifting Appliances used in Subsea Operations

DNVGL-RP-N201 gives guidance on the overall approach to design and operation of subsea lifting appliances. The following excerpts are pertinent to the project:

- Section 1.9.3.2 - Outlines critical lifting phases, including lift off the deck, splash zone and lowering;
- Section 2.4.2.1 - "for engineered lifts, de-rating of the lifting capacity shall normally be provided";
- Section 2.4.3.6 - "Vessel motion characteristics are necessary to carry out (de-rating). Response amplitude operators (RAOs) for the vessel are the preferable basis";
- Section 2.4.3.7 - "… calculated on the basis of Hs, period and spectrum"
- Table 5-2 shows the applicable forces to consider for each lift phase, including snap forces for both splash zone and lowering phases;
- Section 5.9.4 - Considerations for lifting through splash zone, including caution regarding slamming and snap loads;
- Section 5.9.6 - Considerations for lowering through water column, including dynamic forces on cable and increasing crane line weight.

3.1.4 DNVGL-RP-N103 Modelling and Analysis of Marine Operations

DNVGL-RP-N103 provides specific guidance for analysing subsea lifting, including the critical phases of passing through the splash zone and lowering in deepwater. The RP also offers a simplified method for the splash zone analysis. DNVGL-RP-N103 has been followed for a majority of the calculations for this project.

3.2 Dynamic Forces during Deepwater Lifting Operations

T. Bøe and A. Nestegård developed a simplified approach to dynamic load calculations in *Dynamic Forces during Deepwater Lifting Operations.* The paper followed the newly issued DNV-RP-N103 Section 5: Deepwater Lowering Operations and offered a method for applying the standard to a lift scenario and outputting the seastate operating limits. The general sequence is summarised in **Figure *3-1***. The paper makes several simplifications such as;

- No crane heave compensation is considered;
- Splash zone hydrodynamic forces are not considered;
- Slack line conditions are checked, but the snap forces are not calculated.

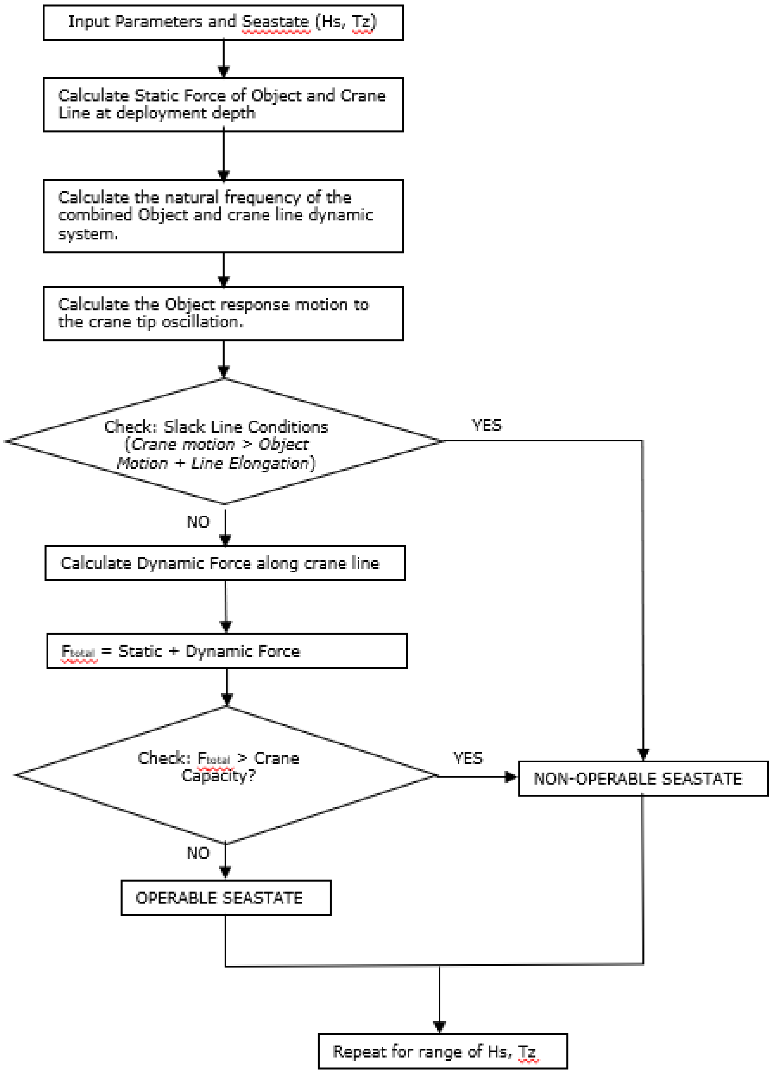


Figure 3-1 Subsea Lifting Analysis Sequence proposed by T. Boe et al

The proposed method was demonstrated with a case study involving a deepwater lowering of a 97 t load to a depth of 3000 m. The results were compared to a time-domain simulation using Orcaflex which closely matched the numerical calculation (see **Figure *3-2***).

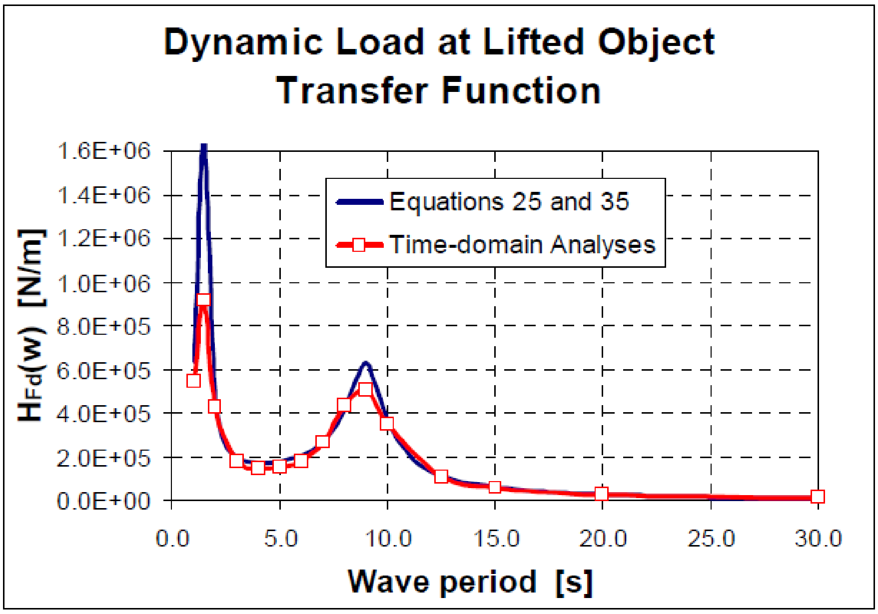


Figure 5. Transfer function for dynamic load in cable at lifted object

Figure 3-2 Numerical calculation vs. software simulation (T. Boe et al)

The results were tabulated in a format that can be used by the crane operator as a seastate operating limit for the specific lift scenario, clearly showing the Hs and Tz combinations which are operable and non-operable (see **Figure *3-3***).

Most probable largest dynamic force in cable, Fd [tonnes]								
Tz\Hs	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
2.0	0.1	Outside	Outside	Outside	Outside	Outside	Outside	Outside
2.5	0.1	Outside	Outside	Outside	Outside	Outside	Outside	Outside
3.0	0.4	0.3	Outside	Outside	Outside	Outside	Outside	Outside
3.5	1.2	2.1	1.2	Outside	Outside	Outside	Outside	Outside
4.0	5.3	8.5	7.0	4.0	Outside	Outside	Outside	Outside
4.5	11.4	17.9	23.4	18.2	13.4	Outside	Outside	Outside
5.0	17.0	26.2	33.6	39.1	34.1	28.8	Outside	Outside
5.5	20.6	31.4	39.7	47.2	52.8	51.5	47.3	Outside
6.0	22.4	34.0	43.3	51.4	58.8	66.1	69.9	69.4
6.5	23.0	34.9	44.5	52.7	60.2	67.0	75.1	85.5
7.0	22.9	34.9	44.1	52.4	59.8	66.6	72.9	79.8
7.5	22.2	33.8	42.8	50.9	58.2	65.0	71.2	76.9
8.0	21.3	32.4	41.3	49.1	56.1	62.5	68.5	74.1
8.5	20.4	31.0	39.5	46.9	53.5	59.7	65.4	70.8
9.0	19.4	29.5	37.6	44.6	50.9	56.7	62.2	67.3
9.5	18.4	27.9	35.6	42.3	48.3	53.8	58.9	63.8
10.0	17.5	26.5	33.8	40.1	45.7	50.9	55.8	60.4
10.5	16.6	25.1	32.0	37.9	43.3	48.2	53.0	57.3
11.0	15.8	23.8	30.3	35.9	41.0	45.9	50.0	54.0
11.5	15.0	22.6	28.7	34.0	38.8	43.2	47.5	51.3
12.0	14.2	21.5	27.3	32.3	36.8	40.9	44.8	48.4
12.5	13.6	20.4	25.9	30.6	34.9	38.8	42.6	46.0
13.0	12.9	19.4	24.6	29.1	33.1	36.8	40.3	43.5

Figure 3-3 Operating Limits Table (T. Boe et al)

T. Bøe and A. Nestegård concluded that both the DNV-RP-H103 standard and their proposed method of applicable were well-suited for fast determination of crane operating limits but noted that more sophisticated analysis should be undertaken for critical lifts that near the crane capacity.

3.3 Development of Operational Limit Diagrams for Offshore Lifting Procedures

L. Roncetti et al proposed a method for presenting offshore crane limits in the paper *Development of Operational Limit Diagrams for Offshore Lifting Procedures*. The authors were concerned that crane load charts typically provide wave height limits only and do not consider the effects of varying wave periods, heading and crane cable length. They used the time-domain simulation software SITUA to model an example lifting scenario with a range of wave heights and periods and produced operating limit charts. **Figure 3-4** shows a DAF contour chart which an operator could extract a DAF and de-rate the original crane load chart for each lift. **Figure 3-5** shows the final Offshore Crane Operational Limit Diagram (OCOLD) which is a simple "go/no-go" chart, specific to a given lift scenario including the object properties and the boom reach.

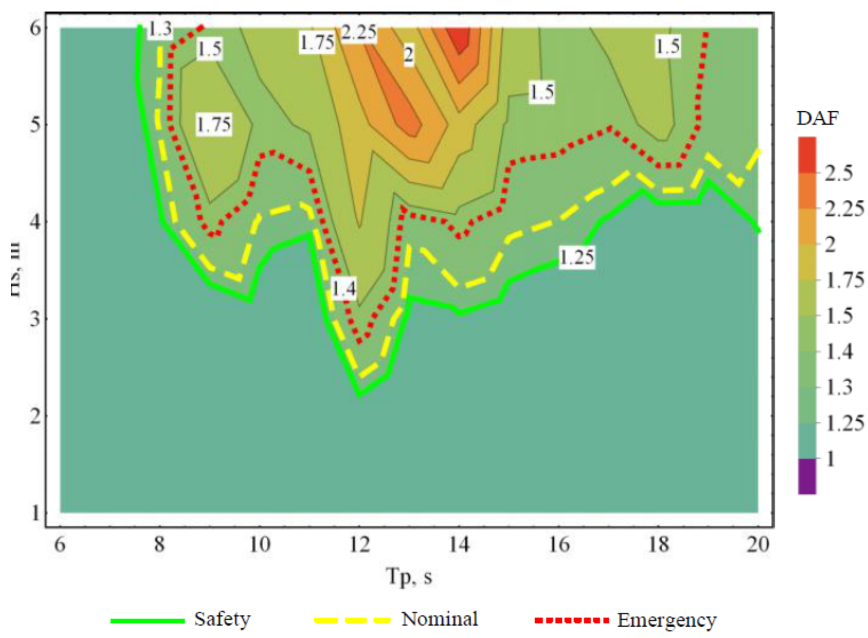


Figure 3-4 DAF Contour Chart (L. Roncetti et al)

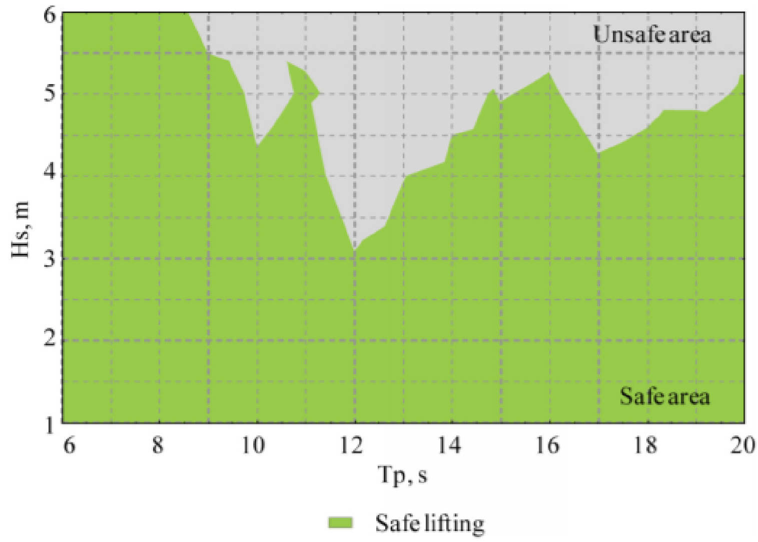


Figure 3-5 OCOLD Diagram (L. Roncetti et al)

3.4 Re-evaluation of DNV Simplified Formula for Crane Tip Motions

DNVGL-RP-N103 Section 9.2.1 provides formulae for transforming the six degrees of vessel motion into characteristic crane tip motions (see Equations 3.1, 3.2 and 3.3).

$$Crane\ Tip\ Displ.: \eta_{ct} = \sqrt{{\eta_H}^2 + (b\sin(\varphi_R))^2 + (l\sin(\varphi_P))^2} \tag{3.1}$$

$$Crane\ Tip\ Velocity: v_{ct} = 2\pi\sqrt{\left(\frac{\eta_H}{T_H}\right)^2 + \left(\frac{bsin(\varphi_R)}{T_R}\right)^2 + \left(\frac{lsin(\varphi_P)}{T_P}\right)^2} \tag{3.2}$$

$$Crane\ Tip\ Acceleration: a_{ct} = 4\pi^2\sqrt{\left(\frac{\eta_H}{{T_H}^2}\right)^2 + \left(\frac{b\ sin(\varphi_R)}{{T_R}^2}\right)^2 + \left(\frac{l\ sin(\varphi_P)}{{T_P}^2}\right)^2} \tag{3.3}$$

According to X. Gu et al, the DNV formulae are considered overly conservative, leading to vessel operators placing unnecessarily restrictive limits on lifting operations. X. Gu et al investigated the formulae in "*Re-evaluation of DNV Simplified Formula for Crane Tip Motions*" by running the calculations on an example vessel and comparing the results to a time-domain simulation using Orcaflex. The comparison showed inconsistent discrepancies, as summarised in **Table *3-1***.

Table 3-1 DNV Crane Tip Motion vs Orcaflex simulation (X. Gu et al)

Crane Tip Motion	**DNVGL-RP-N103 Section 9.2.1 Results (compared to Orcaflex simulation)**
Displacement	Underestimated by 10 – 35%
Velocity	Overestimated by 20 – 60%
Acceleration	Overestimated by 40 – 200%

X. Gu et al considered the results for the velocity formula to be an acceptable level of over-estimation. They developed additional factors and offered a modified set of formulae for crane tip displacement and acceleration so that all three formulae would be consistently over-estimated by 20 – 60%. Equations 3.4, 3.5 and 3.6 show X. Gu et al modified formulae. **Table *3-2*** shows how the modified formulae compare to the ORcaflex modelling results. The modified formula set has been used in the numerical calculation for this project.

$$Crane\ Tip\ Displ.: \eta_{ct} = \sqrt{{\eta_H}^2 \frac{P_y T_z}{T_H} + (b\sin(\varphi_R))^2 \frac{P_y T_z}{T_R} + (l\sin(\varphi_P))^2 \frac{P_y T_z}{T_P}} \quad (3.4)$$

$$Crane\ Tip\ Velocity: v_{ct} = 2\pi\sqrt{\left(\frac{\eta_H}{T_H}\right)^2 + \left(\frac{bsin(\varphi_R)}{T_R}\right)^2 + \left(\frac{lsin(\varphi_P)}{T_P}\right)^2} \quad (3.5)$$

$$Crane\ Tip\ Acceleration: a_{ct} = 4\pi^2\sqrt{\left(\frac{\eta_H}{{P_{TH}}^2}\right)^2 + \left(\frac{b\ sin(\varphi_R)}{{P_{TR}}^2}\right)^2 + \left(\frac{l\ sin(\varphi_P)}{{P_{TP}}^2}\right)^2} \quad (3.6)$$

Table 3-2 Crane Tip Motion vs. Orcaflex simulation (X. Gu et al)

Crane Tip Motion	**X. Gu et al Modified Formulae Results (compared to Orcaflex modelling)**
Displacement	Overestimated by 25 – 55%
Velocity	Overestimated by 20 – 60%
Acceleration	Overestimated by 25 – 65%

4.0 LIFTING ANALYSIS METHODOLOGY

The following sections outline the basis for the numerical analysis. The analysis was performed on three example subsea lifts typically performed by a DSV.

4.1 Lifting Phases

Analysis was performed on two phases of a subsea lift; (1) Passing through the splash zone and (2) lowering in deepwater. The two phases were chosen as high potential for hydrodynamic loads.

4.1.1 Phase 1: Passing through the Splash Zone

Passing through the splash zone is a critical phase of a subsea lift due to the free surface wave impacts and rapid changes in drag, added mass inertia and wave slamming. The following forces were calculated in the numerical analysis;

- Drag Force – A downward force, which considers the relative velocity of the crane tip motion and water particle velocity;
- Characteristic Mass Force – A downward force which includes the relative acceleration of water particles to the object and the inertia force of the object;
- Varying Buoyancy Force – An upward force due to change in density from air to water;
- Static Force – The weight of the object in air.

Wave slamming was omitted to simplify the numerical calculation. A full analysis of the lifted object geometry is required to properly consider wave slamming at several instances of varying object submergence (DNV 2017).

A slack line will occur during the splash zone crossing if the total hydrodynamic forces is greater than the static weight of the object (DNV 2017). **Figure *4-1*** shows the general arrangement for analysis of the splash zone crossing phase.

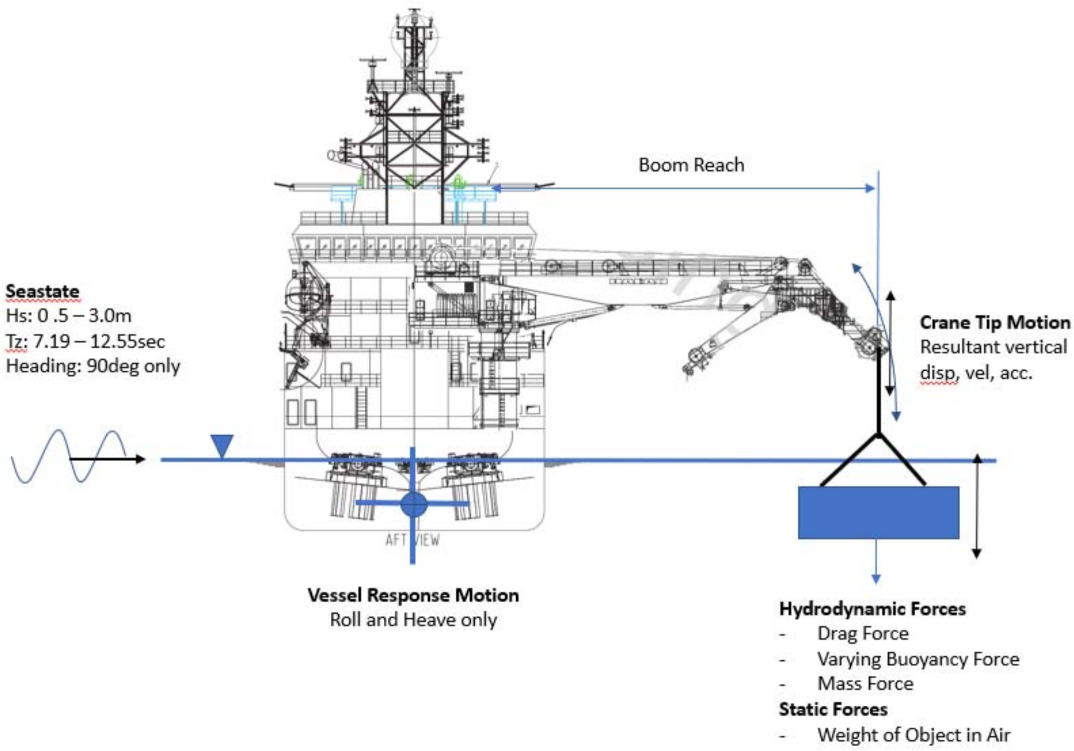


Figure 4-1 Dynamic Load Analysis – Lifting Phase 1: Splash Zone

4.1.2 Phase 2: Lowering in Deepwater

As the object is lowered through the water column, weight and drag forces of the crane line are introduced. For many deepwater lifts, the weight of the crane line is greater than the weight of the object itself. The dynamic forces on the object are dependent on the stiffness of the crane line as the line will stretch under the loads from the crane tip motion and thus provide spring damping to the object oscillation.

During the deepwater lowering phase a slack crane line will occur if the displacement of the crane tip is greater than the displacement of the object, such that the difference is greater than the stretched crane line (DNV 2017). The impact force occurs when the line reaches maximum elongation as the crane tip is still travelling in opposition to the object. **Figure *4-2*** shows the general arrangement for analysis of the deepwater lowering phase.

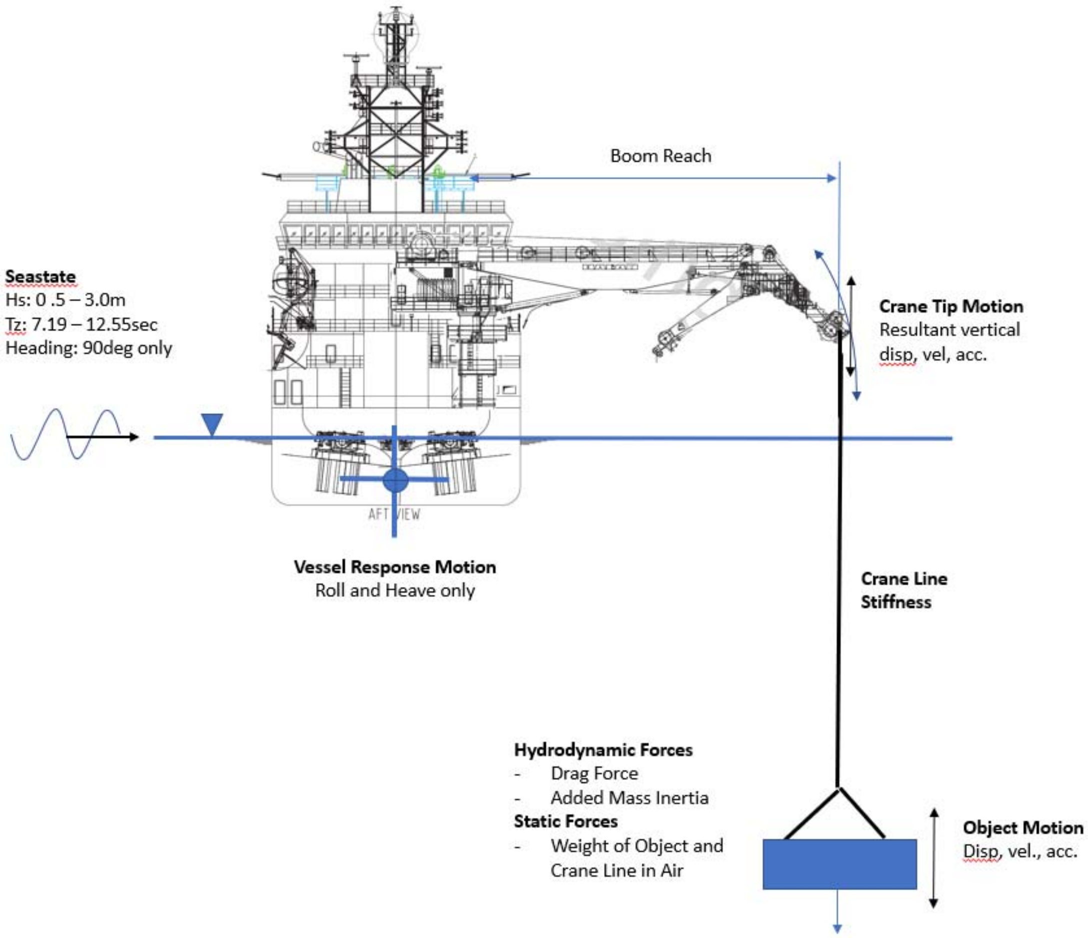


Figure 4-2 Dynamic Load Analysis – Lifting Phase 2: Deepwater Lowering

4.2 Dive Support Vessel

The MMA Prestige was used as the DSV for testing the numerical calculation method. MMA Prestige is an 80 m class 2 dynamically positioned (DP2) DSV with a MacGregor 100 t AHC subsea knuckle-boom pedestal crane. Crane load charts are included in Appendix A which show the maximum static weight for all positions of the crane hook with a nominal DAF of 1.33 applied to the chart. **Figure *4-3*** shows the MMA Prestige with a portable saturation diving system fixed to the mezzanine deck.

Figure 4-3 MMA Prestige (courtesy of Shelf Subsea)

4.2.1 Response Amplitude Operators (RAO)

Response Amplitude Operators (RAO) are empirical data which express the motion of a vessel as it is excited by a given sea condition (RGU 2015b). RAOs are typically given for all 6 degrees of motion as shown in **Figure *4-4*** for a range of wave headings. The RAO values are in terms of wave height, for example displacements are given a "m per m Hs" and rotations as "radian s per m Hs". RAOs depend on the vessel size, hull profile and displacement (Clauss 1990).

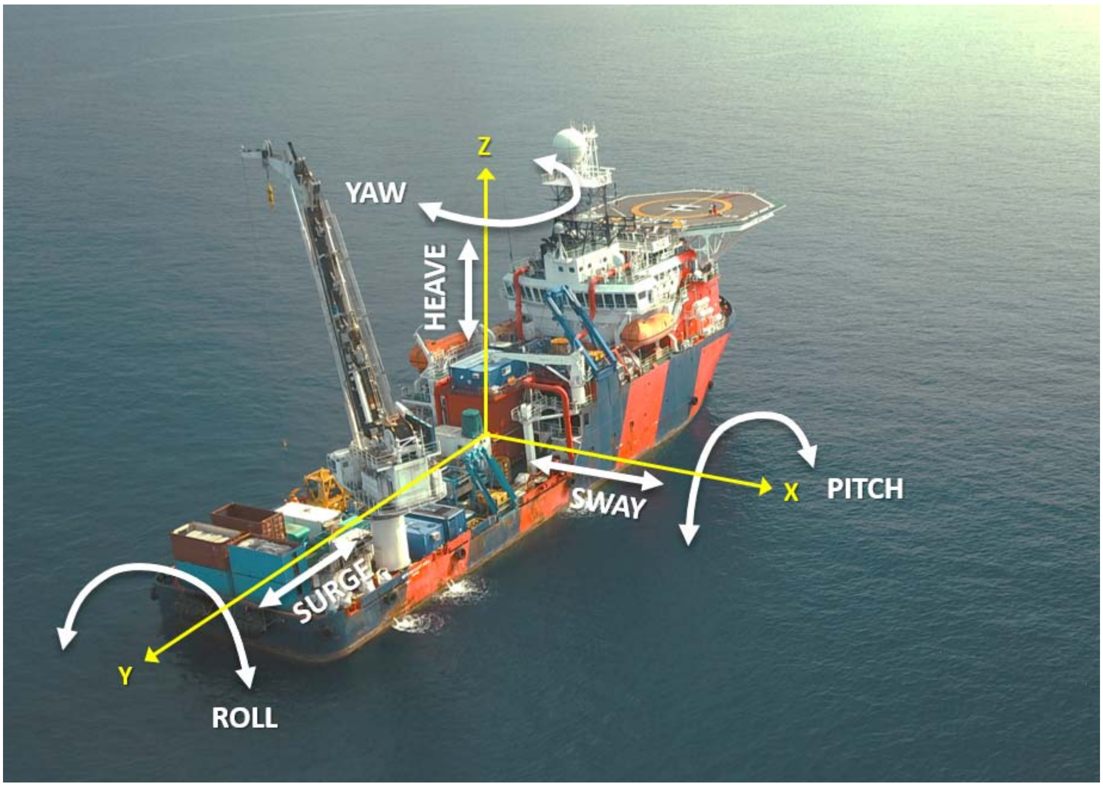


Figure 4-4 Vessel 6 Degrees of Motion (photo courtesy of Shelf Subsea)

Vessel RAOs for a near-identical vessel to the MMA Prestige were obtained and used for the numerical calculations. For simplicity, only heave and roll RAOs were used and a wave heading of 90 deg (beam-on) was applied as a worst-case condition. This scenario was also chosen to give highly exaggerated crane tip motions to allow for clear comparisons between different lifts. RAO tables for the 90 degree wave heading are provided in Appendix B.

4.2.2 DSV Deck Crane

The crane load charts for the 100 t McGregor deck crane include a DAF of 1.33 and the chart states a validity up to wave heights of 1.5 m (refer to Appendix A). The chart also notes "*the max dynamic load capacity must be divided by the actual DAF which should be calculated according to each specific subsea lift at the actual sea state*".

The numerical calculation method compared the results of the lifting analysis to the actual crane capacity of 133 t, which is the capacity without the DAF of 1.33 applied.

4.3 Seastate Range

Analysis was performed for a range of significant wave heights (Hs) and zero up-crossing wave periods (Tz). The Hs was varied from 0.5 m up to 3.0 m as this was considered the maximum conditions any deck operations would normally be allowed on a DSV-sized vessel.

The Tz range was chosen by analysis of the DSV's RAO data. DSV heave and roll responses per metre of Hs were calculated and charted in **Figure *4-5***. **Figure *4-6*** shows the resultant crane tip displacement per m of Hs, using the modified formula from X. Gu et al. Five Tz values around the peak were chosen as the range for the numerical analysis.

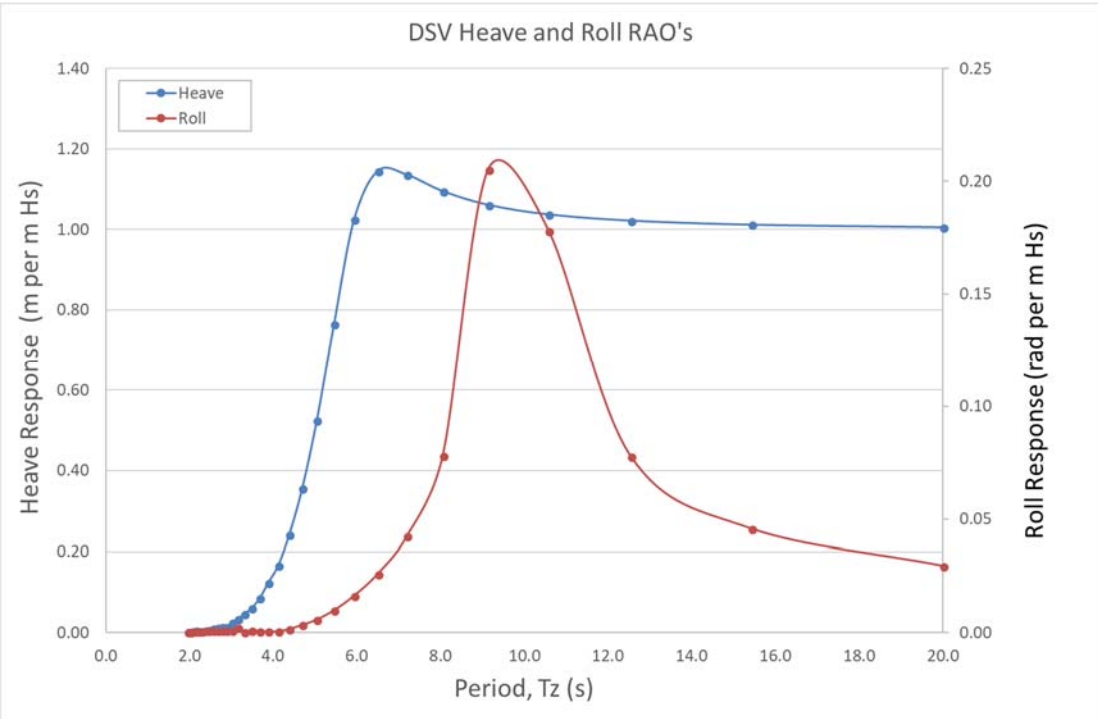


Figure 4-5 DSV RAO's – Heave and Roll Responses

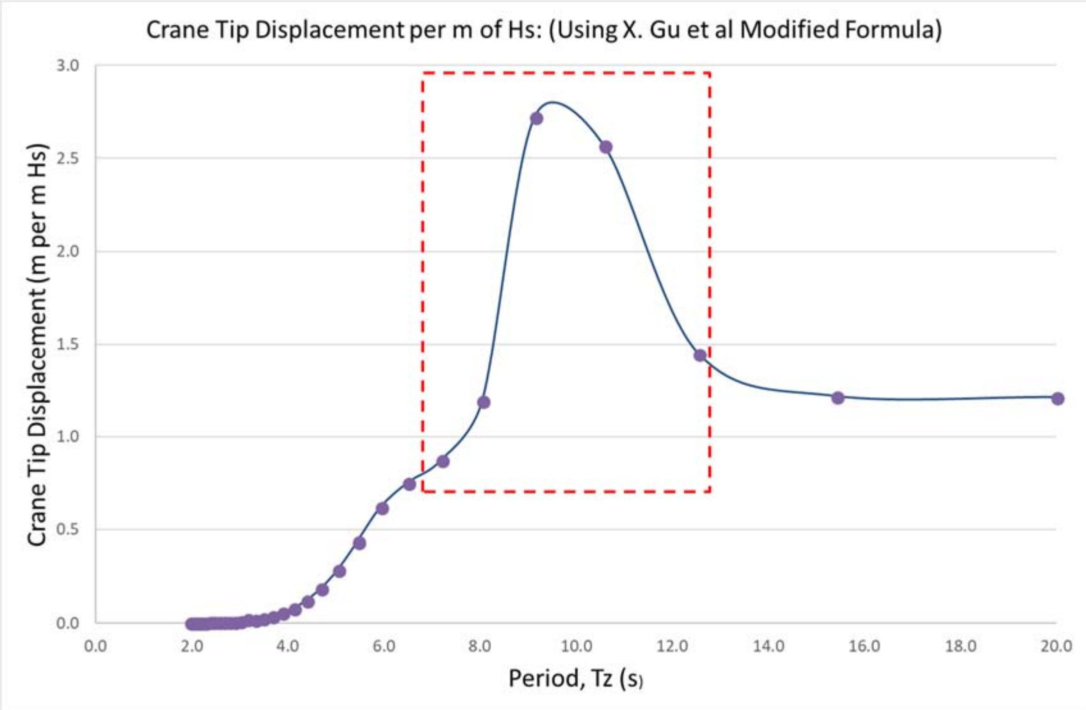


Figure 4-6 Crane Tip Displacement per m Hs with chosen period range

4.4 Criteria for Operable Seastates

The following two criteria were applied to the analysis results to determine if the seastate combinations were operable or non-operable:

4.4.1 Criterion A: Total Hook Load

The total forces on the crane line comprise the total hydrodynamic and static forces. The total force for each of the lifting phases was calculated and the largest was compared to the published crane load limit. Seastate combinations that resulted in forces higher than the crane load limit were deemed non-operable conditions.

4.4.2 Criterion B: No Snap Loads

Snap loading occurs when the hoisting wire becomes slack and is rapidly tensioned causing an impact force. Snap loading is typically many times greater than any other dynamic force and should be avoided by limiting the operating seastates. Conditions for slack crane line occurrence were checked for each seastate combination. Where slack line conditions were identified, the seastate was deemed non-operable.

4.5 Calculation Inputs

The following data was inputted into the calculation:

- Seastate (Hs and Tz)
- Vessel Response Amplitude Operator (RAO) tables
- Crane boom reach
- Deployment water depth
- Crane Line Properties:
  - Unit mass
  - Stiffness
  - Longitudinal friction coefficient
- Lifted Object properties:
  - Mass (in air and water)
  - Vertical projected area
  - Drag coefficient
  - Added Mass coefficient
  - Slamming Coefficient

4.6 Calculation Outputs

The following data was outputted by the calculation:

- Lift Phase 1 - Splash Zone:
  - Total Force (Static + Hydrodynamic)
  - Slack line condition
- Lift Phase 2 – Deepwater Lowering:
  - Total Force (Static + Dynamic)
  - Slack line condition
- DAF – based on highest Total Force.

4.7 Presentation of Results

The OCOLD as proposed by L. Roncetti et al was considered unnecessarily complex for the scale of lifts performed by a DSV. was considered more appropriate for a DSV operator to used. The example operating limits table in **Figure *4-7*** was proposed. It is a go/no-go type of chart similar to the type used T. Boe et al (see **Figure *3-3***) with the additional notation of slack line potential. The values in the cells relate to the largest combined static and dynamic hook load of the two lift phases (splash zone crossing and deepwater lowering). The asterisk denotes where slack line conditions have been met for either of the two lift phases. This format has been used to present the results of the calculation trial lifts.

The example below suggests that the lift could proceed in wave heights up to Hs of 3.0 m, as long as the wave period is short. This gives the operator more flexibility rather than over-constraining by Hs alone, or by a single DAF value.

		Period (Tz)				
		7	8	9	10.5	12.5
Sig. Wave Height (Hs)	0.5	72.7	73.4	80.6	75.9	73.6
	1.0	79.9	81.9	103.3	90.8	85.5
	1.5	88.0	92.2	135.9	112.5	103.1
	2.0	97.3	104.8	177.1 *	140.6 *	126.4 *
	2.5	108.1	119.7	224.3 *	174.3 *	154.5 *
	3.0	120.3	136.9 *	275.1 *	212 *	186.4 *

Operable	Hook Load < Crane Limit, No Slack Line
Non-Operable	Hook Load > Crane Limit, No Slack Line
Non-Operable *	Slack Line

Figure 4-7 Example Operating Limits Table used in the analysis

4.8 Comparison to Guideline Operating Limits

The results of the numerical analysis were compared to several guideline operating limits to determine whether they were over or under-conservative. The following sources were compared:

4.8.1 DNV-ST-0378

DNV-ST-0378 Section 9.2.2.1 "*Cranes Intended for Subsea Lifts*" suggests a minimum DAF of 1.7 for wave heights up to 2.0 m, in lieu of an engineered lift. This factor is independent of the static weight of the object, hydrodynamic properties and wave period.

4.8.2 DNV-ST-0377

DNV-ST-0377 Section 5.4.3 "*Sea Operations*" provides a simple formula for determining a guideline minimum DAF (or hoist load coefficient) for sea operations on a floating vessel (see Equation 4.1). The formula considers actual vessel motions and crane stiffness, but does not consider physical properties of the object being lifted:

$$Hoist\ Load\ Coefficient\colon \psi_{see} = 1 + \frac{v_r}{9.81}\sqrt{\frac{C_S}{L_{Nsee}}} \qquad 4.1$$

4.8.3 DSV Crane Load Chart

The load chart for the crane has a suggested operating limit of Hs 1.5 m and has a DAF of 1.33 already applied to the load values (see Appendix A). The load chart does not consider wave period or the properties of the lifted object.

The numerical analysis results were compared to the crane limit without the DAF applied and the resulting DAF was calculated for each seastate combination. Both the DAF of 1.33 and the Hs limit of 1.5 m were compared to the numerical results.

4.9 Analysis Limitations

The lifting analysis was limited by the following;

1. Only 'light lifts' were considered, defined by Det Norske Veritas (DNV) as the object mass being less than 1 – 2% of the vessel displacement, or less than a few hundred tons. Thus, the effect of the object loads on the vessel motion were ignored and the crane boom was considered as stiff. (in accordance with DNV-RP-N103 – Section 9.1.1.6);
2. Only vertical motions of the object were considered;
3. The effect of current was not considered;
4. Vessel response was limited to Heave and Roll only and wave heading 90° to beam (worse-case for crane tip motion response);
5. The maximum crane speed of 0.5 m/s was used.

4.10 Calculation Sequence

The steps in **Figure *4-8*** were developed to compute the total force at the crane tip for the selected range of Hs and Tz. The sequence builds on the method proposed by T. Boe et al, with the addition of slack line checks and the spash zone lift phase. Example calculation sheets are included in Appendix C. All numbered formulae are referenced from DNV-RP-N103.

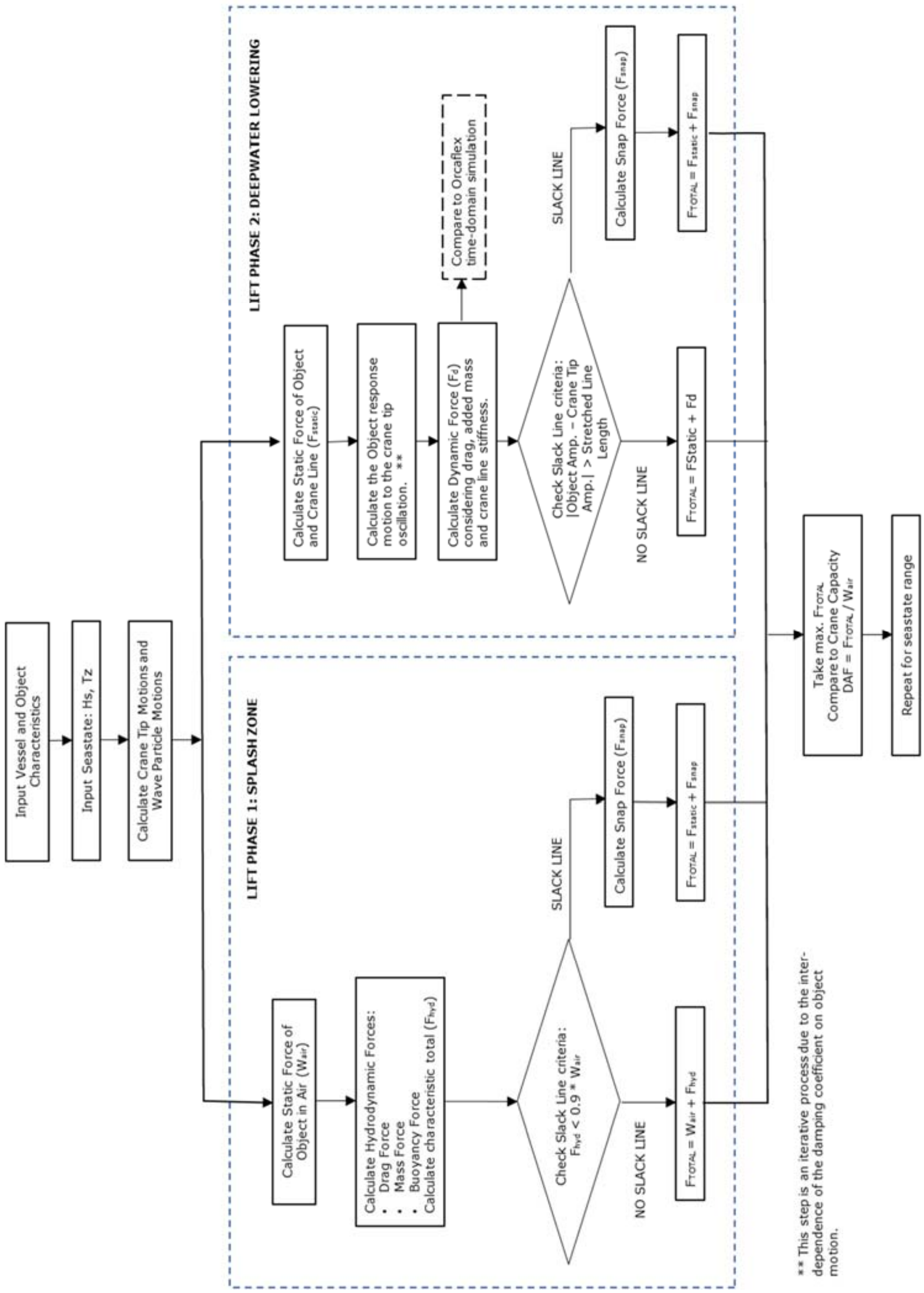


Figure 4-8 Sequence developed for Numerical Calculation

4.11 Time-Domain Simulation

The software Orcaflex was used to model the lifting scenarios to validate the accuracy of the results of the numerical analysis. Orcaflex uses dynamic, non-linear time-domain modelling to simulate marine operations, including the behaviour of flexible lines such as crane wires (Orcina 2007).

The deepwater lowering phase was simulated for each object. The following were inputted into the model:

- DSV RAO's for Roll and Heave for wave heading of 90 degrees;
- Crane stiffness, unit mass, length and position relative to the vessel;
- Object mass, volume, projected area, drag coefficient and hydrodynamic mass.

Regular waves were used (rather than random wave models such as JONSWAP) to give uniform results and avoid the need for long simulation durations. The linear Airy wave theory was used to reduce computational time, rather than the more advanced non-linear wave theories such as Stokes 5th order or Dean stream (Stewart 2008). Of the regular wave types, the Airy wave theory was chosen over Stokes theory for similar ease of computation. Both are appropriate for a simplistic model simulation (Orcina 2007).

The simulation was run for each lift, applying wave heights of 1.0 m, 2.0 m and 3.0 m. The critical wave period of 9.14 seconds was used. Each simulation was run for 30 seconds to obtain crane line tension and object motions.

Figure 4-9 shows the DSV and crane line arrangement in Orcaflex. The vessel shape is purely pictorial, as the response motions are governed by the inputted RAO data. The top of the crane line is coupled to the DSV but offset so that its motion mimics a crane tip. The lifted object is shown as an arbitrary box shape; however, the hydrodynamic loads are calculated by the inputted properties.

Figure *4-10* shows example results charts as follows:

a) Crane Wire Effective Tension
b) Vessel Roll (to check the response motions are as expected)
c) Crane Wire (or 'crane tip') displacement
d) Object displacement

The example is a simulated subsea lift of a 90 t Subsea Cooling Skid from the MMA Prestige with wave height of Hs 2.0 m. The crane wire effective tension chart shows the tension dropping to zero which would signify a slack line and the potential for snap loading.

Figure 4-9 Orcaflex – Simulation Model of DSV Subsea Lift (Orcina)

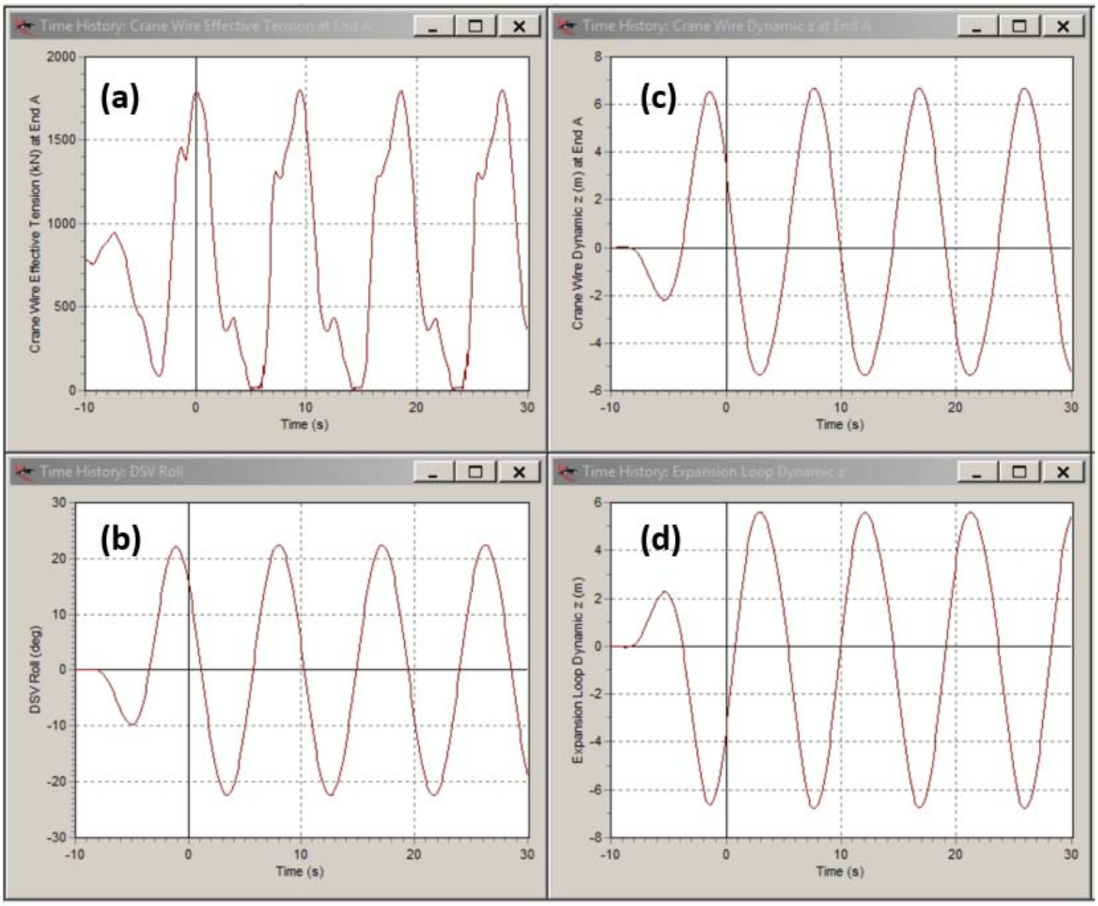


Figure 4-10 Orcaflex – Example Results Data (Orcina)

5.0 CALCULATION DEMONSTRATIONS

Three lifting scenarios were analysed using the numerical calculation method. All three scenarios used the MMA Prestige 100 t deck crane at a reach of 15 m to keep the comparisons uniform. The AHC was not considered. Each example object differed in hydrodynamic properties and deployment depths to observe the effects independently. **Table *5-1*** summarises the properties of the three example objects.

Table 5-1 Summary of example object properties

Property	**Object 1:** Subsea Cooling Skid	**Object 2:** Subsea Pig Launcher	**Object 3:** Expansion Loop Spool
Mass in air (t)	90.0	35.5	39.0
Mass in water (t)	77.7	31.4	38.3
Displaced Volume (m^3)	12.0	4.0	6.0
Projected Area (m^2)	85.2	18.0	26.0
Drag Coefficient	1.16	1.16	1.00
Added Mass Coefficient	0.76	0.76	1.00
Reference Volume (m^3)	12.0	4.0	6.0
Deployment Depth (m)	100	2,000	2,000

5.1 Object 1: Subsea Cooling Skid

The first simulated lift was for a 90 t Subsea Cooling Skid deployed to the maximum design water depth of 100 m. The object serves as a benchmark to compare other lifts due to the following features:

- Mass (in air) of 90 t is close to the published crane limit of 100 t with the recommended minimum DAF of 1.33, which means it is a god test of the crane's ultimate subsea lifting capacity;
- The limited deployment depth of 100 m means the crane line weight and stiffness do not have a significant effect on the lift;
- The skid is rectangular with a flat, perforated bottom which is typical of many subsea structures.

Figure 5-1 Typical Subsea Cooling Skid (Quadrant Energy)

5.2 Object 2: Subsea Automatic Pig Launcher (SAPL)

The second example lift was a 35 t subsea automatic pig launcher (SAPL) being recovered from a subsea template at water depth of 2,000 m. The SAPL was chosen to compare against the benchmark Subsea Cooling Skid for the following reasons;

- The SAPL has a similar geometry to the Subsea Cooling Skid, but a smaller mass. Drag and added mass coefficients are the same;
- The deepwater recovery from 2,000 m introduces an additional static weight of 39.8 t for the crane line, bringing the total static hook load to 74.8 t, relatively close to the Subsea Cooling Skid. The long crane line introduces the damping effects of the crane line stiffness.

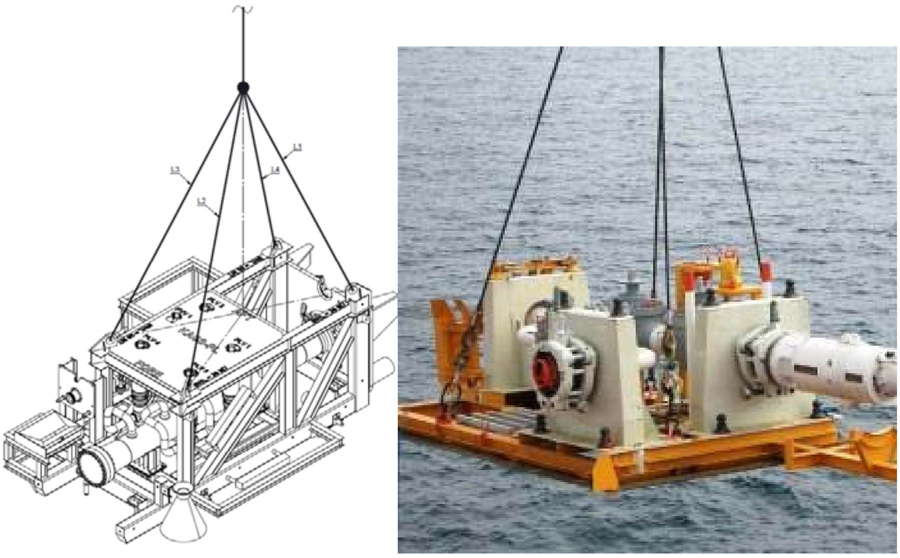


Figure 5-2 Subsea Automatic Pig Launcher (SAPL) (Petronas)

5.3 Object 3: Expansion Loop Spool

The third example lift was a 12” diameter, 55 m long expansion loop spool with concrete weight coat (CWC) and a total dry weight of 39 t. It was to be deployed to the maximum water depth of 2,000 m and installed with the aid of ROVs. The lift requires a minimum 15.0 m boom reach to clear the spool over the side.

The Expansion Loop Spool was chosen for the following reasons;

- The mass (in air) is similar to the SAPL and crane line length remained the same, giving similar total static hook load;
- The submerged volume, projected area and drag coefficient are all higher than the SAPL, which offers a generalised comparison of these effects on the hydrodynamic loads, independent of the deployment depth and static loads.

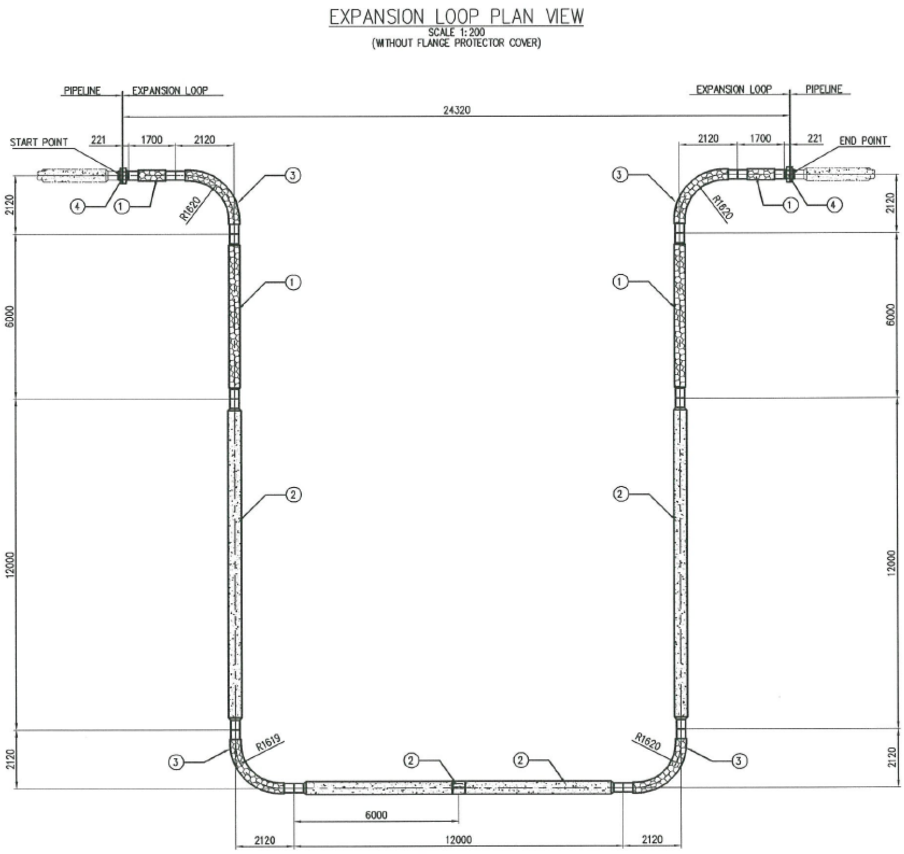


Figure 5-3 Example Expansion Loop Spool (Saka Petroleum)

6.0 SUMMARY OF RESULTS

6.1 General

Numerical calculations were performed for the three example lift scenarios and the results were presented in the seastate matrix form. The lift scenarios were also modelled in Orcaflex to validate the calculation. Numerical calculation sheets are included in Appendix C for each of the three objects and full tabulated results in Appendix D. Orcaflex simulation data is provided in Appendix E.

The following observations were common for all three lifting scenarios:

- The largest vessel motion responses occurred at wave period 9.14 s which is assumed to be the natural harmonic period for the vessel. This gave the largest crane tip motions and subsequent largest dynamic forces;
- The natural frequency for the crane line and object system was around 0.5 to 0.8 s, which placed it far outside the wave period range and not subject to resonance, according to Boe (2010);
- Slack line conditions were not met during the deepwater phase. This is due to both the crane line flexibility and the small projected area and drag of the lifted objects.

6.2 Object 1: Subsea Cooling Skid

6.2.1 Numerical Analysis Results

The results of the numerical analysis are included in Appendix D and presented as Operating Limits Table in **Table *6-1***. The following observations were made;

- The lift was determined to be operable at Hs ≤ 0.5 m, with limited operability at Hs of 1.0 m at wave periods outside the vessel natural roll period;
- Operating conditions were limited coincidently with both the splash zone and deepwater lowering phases at Hs of 1.0 m;
- Slack line conditions were observed at Hs ≥ 1.5 m.

Table 6-1 Object 1: Subsea Cooling Skid – Operating Limits Table

Sig. Wave Height (Hs)	Period (Tz) → 7	8	9	10.5	12.5
0.5	111.9	112.9	122.5	119.4	119.1
1.0	124.5	128.7	166.6	154.1	153.5
1.5	140.1	149.3	265.5 *	204 *	203.1 *
2.0	158.4	174.3 *	398.2 *	293.1 *	266 *
2.5	179 *	204.2 *	559.3 *	403.6 *	350.4 *
3.0	202.1 *	255.3 *	742.3 *	531.6 *	457.8 *

6.2.2 Time-Domain Simulation Results

Table *6-2* shows the results of the Orcaflex simulation compared to the numerical calculation for the deepwater lowering phase. The full data is included in Appendix E. The object displacement had close agreement between the methods, but the loads differed dramatically by 18 to 54%. It can be seen from the chart that 'zero' load occurs during each oscillation for wave heights of 2.0 m and 3.0m. This signifies a slack line condition which concurred with the numerical calculation results.

Table 6-2 Object 1: Subsea Cooling Skid – Orcaflex Results

Hs	Numerical Analysis		Orcaflex Simulation	
	Object Displ. (m)	Max. Hook Load (t)	Object Displ. (m)	Max. Hook Load (t)
1.0 m	6.3	166.6	6.2	112.3
2.0 m	12.3	398.2	12.2	182.2
3.0 m	17.8	742.3	18.5	607.1

6.2.3 Discussion

The operating limits for the Subsea Cooling Skid lift were as expected, considering the static load was close to the crane capacity of 100 t with the manufacturer's recommended DAF of 1.33 applied. This shows that the recommended DAF of 1.33 is quite suitable and not overly restrictive.

Dynamic forces during the deepwater lowering phase were considerably high due to the large vertical projected area creating high drag forces during heaving. The short crane line offered little spring damping.

Table *6-3* shows how various sources of guideline operating limits compare to the results of the numerical analysis.

Table 6-3 Object 1: Subsea Cooling Skid – Comparison to Guideline Limits

Source	Comparison to Numerical Analysis
DNV-ST-0378 (DAF of 1.7)	Slightly Under-conservative
DNV-ST-0377 (DAF varies by Hs)	Highly Under-conservative
Crane Load Chart (DAF of 1.33, Hs ≤ 1.5 m)	Moderately Over-conservative

DNV-ST-0378 (DAF of 1.7) — ST-0378 CUTOFF

Sig. Wave Height (Hs)	Period (Tz) 7	8	9	10.5	12.5
0.5	111.9	112.9	122.5	119.4	119.1
1.0	124.5	128.7	166.6	154.1	153.5
1.5	140.1	149.3	265.5 *	204 *	203.1 *
2.0	158.4	174.3 *	398.2 *	293.1 *	266 *
2.5	179 *	204.2 *	559.3 *	403.6 *	350.4 *
3.0	202.1 *	255.3 *	742.3 *	531.6 *	457.8 *

Comparison to Numerical Analysis: Slightly Under-conservative

DNV-ST-0377 (DAF varies by Hs) — ST-0377 CUTOFF

Sig. Wave Height (Hs)	Period (Tz) 7	8	9	10.5	12.5
0.5	111.9	112.9	122.5	119.4	119.1
1.0	124.5	128.7	166.6	154.1	153.5
1.5	140.1	149.3	265.5 *	204 *	203.1 *
2.0	158.4	174.3 *	398.2 *	293.1 *	266 *
2.5	179 *	204.2 *	559.3 *	403.6 *	350.4 *
3.0	202.1 *	255.3 *	742.3 *	531.6 *	457.8 *

Comparison to Numerical Analysis: Highly Under-conservative

Crane Load Chart (DAF of 1.33, Hs ≤ 1.5 m) — CRANE CURVE CUTOFF

Sig. Wave Height (Hs)	Period (Tz) 7	8	9	10.5	12.5
0.5	111.9	112.9	122.5	119.4	119.1
1.0	124.5	128.7	166.6	154.1	153.5
1.5	140.1	149.3	265.5 *	204 *	203.1 *
2.0	158.4	174.3 *	398.2 *	293.1 *	266 *
2.5	179 *	204.2 *	559.3 *	403.6 *	350.4 *
3.0	202.1 *	255.3 *	742.3 *	531.6 *	457.8 *

Comparison to Numerical Analysis: Moderately Over-conservative

6.3 Object 2: Subsea Automatic Pig Launcher (SAPL)

6.3.1 Numerical Analysis Results

The results of the numerical analysis are included in Appendix D and presented as Operating Limits Table in **Table *6-4***. The following observations were made;

- The lift was determined to be fully operable at Hs ≤ 1.0 m and partially operable up to Hs of 3.0 m provided the wave period is short;
- Operating conditions were limited by dynamic loads during the deepwater lowering phase only. Crane limits were exceeded during the splash zone crossing phase;
- Slack line conditions were observed at Hs ≥ 2.0 m.

Table 6-4 Object 2: SAPL – Operating Limits Table

Sig. Wave Height (Hs)	Period (Tz) → 7	8	9	10.5	12.5
0.5	72.7	73.4	80.6	75.9	73.6
1.0	79.9	81.9	103.3	90.8	85.5
1.5	88.0	92.2	135.9	112.5	103.1
2.0	97.3	104.8	177.1 *	140.6 *	126.4 *
2.5	108.1	119.7	224.3 *	174.3 *	154.5 *
3.0	120.3	136.9 *	275.1 *	212 *	186.4 *

6.3.2 Time-Domain Simulation Results

Table 6-5 shows the results of the Orcaflex simulation compared to the numerical calculation for the deepwater lowering phase. The full data is included in Appendix E. The object displacement was reasonably close to the numerical analysis results and the maximum loads were within 9 to 30%. A slack line was observed at wave height of 3.0 m, whereas the numerical analysis suggested this would occur at 2.0 m.

Table 6-5 Object 2: SAPL – Orcaflex Results

Hs	Numerical Analysis		Orcaflex Simulation	
	Object Displ. (m)	Max. Hook Load (t)	Object Displ. (m)	Max. Hook Load (t)
1.0 m	6.9	103.3	7.4	88.0
2.0 m	13.2	177.1	14.8	124.3
3.0 m	18.4	275.1	22.0	249.6

6.3.3 Discussion

The smaller mass and dimensions of the SAPL compared to the Cooling Skid resulted in significantly lower hydrodynamic loads in the splash zone. During deepwater lowering the effects of the 2000 m crane line produced comparable total hook loads.

The results showed operable seastates up to Hs of 3.0 m, however the restricted wave periods would likely prevent any operations Hs of 1.5 m.

Table *6-6* shows how various sources of guideline operating limits compare to the results of the numerical analysis.

Table 6-6 Object 2: SAPL – Comparison to Guideline Limits

Source	Comparison to Numerical Analysis
DNV-ST-0378 (DAF of 1.7)	Slightly Over-conservative
DNV-ST-0377 (DAF varies by Hs)	Moderately Over-conservative
Crane Load Chart (DAF of 1.33, Hs ≤ 1.5 m)	Highly Over-conservative

DNV-ST-0378 (DAF of 1.7) — ST-0378 CUTOFF

Sig. Wave Height (Hs)	Period (Tz) 7	8	9	10.5	12.5
0.5	72.7	73.4	80.6	75.9	73.6
1.0	79.9	81.9	103.3	90.8	85.5
1.5	88.0	92.2	135.9	112.5	103.1
2.0	97.3	104.8	177.1 *	140.6 *	126.4 *
2.5	108.1	119.7	224.3 *	174.3 *	154.5 *
3.0	120.3	136.9 *	275.1 *	212 *	186.4 *

DNV-ST-0377 (DAF varies by Hs) — ST-0377 CUTOFF

Sig. Wave Height (Hs)	Period (Tz) 7	8	9	10.5	12.5
0.5	72.7	73.4	80.6	75.9	73.6
1.0	79.9	81.9	103.3	90.8	85.5
1.5	88.0	92.2	135.9	112.5	103.1
2.0	97.3	104.8	177.1 *	140.6 *	126.4 *
2.5	108.1	119.7	224.3 *	174.3 *	154.5 *
3.0	120.3	136.9 *	275.1 *	212 *	186.4 *

Crane Load Chart (DAF of 1.33, Hs ≤ 1.5 m) — CRANE CURVE CUTOFF

Sig. Wave Height (Hs)	Period (Tz) 7	8	9	10.5	12.5
0.5	72.7	73.4	80.6	75.9	73.6
1.0	79.9	81.9	103.3	90.8	85.5
1.5	88.0	92.2	135.9	112.5	103.1
2.0	97.3	104.8	177.1 *	140.6 *	126.4 *
2.5	108.1	119.7	224.3 *	174.3 *	154.5 *
3.0	120.3	136.9 *	275.1 *	212 *	186.4 *

6.4 Object 3: Expansion Loop Spool

6.4.1 Numerical Analysis Results

The results of the numerical analysis are included in Appendix D and presented as Operating Limits Table in **Table *6-7***. The following observations were made;

- The lift was determined to be fully operable at Hs ≤ 1.0 m and partially operable up to Hs of 3.0 m provided the wave period is short;
- Operating conditions were limited by dynamic loads during the deepwater lowering phase only. Crane limits were only exceeded during the splash zone crossing phase at the most extreme seastate condition;
- Slack line conditions were observed at Hs ≥ 1.5 m.

Table 6-7 Object 3: Expansion Loop - Operating Limits Table

		Period (Tz)				
		7	8	9	10.5	12.5
Sig. Wave Height (Hs)	0.5	74.9	75.7	83.9	78.5	75.9
	1.0	83.0	85.3	110.4	95.9	89.8
	1.5	92.3	97.2	148.4 *	121.4	110.6
	2.0	103.2	111.9	195.6 *	154.3 *	137.9 *
	2.5	115.7	129.3	248.6 *	193.1 *	170.7 *
	3.0	129.7	149.1 *	304.6 *	236 *	207.7 *

6.4.2 Time-Domain Simulation Results

Table *6-8* shows the results of the Orcaflex simulation compared to the numerical calculation for the deepwater lowering phase. The full data is included in Appendix E. Again, the object displacement was reasonably close between the methods and the maximum loads were within 8 to 22%. The Orcaflex results suggested a slack line would occur at wave height of 3.0 m, compared to the numerical analysis at 1.5 m.

Table 6-8 Object 3: Expansion Loop – Orcaflex Results

Hs	Numerical Analysis		Orcaflex Simulation	
	Object Displ. (m)	Max. Hook Load (t)	Object Displ. (m)	Max. Hook Load (t)
1.0 m	6.9	110.4	7.7	94.0
2.0 m	13.1	195.6	15.0	152.0
3.0 m	18.1	304.6	17.0	280.0

6.4.3 Discussion

The operating limits table for the Expansion Loop Spool was identical to the SAPL in terms of operable seastates. However, the total hook loads were around 5 to 10% higher across all seastates and slack line conditions occurred at a lower Hs of 1.0 m. This was due to the higher drag, volume and projected area of the Expansion Loop.

Table *6-9* shows how various sources of guideline operating limits compare to the results of the numerical analysis.

Table 6-9 Object 3: Expansion Loop Spool – Comparison to Guideline Limits

Source	Comparison to Numerical Analysis
DNV-ST-0378 (DAF of 1.7)	Moderately Over-conservative
DNV-ST-0377 (DAF varies by Hs)	Highly Over-conservative
Crane Load Chart (DAF of 1.33, Hs ≤ 1.5 m)	Highly Over-conservative

DNV-ST-0378 (DAF of 1.7)

Sig. Wave Height (Hs)	Period (Tz)				
	7	8	9	10.5	12.5
0.5	74.9	75.7	83.9	78.5	75.9
1.0	83.0	85.3	110.4	95.9	89.8
1.5	92.3	97.2	148.4 *	121.4	110.6
2.0	103.2	111.9	195.6 *	154.3 *	137.9 *
2.5	115.7	129.3	248.6 *	193.1 *	170.7 *
3.0	129.7	149.1 *	304.6 *	236 *	207.7 *

ST-0378 CUTOFF

Moderately Over-conservative

DNV-ST-0377 (DAF varies by Hs)

Sig. Wave Height (Hs)	Period (Tz)				
	7	8	9	10.5	12.5
0.5	74.9	75.7	83.9	78.5	75.9
1.0	83.0	85.3	110.4	95.9	89.8
1.5	92.3	97.2	148.4 *	121.4	110.6
2.0	103.2	111.9	195.6 *	154.3 *	137.9 *
2.5	115.7	129.3	248.6 *	193.1 *	170.7 *
3.0	129.7	149.1 *	304.6 *	236 *	207.7 *

ST-0377 CUTOFF

Highly Over-conservative

Crane Load Chart (DAF of 1.33, Hs ≤ 1.5 m)

Sig. Wave Height (Hs)	Period (Tz)				
	7	8	9	10.5	12.5
0.5	74.9	75.7	83.9	78.5	75.9
1.0	83.0	85.3	110.4	95.9	89.8
1.5	92.3	97.2	148.4 *	121.4	110.6
2.0	103.2	111.9	195.6 *	154.3 *	137.9 *
2.5	115.7	129.3	248.6 *	193.1 *	170.7 *
3.0	129.7	149.1 *	304.6 *	236 *	207.7 *

CRANE CURVE CUTOFF

Highly Over-conservative

7.0 DISCUSSION

The following sections discuss various observations on the performance and suitability of the numerical calculation method.

7.1 General Validity of the Numerical Calculation Method

The results of the numerical calculation trials appear to be reasonable, given their close comparison with both the Orcaflex simulation and the various guideline DAFs. The results must certainly be of similar magnitude to reality. In calm seastates the dynamic loads are typically less than the static weight (DAF of less than 2.0). The extreme dynamic loads seen at Hs of 3.0 m and wave period equal to the vessel harmonic should be expected given the vessel is beam-to the prevailing wave with the crane boom directly outboard. In a real operation this would be avoided by turning the vessel into the weather.

7.2 Orcaflex Validity Check

The dynamic loads from the Orcaflex simulations were lower than the numerical calculation by varying degrees. The simulation software is highly sophisticated and relies on detailed inputs for many more properties than those given for the trials. It is presumed that many of the inputs that were neglected for the trials would influence the resulting dynamic loads. Therefore, the results were only used as a general guide to check that the numerical calculation results were within reasonable closeness. The difference of 8 to 54% was considered a confirmation of the validity of the numerical calculation.

7.3 Numerical Calculation Method Trials

The results of the three trials successfully proved the performance of the calculation method by modifying object properties and crane line lengths. The effects of the changes were as expected. Namely;

- Object 1 (Subsea Cooling Skid) produced high total loads due to the large static weight being close to the crane limit;
- Object 2 (SAPL) had similar properties and total static weight but was subject to a long crane line. The effect was significantly lower total loads to Object 1;

- Object 3 (Expansion Loop Spool) was similar to Object 2 but had higher drag and added mass properties. Results showed a slight increase in dynamic loads.

7.4 Improvements to the Numerical Calculation Method

The following could be considered for further improving the numerical calculation method.

7.4.1 Lifting Phases

The numerical calculations were limited to only two phases of a lift: Splash zone crossing and deepwater lowering. Other phases that generate dynamic loads include; Lift-off from the deck, landing on the seabed and landing on another vessel at sea. These phases can have high potential for snap loading due to the object being at rest on a surface while still connected to the moving crane tip.

7.4.2 Crane Tip Motion Formulae

The modified formulae proposed by X. Gu et al were used for the crane tip motion rather than those presented in DNV-RP-N103. **Figure *7-1*** shows the difference between the two formulae sets specifically for the lifting trials. The crane tip acceleration and displacement are higher than the DNV-RP-N103 formulae by 35% and 13% respectively. Crane tip motions directly influence the resulting dynamic loads. It was therefore expected that if the original DNV-RP-N103 formulae were used in the numerical analysis then the results would closely match Orcaflex. However, since the Orcaflex model was rudimentary and only moderately reliable, it was decided that the X. Gu et al should be continued.

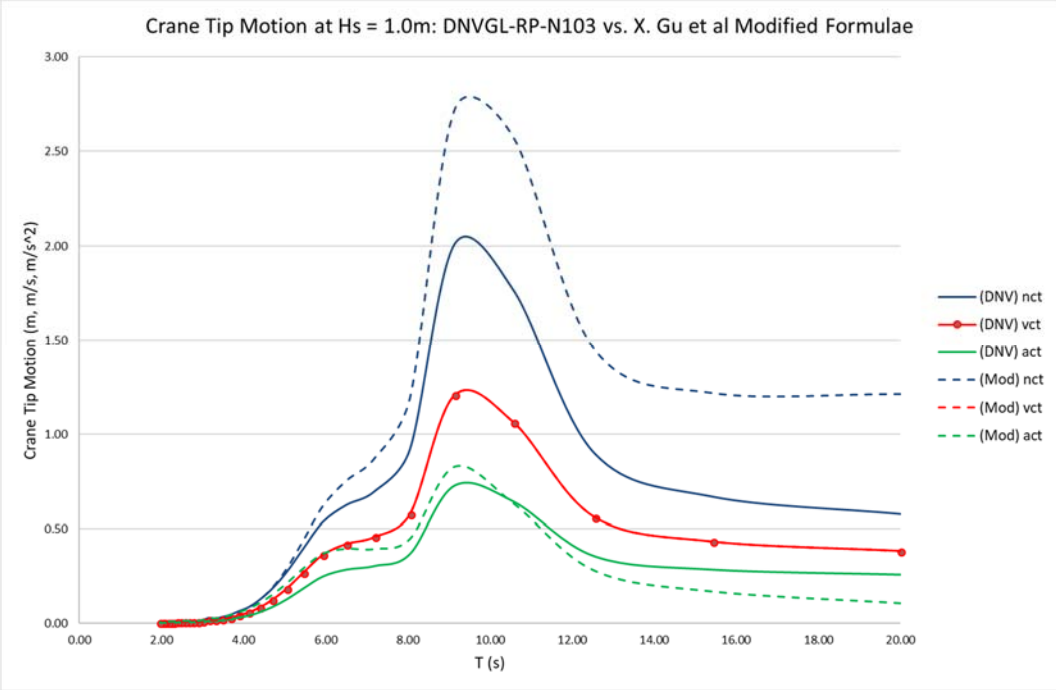


Figure 7-1 Crane Tip Motions - X. Gu et al vs DNV-RP-N103

7.4.3 Operating Limits Tables

The numerical calculations and resultant operating limits tables were both in terms of Hs as this is common language in the industry and vessel operators are accustomed to determining Hs when monitoring seastate conditions. However, Hs is not the highest possible wave height that a lifting operation may encounter. The maximum expected wave height is a statistical determination based on the probability of its occurrence during the lift, as shown in Equation 7.1 (RGU 2015a):

$$H_{max} = H_s \sqrt{-\frac{1}{2}\ln\left(1-(1-P)^{\frac{1}{N_z}}\right)} \qquad (7.1)$$

H_{max} = Maximum probable wave height

P = Probability of H_{max} occurring during operation

N_z = No. of Waves during operation

An example case was calculated for the seastate Hs 3.0 m and Tz 9.14 s. During a 10 minute lifting operation a maximum wave height of 4.4 m has a probability of 5% of occurring. This wave height would significantly increase the dynamic loads calculated based on Hs alone. Clauss (1990) claim that lifting operations are generally too short to consider H_{max}, however it is proposed that subsea lifts be risk assessed in terms of the expected duration and the acceptable probability of H_{max} occurrence. The numerical calculation could then be based on the probable H_{max} rather than Hs.

7.5 Comparison of Numerical Calculation Method to Common Guidelines

The numerical calculation method was compared to some guideline DAFs to observe how they limit the lifting operation, but ultimately to decide whether the additional work involved in performing the numerical method was worthwhile;

7.5.1 DNV-ST-0378

The simple guideline DAF of 1.7 suggested by DNV-ST-0378 section 9.2.2.1 proved to be slightly under-conservative for the large load of Object 1, but over-conservative for Objects 2 and 3. If used for Objects 2 and 3, the DSV lifting operations may be overly restricted, hence using the numerical method would offer greater operational time.

7.5.2 DNV-ST-0377

The formula for DAF given in DNV-ST-0377 section 5.4.3.2.1 appeared to be simple, however it still required the relative velocity between the crane hook and the object. This would require some extensive analysis similar to what was performed for the numerical calculation method, or else reference some statistical data. The crane stiffness is also required which may not be easily acquired. The results were highly under-conservative for Object 1 and highly over-conservative for Objects 2 and 3. Again, the numerical calculation method would be recommended for all three lifts.

7.5.3 Crane Curve

The crane curve nominal DAF of 1.33 and Hs limit of 1.5 m was over-conservative for all three lifts. It is noted that the crane curve recommends a full numerical calculation for subsea lifts.

8.0 CONCLUSIONS

The following conclusions were made based on the aims of the project: (a) Produce a valid numerical calculation method for subsea lifting and (b) Assess the suitability compared to more simple methods to determine operating limits.

8.1 Performance of the numerical calculation method

The numerical calculation method was developed and validated by comparing to time-domain simulation modelling and by observing the results during three trial lifts. The simulation modelling was only moderately aligned with the numerical calculation due to only partial utilisation of all the features and sophistication of the software.

The numerical calculation method was limited to only two phases of a subsea lift and could be improved by considering the entire sequence from lift-off to touch-down of the load. Other improvement potentials include consideration for maximum wave heights and investigation into the suitability of the crane tip motion formulae.

The numerical calculation method outputted a simple operating limits table. This style of presentation was considered an improvement on simply stating a Hs or DAF value alone, as it considers both Hs and Tz, offering potential for more flexibility by the operator.

8.2 Value of the Numerical Calculation Method

The value of performing a full engineering analysis for small-scale subsea lifts was investigated by comparing the results to simple guidelines. The guidelines proved to be both under and over-conservative for different lifting scenarios. Where guidelines are under-conservative they have the potential to place the lift at risk. Where guidelines are over-conservative they restrict the lifting operation unnecessarily, causing expensive project delays.

The comparison demonstrated the value of performing full engineering analysis for small-scale subsea lifts to ensure that seastate operating limits are safe and suitably conservative.

9.0 REFERENCES

BOE, T. and NESTEGARD, A., 2010. *Dynamic Forces during Deepwater Lifting Operations.* Det Norske Veritas, Norway. June 2010.

CLAUSS, G. F. et al., 1990. *Operational Limitations of Offshore Crane Vessels.* Offshore Technology Conference. Houston, 7 May 1990.

DASGUPTA, S., 2016. *Skandi Arctic: The Biggest Saturation Dive Support Vessel* [online]. Marine Insight. Available from: https://www.marineinsight.com/types-of-ships/skandi-arctic-the-biggest-saturation-dive-support-vessel/ [Accessed 10 June 2018]

DET NORSKE VERITAS, 2017. *DNV-RP-N103 Modelling and Analysis of marine Operations.* Norway. July 2017.

DET NORSKE VERITAS, 2016. *DNV-ST-0377 Standard for Shipboard Lifting Appliances.* Norway. May 2016.

DET NORSKE VERITAS, 2016. *DNV-ST-0378 Standard for Offshore and Platform Lifting Appliances.* Norway. May 2016.

GU, X et al., 2017. *Re-Evaluation of DNV Simplified Formulae for Crane Tip Motions.* IKM. Norway, December 2017.

ORCINA, 2007. *Orcaflex Manual Version 9.1a.* Cumbria, UK. 2007.

RGU, 2015a. *ENM215: Oceans - Lecture Notes – Topic 2c: Statistical Analysis of Seastates.* Robert Gordon University. Delivered March 2015.

RGU, 2015b. *ENM215: Oceans - Lecture Notes – Topic 2f: The Effects of Waves on Floating Vessels.* Robert Gordon University. Delivered March 2015.

STEWART, R. H., 2008. *Introduction to Physically Oceanography.* Texas A & M University. September 2008 Edition.

APPENDIX A

CRANE LOAD CHARTS

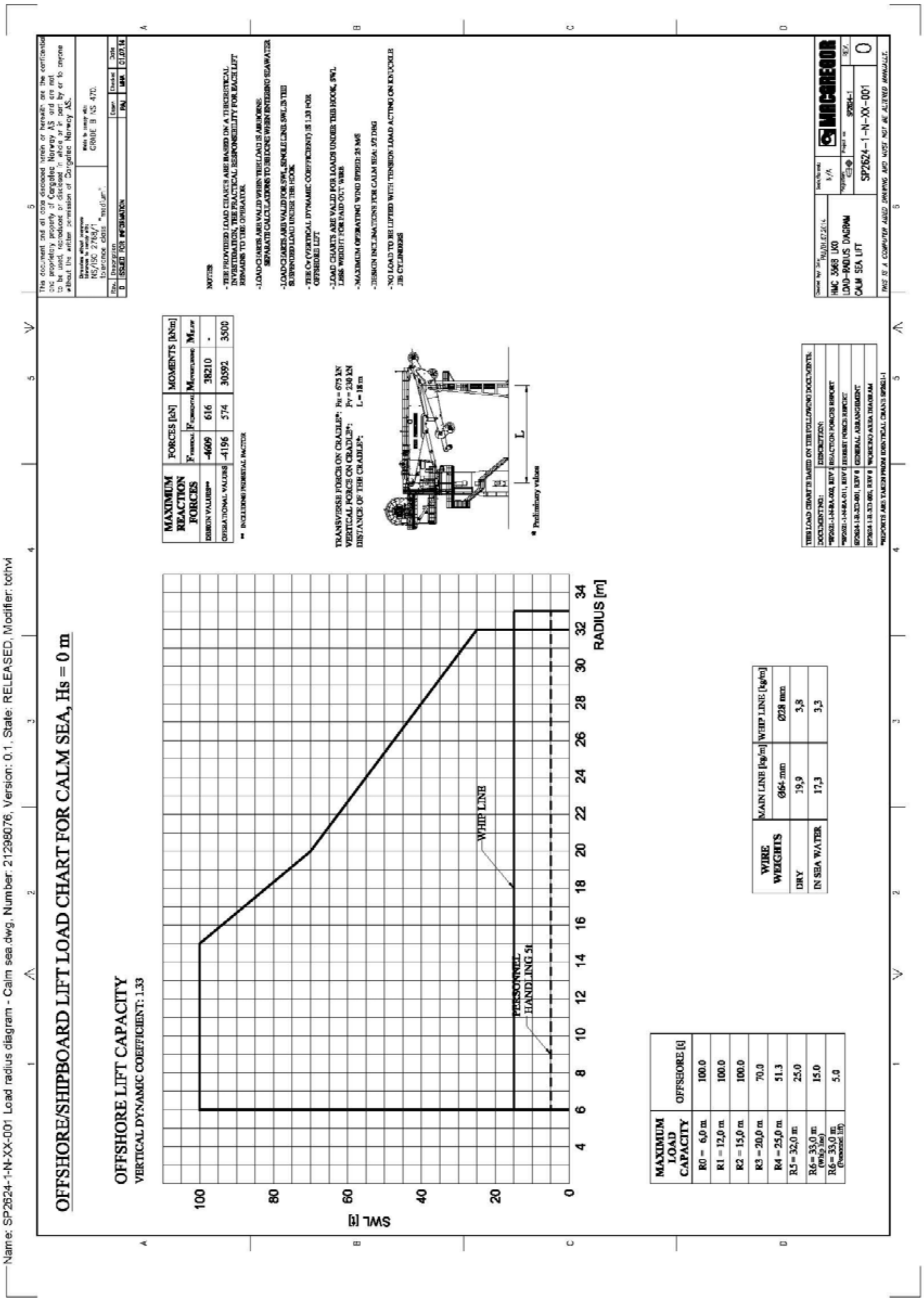


Figure 9-1 MMA Prestige 100 t Crane Load Chart (Sheet 1)

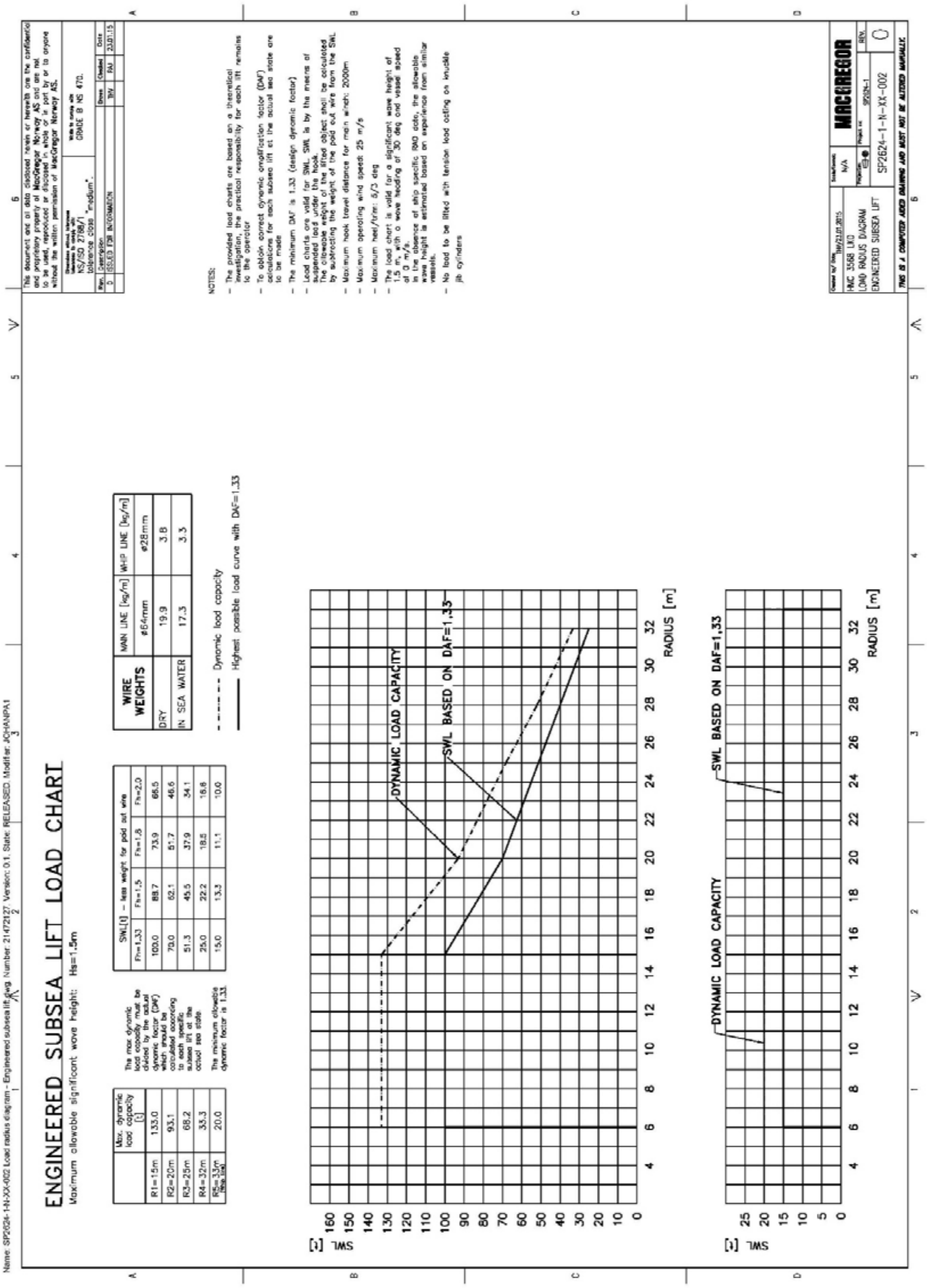


Figure 9-2 MMA Prestige 100 t Crane Load Chart (Sheet 2)

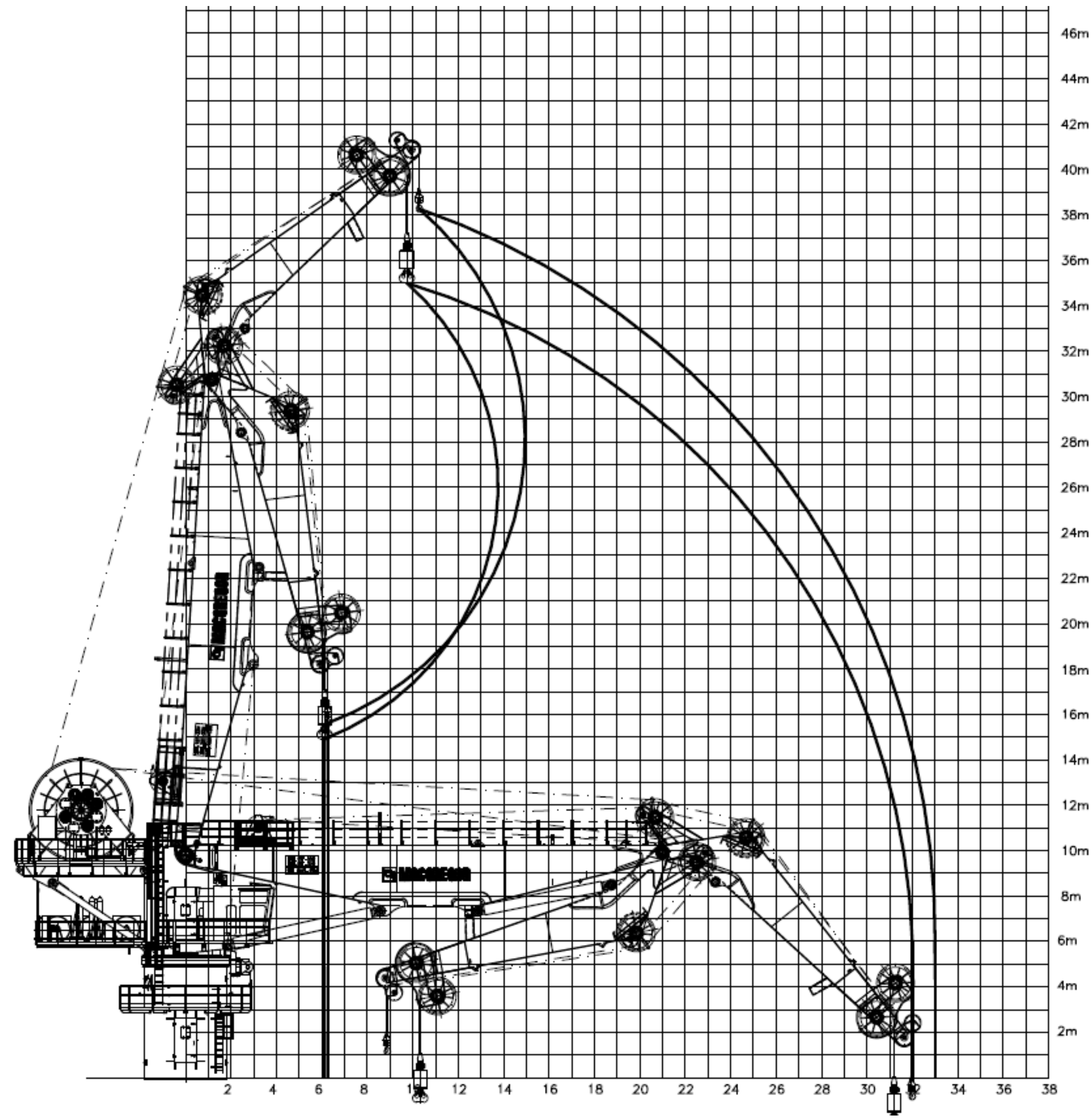


Figure 9-3 MMA Prestige 100 t Crane Load Chart (Sheet 3)

APPENDIX B

DSV RAO DATA

RAO Data for NPP Nusantara (80m DSV) - 90º Wave Heading

Period	Surge		Sway		Heave		Roll		Pitch		Yaw	
	X		Y		Z		RX		RY		RZ	
s	Amp	Phase	Amp	Phase	Amp	Phase	Amp	Phase	Amp	Phase	Amp	Phase
20.00	0.01	179.45	2.38	-90.03	1.01	0.04	1.69	-85.91	0.01	-179.61	0.01	99.42
15.42	0.01	178.89	1.81	-90.06	1.01	0.16	2.63	-83.36	0.02	-178.71	0.03	103.33
12.55	0.01	177.30	1.45	-89.93	1.02	0.45	4.45	-77.88	0.04	-176.68	0.06	111.03
10.58	0.01	173.13	1.20	-88.02	1.04	1.09	10.20	-56.98	0.07	-172.72	0.18	135.56
9.14	0.01	164.24	0.88	-91.40	1.06	2.37	11.77	39.38	0.12	-165.70	0.30	-122.43
8.05	0.02	154.39	0.78	-95.77	1.10	4.93	4.48	66.34	0.21	-154.09	0.17	-87.48
7.19	0.03	154.98	0.68	-98.63	1.14	10.10	2.44	70.83	0.34	-136.31	0.14	-72.94
6.50	0.05	170.20	0.58	-102.45	1.15	19.92	1.50	70.93	0.52	-110.94	0.13	-61.90
5.93	0.06	-163.80	0.50	-107.39	1.02	34.38	0.94	68.83	0.66	-77.94	0.12	-54.27
5.45	0.06	-135.48	0.43	-113.56	0.77	46.41	0.57	63.65	0.62	-44.34	0.12	-52.65
5.04	0.05	-113.62	0.37	-121.18	0.53	50.78	0.33	53.19	0.46	-21.09	0.12	-56.12
4.69	0.04	-101.46	0.32	-130.35	0.36	49.34	0.20	39.57	0.31	-12.33	0.13	-58.08
4.38	0.03	-97.92	0.27	-140.83	0.24	43.19	0.10	25.13	0.22	-14.66	0.13	-58.72
4.12	0.02	-99.45	0.23	-152.40	0.17	33.22	0.03	-28.38	0.17	-21.64	0.13	-63.05
3.88	0.02	-104.67	0.19	-165.50	0.12	20.98	0.04	-107.39	0.13	-32.73	0.13	-69.69
3.67	0.01	-111.52	0.16	179.65	0.09	5.16	0.05	-151.46	0.10	-47.75	0.12	-76.21
3.48	0.01	-97.88	0.14	163.29	0.06	-9.13	0.06	177.75	0.16	-67.05	0.11	-84.67
3.31	0.01	-125.94	0.12	146.22	0.05	-25.49	0.02	-134.18	0.08	-79.29	0.10	-94.44
3.15	0.01	-136.70	0.08	117.48	0.04	-45.78	0.12	115.85	0.07	-94.76	0.09	-93.09
3.01	0.01	-149.72	0.08	104.63	0.03	-65.75	0.05	104.93	0.06	-112.38	0.08	-121.09
2.88	0.00	-160.71	0.07	82.12	0.01	-84.33	0.05	75.86	0.05	-130.32	0.07	-137.91
2.77	0.00	177.88	0.06	57.22	0.02	-114.68	0.06	50.05	0.04	-149.64	0.05	-154.64
2.66	0.00	155.10	0.05	33.14	0.01	-137.11	0.06	22.71	0.04	-172.57	0.05	-175.19
2.56	0.00	129.32	0.05	8.07	0.01	-160.09	0.06	-0.61	0.03	161.91	0.04	156.73
2.46	0.00	80.25	0.04	-20.66	0.01	170.90	0.06	-28.17	0.03	139.78	0.03	125.51
2.38	0.00	34.27	0.04	-47.17	0.01	143.48	0.05	-52.30	0.02	115.02	0.03	92.46
2.29	0.00	10.27	0.03	-73.55	0.00	114.33	0.05	-81.87	0.02	86.37	0.03	59.51
2.22	0.00	-28.41	0.03	-101.85	0.00	74.10	0.05	-105.57	0.02	57.51	0.03	26.05
2.15	0.00	-45.36	0.02	-130.65	0.00	51.49	0.04	-133.34	0.02	34.22	0.03	-2.96
2.08	0.00	-69.87	0.02	-158.93	0.00	24.85	0.04	-159.56	0.01	9.35	0.02	-36.00
2.02	0.00	-85.24	0.02	161.05	0.00	-3.48	0.03	157.43	0.01	-25.37	0.03	-59.70
1.96	0.00	-111.59	0.02	129.16	0.00	-36.52	0.03	127.48	0.01	-57.14	0.02	-92.36

Data used for the numerical calculation trials

Table 9-1 DSV Response Amplitude Operators (RAO)

APPENDIX C

NUMERICAL CALCULATION SHEETS

SUBSEA LIFTING ANALYSIS

Object 1: Subsea Cooling Skid - Deployed to 100 m

Constants:

Density of seawater	$\rho := 1025 \frac{kg}{m^3}$	
Complex number	$i := \sqrt{-1}$	
Gravity	$g := 9.81 \frac{m}{s^2}$	
Position along crane line	$z := 0\ m$	

General:

Significant Wave Height	$H_s := 3.0\ m$	
Crane Tip Period	$T := 9.14\ s$	*Must use values from RAO data: [7.19, 8.05, 9.14, 10.58, 12.55]*

Object Properties:

Object Mass (in Air)	$M := 90000\ kg$	
Object Weight (in Air)	$W_{air} := M \cdot g$	$W_{air} = 882900\ N$
Object Displaced Volume	$V_{sub} := 12.00\ m^3$	
Object Mass (in water)	$M_{sub} := M - \rho \cdot V_{sub}$	$M_{sub} = 77700\ kg$
Object Weight (in water)	$W_{sub} := M_{sub} \cdot g$	$W_{sub} = 762237\ N$
Object z-projected area	$A_P := 85.2\ m^2$	
Object Vertical drag coefficient	$C_{Dz} := 1.16$	*DNVGL-RP-N103 Table B-1*
Object Reference Volume	$V_R := 12.00\ m^3$	*DNVGL-RP-N103 Table A-2*
Object Added Mass Coefficient	$C_A := 0.757$	*DNVGL-RP-N103 Table A-2*
Object Added mass	$A_{33} := \rho \cdot V_R \cdot C_A$	$A_{33} = 9311\ kg$
Object Total hydrodynamic mass	$M' := M + A_{33}$	$M' = 99311\ kg$

Crane Line Properties:

Crane line speed	$v_c := 0.5 \frac{m}{s}$	
Crane line length	$L := 100\ m$	
Crane line diameter	$D_C := 0.064\ m$	
Crane line cross-sectional area	$A_L := \pi \cdot (0.5 \cdot D_C)^2$	$A_L = 0.00322\ m^2$
Crane line unit mass (in Air)	$m_L := 19.9 \frac{kg}{m}$	
Crane line unit weight (in Water)	$w := 17.3 \frac{kg}{m} \cdot g$	$w = 169.7 \frac{kg}{s^2}$
Crane line stiffness	$EA := 4.9 \cdot 10^8\ N$	
Crane line unit stiffness	$K := \frac{EA}{L}$	$K = 4900000 \frac{kg}{s^2}$
Crane line longitudinal friction coefficent	$C_{Df} := 0.02$	
Mass ratio	$\varepsilon := m_L \cdot \frac{L}{(M')} = 0.02$	
Stretched Line Length	$L_s := L + L \cdot \left(\frac{(W_{sub} + 0.5 \cdot w \cdot L)}{EA}\right)$	$L_s = 100.2\ m$
Static Stretch	$\eta_{st} := L_s - L$	$\eta_{st} = 0.157\ m$

Page 1 of 7

Vessel Properties:

Vessel Natural Period - Heave	$T_H := 9.14\ s$	
Vessel Natural Period - Roll	$T_R := 10.58\ s$	
Crane Boom Length	$Boom := 15.0\ m$	
Vessel Horiz. Dist. Centreline to Crane Tip	$b := 6.93\ m + Boom$	

$$RAO := \begin{bmatrix} 7.19 & 8.05 & 9.14 & 10.58 & 12.55 \\ 1.14 & 1.10 & 1.06 & 1.04 & 1.02 \\ 0.043 & 0.078 & 0.205 & 0.178 & 0.178 \end{bmatrix} \quad Period := \frac{T}{s} \quad RAO_{Heave} := 1 \quad RAO_{Roll} := 2$$

$$\eta_{Vheave} := H_s \cdot \text{hlookup}(Period, RAO, 1)_0 \qquad \eta_{Vheave} = 3.18\ m$$

$$\eta_{Vroll} := H_s \cdot \text{hlookup}(Period, RAO, 2)_0 \cdot \frac{rad}{m} \qquad \eta_{Vroll} = 0.615\ rad$$

Crane Tip Motions

Peak Spectral Period $\quad T_P := 1.4 \cdot T \qquad T_P = 12.796\ s$

Correction Factor $\quad P_\gamma := 1.5 \cdot \frac{T_P}{T} \qquad P_\gamma = 2.1$

$$P_{TH} := \max\left(\frac{(T_H + T)}{2}, 0.7 \cdot T\right) \qquad P_{TH} = 9.14\ s$$

$$P_{TR} := \max\left(\frac{(T_R + T)}{2}, 0.7 \cdot T\right) \qquad P_{TR} = 9.86\ s$$

[9.2.1.3 (Modified)] Characteristic vertical crane tip motion

$$\eta_a := \sqrt{\eta_{Vheave}{}^2 \cdot \frac{P_\gamma \cdot T}{T_H} + (b \cdot \sin(\eta_{Vroll}))^2 \cdot \frac{P_\gamma \cdot T}{T_R}} \qquad \eta_a = 17.654\ m$$

[9.2.1.4 (Modified)] Characteristic vertical crane tip velocity

$$v_{ct} := 2 \cdot \pi \sqrt{\left(\frac{\eta_{Vheave}}{T_H}\right)^2 + \left(\frac{b \cdot \sin(\eta_{Vroll})}{T_R}\right)^2} \qquad v_{ct} = 7.826\ \frac{m}{s}$$

[9.2.1.4 (Modified)] Characteristic vertical crane tip acceleration

$$a_{ct} := 4 \cdot \pi^2 \sqrt{\left(\frac{\eta_{Vheave}}{P_{TH}{}^2}\right)^2 + \left(\frac{b \cdot \sin(\eta_{Vroll})}{P_{TR}{}^2}\right)^2} \qquad a_{ct} = 5.353\ \frac{m}{s^2}$$

Wave Particle Motions at Surface (z = -1m)

[4.3.4.5] Characteristic vertical water velocity at Surface

$$v_w := 0.3 \cdot \sqrt{\pi \cdot g \cdot H_s} \cdot e^{\frac{-0.35 \cdot |z|}{H_s}} \qquad v_w = 2.885\ \frac{m}{s}$$

[4.3.4.5] Characteristic wave particle acceleration at Surface

$$a_w := 0.10\ \pi \cdot g \cdot e^{-\left(\frac{0.35 \cdot -z}{H_s}\right)} \qquad a_w = 3.082\ \frac{m}{s^2}$$

Page 2 of 7

[4.7.3.1] Snap Velocity (at Surface)

$v_{snapSurf} := v_{ffSurf} + C_{Surf} \cdot v_{rSurf}$ $\qquad v_{snapSurf} = 7.258\ \frac{m}{s}$

[4.7.2.1] Snap Force (at Surface)

$F_{snapSurf} := v_{snapSurf} \cdot \sqrt{\left(\frac{EA}{8.3\ m}\right) \cdot M'}$ $\qquad F_{snapSurf} = 17575307\ N$

Total Forces at Surface

[4.4.3.3] Characteristic Total Force at Surface (if no slack line)

$F_{TotalSurf} := F_{Hyd} + W_{air}$ $\qquad F_{TotalSurf} = 4879333\ N$

Dynamic Amplification Factor (DAF) at Surface

$DAF_{Surf} := \frac{F_{TotalSurf}}{W_{air}}$ $\qquad DAF_{Surf} = 5.526$

Slack Line Check

[4.4.3.3] Slack Sling Criterion at Surface

$Slack_{Surf} := \begin{cases} \text{if } F_{Hyd} > 0.9 \cdot W_{air} & \text{“SLACK”} \\ \text{if } F_{Hyd} \le 0.9 \cdot W_{air} & \text{“NO SLACK”} \end{cases}$ $\qquad Slack_{Surf} = \text{“SLACK”}$

Page 4 of 7

Lift Phase 1: Lifting Through Splashzone

Hydrodynamic Forces at Surface

[4.7.3.2] Object characteristic velocity relative to water

$$v_{rSurf} := \sqrt{v_{ct}^2 + v_w^2} + v_c \qquad v_{rSurf} = 8.84\ \frac{m}{s}$$

[4.3.6.2] Change in Displaced Water Volume

$$\delta V := V_{sub} \qquad \delta V = 12\ m^3$$

[4.3.6.1] Varying Buoyancy Force

$$F_\rho := \rho \cdot V_{sub} \cdot g \qquad F_\rho = 120663\ N$$

[4.3.7.1] Characteristic Mass Force (Froude Kriloff Force)

$$F_M := \sqrt{\left(\left(M + A_{33}\right) \cdot a_{ct}\right)^2 + \left(\left(\rho \cdot V_{sub} + A_{33}\right) \cdot a_w\right)^2} \qquad F_M = 535788\ N$$

[4.3.8.1] Drag Force

$$F_D := 0.5 \cdot \rho \cdot C_{Dz} \cdot A_P \cdot v_{rSurf}^2 \qquad F_D = 3958516\ N$$

[4.3.9.2] Total Hydrodynamic Force

$$F_{Hyd} := \sqrt{F_D^2 + F_M^2 + F_\rho^2} \qquad F_{Hyd} = 3996433\ N$$

Snap Forces at Surface

[4.7.3.5] Object free-fall velocity at Surface

$$v_{ffSurf} := \sqrt{\frac{2 \cdot W_{sub}}{\rho \cdot A_P \cdot C_{Dz}}} \qquad v_{ffSurf} = 3.879\ \frac{m}{s}$$

[4.7.3.4] Correction factor for Object velocity at Surface

$$C_{Surf} := \begin{cases} 1 & \text{if } v_{ffSurf} \le 0.2\ v_{rSurf} \\ \cos\left(\pi \cdot \left(\frac{v_{ffSurf}}{v_{rSurf}}\right) - 0.2\right) & \text{if } 0.2\ v_{rSurf} < v_{ffSurf} \le 0.7\ v_{rSurf} \\ 0 & \text{if } v_{ffSurf} > 0.7\ v_{rSurf} \end{cases} \qquad C_{Surf} = 0.382$$

Page 3 of 7

Dynamic Force

[5.3.7.8] Amplitude of dynamic force at Crane Hook

$$k_E := \frac{EA}{L}$$

$$h := -\left(\frac{2\pi}{T}\right)^2 \cdot M' + i \cdot \left(\frac{2\pi}{T}\right) \cdot \Sigma(\eta_L) \qquad h = \left(-4.693 \cdot 10^4 + 3.612i \cdot 10^5\right) \frac{kg}{s^2}$$

$$F_d := \eta_a \cdot k_E \cdot \left|\left(\frac{\left(-(k \cdot L)^2 \cdot k_E \cdot \sin(k \cdot (z+L)) + (k \cdot L) \cdot h \cdot \cos(k \cdot (z+L))\right)}{(k \cdot L) \cdot k_E \cdot \cos(k \cdot L) + h \cdot \sin(k \cdot L)}\right)\right| \qquad F_d = 6502345\ N$$

[5.3.7.8] Amplitude of dynamic force at Object

$$F_{dL} := \frac{\eta_a \cdot k_E \cdot |(h)|}{\left|\left(k_E \cdot \cos(k \cdot L) + h \cdot \frac{\sin(k \cdot L)}{k \cdot L}\right)\right|} \qquad F_{dL} = 6475070\ N$$

Static Force at Depth

Total static force at crane tip when Object at Depth

$$F_{static} := W_{sub} + w \cdot L \qquad F_{static} = 779208\ N$$

Snap Force

[4.7.3.2] Object velocity relative to water (at Depth)

$$v_{rSub} := \sqrt{{v_{ct}}^2} \qquad v_{rSub} = 7.826\ \frac{m}{s}$$

[4.7.3.5] Object free-fall velocity (at Depth)

$$v_{ffSub} := \sqrt{\frac{2 \cdot F_{static}}{\rho \cdot A_P \cdot C_{Dz}}} \qquad v_{ffSub} = 3.922\ \frac{m}{s}$$

[4.7.3.4] Correction factor for Object velocity (at Depth)

$$C := \begin{cases} 1 & \text{if } v_{ffSub} \le 0.2\ v_{rSub} \\ \cos\left(\pi \cdot \left(\frac{v_{ffSub}}{v_{rSub}}\right) - 0.2\right) & \text{if } 0.2\ v_{rSub} < v_{ffSub} \le 0.7\ v_{rSub} \\ 0 & \text{if } v_{ffSub} > 0.7\ v_{rSub} \end{cases} \qquad C = 0.195$$

Page 6 of 7

Lift Phase 2: Deepwater Lowering

Natural frequency of crane line system

[5.3.4.2] Wavenumbers for natural frequency

$v_x := 0.001 \left(\frac{1}{m}\right)$ ** Initial Guess for Root Function*

$v_x := \mathbf{root}\left(\varepsilon - v_x \cdot L \cdot \tan\left(v_x \cdot L\right), v_x\right)$ $v_x = 0.001 \frac{1}{m}$

[5.3.4.1] Natural frequency of straight crane line system

$\omega_f := v_x \cdot \sqrt{\left(\frac{EA}{m_L}\right)} = 7.001 \frac{1}{s}$

$T_f := \frac{(2 \cdot \pi)}{\omega_f} = 0.897\ s$

Object response to crane tip oscillation

[5.3.7.4] Linear damping coefficient for motion of crane line

$\sigma := \left(\frac{4}{3}\right) \cdot \rho \cdot C_{Df} \cdot D_C \cdot \left(\frac{2\ \pi}{T}\right) \cdot \eta_a$ $\sigma = 21.23 \frac{kg}{m \cdot s}$

[5.3.7.5] Linear damping coefficient for motion of object

$\Sigma\left(\eta_L\right) := \left(\frac{4}{3 \cdot \pi}\right) \cdot \rho \cdot C_{Dz} \cdot A_P \cdot \left(\frac{2\ \pi}{T}\right) \cdot \eta_L$

[5.3.7.3] Complex wavenumber

$k := \sqrt{\frac{m_L}{EA}} \cdot \sqrt{\left(\left(\frac{2\ \pi}{T}\right)^2 - i \cdot \left(\frac{2\ \pi}{T}\right) \cdot \left(\frac{\sigma}{m_L}\right)\right)}$ $k = \left(1.653 \cdot 10^{-4} - 9.011i \cdot 10^{-5}\right) \frac{1}{m}$

[5.3.7.6] Vertical motion of object at Depth (z=L)

$\eta_L := 1\ m$ ** Initial Guess for Root Function*

$$\eta_L := \mathbf{root}\left(\eta_L - \eta_a \cdot \left|\left(\frac{(k \cdot EA)}{\left(k \cdot EA \cdot \cos(k \cdot L) + \left(\left(-\left(\frac{2\ \pi}{T}\right)^2 \cdot M' + i \cdot \left(\frac{2\ \pi}{T}\right) \cdot \Sigma\left(\eta_L\right)\right) \cdot \sin(k \cdot L)\right)\right)}\right)\right|, \eta_L\right)$$

$\eta_L = 17.777\ m$

$\Sigma\left(\eta_L\right) = 525424 \frac{kg}{s}$

Page 5 of 7

[4.7.3.1] Snap Velocity at Depth

$v_{snapSub} := v_{ffSub} + C \cdot v_{rSub}$ $\quad v_{snapSub} = 5.448 \ \frac{m}{s}$

[4.7.2.1] Snap Force at Depth

$F_{snapSub} := v_{snapSub} \cdot \sqrt{K \cdot M'}$ $\quad F_{snapSub} = 3800440 \ N$

Total Force on Crane Hook at Depth

$F_{TotalSub} := F_d + F_{static}$ $\quad F_{TotalSub} = 7281554 \ N$

Dynamic Amplification Factor (DAF) at Depth

$DAF_{Sub} := \frac{F_{TotalSub}}{W_{air}}$ $\quad DAF_{Sub} = 8.247$

Check Slack Line Conditions

Slack line conditions will occur if the crane tip amplitude is greater than the Object amplitude, such that the difference exceeds the stretched length of the line.

[5.3.8.1] Slack line Check at Depth:

$$Slack_{Sub} := \begin{cases} \text{if } |\eta_L - \eta_a| \le \eta_{st} \\ \quad \text{"NO SLACK"} \\ \text{if } |\eta_L - \eta_a| > \eta_{st} \\ \quad \text{"SLACK"} \end{cases}$$

$Slack_{Sub} = \text{"NO SLACK"}$

Results Summary

	$F_{Hyd} + F_{static}$ **(t)**	**Slack Line?**
Phase 1: Splashzone	$SurfTotal := \frac{F_{TotalSurf}}{g \cdot 1000 \ kg} = 497.4$	$Slack_{Surf} = \text{"SLACK"}$
Phase 2: Deepwater	$DepthTotal := \frac{F_{TotalSub}}{g \cdot 1000 \ kg} = 742.3$	$Slack_{Sub} = \text{"NO SLACK"}$

Page 7 of 7

SUBSEA LIFTING ANALYSIS

Object 2: Subsea Automatic Pig Launcher (SAPL) - Deployed to 2,000 m

Constants:

Density of seawater	$\rho := 1025 \frac{kg}{m^3}$	
Complex number	$i := \sqrt{-1}$	
Gravity	$g := 9.81 \frac{m}{s^2}$	
Position along crane line	$z := 0\ m$	

General:

Significant Wave Height	$H_s := 3.0\ m$	
Crane Tip Period	$T := 9.14\ s$	

Object Properties:

Crane line speed	$v_c := 0.5 \frac{m}{s}$	
Object Mass (in Air)	$M := 35480\ kg$	
Object Weight (in Air)	$W_{air} := M \cdot g$	$W_{air} = 348059\ N$
Object Displaced Volume	$V_{sub} := 4.00\ m^3$	
Object Mass (in water)	$M_{sub} := M - \rho \cdot V_{sub}$	$M_{sub} = 31380\ kg$
Object Weight (in water)	$W_{sub} := M_{sub} \cdot g$	$W_{sub} = 307838\ N$
Object z-projected area	$A_P := 18.00\ m^2$	
Object Vertical drag coefficient	$C_{Dz} := 1.16$	*DNVGL-RP-N103 Table B-1*
Object Reference Volume	$V_R := 4.00\ m^3$	*DNVGL-RP-N103 Table A-2*
Object Added Mass Coefficient	$C_A := 0.757$	*DNVGL-RP-N103 Table A-2*
Object Added mass	$A_{33} := \rho \cdot V_R \cdot C_A$	$A_{33} = 3104\ kg$
Object Total hydrodynamic mass	$M' := M + A_{33}$	$M' = 38584\ kg$

Crane Line Properties:

Crane line length	$L := 2000\ m$	
Crane line diameter	$D_C := 0.064\ m$	
Crane line cross-sectional area	$A_L := \pi \cdot (0.5 \cdot D_C)^2$	$A_L = 0.00322\ m^2$
Crane line unit mass (in Air)	$m_L := 19.9 \frac{kg}{m}$	
Crane line unit weight (in Water)	$w := 17.3 \frac{kg}{m} \cdot g$	$w = 169.7 \frac{kg}{s^2}$
Crane line stiffness	$EA := 4.9 \cdot 10^8\ N$	
Crane line unit stiffness	$K := \frac{EA}{L}$	$K = 245000 \frac{kg}{s^2}$
Crane line longitudinal friction coefficent	$C_{Df} := 0.02$	
Mass ratio	$\varepsilon := m_L \cdot \frac{L}{(M')} = 1.032$	
Stretched Line Length	$L_s := L + L \cdot \left(\frac{(W_{sub} + 0.5 \cdot w \cdot L)}{EA}\right)$	$L_s = 2001.9\ m$
Static Stretch	$\eta_{st} := L_s - L$	$\eta_{st} = 1.949\ m$

Page 1 of 7

Vessel Properties:

Vessel Natural Period - Heave $T_H := 9.14\ s$
Vessel Natural Period - Roll $T_R := 10.58\ s$
Crane Boom Length $Boom := 15.0\ m$
Vessel Horiz. Dist. Centreline to Crane Tip $b := 6.93\ m + Boom$

$$RAO := \begin{bmatrix} 7.19 & 8.05 & 9.14 & 10.58 & 12.55 \\ 1.14 & 1.10 & 1.06 & 1.04 & 1.02 \\ 0.043 & 0.078 & 0.205 & 0.178 & 0.178 \end{bmatrix} \quad Period := \frac{T}{s} \quad RAO_{Heave} := 1 \quad RAO_{Roll} := 2$$

$\eta_{Vheave} := H_s \cdot \text{hlookup}(Period, RAO, 1)_0$ $\eta_{Vheave} = 3.18\ m$

$\eta_{Vroll} := H_s \cdot \text{hlookup}(Period, RAO, 2)_0 \cdot \frac{rad}{m}$ $\eta_{Vroll} = 0.615\ rad$

Crane Tip Motions

Peak Spectral Period $T_P := 1.4 \cdot T$ $T_P = 12.796\ s$

Correction Factor $P_\gamma := 1.5 \cdot \frac{T_P}{T}$ $P_\gamma = 2.1$

$P_{TH} := \max\left(\frac{(T_H + T)}{2}, 0.7 \cdot T\right)$ $P_{TH} = 9.14\ s$

$P_{TR} := \max\left(\frac{(T_R + T)}{2}, 0.7 \cdot T\right)$ $P_{TR} = 9.86\ s$

[9.2.1.3 (Modified)] Characteristic vertical crane tip motion

$$\eta_a := \sqrt{{\eta_{Vheave}}^2 \cdot \frac{P_\gamma \cdot T}{T_H} + (b \cdot \sin(\eta_{Vroll}))^2 \cdot \frac{P_\gamma \cdot T}{T_R}} \qquad \eta_a = 17.654\ m$$

[9.2.1.4 (Modified)] Characteristic vertical crane tip velocity

$$v_{ct} := 2 \cdot \pi \sqrt{\left(\frac{\eta_{Vheave}}{T_H}\right)^2 + \left(\frac{b \cdot \sin(\eta_{Vroll})}{T_R}\right)^2} \qquad v_{ct} = 7.826\ \frac{m}{s}$$

[9.2.1.4 (Modfied)] Characteristic vertical crane tip acceleration

$$a_{ct} := 4 \cdot \pi^2 \sqrt{\left(\frac{\eta_{Vheave}}{{P_{TH}}^2}\right)^2 + \left(\frac{b \cdot \sin(\eta_{Vroll})}{{P_{TR}}^2}\right)^2} \qquad a_{ct} = 5.353\ \frac{m}{s^2}$$

Wave Particle Motions at Surface (z = -1m)

[4.3.4.5] Characteristic vertical water velocity at Surface

$$v_w := 0.3 \cdot \sqrt{\pi \cdot g \cdot H_s} \cdot e^{\frac{-0.35 \cdot |z|}{H_s}} \qquad v_w = 2.885\ \frac{m}{s}$$

[4.3.4.5] Characteristic wave particle acceleration at Surface

$$a_w := 0.10\ \pi \cdot g \cdot e^{-\left(\frac{0.35 \cdot -z}{H_s}\right)} \qquad a_w = 3.082\ \frac{m}{s^2}$$

Page 2 of 7

Lift Phase 1: Lifting Through Splashzone

Hydrodynamic Forces at Surface

[4.7.3.2] Object characteristic velocity relative to water

$$v_{rSurf} := \sqrt{v_{ct}^2 + v_w^2} + v_c \qquad v_{rSurf} = 8.84\ \frac{m}{s}$$

[4.3.6.2] Change in Displaced Water Volume

$$\delta V := V_{sub} \qquad \delta V = 4\ m^3$$

[4.3.6.1] Varying Buoyancy Force

$$F_\rho := \rho \cdot V_{sub} \cdot g \qquad F_\rho = 40221\ N$$

[4.3.7.1] Characteristic Mass Force (Froude Kriloff Force)

$$F_M := \sqrt{\left(\left(M + A_{33}\right) \cdot a_{ct}\right)^2 + \left(\left(\rho \cdot V_{sub} + A_{33}\right) \cdot a_w\right)^2} \qquad F_M = 207736\ N$$

[4.3.8.1] Drag Force

$$F_D := 0.5 \cdot \rho \cdot C_{Dz} \cdot A_P \cdot v_{rSurf}^2 \qquad F_D = 836306\ N$$

[4.3.9.2] Total Hydrodynamic Force

$$F_{Hyd} := \sqrt{F_D^2 + F_M^2 + F_\rho^2} \qquad F_{Hyd} = 862659\ N$$

Snap Forces at Surface

[4.7.3.5] Object free-fall velocity at Surface

$$v_{ffSurf} := \sqrt{\frac{2 \cdot W_{sub}}{\rho \cdot A_P \cdot C_{Dz}}} \qquad v_{ffSurf} = 5.364\ \frac{m}{s}$$

Page 3 of 7

[4.7.3.4] Correction factor for Object velocity at Surface

$$C_{Surf} := \begin{cases} 1 & \text{if } v_{ffSurf} \le 0.2\ v_{rSurf} \\ \cos\left(\pi \cdot \left(\frac{v_{ffSurf}}{v_{rSurf}}\right) - 0.2\right) & \text{if } 0.2\ v_{rSurf} < v_{ffSurf} \le 0.7\ v_{rSurf} \\ 0 & \text{if } v_{ffSurf} > 0.7\ v_{rSurf} \end{cases}$$

$C_{Surf} = -0.135$

[4.7.3.1] Snap Velocity (at Surface)

$$v_{snapSurf} := v_{ffSurf} + C_{Surf} \cdot v_{rSurf}$$

$v_{snapSurf} = 4.172\ \frac{m}{s}$

[4.7.2.1] Snap Force (at Surface)

$$F_{snapSurf} := \frac{\left(v_{snapSurf} \cdot \sqrt{\left(\frac{EA}{8.3\ m}\right) \cdot M'}\right)}{g}$$

$F_{snapSurf} = 641806\ kg$

Total Forces at Surface

[4.4.3.3] Characteristic Total Force at Surface (if no slack line)

$$F_{TotalSurf} := F_{Hyd} + W_{air}$$

$F_{TotalSurf} = 1210718\ N$

Dynamic Amplification Factor (DAF) at Surface

$$DAF_{Surf} := \frac{F_{TotalSurf}}{W_{air}}$$

$DAF_{Surf} = 3.478$

Slack Line Check

[4.4.3.3] Slack Sling Criterion at Surface

$$Slack_{Surf} := \begin{cases} \text{"SLACK"} & \text{if } F_{Hyd} > 0.9 \cdot W_{air} \\ \text{"NO SLACK"} & \text{if } F_{Hyd} \le 0.9 \cdot W_{air} \end{cases}$$

$Slack_{Surf} = \text{"SLACK"}$

Page 4 of 7

Lift Phase 2: Deepwater Lowering

Natural frequency of crane line system

[5.3.4.2] Wavenumbers for natural frequency

$v_x := 0.001 \left(\frac{1}{m}\right)$ ** Initial Guess for Root Function*

$v_x := \textbf{root}\left(\varepsilon - v_x \cdot L \cdot \tan\left(v_x \cdot L\right), v_x\right)$ $v_x = 0.002 \frac{1}{m}$

[5.3.4.1] Natural frequency of straight crane line system

$\omega_f := v_x \cdot \sqrt{\left(\frac{EA}{m_L}\right)} = 8.519 \frac{1}{s}$

$T_f := \frac{(2 \cdot \pi)}{\omega_f} = 0.738 \ s$

Object response to crane tip oscillation

[5.3.7.4] Linear damping coefficient for motion of crane line

$\sigma := \left(\frac{4}{3}\right) \cdot \rho \cdot C_{Df} \cdot D_C \cdot \left(\frac{2\ \pi}{T}\right) \cdot \eta_a$ $\sigma = 21.23 \frac{kg}{m \cdot s}$

[5.3.7.5] Linear damping coefficient for motion of object

$\Sigma\left(\eta_L\right) := \left(\frac{4}{3 \cdot \pi}\right) \cdot \rho \cdot C_{Dz} \cdot A_P \cdot \left(\frac{2\ \pi}{T}\right) \cdot \eta_L$

[5.3.7.3] Complex wavenumber

$k := \sqrt{\frac{m_L}{EA}} \cdot \sqrt{\left(\left(\frac{2\ \pi}{T}\right)^2 - i \cdot \left(\frac{2\ \pi}{T}\right) \cdot \left(\frac{\sigma}{m_L}\right)\right)}$ $k = \left(1.653 \cdot 10^{-4} - 9.011\mathrm{i} \cdot 10^{-5}\right) \frac{1}{m}$

[5.3.7.6] Vertical motion of object at Depth (z=L)

$\eta_L := 1\ m$ ** Initial Guess for Root Function*

$$\eta_L := \textbf{root}\left(\eta_L - \eta_a \cdot \left|\left(\frac{(k \cdot EA)}{\left(k \cdot EA \cdot \cos(k \cdot L) + \left(\left(-\left(\frac{2\ \pi}{T}\right)^2 \cdot M' + i \cdot \left(\frac{2\ \pi}{T}\right) \cdot \Sigma\left(\eta_L\right)\right) \cdot \sin(k \cdot L)\right)\right)}\right)\right|, \eta_L\right)$$

$\eta_L = 18.423\ m$

$\Sigma\left(\eta_L\right) = 115035 \frac{kg}{s}$

Page 5 of 7

Dynamic Force

[5.3.7.8] Amplitude of dynamic force at Crane Hook

$$k_E := \frac{EA}{L}$$

$$h := -\left(\frac{2\,\pi}{T}\right)^2 \cdot M' + i \cdot \left(\frac{2\,\pi}{T}\right) \cdot \Sigma(\eta_L) \qquad h = \left(-1.823 \cdot 10^4 + 7.908i \cdot 10^4\right)\,\frac{kg}{s^2}$$

$$F_d := \eta_a \cdot k_E \cdot \left|\left(\frac{\left(-(k \cdot L)^2 \cdot k_E \cdot \sin(k \cdot (z+L)) + (k \cdot L) \cdot h \cdot \cos(k \cdot (z+L))\right)}{(k \cdot L) \cdot k_E \cdot \cos(k \cdot L) + h \cdot \sin(k \cdot L)}\right)\right| \qquad F_d = 2051168\ N$$

[5.3.7.8] Amplitude of dynamic force at Object

$$F_{dL} := \frac{\eta_a \cdot k_E \cdot |(h)|}{\left|\left(k_E \cdot \cos(k \cdot L) + h \cdot \frac{\sin(k \cdot L)}{k \cdot L}\right)\right|} \qquad F_{dL} = 1495092\ N$$

Static Force at Depth

Total static force at crane tip when Object at Depth

$$F_{static} := W_{sub} + w \cdot L \qquad F_{static} = 647264\ N$$

Snap Force

[4.7.3.2] Object velocity relative to water (at Depth)

$$v_{rSub} := \sqrt{{v_{ct}}^2} \qquad v_{rSub} = 7.826\ \frac{m}{s}$$

[4.7.3.5] Object free-fall velocity (at Depth)

$$v_{ffSub} := \sqrt{\frac{2 \cdot F_{static}}{\rho \cdot A_P \cdot C_{Dz}}} \qquad v_{ffSub} = 7.777\ \frac{m}{s}$$

[4.7.3.4] Correction factor for Object velocity (at Depth)

$$C := \begin{cases} 1 & \text{if } v_{ffSub} \le 0.2\ v_{rSub} \\ \cos\left(\pi \cdot \left(\frac{v_{ffSub}}{v_{rSub}}\right) - 0.2\right) & \text{if } 0.2\ v_{rSub} < v_{ffSub} \le 0.7\ v_{rSub} \\ 0 & \text{if } v_{ffSub} > 0.7\ v_{rSub} \end{cases} \qquad C = 0$$

Page 6 of 7

[4.7.3.1] Snap Velocity at Depth

$v_{snapSub} := v_{ffSub} + C \cdot v_{rSub}$ $\qquad v_{snapSub} = 7.777 \ \frac{m}{s}$

[4.7.2.1] Snap Force at Depth

$F_{snapSub} := v_{snapSub} \cdot \sqrt{K \cdot M'}$ $\qquad F_{snapSub} = 756160 \ N$

Total Force on Crane Hook at Depth

$F_{TotalSub} := F_d + F_{static}$ $\qquad F_{TotalSub} = 2698432 \ N$

Dynamic Amplification Factor (DAF) at Depth

$DAF_{Sub} := \frac{F_{TotalSub}}{W_{air}}$ $\qquad DAF_{Sub} = 7.753$

Check Slack Line Conditions

Slack line conditions will occur if the crane tip amplitude is greater than the Object amplitude, such that the difference exceeds the stretched length of the line.

[5.3.8.1] Slack line Check at Depth:

$$Slack_{Sub} := \begin{cases} \text{if } |\eta_L - \eta_a| \le \eta_{st} & \text{"NO SLACK"} \\ \text{if } |\eta_L - \eta_a| > \eta_{st} & \text{"SLACK"} \end{cases}$$

$Slack_{Sub} = \text{"NO SLACK"}$

Results Summary

	$F_{Hyd} + F_{static}$ **(t)**	**Slack Line?**
Phase 1: Splashzone	$SurfTotal := \frac{F_{TotalSurf}}{g \cdot 1000 \ kg} = 123.4$	$Slack_{Surf} = \text{"SLACK"}$
Phase 2: Deepwater	$DepthTotal := \frac{F_{TotalSub}}{g \cdot 1000 \ kg} = 275.1$	$Slack_{Sub} = \text{"NO SLACK"}$

Page 7 of 7

SUBSEA LIFTING ANALYSIS

Object 3: Expansion Loop Spool - Deployed to 2,000 m

Constants:

Density of seawater	$\rho := 1025\ \frac{kg}{m^3}$	
Complex number	$i := \sqrt{-1}$	
Gravity	$g := 9.81\ \frac{m}{s^2}$	
Position along crane line	$z := 0\ m$	

General:

Significant Wave Height	$H_s := 3.0\ m$	
Crane Tip Period	$T := 12.55\ s$	

Object Properties:

Object Mass (in Air)	$M := 39000\ kg$	
Object Weight (in Air)	$W_{air} := M \cdot g$	$W_{air} = 382590\ N$
Object Displaced Volume	$V_{sub} := 6.02\ m^3$	
Object Mass (in water)	$M_{sub} := M - \rho \cdot V_{sub}$	$M_{sub} = 32830\ kg$
Object Weight (in water)	$W_{sub} := M_{sub} \cdot g$	$W_{sub} = 322057\ N$
Object z-projected area	$A_P := 26.07\ m^2$	
Object Vertical drag coefficient	$C_{Dz} := 1.0$	*DNVGL-RP-N103 Table B-1*
Object Reference Volume	$V_R := 6.02\ m^3$	*DNVGL-RP-N103 Table A-2*
Object Added Mass Coefficient	$C_A := 1.0$	*DNVGL-RP-N103 Table A-2*
Object Added mass	$A_{33} := \rho \cdot V_R \cdot C_A$	$A_{33} = 6171\ kg$
Object Total hydrodynamic mass	$M' := M + A_{33}$	$M' = 45171\ kg$

Crane Line Properties:

Crane line speed	$v_c := 0.5\ \frac{m}{s}$	
Crane line length	$L := 2000\ m$	
Crane line diameter	$D_C := 0.064\ m$	
Crane line cross-sectional area	$A_L := \pi \cdot (0.5 \cdot D_C)^2$	$A_L = 0.00322\ m^2$
Crane line unit mass (in Air)	$m_L := 19.9\ \frac{kg}{m}$	
Crane line unit weight (in Water)	$w := 17.3\ \frac{kg}{m} \cdot g$	$w = 169.7\ \frac{kg}{s^2}$
Crane line stiffness	$EA := 4.9 \cdot 10^8\ N$	
Crane line unit stiffness	$K := \frac{EA}{L}$	$K = 245000\ \frac{kg}{s^2}$
Crane line longitudinal friction coefficent	$C_{Df} := 0.02$	
Mass ratio	$\varepsilon := m_L \cdot \frac{L}{(M')} = 0.881$	
Stretched Line Length	$L_s := L + L \cdot \left(\frac{(W_{sub} + 0.5 \cdot w \cdot L)}{EA}\right)$	$L_s = 2002.0\ m$
Static Stretch	$\eta_{st} := L_s - L$	$\eta_{st} = 2.007\ m$

Page 1 of 7

Vessel Properties:

Vessel Natural Period - Heave	$T_H := 9.14\ s$
Vessel Natural Period - Roll	$T_R := 10.58\ s$
Crane Boom Length	$Boom := 15.0\ m$
Vessel Horiz. Dist. Centreline to Crane Tip	$b := 6.93\ m + Boom$

$$RAO := \begin{bmatrix} 7.19 & 8.05 & 9.14 & 10.58 & 12.55 \\ 1.14 & 1.10 & 1.06 & 1.04 & 1.02 \\ 0.043 & 0.078 & 0.205 & 0.178 & 0.178 \end{bmatrix} \qquad Period := \frac{T}{s} \quad RAO_{Heave} := 1 \quad RAO_{Roll} := 2$$

$$\eta_{Vheave} := H_s \cdot \text{hlookup}(Period, RAO, 1)_0 \qquad \eta_{Vheave} = 3.06\ m$$

$$\eta_{Vroll} := H_s \cdot \text{hlookup}(Period, RAO, 2)_0 \cdot \frac{rad}{m} \qquad \eta_{Vroll} = 0.534\ rad$$

Crane Tip Motions

Peak Spectral Period $T_P := 1.4 \cdot T$ $\quad T_P = 17.57\ s$

Correction Factor $P_\gamma := 1.5 \cdot \frac{T_P}{T}$ $\quad P_\gamma = 2.1$

$$P_{TH} := \max\left(\frac{(T_H + T)}{2}, 0.7 \cdot T\right) \qquad P_{TH} = 10.845\ s$$

$$P_{TR} := \max\left(\frac{(T_R + T)}{2}, 0.7 \cdot T\right) \qquad P_{TR} = 11.565\ s$$

[9.2.1.3 (Modified)] Characteristic vertical crane tip motion

$$\eta_a := \sqrt{{\eta_{Vheave}}^2 \cdot \frac{P_\gamma \cdot T}{T_H} + (b \cdot \sin(\eta_{Vroll}))^2 \cdot \frac{P_\gamma \cdot T}{T_R}} \qquad \eta_a = 18.367\ m$$

[9.2.1.4 (Modified)] Characteristic vertical crane tip velocity

$$v_{ct} := 2 \cdot \pi \sqrt{\left(\frac{\eta_{Vheave}}{T_H}\right)^2 + \left(\frac{b \cdot \sin(\eta_{Vroll})}{T_R}\right)^2} \qquad v_{ct} = 6.955\ \frac{m}{s}$$

[9.2.1.4 (Modfied)] Characteristic vertical crane tip acceleration

$$a_{ct} := 4 \cdot \pi^2 \sqrt{\left(\frac{\eta_{Vheave}}{{P_{TH}}^2}\right)^2 + \left(\frac{b \cdot \sin(\eta_{Vroll})}{{P_{TR}}^2}\right)^2} \qquad a_{ct} = 3.451\ \frac{m}{s^2}$$

Wave Particle Motions at Surface (z = -1m)

[4.3.4.5] Characteristic vertical water velocity at Surface

$$v_w := 0.3 \cdot \sqrt{\pi \cdot g \cdot H_s} \cdot e^{\frac{-0.35 \cdot |z|}{H_s}} \qquad v_w = 2.885\ \frac{m}{s}$$

[4.3.4.5] Characteristic wave particle acceleration at Surface

$$a_w := 0.10\ \pi \cdot g \cdot e^{-\left(\frac{0.35 \cdot -z}{H_s}\right)} \qquad a_w = 3.082\ \frac{m}{s^2}$$

Page 2 of 7

Lift Phase 1: Lifting Through Splashzone

Hydrodynamic Forces at Surface

[4.7.3.2] Object characteristic velocity relative to water

$v_{rSurf} := \sqrt{v_{ct}^2 + v_w^2} + v_c$ $\qquad v_{rSurf} = 8.029 \ \frac{m}{s}$

[4.3.5.2] Slamming Impact Velocity

$v_s := \sqrt{v_{ct}^2 + v_w^2}$ $\qquad v_s = 7.529 \ \frac{m}{s}$

[4.3.6.2] Change in Displaced Water Volume

$\delta V := V_{sub}$ $\qquad \delta V = 6.02 \ m^3$

[4.3.6.1] Varying Buoyancy Force

$F_\rho := \rho \cdot V_{sub} \cdot g$ $\qquad F_\rho = 60533 \ N$

[4.3.7.1] Characteristic Mass Force (Froude Kriloff Force)

$F_M := \sqrt{\left(\left(M + A_{33}\right) \cdot a_{ct}\right)^2 + \left(\left(\rho \cdot V_{sub} + A_{33}\right) \cdot a_w\right)^2}$ $\qquad F_M = 160458 \ N$

[4.3.8.1] Drag Force

$F_D := 0.5 \cdot \rho \cdot C_{Dz} \cdot A_P \cdot v_{rSurf}^2$ $\qquad F_D = 861322 \ N$

[4.3.9.2] Total Hydrodynamic Force

$F_{Hyd} := \sqrt{F_D^2 + F_M^2 + F_\rho^2}$ $\qquad F_{Hyd} = 878229 \ N$

Snap Forces at Surface

[4.7.3.5] Object free-fall velocity at Surface

$v_{ffSurf} := \sqrt{\frac{2 \cdot W_{sub}}{\rho \cdot A_P \cdot C_{Dz}}}$ $\qquad v_{ffSurf} = 4.91 \ \frac{m}{s}$

Page 3 of 7

[4.7.3.4] Correction factor for Object velocity at Surface

$$C_{Surf} := \begin{cases} 1 & \text{if } v_{ffSurf} \le 0.2\ v_{rSurf} \\ \cos\left(\pi \cdot \left(\frac{v_{ffSurf}}{v_{rSurf}}\right) - 0.2\right) & \text{if } 0.2\ v_{rSurf} < v_{ffSurf} \le 0.7\ v_{rSurf} \\ 0 & \text{if } v_{ffSurf} > 0.7\ v_{rSurf} \end{cases}$$

$C_{Surf} = -0.15$

[4.7.3.1] Snap Velocity (at Surface)

$$v_{snapSurf} := v_{ffSurf} + C_{Surf} \cdot v_{rSurf}$$

$v_{snapSurf} = 3.708\ \frac{m}{s}$

[4.7.2.1] Snap Force (at Surface)

$$F_{snapSurf} := v_{snapSurf} \cdot \sqrt{\left(\frac{EA}{8.3\ m}\right) \cdot M'}$$

$F_{snapSurf} = 6055075\ N$

Total Forces at Surface

[4.4.3.3] Characteristic Total Force at Surface (if no slack line)

$$F_{TotalSurf} := F_{Hyd} + W_{air}$$

$F_{TotalSurf} = 1260819\ N$

Dynamic Amplification Factor (DAF) at Surface

$$DAF_{Surf} := \frac{F_{TotalSurf}}{W_{air}}$$

$DAF_{Surf} = 3.295$

Slack Line Check

[4.4.3.3] Slack Sling Criterion at Surface

$$Slack_{Surf} := \begin{cases} \text{"SLACK"} & \text{if } F_{Hyd} > 0.9 \cdot W_{air} \\ \text{"NO SLACK"} & \text{if } F_{Hyd} \le 0.9 \cdot W_{air} \end{cases}$$

$Slack_{Surf} = \text{"SLACK"}$

Page 4 of 7

Lift Phase 2: Deepwater Lowering

Natural frequency of crane line system

[5.3.4.2] Wavenumbers for natural frequency

$v_x := 0.001 \left(\frac{1}{m}\right)$ ** Initial Guess for Root Function*

$v_x := \mathbf{root}\left(\varepsilon - v_x \cdot L \cdot \tan\left(v_x \cdot L\right), v_x\right)$ $v_x = 0.002 \frac{1}{m}$

[5.3.4.1] Natural frequency of straight crane line system

$$\omega_f := v_x \cdot \sqrt{\left(\frac{EA}{m_L}\right)} = 8.424 \frac{1}{s}$$

$$T_f := \frac{(2 \cdot \pi)}{\omega_f} = 0.746 \, s$$

Object response to crane tip oscillation

[5.3.7.4] Linear damping coefficient for motion of crane line

$$\sigma := \left(\frac{4}{3}\right) \cdot \rho \cdot C_{Df} \cdot D_C \cdot \left(\frac{2 \pi}{T}\right) \cdot \eta_a \qquad \sigma = 16.086 \frac{kg}{m \cdot s}$$

[5.3.7.5] Linear damping coefficient for motion of object

$$\Sigma\left(\eta_L\right) := \left(\frac{4}{3 \cdot \pi}\right) \cdot \rho \cdot C_{Dz} \cdot A_P \cdot \left(\frac{2 \pi}{T}\right) \cdot \eta_L$$

[5.3.7.3] Complex wavenumber

$$k := \sqrt{\frac{m_L}{EA}} \cdot \sqrt{\left(\left(\frac{2 \pi}{T}\right)^2 - i \cdot \left(\frac{2 \pi}{T}\right) \cdot \left(\frac{\sigma}{m_L}\right)\right)} \qquad k = \left(1.215 \cdot 10^{-4} - 6.765i \cdot 10^{-5}\right) \frac{1}{m}$$

[5.3.7.6] Vertical motion of object at Depth (z=L)

$\eta_L := 1 \, m$ ** Initial Guess for Root Function*

$$\eta_L := \mathbf{root}\left(\eta_L - \eta_a \cdot \left|\left(\frac{(k \cdot EA)}{\left(k \cdot EA \cdot \cos(k \cdot L) + \left(\left(-\left(\frac{2 \pi}{T}\right)^2 \cdot M' + i \cdot \left(\frac{2 \pi}{T}\right) \cdot \Sigma\left(\eta_L\right)\right) \cdot \sin(k \cdot L)\right)\right)}\right)\right|, \eta_L\right)$$

$\eta_L = 19.041 \, m$

$\Sigma\left(\eta_L\right) = 108114 \frac{kg}{s}$

Page 5 of 7

Dynamic Force

[5.3.7.8] Amplitude of dynamic force at Crane Hook

$$k_E := \frac{EA}{L}$$

$$h := -\left(\frac{2\ \pi}{T}\right)^2 \cdot M' + i \cdot \left(\frac{2\ \pi}{T}\right) \cdot \Sigma(\eta_L) \qquad h = \left(-1.132 \cdot 10^4 + 5.413\mathrm{i} \cdot 10^4\right) \frac{kg}{s^2}$$

$$F_d := \eta_a \cdot k_E \cdot \left|\left(\frac{\left(-(k \cdot L)^2 \cdot k_E \cdot \sin(k \cdot (z+L)) + (k \cdot L) \cdot h \cdot \cos(k \cdot (z+L))\right)}{(k \cdot L) \cdot k_E \cdot \cos(k \cdot L) + h \cdot \sin(k \cdot L)}\right)\right| \qquad F_d = 1376224\ N$$

[5.3.7.8] Amplitude of dynamic force at Object

$$F_{dL} := \frac{\eta_a \cdot k_E \cdot |(h)|}{\left|\left(k_E \cdot \cos(k \cdot L) + h \cdot \frac{\sin(k \cdot L)}{k \cdot L}\right)\right|} \qquad F_{dL} = 1052961\ N$$

Static Force at Depth

Total static force at crane tip when Object at Depth

$$F_{static} := W_{sub} + w \cdot L \qquad F_{static} = 661483\ N$$

Snap Force

[4.7.3.2] Object velocity relative to water (at Depth)

$$v_{rSub} := \sqrt{{v_{ct}}^2} \qquad v_{rSub} = 6.955\ \frac{m}{s}$$

[4.7.3.5] Object free-fall velocity (at Depth)

$$v_{ffSub} := \sqrt{\frac{2 \cdot F_{static}}{\rho \cdot A_P \cdot C_{Dz}}} \qquad v_{ffSub} = 7.036\ \frac{m}{s}$$

[4.7.3.4] Correction factor for Object velocity (at Depth)

$$C := \begin{cases} 1 & \text{if } v_{ffSub} \le 0.2\ v_{rSub} \\ \cos\left(\pi \cdot \left(\frac{v_{ffSub}}{v_{rSub}}\right) - 0.2\right) & \text{if } 0.2\ v_{rSub} < v_{ffSub} \le 0.7\ v_{rSub} \\ 0 & \text{if } v_{ffSub} > 0.7\ v_{rSub} \end{cases} \qquad C = 0$$

Page 6 of 7

[4.7.3.1] Snap Velocity at Depth

$v_{snapSub} := v_{ffSub} + C \cdot v_{rSub}$ $\qquad v_{snapSub} = 7.036 \ \frac{m}{s}$

[4.7.2.1] Snap Force at Depth

$F_{snapSub} := v_{snapSub} \cdot \sqrt{K \cdot M'}$ $\qquad F_{snapSub} = 740206 \ N$

Total Force on Crane Hook at Depth

$F_{TotalSub} := F_d + F_{static}$ $\qquad F_{TotalSub} = 2037707 \ N$

Dynamic Amplification Factor (DAF) at Depth

$DAF_{Sub} := \frac{F_{TotalSub}}{W_{air}}$ $\qquad DAF_{Sub} = 5.326$

Check Slack Line Conditions

Slack line conditions will occur if the crane tip amplitude is greater than the Object amplitude, such that the difference exceeds the stretched length of the line.

[5.3.8.1] Slack line Check at Depth:

$$Slack_{Sub} := \begin{cases} \text{if } |\eta_L - \eta_a| \le \eta_{st} & \text{"NO SLACK"} \\ \text{if } |\eta_L - \eta_a| > \eta_{st} & \text{"SLACK"} \end{cases}$$

$Slack_{Sub} = \text{"NO SLACK"}$

Results Summary

	$F_{Hyd} + F_{static}$ (t)	Slack Line?
Phase 1: Splashzone	$SurfTotal := \frac{F_{TotalSurf}}{g \cdot 1000 \ kg} = 128.5$	$Slack_{Surf} = \text{"SLACK"}$
Phase 2: Deepwater	$DepthTotal := \frac{F_{TotalSub}}{g \cdot 1000 \ kg} = 207.7$	$Slack_{Sub} = \text{"NO SLACK"}$

Page 7 of 7

APPENDIX D

NUMERICAL CALCULATION RESULTS

Table 9-2 Object 1: Subsea Cooling Skid – Results Table

		Splash Zone		Deepwater Lowering			
Hs	Tz	Ftotal (F_{hyd} + W_{air})	Snap Load?	Ftotal (F_{dyn} + F_{static})	Snap Load?	Max DAF	OK?
m	s	N		N			
0.5	7.19	111.9	NO	87.4	NO	1.24	111.9
0.5	8.05	112.9	NO	89.1	NO	1.25	112.9
0.5	9.14	122.5	NO	105.1	NO	1.36	122.5
0.5	10.58	119.4	NO	96.8	NO	1.33	119.4
0.5	12.55	119.1	NO	93.5	NO	1.32	119.1
1.0	7.19	124.5	NO	98.4	NO	1.38	124.5
1.0	8.05	128.7	NO	104.7	NO	1.43	128.7
1.0	9.14	165.1	NO	166.6	NO	1.85	166.6
1.0	10.58	154.1	NO	137.5	NO	1.71	154.1
1.0	12.55	153.5	NO	127.6	NO	1.71	153.5
1.5	7.19	140.1	NO	114.1	NO	1.56	140.1
1.5	8.05	149.3	NO	128.9	NO	1.66	149.3
1.5	9.14	226.5	SNAP	265.5	NO	2.95	265.5 *
1.5	10.58	204.0	SNAP	203.5	NO	2.27	204 *
1.5	12.55	203.1	SNAP	182.8	NO	2.26	203.1 *
2.0	7.19	158.4	NO	135.2	NO	1.76	158.4
2.0	8.05	174.3	SNAP	162.0	NO	1.94	174.3 *
2.0	9.14	304.2	SNAP	398.2	NO	4.42	398.2 *
2.0	10.58	267.2	SNAP	293.1	NO	3.26	293.1 *
2.0	12.55	266.0	SNAP	257.8	NO	2.96	266 *
2.5	7.19	179.0	SNAP	162.0	NO	1.99	179 *
2.5	8.05	203.2	SNAP	204.2	NO	2.27	204.2 *
2.5	9.14	395.5	SNAP	559.3	NO	6.21	559.3 *
2.5	10.58	342.0	SNAP	403.6	NO	4.48	403.6 *
2.5	12.55	340.6	SNAP	350.4	NO	3.89	350.4 *
3.0	7.19	202.1	SNAP	194.5	NO	2.25	202.1 *
3.0	8.05	236.1	SNAP	255.3	NO	2.84	255.3 *
3.0	9.14	497.4	SNAP	742.3	NO	8.25	742.3 *
3.0	10.58	426.7	SNAP	531.6	NO	5.91	531.6 *
3.0	12.55	425.0	SNAP	457.8	NO	5.09	457.8 *

Table 9-3 Object 1: Subsea Cooling Skid – Operating Limits Table

		Period (Tz)				
		7	8	9	10.5	12.5
Sig. Wave Height (Hs)	0.5	111.9	112.9	122.5	119.4	119.1
	1.0	124.5	128.7	166.6	154.1	153.5
	1.5	140.1	149.3	265.5 *	204 *	203.1 *
	2.0	158.4	174.3 *	398.2 *	293.1 *	266 *
	2.5	179 *	204.2 *	559.3 *	403.6 *	350.4 *
	3.0	202.1 *	255.3 *	742.3 *	531.6 *	457.8 *

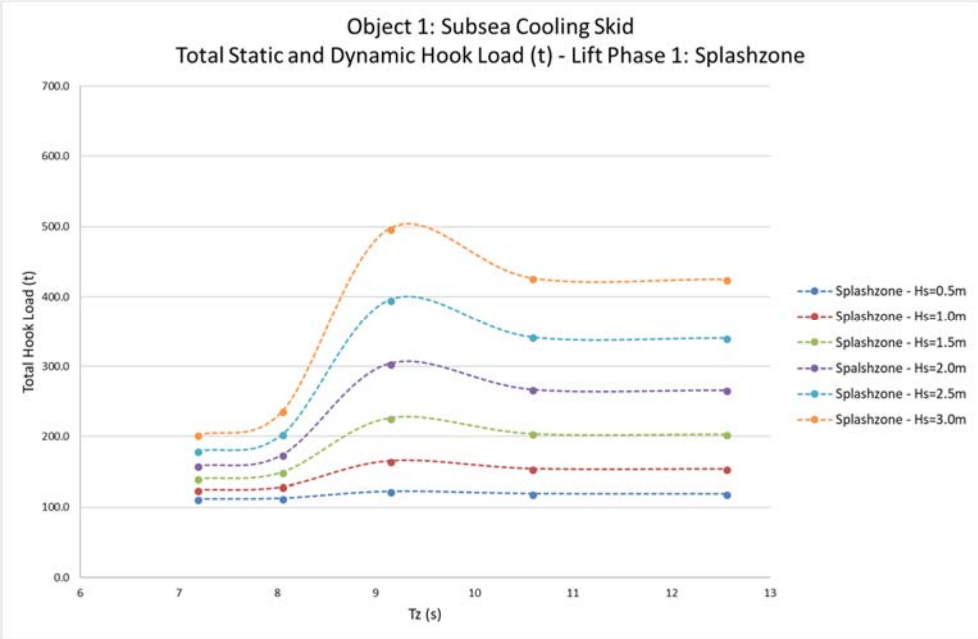


Figure 9-4 Object 1: Subsea Cooling Skid – Results Chart (Lift Phase 1)

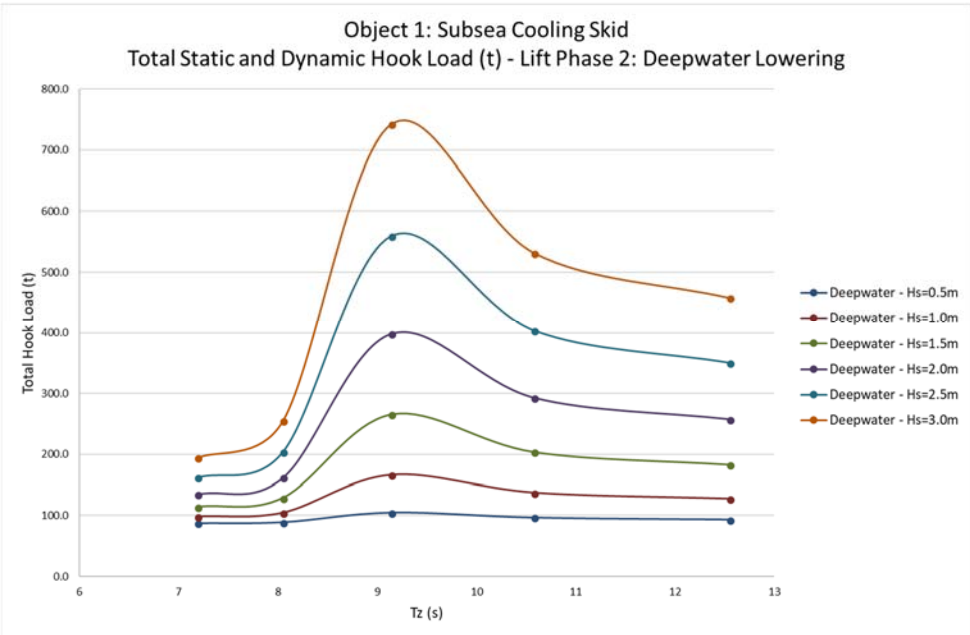


Figure 9-5 Object 1: Subsea Cooling Skid – Results Chart (Lift Phase 2)

Table 9-4 Object 2: SAPL – Results Table

		Splash Zone		Deepwater Lowering			
Hs	Tz	Ftotal (F_{hyd} + W_{air})	Snap Load?	Ftotal (F_{dyn} + F_{static})	Snap Load?	Max DAF	OK?
m	s	N		N			
0.5	7.19	41.5	NO	72.7	NO	1.10	72.7
0.5	8.05	41.7	NO	73.4	NO	1.11	73.4
0.5	9.14	43.8	NO	80.6	NO	1.22	80.6
0.5	10.58	43.0	NO	75.9	NO	1.15	75.9
0.5	12.55	42.9	NO	73.6	NO	1.12	73.6
1.0	7.19	44.1	NO	79.9	NO	1.21	79.9
1.0	8.05	45.0	NO	81.9	NO	1.24	81.9
1.0	9.14	52.9	NO	103.3	NO	1.57	103.3
1.0	10.58	50.3	NO	90.8	NO	1.38	90.8
1.0	12.55	49.9	NO	85.5	NO	1.30	85.5
1.5	7.19	47.4	NO	88.0	NO	1.33	88.0
1.5	8.05	49.4	NO	92.2	NO	1.40	92.2
1.5	9.14	66.0	NO	135.9	NO	2.06	135.9
1.5	10.58	60.8	NO	112.5	NO	1.71	112.5
1.5	12.55	60.4	NO	103.1	NO	1.56	103.1
2.0	7.19	51.3	NO	97.3	NO	1.47	97.3
2.0	8.05	54.7	NO	104.8	NO	1.59	104.8
2.0	9.14	82.5	SNAP	177.1	NO	2.68	177.1 *
2.0	10.58	74.2	SNAP	140.6	NO	2.13	140.6 *
2.0	12.55	73.6	SNAP	126.4	NO	1.92	126.4 *
2.5	7.19	55.8	NO	108.1	NO	1.64	108.1
2.5	8.05	61.0	NO	119.7	NO	1.81	119.7
2.5	9.14	101.8	SNAP	224.3	NO	3.40	224.3 *
2.5	10.58	90.1	SNAP	174.3	NO	2.64	174.3 *
2.5	12.55	89.4	SNAP	154.5	NO	2.34	154.5 *
3.0	7.19	60.8	NO	120.3	NO	1.82	120.3
3.0	8.05	68.0	SNAP	136.9	NO	2.07	136.9 *
3.0	9.14	123.4	SNAP	275.1	NO	4.17	275.1 *
3.0	10.58	108.0	SNAP	212.0	NO	3.21	212 *
3.0	12.55	107.3	SNAP	186.4	NO	2.83	186.4 *

Table 9-5 Object 2: SAPL – Operating Limits Table

		Period (Tz)				
		7	8	9	10.5	12.5
Sig. Wave Height (Hs)	0.5	72.7	73.4	80.6	75.9	73.6
	1.0	79.9	81.9	103.3	90.8	85.5
	1.5	88.0	92.2	135.9	112.5	103.1
	2.0	97.3	104.8	177.1 *	140.6 *	126.4 *
	2.5	108.1	119.7	224.3 *	174.3 *	154.5 *
	3.0	120.3	136.9 *	275.1 *	212 *	186.4 *

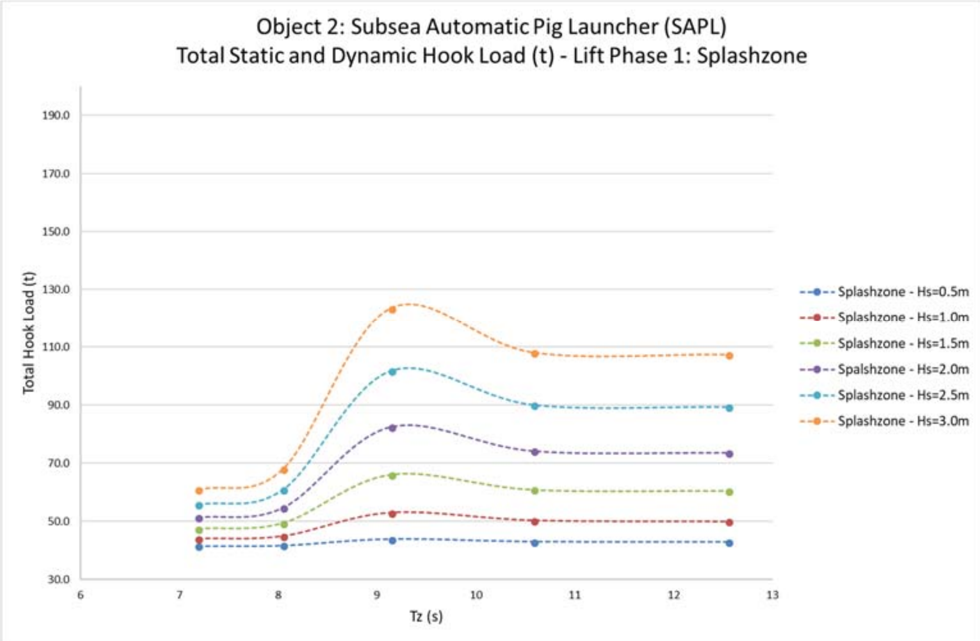


Figure 9-6 Object 2: SAPL – Results Chart (Lift Phase 1)

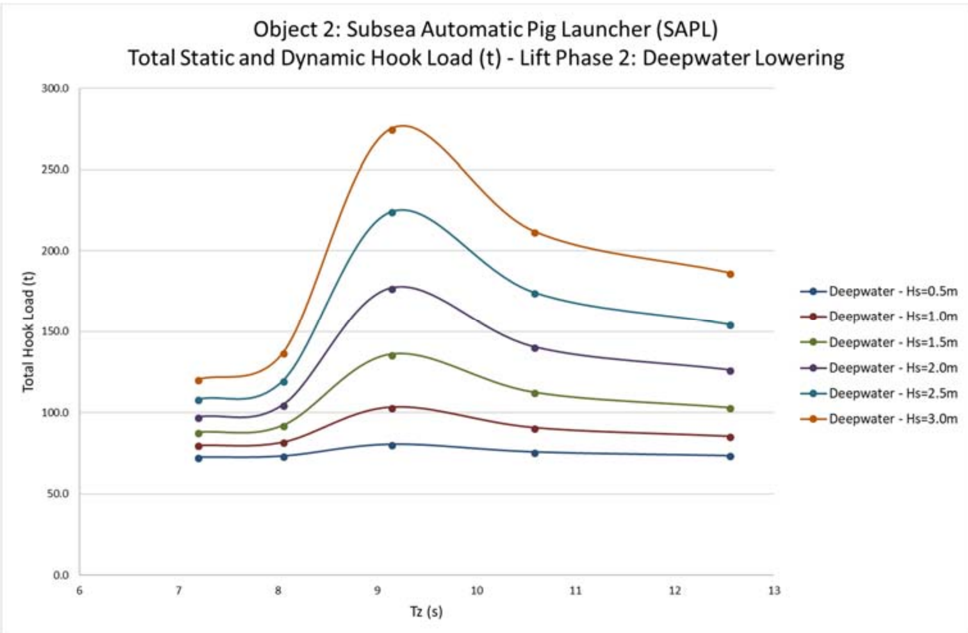


Figure 9-7 Object 2: SAPL – Results Chart (Lift Phase 2)

Table 9-6 Object 3: Expansion Loop – Results Table

		Splash Zone		Deepwater Lowering			
Hs	Tz	Ftotal (F_{hyd} + W_{air})	Snap Load?	Ftotal (F_{dyn} + F_{static})	Snap Load?	Max DAF	OK?
m	s	N		N			
0.5	7.19	47.7	NO	74.9	NO	1.11	74.9
0.5	8.05	47.9	NO	75.7	NO	1.12	75.7
0.5	9.14	50.2	NO	83.9	NO	1.25	83.9
0.5	10.58	49.3	NO	78.5	NO	1.17	78.5
0.5	12.55	49.2	NO	75.9	NO	1.13	75.9
1.0	7.19	50.5	NO	83.0	NO	1.23	83.0
1.0	8.05	51.5	NO	85.3	NO	1.27	85.3
1.0	9.14	60.9	NO	110.4	NO	1.64	110.4
1.0	10.58	57.8	NO	95.9	NO	1.42	95.9
1.0	12.55	57.4	NO	89.8	NO	1.33	89.8
1.5	7.19	54.3	NO	92.3	NO	1.37	92.3
1.5	8.05	56.7	NO	97.2	NO	1.44	97.2
1.5	9.14	77.0	SNAP	148.4	NO	2.21	148.4 *
1.5	10.58	70.7	NO	121.4	NO	1.80	121.4
1.5	12.55	70.2	NO	110.6	NO	1.64	110.6
2.0	7.19	59.1	NO	103.2	NO	1.53	103.2
2.0	8.05	63.2	NO	111.9	NO	1.66	111.9
2.0	9.14	97.5	SNAP	195.6	NO	2.91	195.6 *
2.0	10.58	87.3	SNAP	154.3	NO	2.29	154.3 *
2.0	12.55	86.7	SNAP	137.9	NO	2.05	137.9 *
2.5	7.19	64.5	NO	115.7	NO	1.72	115.7
2.5	8.05	70.9	NO	129.3	NO	1.92	129.3
2.5	9.14	121.6	SNAP	248.6	NO	3.69	248.6 *
2.5	10.58	107.1	SNAP	193.1	NO	2.87	193.1 *
2.5	12.55	106.3	SNAP	170.7	NO	2.54	170.7 *
3.0	7.19	70.6	NO	129.7	NO	1.93	129.7
3.0	8.05	79.6	SNAP	149.1	NO	2.22	149.1 *
3.0	9.14	148.5	SNAP	304.6	NO	4.53	304.6 *
3.0	10.58	129.4	SNAP	236.0	NO	3.51	236 *
3.0	12.55	128.5	SNAP	207.7	NO	3.09	207.7 *

Table 9-7 Object 3: Expansion Loop - Operating Limits Table

		Period (Tz)				
		7	8	9	10.5	12.5
Sig. Wave Height (Hs)	0.5	74.9	75.7	83.9	78.5	75.9
	1.0	83.0	85.3	110.4	95.9	89.8
	1.5	92.3	97.2	148.4 *	121.4	110.6
	2.0	103.2	111.9	195.6 *	154.3 *	137.9 *
	2.5	115.7	129.3	248.6 *	193.1 *	170.7 *
	3.0	129.7	149.1 *	304.6 *	236 *	207.7 *

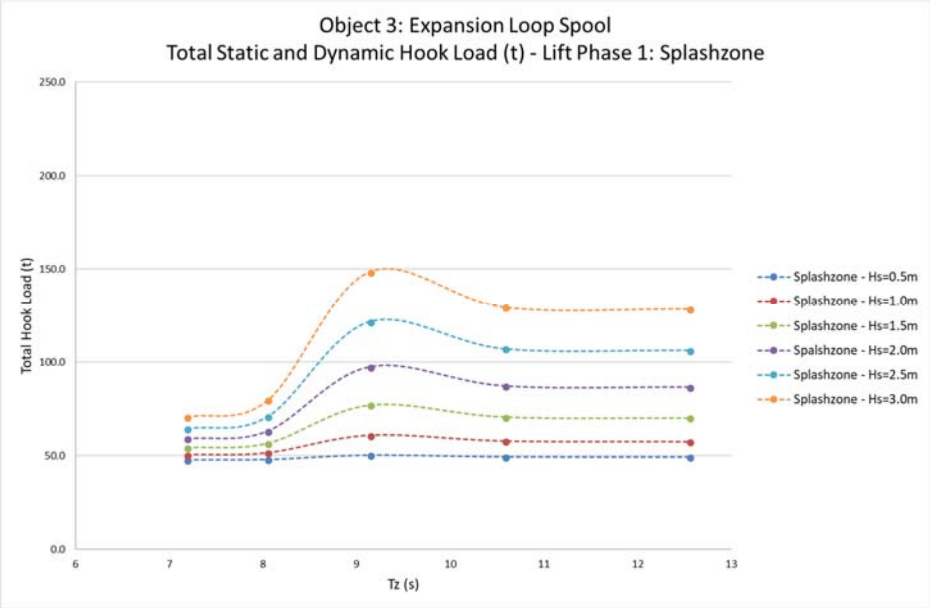


Figure 9-8 Object 3: Expansion Loop Spool – Results Chart (Lift Phase 1)

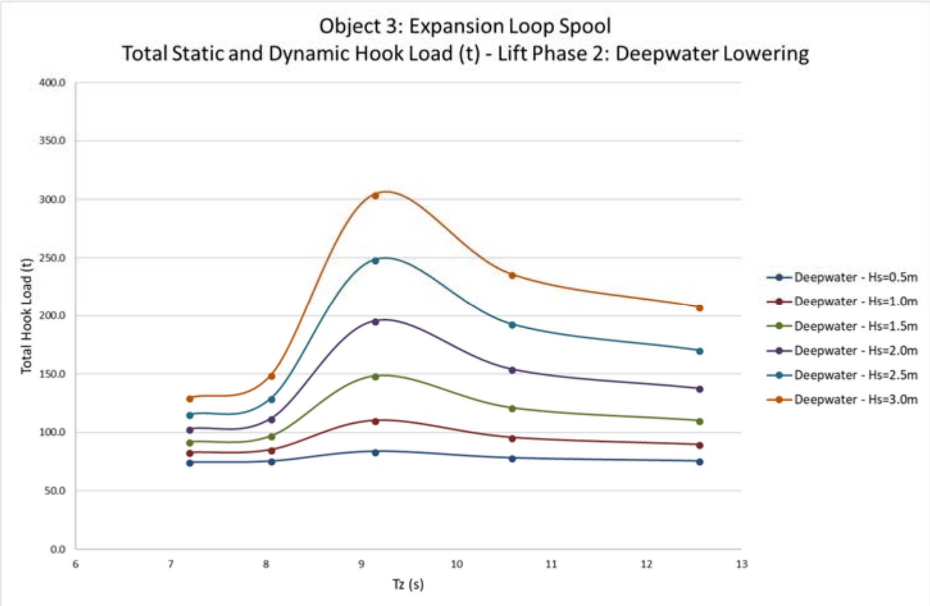


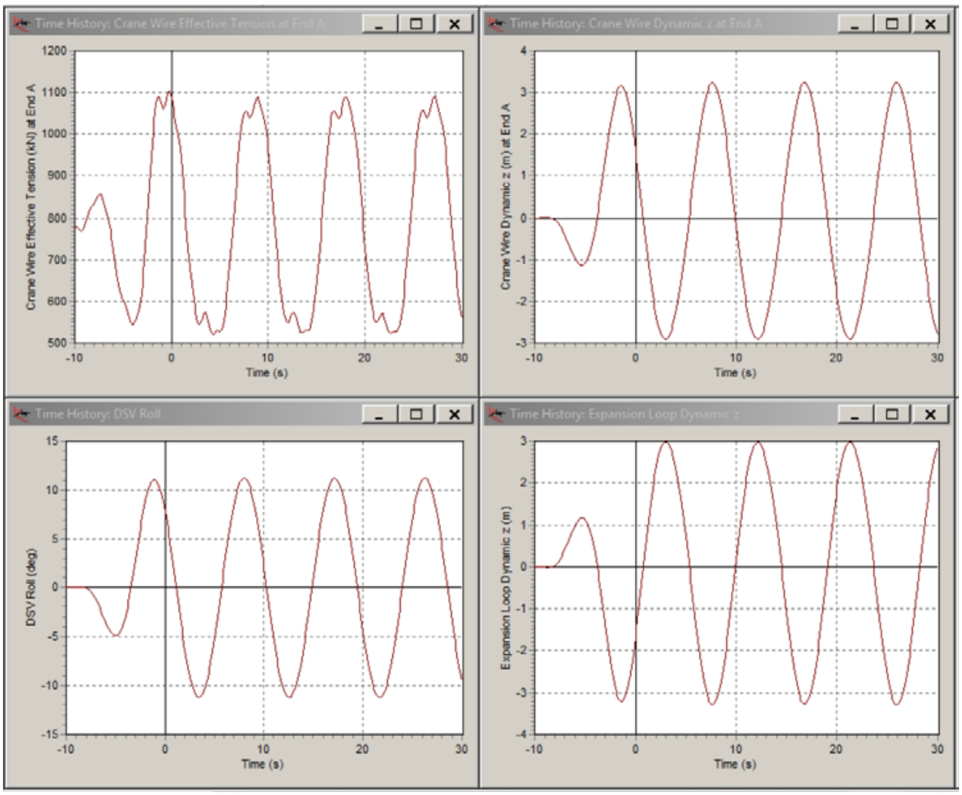
Figure 9-9 Object 3: Expansion Loop Spool – Results Chart (Lift Phase 2)

APPENDIX E

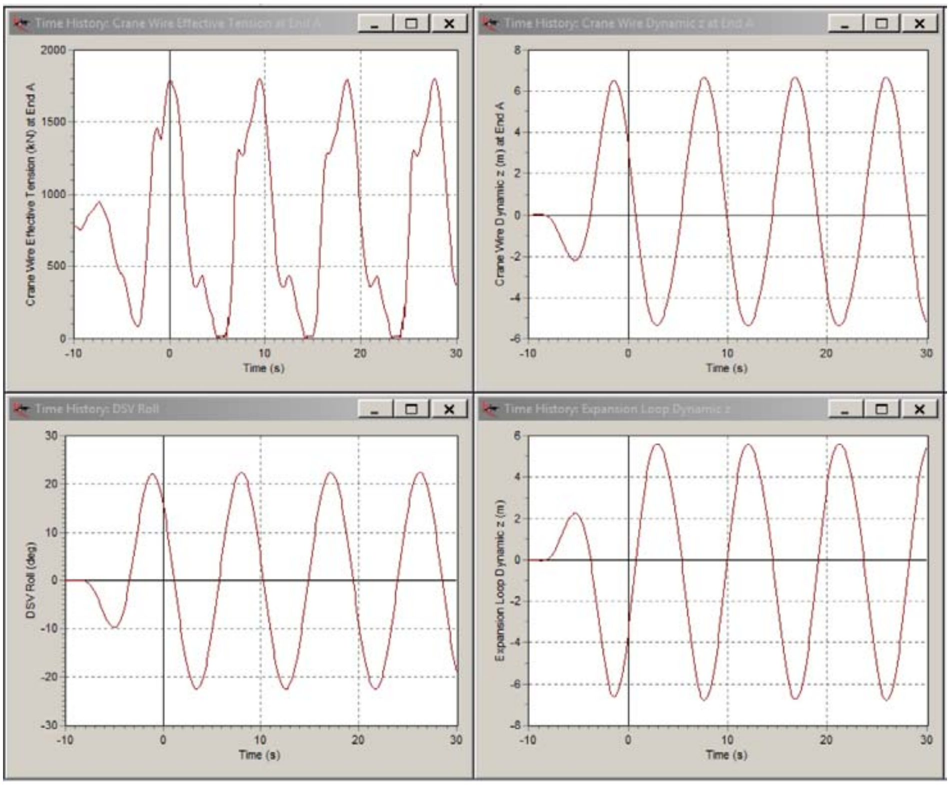
ORCAFLEX SIMULATION RESULTS

Object 1: Subsea Cooling Skid (WD = 100 m)

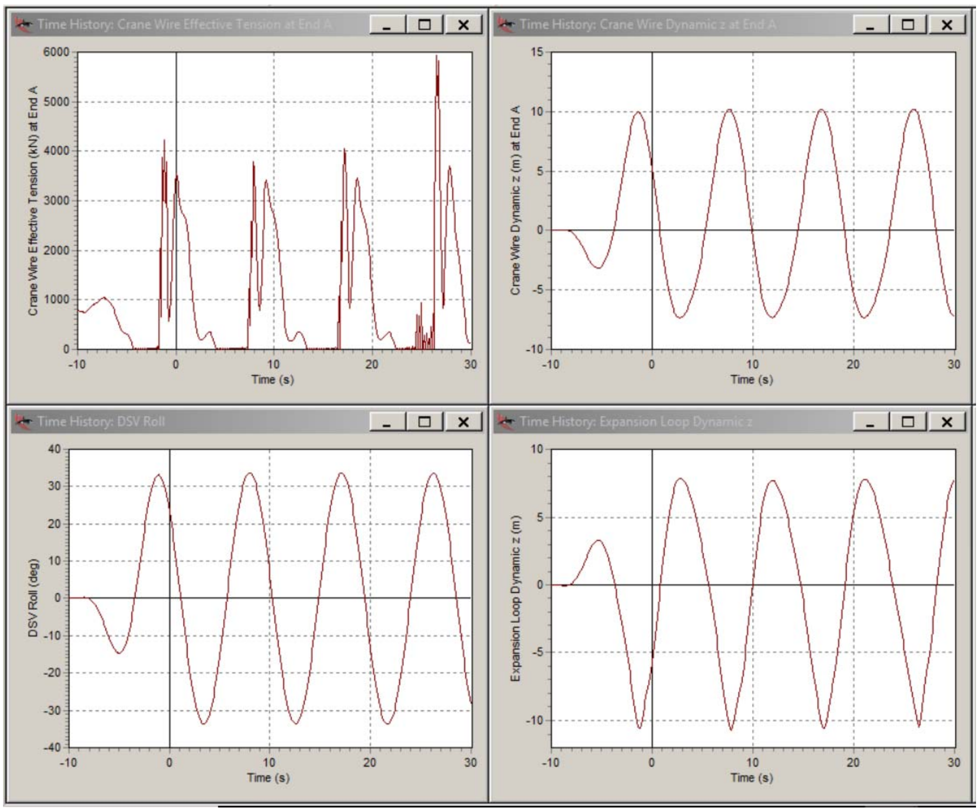
Hs	1.0 m	**Tz**	9.14 s	**Heading**	90°



Hs	2.0 m	**Tz**	9.14 s	**Heading**	90°

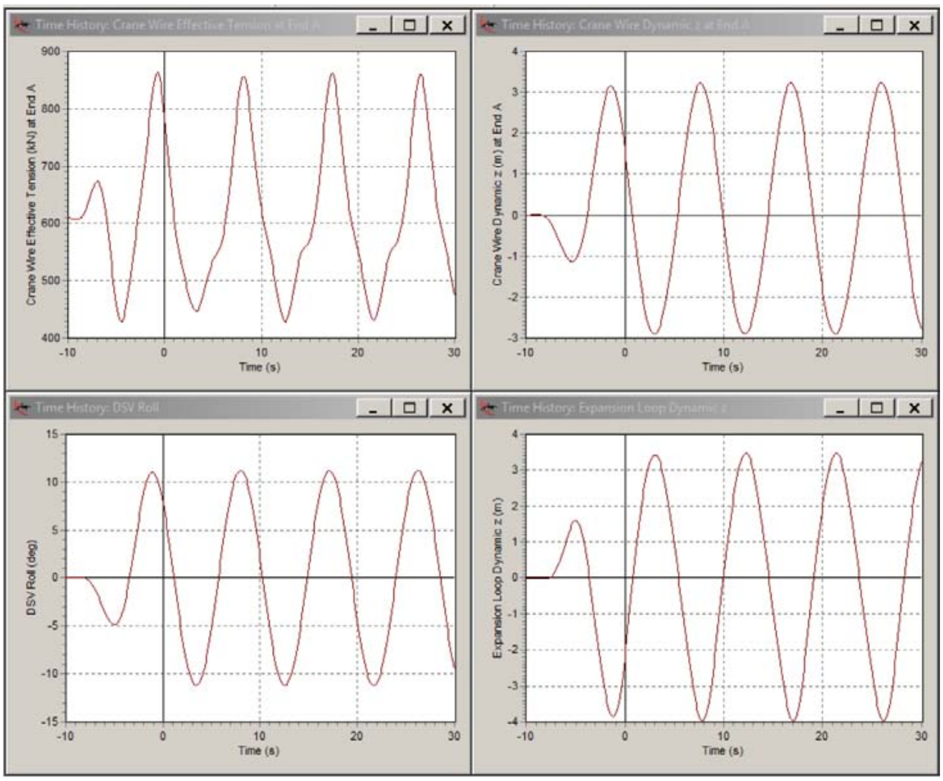


Hs	3.0 m	**Tz**	9.14 s	**Heading**	90°

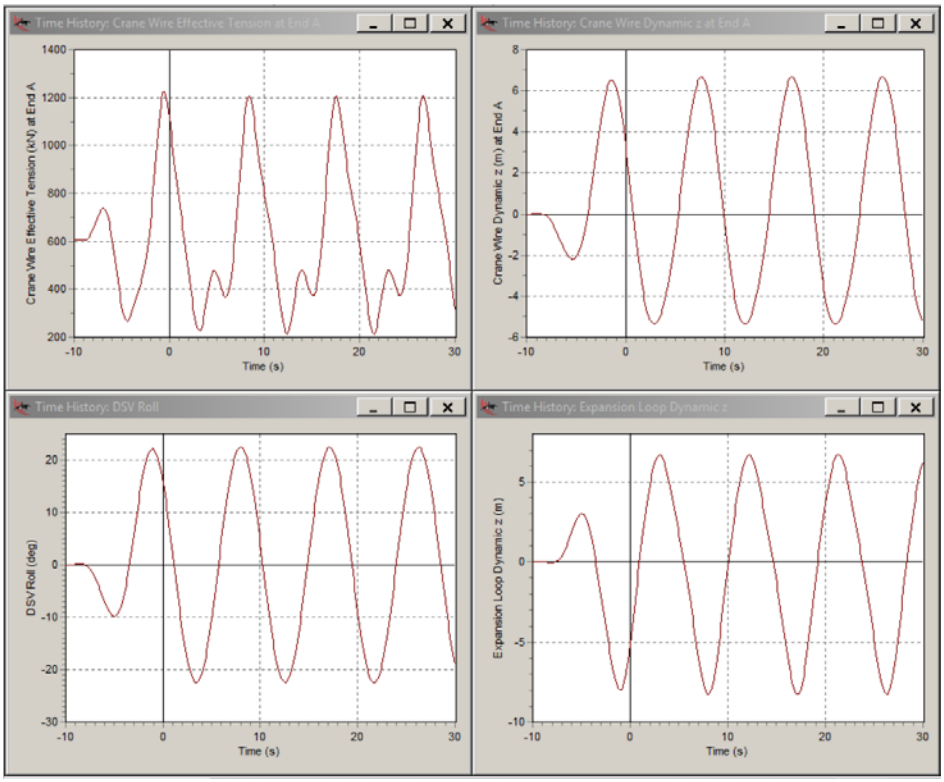


Object 2: Subsea Automated Pig Launcher (WD = 2,000 m)

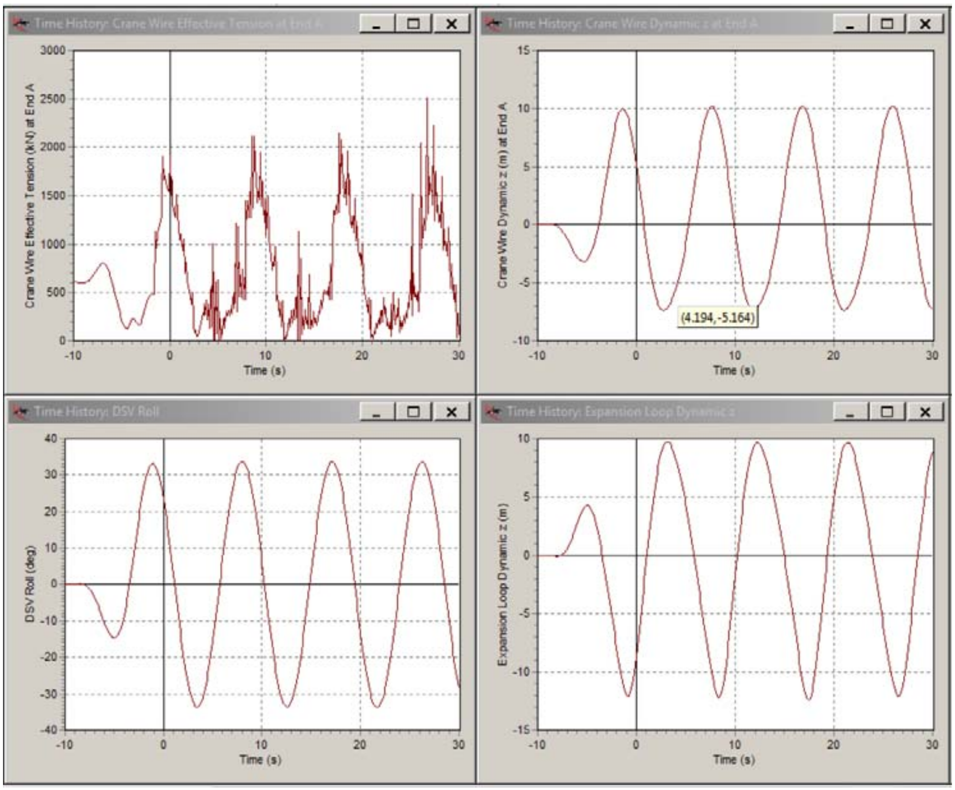
Hs	1.0 m	**Tz**	9.14 s	**Heading**	90°



Hs	2.0 m	**Tz**	9.14 s	**Heading**	90°

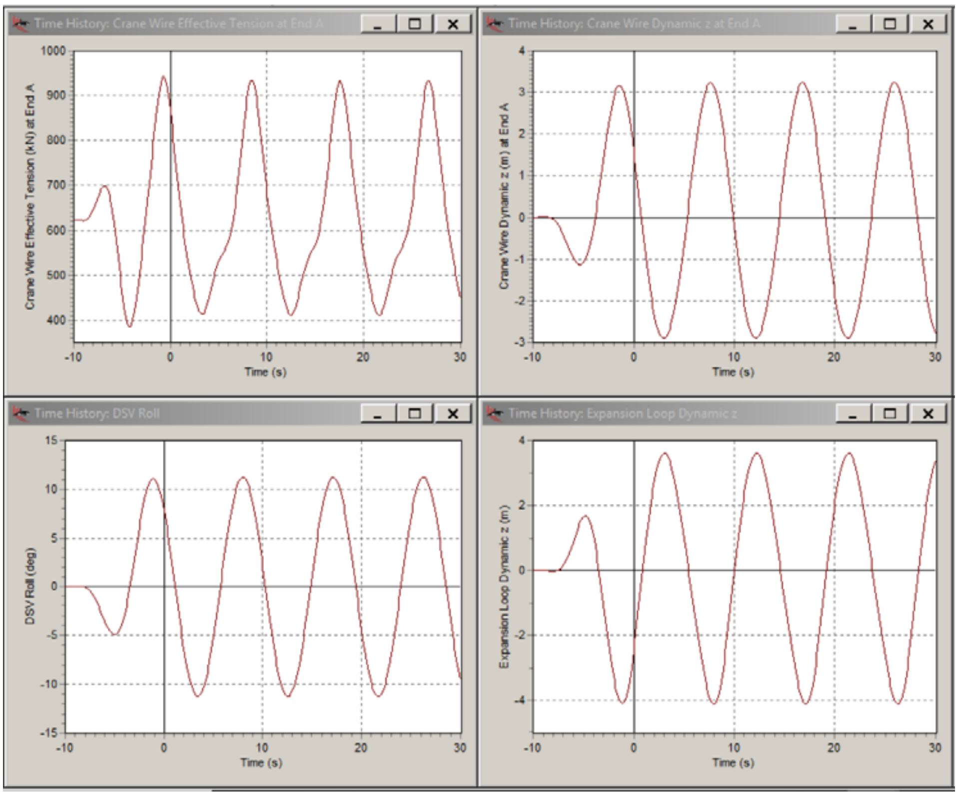


Hs	3.0 m	Tz	9.14 s	Heading	90°

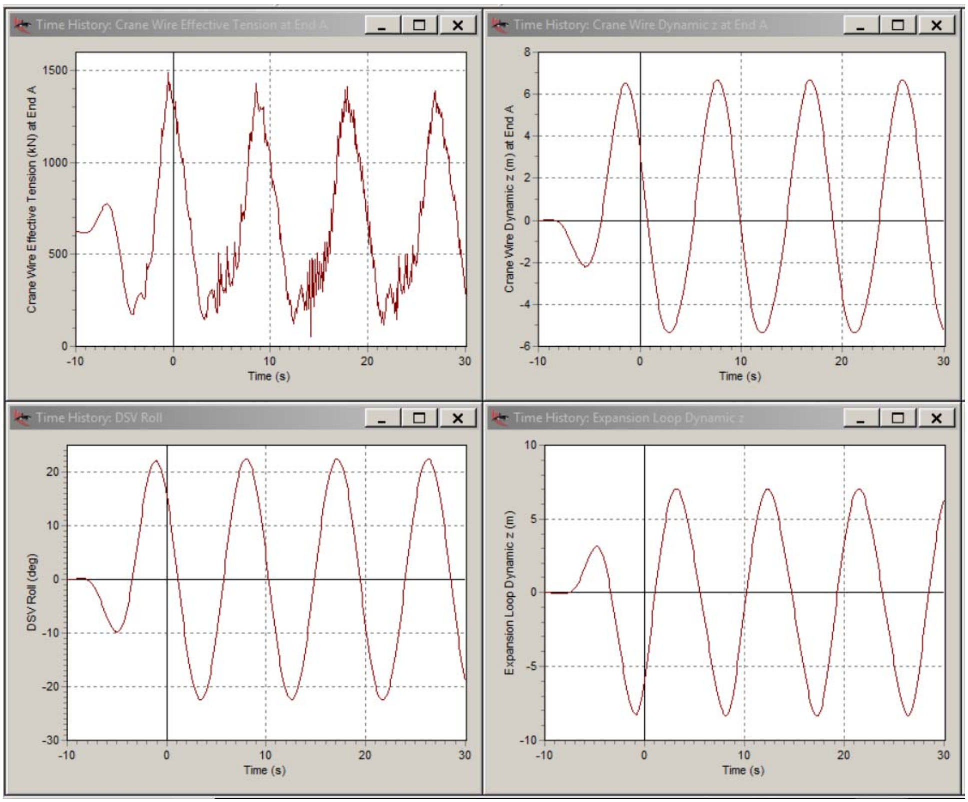


Object 3: Expansion Loop Spool (WD = 2,000 m)

Hs	1.0 m	**Tz**	9.14 s	**Heading**	90°



Hs	2.0 m	**Tz**	9.14 s	**Heading**	90°



Hs	3.0 m	Tz	9.14 s	Heading	90°