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Vessel-Structure Interaction in Exposed Aquaculture

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PROJECT THESIS
Department of Marine Technology
Norwegian University of Science and Technology

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Review
PROJECT THESIS IN MARINE TECHNOLOGY

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Vessel-Structure Interaction in Exposed Aquaculture

Background

To satisfy the increasing demand for seafood, operators in the marine aquaculture are looking towards new possibilities to develop and continue the growth of the industry. The aquaculture industry in Norway has grown considerably over the last couple of decades. However, in the last few years the growth has slowed down due to restrictions regarding licensing from the authorities. The restrictions can mainly be attributed to issues concerning environmental sustainability such as fish diseases, lice and escapes from fish farms. Operators in the industry are looking for solutions, and moving farming facilities further from shore in more exposed waters or even offshore, may prove to be a solution to the issues currently inhibiting the development of the industry.

More exposed operational environments will increase the demands for vessels, equipment and structures involved in the operations. Among the biggest challenges of more exposed locations is the interaction between the vessels and the farming facility. Finding solutions to these challenges will be of significant importance to maintain a sufficiently high level of safety, operability and efficiency throughout the operations. Initiating the development of exposed aquaculture will also provide unique opportunities to develop new designs and solutions to find common optimized solutions for the aquaculture industry as a whole.

This project thesis will be written in collaboration with SFI EXPOSED, which is an established centre for research and innovation, aiming to develop knowledge and technology to create a robust, safe and efficient aquaculture environment in exposed waters along the Norwegian coast.

Objective

To obtain a sufficiently large operational window of wellboat operations at exposed aquaculture locations, new ways of thinking in terms of vessel design and operational procedures may be required. In order to make such improvements, it is important to identify the most critical challenges in terms of operability, and to investigate how these challenges may be dealt with. The objective of this project thesis is to obtain an understanding of the operations at exposed aquaculture locations, identify critical challenges of the vessel-structure interaction and consider alternative concept solutions. Further it will be relevant to apply vessel response analysis to see how design changes may affect the vessel motions during operations and to show, by use of a simulation model, how the applied changes may affect the operability.

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Tasks

a. Review relevant literature to understand state-of-the-art operational methods used in the Norwegian aquaculture, with a focus on the interaction between the wellboats and fish farm installations.
b. Identify and describe operational challenges of the interaction between wellboats and facility structures at exposed aquaculture locations. Investigate how the identified challenges may affect the operations and suggest, if possible, alternative concept solutions.
c. Develop a model for vessel response analysis to investigate how different design considerations may affect the vessel motions.
d. Develop a simple simulation model to demonstrate the effect of design changes in terms of operability and critical limits.
e. State a set of recommended tasks to be covered in the master thesis.

General
In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work. Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction. The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work. The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Deliverable
- The thesis shall be submitted in two (2) copies:
- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints that cannot be bound should be organized in a separate folder.
- The bound volume shall be accompanied by a CD or DVD containing the written thesis in Word or PDF format. In case computer programs have been made as part of the thesis work, the source code shall be included. In case of experimental work, the experimental results shall be included in a suitable electronic format.

Supervision:
Main supervisor:

Sub-supervisor:

Company contact:
Deadline: 16.12.2016

Preface

This report is the final delivery of the specialisation project in Marine Systems Design at the Department of Marine Technology, Norwegian University of Science and Technology, Trondheim.

The report is covering vessel-structure interaction in exposed aquaculture and is based on an on-going research project by SFI Exposed Aquaculture Operations. The work has consisted of a literature study, operability analysis and the implementation of system simulation in operability assessment.

I would like to thank my supervisor, Professor Bjørn Egil Asbjørnslett for his guidance and support throughout the project. I would also like to thank PhD student at MARINTEK, Martin Gutchs, for helpful guidance on vessel response analysis. Finally I would like to thank PhD student at NTNU, Endre Sandvik, for useful inputs regarding the combination of vessel operability and simulation.

Runar Stemland
Trondheim, December 16, 2016

Abstract

Vessel operations at exposed aquaculture locations introduce higher demands for vessels, equipment and systems involved in the operations. The interaction between vessels and installations can be critical during the operations, particularly during harsh weather conditions. Optimising the vessel-structure interface, or finding new design concepts which eliminates the interactions, is important to improve the safety and to expand the operational window at exposed locations.

Increased reliability and operability of vessel operations is a key factor if the industry shall be able to grow in the future. Challenges of the vessel-structure interaction was identified by studying previous projects on exposed aquaculture, operability and offshore aquaculture. The research shows that crane operations, transfer of fish and vessel navigation and approach were critical parts of the operations.

A qualitative analysis was then conducted to evaluate how the operational challenges could affect the operations and possible consequences. Any parts of an operation which can cause damage to the net structure is critical, as this may lead to fish escapes. It was also found that the large dimensions of the wellboats can cause serious problems in terms of high load transfers to the cage structure, and possible structural collapse of floating collars and mooring systems. Alternative concept designs were then considered to assess whether they could reduce or eliminate some of the challenges experienced in the industry. It seems clear that eliminating the direct interaction between the vessel and facility could contribute to solve many of the challenges. However, in order to do this, new concept designs are required to replace the current procedures.

One of the main concerns in the vessel-structure interaction is the relative motion between the two elements. Vessel response analyses were performed for different concepts and hull design configurations. Allowable sea states for performing an operation were then determined by defining operational criteria. By combining the results from the analyses with long-term wave statistics from the Norwegian Sea, the percentage operability for each case was found. The highest operability was obtained by increasing draught and decreasing beam, while the lowest operability was found by decreasing draught and increasing beam. The results also shows that the wave heading during the operation is important and that the operational limits are significantly higher for head sea than for beam sea.

A vessel response analysis can be used to assess a specific vessel design in an early stage of

the design process, which can be both efficient and cost-saving. It can also provide useful information about operational limits that can be used as a tool for decision-making in real-world operations. A drawback of the method is the independent assessment of each sea state which, over time, is likely to provide over-estimated operability. By developing a stochastic simulation model with operational limits and weather forecasting as inputs, a decision of whether or not to carry out an operation can be taken based on the expected environmental conditions throughout the duration of the operation.

The basic structure of a simulation model has been developed and presented. However, to obtain reliable results, a more detailed study on model inputs like weather forecasting and system logistics must be performed. For further study in a master's thesis, it could be interesting to look more into the combination of vessel response, operability and simulation, and try to develop a model which can provide useful information of the performance of an aquaculture system.

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Abbreviations

CF centre of flotation.

COG Center of Gravity.

DP Dynamic Positioning.

GA general arrangement.

GM metacentric height.

HSE Health, Safety and Environment.

JONSWAP Joint North Sea Wave Project.

KB vertical centre of buoyancy.

KG distance from keel to vertical centre of gravity.

KPI Key Performance Indicators.

RAO Response Amplitude Operator.

RMS Root Mean Square.

SFI Centre for Research-Based Innovation.

TCF transverse centre of flotation.

VCG vertical centre of gravity.

VERES Vessel Response Program.

WP Work Packages.

Nomenclature

A_p projected cross-sectional area of duct.

D duct diameter.

H_s significant wave height.

K_T thrust force coefficient.

P_{net} net pressure.

T_0 total thrust of impeller.

T_w wave period.

U_A thrust momentum mean outflow velocity.

∇ volume displacement.

ρ mass density of sea water.

σ' cavitation index.

n impeller frequency of revolution.

$\mathbf{I}$ second moment of area.

Chapter 1

Introduction

Background
To satisfy the increasing demand for seafood, operators within the aquaculture industry are looking towards new possibilities to develop and continue the growth. Aquaculture in Norway has grown considerably over the last couple of decades. However, in the last few years, restrictions regarding licensing and concessions from the authorities have inhibited the growth. This can mainly be attributed to issues concerning environmental sustainability such as salmon lice, diseases and escapes from the fish farms. The industry is continuously looking for solutions to the issues currently inhibiting the development. Moving farming facilities further out from shore into more exposed waters or even offshore, may prove to be a solution that is both economically and environmentally sustainable.

More exposed operational environments impose new requirements for vessels, equipment and structures involved in the operations. New design or alternative concepts may be required as a results of larger vessels and harsh environmental conditions. Consequently, the interface between vessels and cage structure will be essential. Finding solutions to these challenges will be of significant importance to maintain a sufficiently high level of operability and efficiency throughout the operations. Developing new concept designs for exposed aquaculture can also provide unique opportunities to develop common optimized designs for the aquaculture industry as a whole.

State of the Art
Research projects on exposed aquaculture in recent years show that the industry is facing significant challenges when moving operations towards more exposed locations. Even though key issues has been identified and analysed, there are no solutions yet that actually solve these problems. Part of this may be due to an uncertainty of the direction of which the industry should develop. Different designs have been suggested and discussed, but a common solution is yet to be defined. A few actors of the industry are currently about to realize huge test projects in offshore aquaculture. The results from these projects will be of great importance for the future of the aquaculture industry, as it will give answers to many questions currently hampering the growth.

Objective

To increase operational windows and reliability of vessel operations at exposed locations, new ways of thinking in terms of design and operational procedures are required. In order to make improvements, it is important to identify the critical issues and to investigate how these can be dealt with. The objective of this project thesis is to obtain an understanding of the challenges in the vessel-structure interaction, consider alternative concept solutions and to analyse how design changes can affect the operational limits of the vessels. Further, it will be relevant to learn how a generic simulation model can be developed to see how an entire system reacts to design changes or alternative concept solutions.

Based on the objective, the thesis aims to answer the following questions:

- What are the main challenges of the vessel-structure interaction in exposed aquaculture, and can alternative concepts cope with these challenges?
- Will variation of vessel design parameters affect the operability?
- How can a generic simulation model be developed to simulate the performance and operability of a real-world system?

Report Structure

The report is organized according to the "IMRaD" principle. Chapter 2 can be considered an extension of the introduction, as it describes the system to be investigated and how different system elements may give rise to the challenges in the industry. A literature review presenting knowledge obtained from previous projects on relevant subjects and the ongoing pilot projects in offshore aquaculture is presented in Chapter 3. Based on the literature review, Chapter 4 discuss relevant challenges of exposed aquaculture operations in more detail. A vessel response analysis is performed in Chapter 5 to see how operational limits may vary as a result of changing design parameters. Chapter 6 discuss how a response analysis can be implemented in a system context through a simulation model. A discussion of the work is presented in Chapter 7, followed by concluding remarks and recommendations for further work.

Chapter 2

System Description

This chapter describes the system of this project thesis. The aim is to describe the elements included, and to clarify any assumptions and simplifications made. Through considerations from literature studies, previous work on the topic and conversations, it was decided to exclude certain elements and factors from the system. These simplifications were made to limit the scope of work, and to establish clearly defined boundaries for the problem.

To fully understand the challenges related to the interaction between vessels and fish farms, it is important to attain an overview of how the operations are carried out today. In order to attain this overview, it is important to have a clearly defined system to work with. The subsequent sections describe central elements of the system and what makes them part of the challenges in the vessel-structure interaction.

Cage Design

Several different types of fish cages are used in the Norwegian aquaculture today. Plastic cages with a circular shape is the most common, but steel cages with a rectangular shape are also used. The diameter of the circular cages ranges from about 15 to 65 metres (AkvaGroup, 2016a). In exposed locations along the Norwegian coast, cages with a diameter of about 50 metres is among the most used cages (Teknologirådet, 2016). NS9415 regulates the requirements for marine fish farms in Norway. In addition to design, the regulation includes requirements for site survey, risk analyses, dimensioning, production, installation and operation (Standard Norge, 2009). The design regulations include requirements for all major components in a farm, i.e. net bag, mooring and float collar. A simple illustration of how a typical fish cage may look is shown in Figure 2.1.

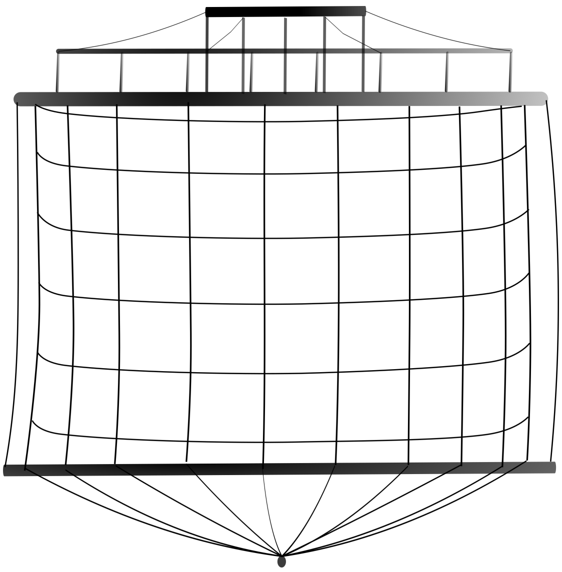


Figure 2.1: A simple sketch showing how a typical fish cage may look (without mooring).

As can be seen from the figure, the cage is a floating, dynamic structure which means it will move as a result of environmental loads. The construction is also characterised by light and cost-effective materials, which makes it less resistant towards loads from large vessels. As the vessels become larger and the locations are moved further out from shore, this gives rise to significant challenges both in terms of operations and structural integrity.

Vessel Design

The development of wellboats has been towards larger vessels, with increasing capacity, equipment and technology. This is supported by the data presented in Appendix A. The same development can be said about service vessels, even though they still significantly smaller than the wellboats.

For the purpose of this project thesis, it is decided to use M/S "Ro Fjell" as reference vessel. As of today (2016), this is the largest wellboat in the world (Rostein AS, 2016). The vessel is 87 meters long, and has a draught of 5.3 meters. The well capacity is 4500 m^3, and for handling the various tasks during the operations; six cranes are mounted on the deck. A more detailed vessel specification can be found in Appendix B.

The reason for choosing a wellboat as reference vessel is the fact that they are much larger than the service vessels and thus constitute bigger challenges in terms of interaction with, but also considering manoeuvring in and around the facility structures. Another aspect of this choice, is that in the new concept designs for offshore aquaculture, the need of service vessels are eliminated. This can be interpreted as an indication of that this type of vessel is not considered suitable for offshore aquaculture operations.

Facility Design and Mooring Configuration

Most fish farm facilities consists of a network of cages aggregated in modules, typically 6-12 cages. In sheltered locations, the modules may be even larger. To avoid too much local pollution of waste and excrement, the facilities should be placed in areas with favourable currents and water depth. Temperature and level of oxygen in the water are important factors to consider, as they affect the growth and physiology of the fish (Remen, Oppedal, Stien, Torgersen, & Olsen, 2013). There are regulations for minimum distance between facilities to avoid spread of fish diseases and lice.

It is obvious that the geographical location is of great importance for the operation of an aquaculture facility. Factors that do influence the operation are the design and configuration of the facility, as well as the environmental conditions like waves, currents and wind. Few cages are preferred in exposed locations, because this allows for a greater number of mooring lines per cage (Cardia & Lovatelli, 2015). Figure 2.2 illustrates a typical fish cage configuration consisting of a network of circular plastic cages like the ones described in Section 2.

The cages are moored in a dynamic square-shaped grid system. The purpose of the system is to hold the cages and dampen external forces from waves, currents and wind (Cardia & Lovatelli, 2015). The mooring system may be split into two main parts; the mooring lines and the grid system. The mooring lines consists of anchors, lines and ground chains, while the grid system consists of frame ropes and bridle lines. These are all components exposed to forces during harsh weather conditions or during a vessel operation at the facility, and is therefore considered as part of the system. The mooring system becomes a particular problem when the vessels are so large that their draught is equal to, or even larger than, the depth of which the mooring lines are located. These issues, along with several other related to the vessel-structure interaction will be further discussed in Chapter 4.

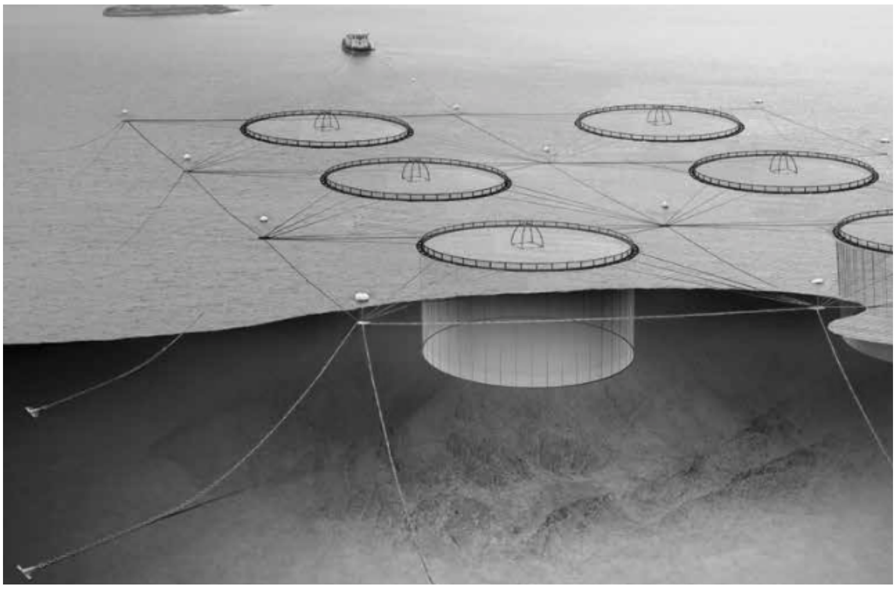


Figure 2.2: Typical configuration and design of a fish farm facility, seen from above. (AkvaGroup, 2016b)

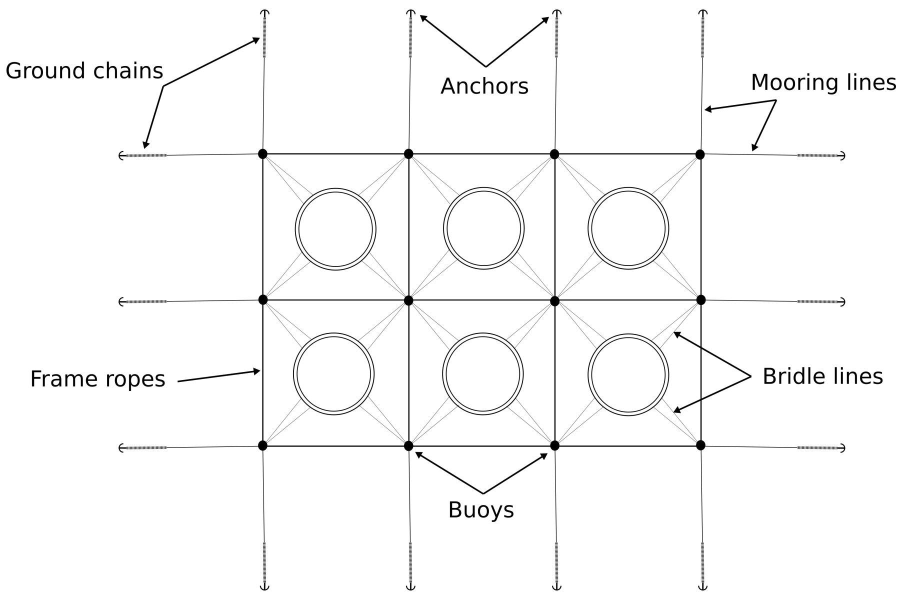


Figure 2.3: Simplified illustration of the mooring system.

Chapter 3

Literature Review

The aim of the review is to identify current knowledge on the challenges of exposed aquaculture. Through the literature review, relevant research projects and theses addressing exposed aquaculture and operability will be investigated. As the aquaculture industry is moving to more and more exposed locations and is on the verge of launching offshore installations, a review on the current status of offshore aquaculture is performed and presented in Section 3.2.

3.1 Previous Work

When reviewing previous work on the subject, it is important to not only summarize what has been done, but to also discuss why and identify the outstanding questions still to be answered.

3.1.1 SustainFarmEx

SustainFarmEx, a research project lead by SINTEF Fisheries and Aquaculture, aimed to clarify operational limits for operations at exposed locations. The project consisted of four so-called Work Packages (WP), covering different scopes of interest. WP1 considers safe operations and Health, Safety and Environment (HSE) for workers in the aquaculture industry (Holmen, 2015). The aim of this work package was to identify risk factors in exposed aquaculture operations and operational guidelines for creating a safe work environment. Through inspections and interviews, it was uncovered that operational limits in general are decided based on experience and discretion, and that developing tools to assist in this experience-based decision-making will be relevant. Analyses of reported accidents show that lift operations has become the largest contributor to deaths in the aquaculture industry.

The aim of WP2 was to investigate different solutions to ensure structural integrity of the facilities and the welfare of the fish (Klebert, 2015). Different design configurations of the cage/mooring-system was considered, and the results indicates that positive effects can be obtained by increasing the distance between net structure and sinker tube. Regarding structural deformation of the floating collar, the importance of the material's dependence of temperature and rate of deformation is clearly pointed out.

The importance of remote monitoring and control at exposed locations is covered in WP3 (Senneset, 2015). The work shows that both installation, operation and maintenance of sensor systems is challenging due to harsh environmental conditions. Based on these findings, it was suggested that a combination of sensors and numerical models can provide real-time monitoring and hence enable condition-based maintenance at the facilities.

Transfer of fish from wellboat to fish cage, or feed from feeding vessel to feed facility is the main focus of WP4 (Lien, 2015). Relative motions between the two floating elements are largely affected by environmental conditions, and hence a relevant issue to consider. The research identifies several challenges of wellboat operations. Lack of procedures, communication, time pressure, manoeuvring of large vessels at the facilities and crane operations is pointed out as the most challenging issues at exposed locations. Based on the identified challenges and available technology, alternative concept designs were developed and evaluated. A selection of the suggested concepts, along with a short discussion, can be found in Section 4.2 and in Appendix C.

A master's thesis on this subject was written by Ellefsen (2014) as a part of the SustainFarmEx - WP4 project. An interesting assertion from this thesis is that the problem with fish transfer is not the transfer operation itself, but rather the hoarding of the fish and the physical interaction between the wellboat and the cage structure.

3.1.2 ERFA - Exposed Aquaculture

ERFA - Exposed Aquaculture was another project lead by SINTEF Fisheries and Aquaculture. The aim of the project was to facilitate the development of research-related issues in operation of exposed aquaculture. This was done by gathering and analysing experience and operation data from four selected exposed aquaculture locations. The main sources of information included interviews, observations and collection of operation- and environmental data.

A survey including 20 actors of the industry, aimed to identify the most important issues in need of improvement. Vessel navigation and approach to the facility structures was most frequently mentioned, along with safety equipment, net technology, monitoring and tools for decision making. In general, the project report concludes that in order to operate safely and efficiently at exposed locations, a better interaction between the system components is needed. Based on these results, recommendations for further studies is presented. Key issues that are mentioned is development of new technology/concepts to expand the operational window, vessel-structure interaction, increased automation to reduce the risk of human failure and the need for operational criteria and limits. For the vessel-structure interaction, it is suggested that two main principles should be investigated through further study. One is to develop and improve the interface during operations, still by use of wellboats. The other is finding completely new ways of operating, without the use of vessels. The latter is likely to require a different type of facility design than what is used today.

3.1.3 SFI - EXPOSED

EXPOSED Aquaculture Operations is a centre for Centre for Research-Based Innovation (SFI) with the aim of developing knowledge and technologies for exposed aquaculture operations, enabling a sustainable expansion of the fish farming industry (Bjelland, 2016). A total of eight research areas has been defined and divided into separate work packages. Project 3 (P3), which encompass the vessel-structure interaction, is also the background for the topic of this project thesis. The objective of P3 is to investigate new concept designs for the vessel-structure interface to increase reliability and expand the operating window. The project is still in an early phase, hence there are no published reports available. However, the first phase of the project, identifying operational challenges, is completed. The results cover challenges regarding both wellboat and service vessel operations. The results are confidential, and therefore not published in this thesis.

The purpose of identifying these challenges is to gain a complete understanding of the operations, and to be aware of the risks involved. This knowledge will be of great importance when the development of new design concepts and subsequent feasibility analyses shall be carried out.

3.1.4 Various Projects

The biology of the fish and technical implications of operations at exposed locations was studied in the project *Exposed Farming*, lead by SINTEF Fisheries and Aquaculture. Their objective was to establish knowledge about the limits of salmon and performance of technologies in high currents and waves. Another project coping with the biology of salmon was the research project *Salmon Dynamics*, lead by the Norwegian Institute of

Marine Research. Their objective was to understand the oxygen experience of individual salmon due to oxygen fluctuations in dynamic farm environments.

Causes for fish escapes in Norwegian fish farms was analysed by researchers through the project *SECURE*. They found that equipment failure or operational errors are the reason for three out of four escapes, while two out of three escapes are due to holes in the net structure (Naas, 2016). Other common structural failures identified was collapsed floating collar and problems with mooring lines. Figure 3.1 shows common escape factors addressed in the project.

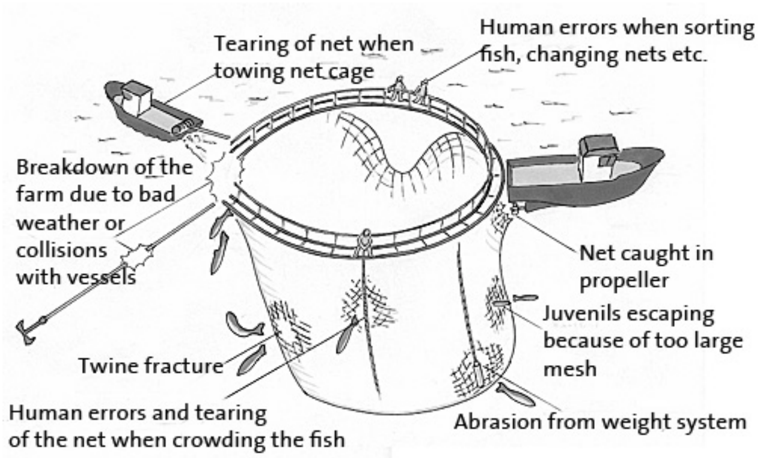


Figure 3.1: Common causes for escape in Norwegian aquaculture. (Naas, 2016)

Heide, Moe, Lien, and Sunde (2013) analysed service vessel operations in Norwegian aquaculture through the project *Servicefartøy 2010*. The main objective of the project was to develop a vessel concept, including procedures and methods for safe and efficient service operations. The project work resulted in several design concepts which can prove their value through realizations of products and systems in the years to come. The project also conducted an operability analysis of four different service vessels. The results show that design can have a significant influence on the vessels operational capabilities.

Regarding vessel operability, a master's thesis by Sandvik (2016) copes with clarifying performance criteria, followed by an analysis of how the operability changes as a result of changing design parameters. The vessels of interest in the thesis is offshore construction vessels, but the approach may also be applied to different types of vessels. The results shows that the operability vary significantly from parameter variations and operational area. It also concluded that neglecting weather windows and uncertainty in weather forecasting would lead to over-estimation of vessel operability.

PhD candidate Gutsch (2016) at the Department of Marine Technology is currently working on a thesis related to investigation of Key Performance Indicators (KPI) for vessel performance parameters for challenging marine operations. As for the master's thesis by Sandvik (2016), an important part of the work is to perform vessel response analysis to define critical operational limits and KPIs.

3.2 Offshore Aquaculture

As mentioned in Chapter 1, the aquaculture industry is facing problems regarding environmental sustainability. Through significant investments in research and development of offshore aquaculture concepts, central actors hope to cope with these challenges and ensure further growth of the industry.

Further out from shore, the tidal currents are less influential and the direction of currents are often more constant. This may prove to be beneficial conditions for the fish farming and its impact on the surroundings. Moving the facilities to open ocean areas means the structures will be exposed to much higher loads from the environment, which in turn will introduce new demands for design and operational procedures.

SalMar is about to launch their *Ocean Farming* project at Frohavet, off the coast of central Norway. This is a pilot installation who's main objective is to gain operational experience in the process of commercialising this type of offshore fish farming (SalMar, 2013). The design, a semi-submerged fixed structure, is a combination of technology from the oil and gas sector and the fish farming industry. One of the key solutions of this concept is that all operations are automated, and the need of service vessels is eliminated. An illustration of the concept along with technical specifications is presented in Appendix D.

Another pilot project is Nordlaks' *Havfarm*. The design is showing resemblance to a large tanker, and is, like the "Ocean Farming" design, a combination of experience and technology from the offshore and aquaculture industry. Single point mooring makes the installation move in sway and cover an area with a radius of about one kilometre (Nordlaks, 2016b). This will ensure a wider spread of the nutrients and waste substance and thus reduce the impact on the environment. The system is also self-sufficient and does not require service vessels. Unlike SalMar's project, this has not yet reached the building phase, and is likely to be launched at a later stage. Technical specifications and an illustration is presented in Appendix E.

3.3 Discussion of Review

Through studying literature, a brief overview of relevant projects has been addressed. Exposed aquaculture is a relatively new area of interest, hence the amount of research and data available is somewhat limited. However, results from the previously discussed projects indicate that the industry is facing significant challenges when moving the operations to more exposed locations. Among the most recurring challenges are:

- Safety of workers
- Crane operations
- Transfer of fish
- Vessel navigation and approach

Indications based on feedback from actors in the industry, tells that key issues are the interface between the vessels and facility structures, need for automation to reduce human risk and establishment of operational criteria and limits. A common factor through many of the projects discussed, is the identification of challenges related to exposed aquaculture operation. This is an important part of understanding the operations, and essential knowledge in the process of developing new and improved system concepts. An important part of this thesis is to attain this knowledge and understanding. Identification and discussion of operational challenges related to the vessel-structure interaction is therefore a natural scope of interest, and will be covered in Section 4.1.

Offshore aquaculture is yet to be proven in real-life operation, and the industry is expectantly waiting for the results of the test projects. The fact that some actors are investing this heavily into pilot projects, indicates that there is an urgent need for new solutions in the industry. If the new designs succeeds, this may open a whole new dimension in the aquaculture industry, that can cause ripple effects into other parts of the industry in terms of new designs and operational procedures.

Chapter 4

Vessel-Structure Interaction In Exposed Aquaculture

From the study of previous work in Chapter 3.1, it was pointed out that a key issue of exposed operations is the interface between vessels and facility structures. The purpose of this chapter is to provide an understanding of these challenges, discuss how they can affect the operations and possible consequences. Further, it will be relevant to consider alternative concept designs and assess whether they reduce or eliminate the challenges.

4.1 Operational Challenges

Operations at exposed aquaculture locations will impose new demands to ensure safe and efficient operations and to expand the operating window. The rest of this chapter will elaborate the results of a qualitative assessment on the operational challenges, and seek to evaluate how they can affect the operations.

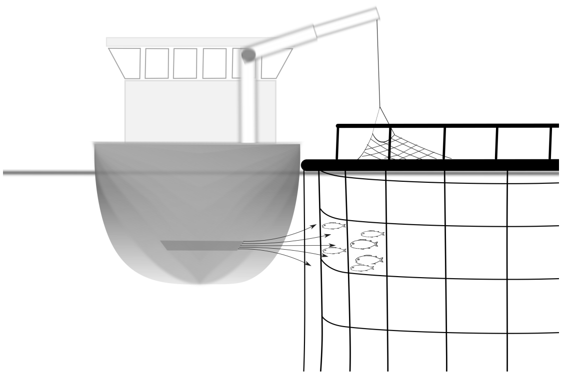
4.1.1 Direct Interaction

This category includes the part of the operation where a wellboat is moored to a fish cage, or otherwise is in direct contact with the cage structure. As the Norwegian aquaculture industry has been growing, so has the size of vessels and facilities. Consequently, both the loads from the environment and loads acting in the vessel-structure interaction increase. Eventually, it will reach a point where it is not viable, or even possible, to keep increasing the dimensions without risking serious consequences in case of an accident. Most fish farm cages are not designed for large wellboats to be moored alongside the cage, particularly not in harsh environmental conditions where the vessel motions may become large. When the vessel is moored to the cage, there will be a direct load interaction between a dynamic and a relatively static element, being the vessel and cage structure, respectively. Loads from waves, currents and wind can easily increase the magnitude of the loads, and consequently cause damage to the moorings or the cage structure itself. If the structure is not strong enough or the relative motions become too excessive, it may result in structural damages and possibly escape of fish.

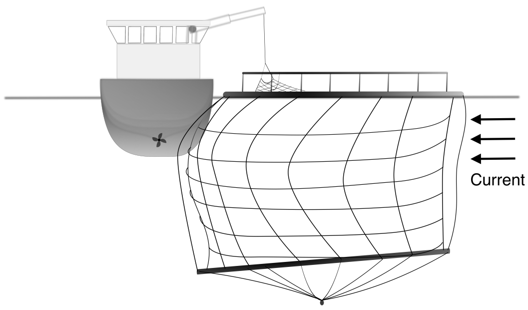
Damage To Net Structure

As the net is the only barrier keeping the fish inside the cage, it is probably the most critical part of the farm to prevent escapes of fish. According to Svåsand et al. (2015), escaped salmon from aquaculture represents a threat to the genetic integrity of the wild salmon populations. The nets are dynamic, and may move as a result of external forces from currents, waves or thruster jets from a nearby vessel. Chafe and tear of the net structure may occur as a result, and should therefore be avoided to prevent large scale escapes of fish.

Figure 4.1b shows the principle of how the net can be affected by external loads from currents and waves and interact with the vessel. This is not a common problem, as preventive measures has been implemented in most cage designs to reduce the nets ability to move. However, net interaction with ropes and components of the mooring system is more common, and may cause wear and eventually tear of the net structure.



(a)



(b)

Figure 4.1: Illustrating the effect of currents (a) and thruster jet flow (b).

As the vessel is moored to the cage, thrusters and propellers may represent a significant problem. Tunnel thrusters are in this situation the most important ones to consider, as the direction of thrust in most cases will be directly towards the cage. A concentrated outflow towards the cage may increase the stress level of, and even kill, the fish. Figure 4.1a shows how the outflow jet stream interact with the fish. Reversing the thrust will create a suction inflow towards the propeller, which can pick up loose objects like ropes, lines or the net, causing damage to both the objects and the vessel. In addition, noise and vibration from thrusters and propellers is disturbing the fish, and contributes to increase their stress level. Due to all the potential problems with thrusters, dynamic positioning is not commonly used by wellboats when operating close to the cages.

Damage To Fish Cage Structure

As mentioned in Chapter 4.1.1, the relative motions between the vessel and the cage structure is a challenge at exposed locations. The floating collar at the cage is flexible, and not designed to handle excessive motions and loads from the vessel. Thus, if a vessel is moored to the cage and the loads from the environment acts in an unfavourable way, the vessel can be forced towards the collar, and even submerge parts of the cage structure. This is illustrated in Figure 4.2.

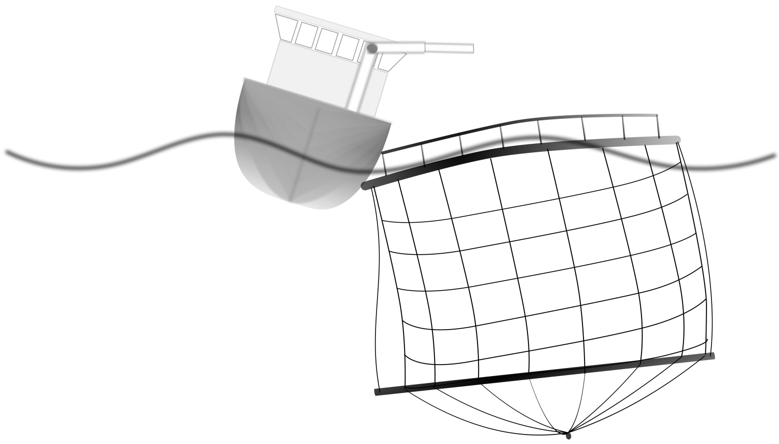


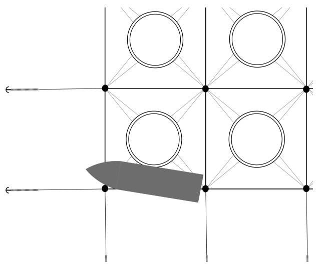
Figure 4.2: Under certain conditions, parts of the cage structure may be submerged due to the loads from the vessel.

The occurrence of such incident is more likely if the vessel is very large and/or the direction of waves, wind and current forces the vessel towards the cage. The consequences are not necessarily critical, since the cage structure is flexible. However, if the loads become too large, the structure may collapse and cause large scale fish escapes.

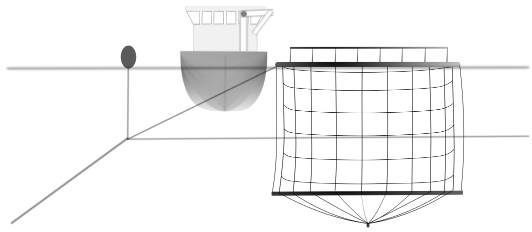
4.1.2 Navigation and Approach

This section covers the part of an operation where a vessel is navigating in an aquaculture facility or approaching a cage. As the vessel dimensions increase, so does the environmental loads acting on the vessel. This makes navigation in small areas such as in between the cages more challenging. Large vessels is likely to enquire larger draught, and so the depth of frame ropes and bridle lines becomes an issue to consider.

If the vessel is too large to fit in between two buoys, direct contact may be inevitable. If the draft of the vessel in addition is so large that it can cause chafing on the bridle lines and/or frame ropes, the presence of the vessel can lead to significant wear of the mooring system. These incidents are illustrated in Figure 4.3a and 4.3b, respectively. Eventually, such incidents may result in critical damage and possibly torn mooring lines. Since the mooring lines are all interconnected, failure of one line can in a worst case scenario lead to a progressive collapse of the entire mooring system.



(a) Wellboat is too big to fit in between the frame buoys, causing wear to the mooring lines.



(b) The vessel may cause chafing on bridle lines and possibly frame ropes due to large draft.

Figure 4.3: Common challenges during navigation and approach due to large vessels dimensions.

The challenges related to vessel dimensions can to some extent be explained by a lack of focus on the system as a whole during the development of the aquaculture industry. This can also be said to be a contributing factor for the challenges related to the direct interaction at exposed locations elaborated in Section 4.1.1. The vessels and the farms have become larger, but the system as a whole has not changed much as a result of this development. The consequence is that the interaction between the vessels and structures at exposed locations to some degree is characterized by operational procedures originally developed for relatively calm and sheltered waters. In that sense, it would be pertinent to raise the question whether new procedures and designs are required if the operations are to be moved further out to sea. SalMar's *Ocean Farming* and Nordlaks' *Havfarm* discussed in Section 3.2, are both ongoing pilot projects for offshore aquaculture, where completely new designs and operational procedures are developed. These projects give further indications of that new ways of thinking in terms of design and procedures are necessary in order to operate safely and efficient at exposed aquaculture locations.

4.2 Consideration of Alternative Concepts

Based on the previously discussed challenges, a few alternative concept designs and possibilities will be considered. The purpose is to see if different design considerations can contribute to cope with some of the challenges experienced in the industry.

4.2.1 Eliminating the Direct Interaction

It is reasonable to say that one of the main issues with the vessel-structure interaction is that the system as a whole is not designed to handle the harsh environmental conditions at exposed locations. Mooring large vessels to under-designed cage structures can lead to unwanted and serious incidents. Developing a system design where this direct interaction is partly or completely eliminated could therefore prove to be a good option.

In a system where the direct interaction is eliminated, new ways of thinking in terms of transferring fish between the vessel and cage is required. This issue has been studied through the project SustainFarmEx (Lien, 2015) and a master thesis by Ellefsen (2014).

The concept shown in Figure 4.4 is developed through the SustainFarmEx project and is based on the idea of eliminating the direct interaction between wellboat and cage structure by the use of a floating tube. The tube is connected to the wellboat and to a fixed connection point at the cage. This enables the vessel to use Dynamic Positioning (DP), and increase the vessel's ability to handle the rigours of harsh and changing environmental conditions. The concept also eliminates the need for cranes on the wellboat, but requires a solution to the hoarding of the fish to the pump inlet inside the cage.

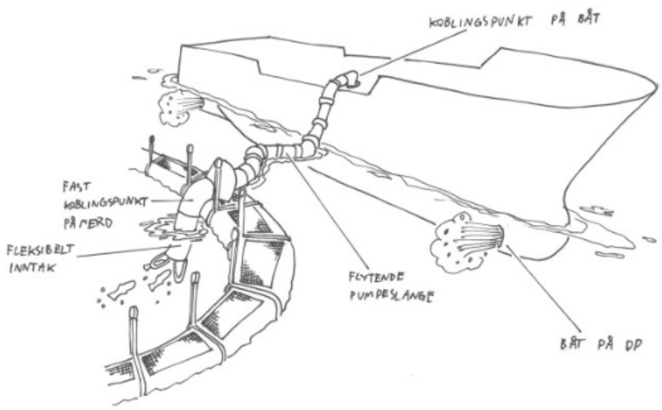


Figure 4.4: Transfer of fish through floating tube (Lien, 2015).

Another concept suggested by Lien is shown in Figure 4.5. This concept also eliminates the direct interaction between the wellboat and the cage. It differs from the former concept in that the vessel is indirectly connected to the cage through an intermediate buoy. In this way the vessel can be positioned even further away from the cages, which can be beneficial in harsh conditions. Another potential advantage is that the buoy can be connected to the cage prior to the arrival of the vessel, and thus reducing the duration of the operation and increasing the degree of automation. However, the implementation of an intermediate buoy will also increase the length of the tube, which can contribute to increased stress level for the fish through a longer and more turbulent transfer process.

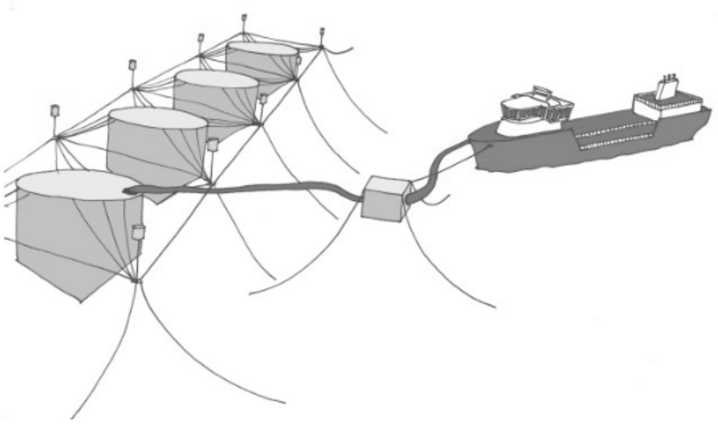


Figure 4.5: Transfer of fish through intermediate buoy(Lien, 2015).

Another two concepts suggested in the same project, which addresses the transfer of fish feed, are presented in Appendix C.

4.2.2 Thruster Design

In exposed locations, vessels may have to use thrusters, rudders or other means to be able to keep their position or to avoid collision with facility structures. This is also the case in Concept 1 and 2, where the vessel is using DP. As previously mentioned in Section 4.1.1, the use of thrusters close to the fish cages may constitute a serious threat to the fish. The concentrated flow from a tunnel thruster can cause stress and even death to the fish. In the following, tunnel thrusters will be considered to evaluate whether a change of design, i.e. duct diameter, can reduce the negative impact on the fish. It is assumed that the thruster diameter equals the duct diameter, i.e. the tip clearance is neglected.

According to Steen (2011), ideal total thrust of a tunnel thruster, T_0, follows from the change of momentum given by,

$$T_0 = \rho A_p U_A^2 \tag{4.1}$$

where $A_p = \pi D^2/4$ is the projected are of the duct. Rearranging and solve for the thrust momentum mean outflow velocity gives,

$$U_A = \sqrt{\frac{T_0}{\rho A_p}} = \frac{9.3}{D} \tag{4.2}$$

A constant (required) thrust of $T_0 = 70\ kN$ and a water density of ρ=1025 kg/m^3 is assumed. It can be seen from Equation 4.2 that increasing the duct diameter, D, will reduce the mean outflow velocity, U_A. The method of approach presented by Beveridge (1972) is used for calculating the effect of a changing duct diameter. Pehrsson (1960) tested the effect of cavitation on design of tunnel thrusters. The results indicated that the cavitation index

$$\sigma' = \frac{P_{net}}{\frac{1}{2}\rho D^2 n^2} \tag{4.3}$$

should be larger than 3.5 to avoid cavitation. P_{net} is the net pressure and n is the impeller frequency of revolution. According to Beveridge (1972), the impeller rate of revolution can be estimated by assuming an optimum impeller pitch ratio of 1.0 and an average impeller thrust coefficient,K_T, of 0.45. It can be shown that the rate of revolution, n, is determined by Equation 4.4.

$$n = \sqrt{\frac{T_0}{\rho D^4 K_T}} \tag{4.4}$$

As previously described, several assumptions and simplifications has been made in the process of obtaining the results in Table 4.1. However, the purpose of this calculation is to show the potential effect of design changes to the duct diameter, not to obtain exact hydrodynamic performance calculations. The cavitation index is included to show that for a required thrust force, the diameter cannot be selected arbitrarily without considering the hydrodynamic performance of the thruster. Other factors such as pitch ratio, tip clearance and boss-/duct length ratio should also be considered, if a complete performance calculation is the objective.

Table 4.1: Change of mean outflow velocity, U_A, as a result of changing duct diameter,D. Corresponding rate of revolution (n) and cavitation index (σ') is also presented.

Duct diameter, D [m]	**Mean outflow velocity,** U_A [m/s]	n [rps]	σ' [$-$]
0.4	23.3	77.0	0.2
0.6	15.5	34.2	0.5
0.8	11.7	19.2	0.9
1.0	9.3	12.3	1.4
1.2	7.8	8.6	2.1
1.4	6.7	6.3	2.9
1.6	5.8	4.8	3.8
1.8	5.2	3.8	4.9

The results have been plotted in Figure 4.6 to visualize the effect of changing duct diameter. From the plot it can be seen that only the two largest diameters will fulfil the requirement of a cavitation index above 3.5. Thus, according to these results, if a smaller thruster is preferred, it will most likely not be able to deliver the entire 70 kN of thrust if the cavitation requirement is to be followed.

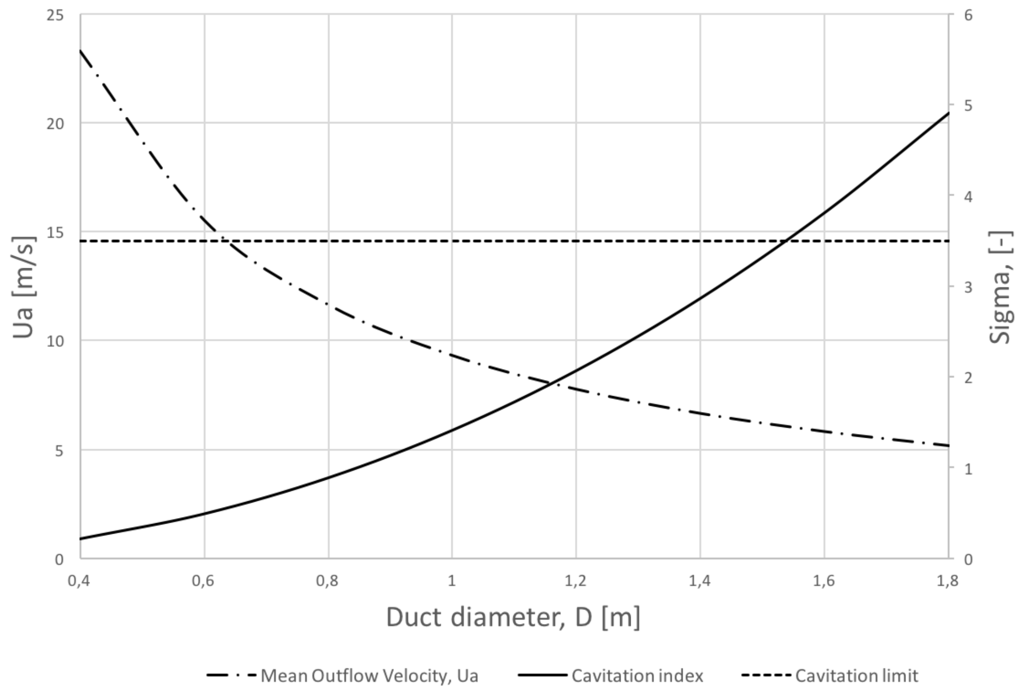


Figure 4.6: Mean outflow velocity and cavitation index plotted against a range of duct diameters.

Based on the calculations above, it is reasonable to say that a change of duct diameter can be considered in order to reduce the outflow water velocity from the thruster. The effect of this can be less harm to the fish, in the event of a water flow directly aimed towards the cage. It is, however, important to emphasize that the hydrodynamic performance of the thruster must be analysed in more detail if such a change is to be considered.

4.2.3 Mooring Configuration

From the literature review in Chapter 3, navigation and approach was identified as one of the most frequently recurring challenges at exposed locations. This was further discussed in Section 4.1.2. In many cases, the wellboats are too big to navigate easily at the facilities. Alternative design for the mooring configuration should therefore be considered.

Figure 4.7 illustrates a single point, high tension mooring inspired by offshore spar platforms. The system consists of a sleeve fixed at the centre of the cage, and a spar buoy inside the sleeve. A configuration like this would probably require more space between the cages, as some horizontal motions would be expected. However, the total footprint area of a facility would not necessarily increase, as the mooring system at current facilities ranges far outside the area of the cages. By having the mooring lines beneath the cage, the vessels would not come in direct interaction and thus allow for more flexible navigation.

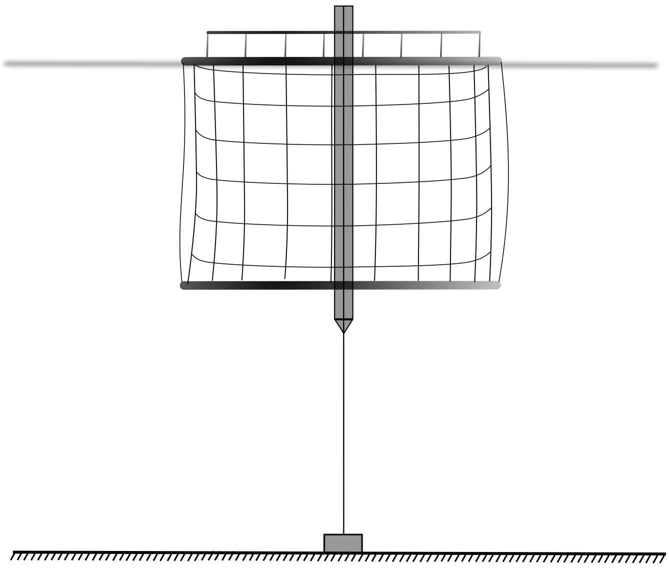


Figure 4.7: Cage mooring system with a single point, high tension mooring.

A setback of a concept like this, is that it would require high investment costs in new cage structures. The lack of restrictions against horizontal motions can also make vessel operations challenging. As the vertical motions of the cage will be limited, large waves could submerge parts or the entire cage. Some sort of net or cover would therefore be required on top of the cage.

Chapter 5

Operability Analysis

The purpose of an operability analysis is to determine the fraction of time the vessel is able to operate, based on a given set of operational criteria. A set of design parameters will be changed to see how it will affect the operability. The software used for the analysis is the ShipX VERES. This chapter aims to describe the methodology applied to the analysis, and to elaborate any assumptions and simplifications made. Section 5.1 will give an overview of the method applied. The rest of the chapter will elaborate parts of the theory behind the calculation, present the operability criteria, design parameter variations and finally present the results from the analysis.

5.1 Method Overview

To be able to calculate the percentage operability, two main inputs are required; operational limits and wave statistics. Wave statistics is obtained from external sources, while the operational limits are calculated through a sequence of steps, shown in Figure 5.1. By combining these inputs, a percentage operability can be obtained.

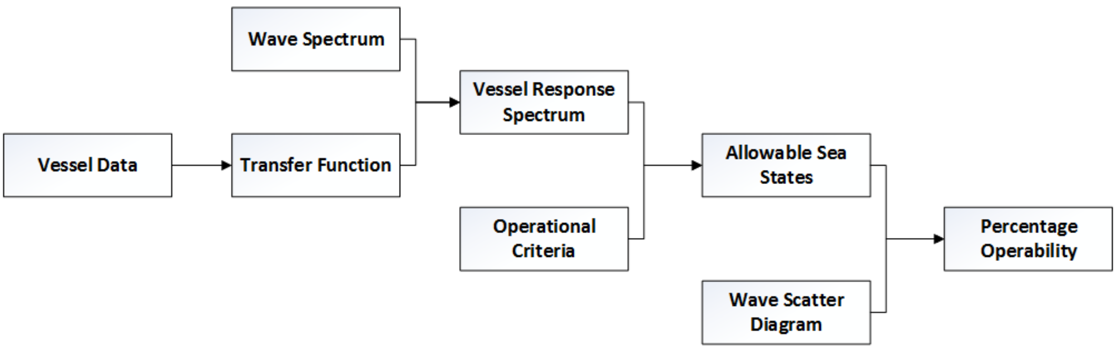


Figure 5.1: Sequence of calculations performed in VERES to obtain vessel operability.

The hull geometry is created in the software *DelftShip*, and as similar to the reference vessel "M/S Ro Fjell" as possible. The geometry is then imported to VERES and used for the response calculations. The response spectrum for the vessel is obtained by combining the transfer function and a specified input wave spectrum. A set of predefined operability criteria is then combined with the response calculations, resulting in operational boundaries (allowable sea states) for the given conditions. The percentage operability is finally obtained by combining the allowable sea states with a long-term wave scatter diagram.

5.2 Vessel Response Calculations

To obtain realistic calculations of the vessel motions in VERES, it is important to understand some of the basic theory behind the calculation and the input data. The input data includes the hull design, viscous damping and environmental conditions in the form of wave periods and direction. This section aims to elaborate the basic principles of the theory, as well as a presentation of the inputs used in the analysis.

Calculations of vessel motion characteristics from VERES are based on several assumptions (Fathi, 2012). In short, these are:

- Traditional strip theory, implying that the three-dimensional hull is divided into two-dimensional "strips". The total forces are found by integrating the forces on each two-dimensional cross-section.
- High speed theory, implying that the interaction from upstream strips is accounted for.
- Slender body is assumed, meaning the hull length is much larger than the beam and draught.
- Linear relation between vessel response and wave amplitude. This is not valid for large wave heights.
- The vessel oscillates harmonically equal to the encounter frequency.
- Potential theory, i.e. homogeneous, incompressible, irrotational and inviscid. However, viscous damping effects can be taken into account by empirical formulas.
- Loads and motions are derived according to the superposition principle.

As can be seen from the list above, VERES uses strip theory and assumes a slender hull. This simplification is used to reduced the calculation time, as the three-dimensional problem can be reduced to many two-dimensional problems along the length of the hull. This method is good for hull designs where three dimensional effects are not dominating, i.e. tankers. For smaller vessels and complex hull shapes, the accuracy may not be as good. Despite the fact that the simplifications may neglect some important effects, the approach has been found to give good results compared to empirical tests (Fathi, 2012).

5.2.1 Variation of Vessel Design Parameters

To see the importance of vessel design in terms of operability, a set of design parameters will be changed and applied to the reference vessel. This method allows to assess the performance of a new design before the ship is actually built. If the performance is not acceptable, changes to the size and/or shape of the hull is easily implemented by the designer. For this analysis, the length, beam and draught are chosen, and for each variation a new vessel response analysis is performed. Table 5.1 shows the dimensions of the reference vessel, used as a basis for the operability analysis.

Table 5.1: Length, beam and draught of the reference vessel created in DelftShip.

Dimension	**Unit [m]**
Length, L	87.2
Beam, B	17.0
Draught, D	5.3

The length and beam is varied without considering the hull shape as a whole. Consequently, the length/beam-ratio will vary and the hull shape will change accordingly. A brief discussion of this assumption is presented in in Section 7.1. An alternative approach would be to keep the hull shape constant while changing the size of the hull. This would require proportional changes to all linear dimensions simultaneously, and thus more detailed calculations. Table 5.2 shows the corresponding changes in design parameters applied in the VERES calculations. A complete hydrodynamic report for the reference vessel can be found in Appendix F.

Table 5.2: The selected design parameters and the corresponding change of values.

Design Parameter	Variation [m]	Unit [m]
Length	+5.0	92.2
	+10.0	97.2
	-5.0	82.2
	-10.0	77.2
Draught	+1.0	6.3
	-1.0	4.3
Beam	+1.0	18.0
	+2.0	19.0
	-1.0	16.0
	-2.0	15.0

5.2.2 Viscous Damping

As mentioned in Section 5.2, viscous roll damping from hull friction and bilge keels can be included in the calculations. For operations at aquaculture facilities, the roll motion can be of major importance to the operability. This is particularly the case during crane operations where the crane tip is often located high and far out from the vessel's centreline.

Due to the shape of a conventional hull, its ability to generate waves in roll is low, and so the level of roll damping is limited. Other means like bilge keels and roll stabilizing fins and tanks can be implemented to increase the damping effects. Roll motions near resonance is highly dependent on the damping, and it is therefore important to include viscous damping in the calculations. If it is neglected, VERES will provide unrealistic response motions (Fathi, 2012).

Some of the viscous effects have a non-linear relation to the wave amplitude. To account for this, a wave amplitude of 2.0 metres is used in this analysis. For short-term statistics, the reference wave amplitude should be chosen with respect to the mean value of the H_s. For the scatter diagram used in this analysis (Norwegian Sea), the highest density of wave data was for wave heights around 2.0 metres. Bilge keels with a breadth of 0.3 metres is included along the hull side. Stabilizing fins or tanks are not included, as they are not commonly used on aquaculture vessels. T_w.

5.2.3 Environmental Conditions

The waves occurring at an exposed aquaculture location may vary a lot both in terms of T_w and H_s. It is therefore determined to include a wave period ranging from 4-30 seconds. This should cover the entire spectrum present in the wave spectrum. An important factor here is the step size between the calculated wave periods close to resonance frequency. If the gap is too large, the calculations may miss out on important peak values in-between the selected T_w. For heave, roll and pitch, the resonance occurs for $T_w < 14$ s, hence a smaller step size is selected for 4 s $< T_w <$ 14 s.

In principle, the vessel motion analysis should be performed for all wave headings (0°-360°). This is not necessary in practice, as the hull is assumed symmetric and thus will obtain the same results for wave headings from 0°-180°as for 180°-360°. This analysis will however, only consider wave headings from 0°-90°. This is based on conversations with PhD candidate Gutsch (2016), who suggested that the results from VERES is not reliable for wave headings aft of the vessel. Without the time to investigate this any further, the choice was made to exclude these wave headings.

5.3 Post-Processing

When the response calculations are completed, the analysis goes on to the post-processing part. This is where operational criteria are defined, wave spectrum chosen and results are obtained in the form of graphs, plots and percentage operability. This section provides some theoretical background for the post-processing, a discussion of the operational criteria and a description of how the percentage operability is obtained by use of long-term statistics.

5.3.1 Wave Spectrum

The choice of wave spectrum is very important for the results of the analysis. A wave spectrum is mathematical representations of a certain sea state. By choosing the right representation, a more realistic result will be obtained. The regular wave spectra, upon which the RAOs are defined, do not exist in a real sea environment. In reality, the wave amplitudes and periods vary over time, causing an irregular sea state. Three standard irregular wave spectra are available in VERES; Pierson-Moskowitz, Joint North Sea Wave Project (JONSWAP) and Torsethaugen.

- **JONSWAP**
  Wave spectrum based on measured data from the North Sea. It does not represent a fully developed sea state, i.e. the wind has not been blowing long enough over a large strech of open water. A peakedness factor, γ, is used to specify the concentration of waves about the peak period.

- **Pierson-Moskowitz**
  Fully developed sea state, which means that high frequency waves due to wind has reached equilibrium (Fathi, 2012). It is equivalent to the JONSWAP spectrum with $\gamma = 1.0$, and waves are on the verge of breaking. It is based on data from the North Atlantic ocean.

- **Torsethaugen Spect**
  Two-peak spectrum, meaning it includes both low-frequent swell and high-frequent wind generated waves. Typically used in analysis of some offshore installations where the sea is a combination of both swell and wind generated waves.

For the purpose of this analysis, the JONSWAP spectrum is selected, as it is expected to provide the most realistic sea state at an exposed aquaculture location. A fully developed sea state would require a area of open ocean around the area of interest, which more likely at offshore installations. If the purpose is to analyse offshore aquaculture installations, the choice of wave spectrum should be evaluated accordingly.

5.3.2 Short-term Statistics

Short-term statistics is a way of expressing the vessel response in a specific sea state. It is found by combining the response transfer functions with a selected wave spectrum representing the sea state in the area of interest. The resulting response spectrum is a function of the wave frequency, as shown in Equation 5.1,

$$S_{\eta\eta}(\omega) = |H(\omega)|^2 S(\omega) \tag{5.1}$$

where $S_{\eta\eta}(\omega)$ is the response spectrum, $|H(\omega)|$ is the transfer function and $S(\omega)$ is the input wave spectrum. A transfer function, also known as the Response Amplitude Operator (RAO), is defined as the ratio between the vessel response amplitude and the amplitude of the incoming wave. In other words, the amplitude of the vessel motion in response to an incident wave. RAO is normally obtained through linear response analysis of regular waves (Steen, 2014). From a hydrodynamical point of view, it is adequate to analyse the behaviour in regular waves, since according to linear theory, results in irregular seas can be obtained by superposing results from regular wave components (Faltinsen, 1999).

The relation in Equation 5.1 is based on linear response theory, and so the effect of second-order, non-linear effects is neglected. It also means that the mean response is zero, and the standard deviation will be equal to the Root Mean Square (RMS) (Fathi, 2012).

5.3.3 Operability Criteria

Different operational criteria can be applied depending on the type of operation and ship subsystem in use. Such limiting criteria can often be found in rules and regulations. For wellboat and service vessels operations, there are no official rules for operational limits. Personal experience and intuition is common practice and exact limits is thus hard to predict.

To find relevant criteria and limitations, a brief literature study was performed. A more thorough study on this subject is presented in a master's thesis written by Sandvik (2016). Through the project "Servicefartøy 2010", discussed in Section 3.1.4, the operability of service vessels was analysed. The limiting criteria applied was based on experience from crane operations at aquaculture facilities, and included maximum vertical motion and lateral acceleration. The same criteria will be used as a basis for this analysis, in addition to a restriction on roll motion. For the purpose of this analysis, these criteria are considered good enough, but further study on this part should be considered at a later stage.

The applied criteria is presented in Table 5.3. For further details on common limiting criteria and typical values for different ship operations, see Appendix G.

Table 5.3: Limiting criteria for the wellboat operations. g = acc. of gravity = 9.81 m/s^2.

	Case 1: moored to cage	**Case 2: on DP**
Vertical motion [m]	0.5	0.8
Lateral acc. [m/s^2]	0.07g	0.10g
Roll motion [deg]	3	3

Two cases is to be analysed and compared. One where the vessel is assumed moored to a cage installation (Case 1), and one where the vessel is not moored and on DP (Case 2).

Vessel and wave data is the same for both cases, but the limiting criteria will be different. The allowed vertical motion in Case 2 is slightly increased due to the assumption that larger vessel motions are accepted when it is not moored to the cage structure. It is in this case also assumed a higher degree of automation, as discussed in Section 4.2.1. The human involvement in the operation is therefore reduced, and a somewhat higher horizontal acceleration is accepted.

5.3.4 Long-term Statistics

Once the operational limits are calculated, the percentage operability can be obtained by calculating the fracture of time the limiting sea states are exceeded. The operational limits are calculated based on short-term statistics, where significant wave height and mean wave period is assumed constant. Obviously, over a long period of time, these parameters will vary, and the vessel will encounter many such short-term sea states. Long-term statistics considers time intervals larger than one sea state, and in that way takes into account the variation of sea states over time. The probability of occurrence for different sea states will vary depending on geographical location. Such data is commonly presented in wave scatter diagrams. Figure 5.2 shows the annual wave scatter diagram for the North Sea.

North sea, area 11. Annual.

Number of occurences

Tz / Hs	3.5	4.5	5.5	6.5	7.5	8.5	10.0	Sum
0.5	19	86	94	41	10	2		252
1.5	3	49	121	99	40	10	2	324
2.5	1	17	63	73	40	13	4	211
3.5		6	27	39	26	10	4	112
4.5		2	11	19	14	6	3	55
5.5		1	4	9	7	4	1	26
6.5			2	4	4	2	1	13
7.5			1	2	2	1	1	7
8.5				1	1	1		3
9.5				1	1			2
Sum	23	161	323	288	145	49	16	1005

Hs and Tz values are the middle values in each interval

Figure 5.2: Wave scatter diagram, showing the annual wave statistics for the North Sea in terms of significant wave height, Hs, and wave period, Tz. (Fathi, 2012).

The diagram shows the number of occurrences of each sea state combination during an entire year. The probability of each occurrence is then simply found by dividing on the total number of sea states. The percentage operability is then obtained by combining the probability of occurrence of the sea states with the operational limiting boundaries.

Wave scatter diagrams for different ocean areas is available in *Global Wave Statistics* (Hogben, Olliver, Dacunha, & British Maritime Technology Ltd., 1986). Data is not available for locally specified areas such as an aquaculture facility. Hence, the Norwegian Sea has been chosen for this analysis as this is the area which is closest to the coast of Trønderlag, one of the most important ocean areas for Norwegian aquaculture.

5.4 Results

This section presents the results from the vessel response analysis in VERES. The total operability in the case of moored to cage (Case 1) and on DP (Case 2) is compared and presented in a diagram. Then the effect of changing the design parameters is presented both in table form and in diagrams. Finally, a few selected design configurations are selected and compared in a polar curve diagram. Transfer functions and additional results from the analysis can be found in Appendix H.

5.4.1 Operability - Case Comparison

Based on the operational criteria and the vessel response, a mean operability is calculated for two different cases. Case 1, where the vessel is assumed moored to the fish cage during the operation, and Case 2 where it is assumed on DP, is shown as black and white columns in Figure 5.3. The only difference between the two cases in the analysis is the operational criteria. The fact that Case 2 is showing slightly higher operability is therefore as expected. It can also be observed that the operability for lateral acceleration is close to 100% is both cases. This indicates that this particular criteria is not a limitation for the operations.

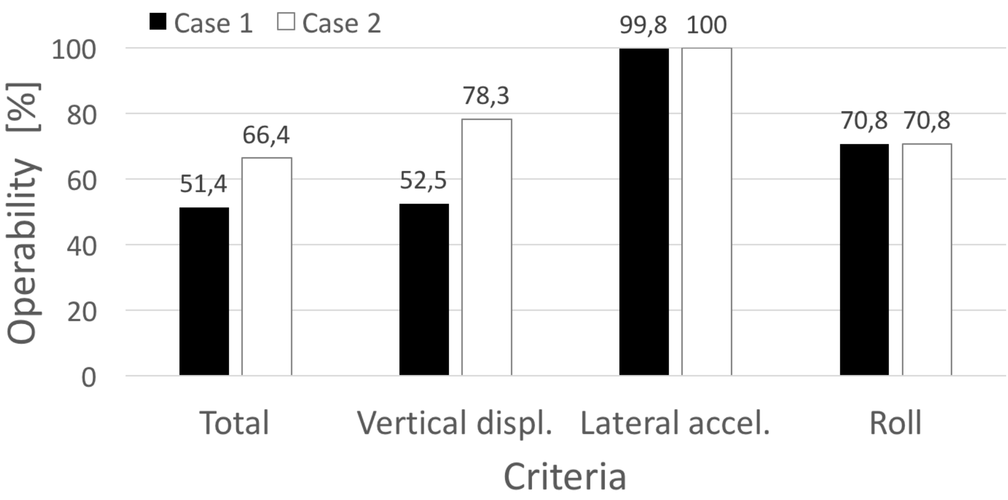


Figure 5.3: Difference in operabilities between Case 1 (moored to cage) and Case 2 (on DP).

Figure 5.4 show how the operability changes as a result of changing wave heading. For both cases, the operability is maximum at head seas and decreasing as the wave heading goes towards 90°. As expected, the operability is higher for case 2 due to the difference in operability criteria.

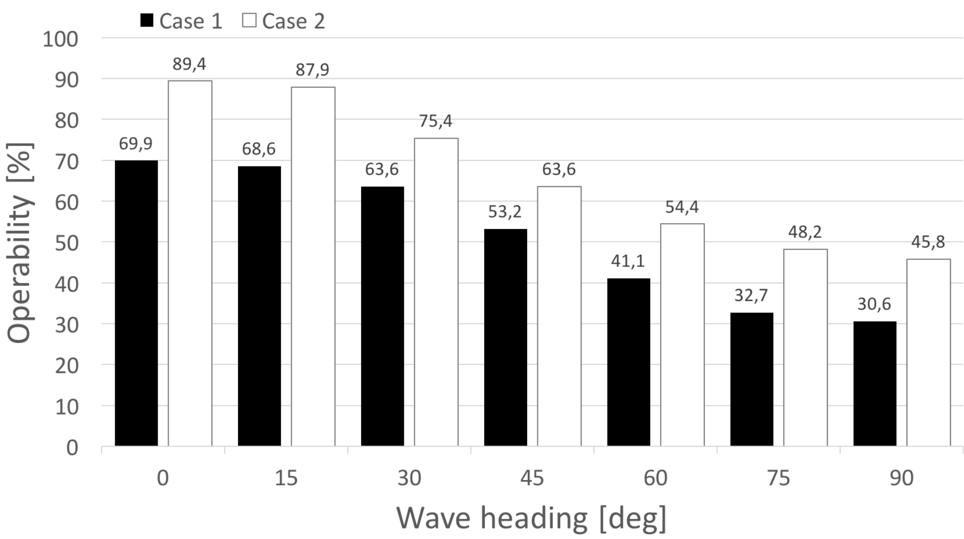


Figure 5.4: Operability for different wave headings for Case 1 (moored to cage) and Case 2 (on DP).

5.4.2 Effect of Parameter Variation

Case 2 was used as base case for the parameter variation. The results show that the influence on operability from changing the parameters vary significantly. Some changes have a large effect, while others have zero or negligible effect. Figure 5.5 show the change in total mean operability due to the respective design changes. It can be seen that the change of length does not influence the operability much, while the change of draft and beam has significant effects. The highest operability is obtained from increasing the draft and reducing the beam.

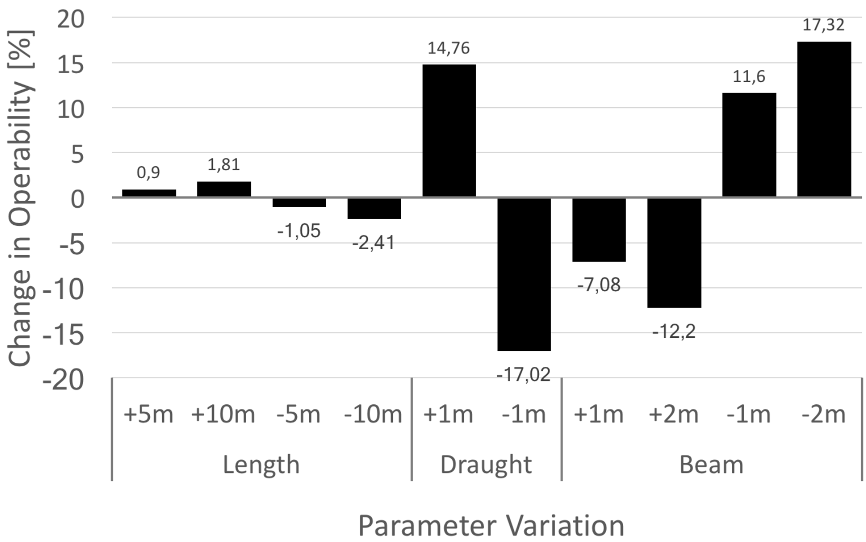


Figure 5.5: Change in operability due to parameter variations, compared to the reference vessel.

A summary of the results is presented in Table 5.4, where the total operability is included as well as the percentage change due to the respective design changes.

Figure 5.6 shows the standard deviation in operability for each operational criterion. A standard deviation of 0.00 in lateral acceleration, means that the design changes did not affect the operability based on this criterion. This is as opposed to the standard deviation in roll, which is 13.50. This means that the operability based on the roll criterion is varying a lot more than for the other two criteria. This can be seen in Figure 5.7, where it is clear that the roll criterion cause a lot more variation in operability than the other vertical displacement. Operability based on lateral acceleration is, as expected, constant at 100% for all design variations.

Table 5.4: Change in operability due to parameter variations, compared to the reference vessel.

Parameter	Variation [m]	Total Operability [%]	ΔOperability [%]
Length	+5.0	67.0	+0.9
	+10.0	67.6	+1.8
	-5.0	65.7	-1.1
	-10.0	64.8	-2.4
Draught	+1.0	76.2	+14.8
	-1.0	55.1	-17.0
Beam	+1.0	61.7	-7.1
	+2.0	58.3	-12.2
	-1.0	74.1	+11.6
	-2.0	77.9	+17.3

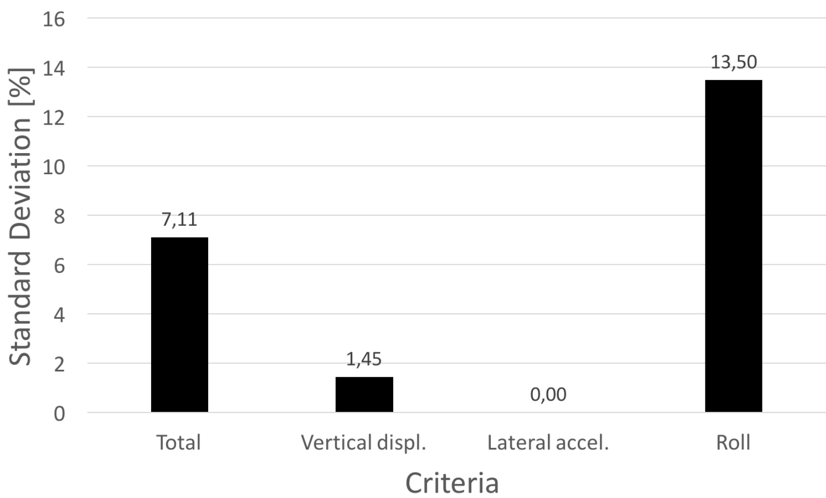


Figure 5.6: Standard deviation, operational criteria.

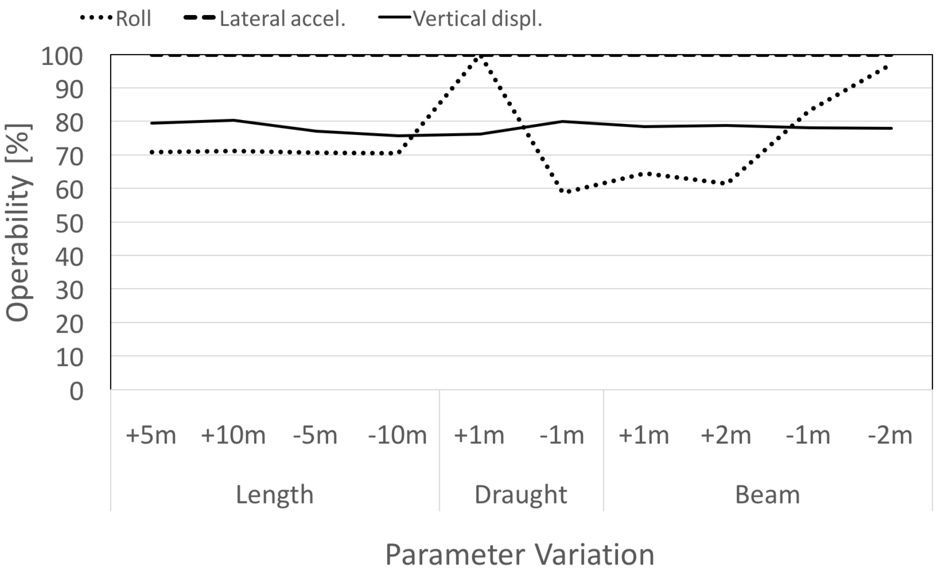


Figure 5.7: Change in operability due to parameter variations for each operational criterion.

Polar curves are useful to get a more intuitive impression of the limiting sea states. Figure 5.8 shows the allowable sea states for the reference vessel. It is compared to the best and worst outcome of parameter changes, being reducing beam by two metres and draught by one metre, respectively. It can also be seen that there are no significant changes for wave headings less than 30°, and that the largest differences occur for wave headings between 45°-90°. For further details and more results see Appendix H.

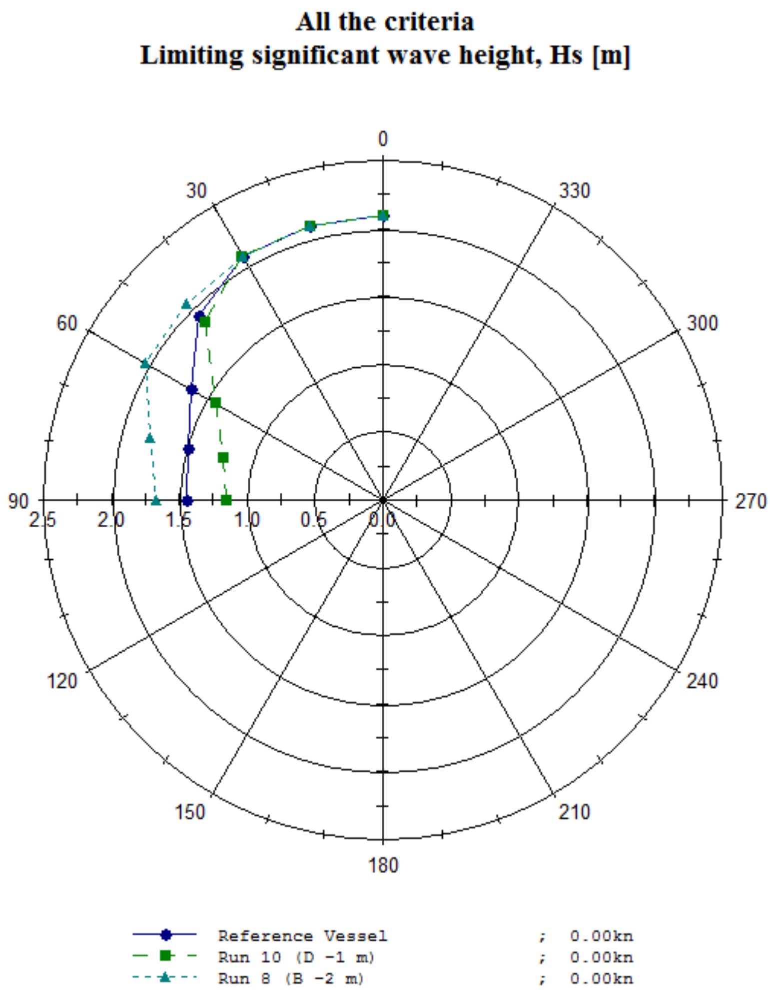


Figure 5.8: Limiting sea states for reference vessel, increased draught and reduced beam.

Chapter 6

Simulation Model

The operability analysis presented in Chapter 5 provides useful information of the vessel's operational capabilities and limiting sea states based on the specified operational criteria. This chapter will discuss the possbility of combining the response-based criteria from VERES with a stochastic, time domain simulation model in *Simulink*. The aim of this combination is to see if the operational limits for individual vessels can be used to assess the operability and performance of an entire system.

6.1 Operability in a System Context

Calculations of percentage operability in VERES are based on sea states which occurs independently and with a typical duration of three hours. This means that in calculations of long-term statistics, the percentage operability is obtained under the assumption that the vessel is able to operate within the duration of a single sea state. Thus, if a sea state is within the limits of operation it will automatically be identified as feasible for operation, even though the preceding and following sea states are exceeding the limits. An attempt of illustrating this is shown in Figure 6.1. The same holds for the opposite case, if there are two sea states within the limiting boundaries separated by a sea state exceeding the limits. Then the two weather windows would be identified as feasible, while in reality the operation could not be performed due to the one violating sea state in between.

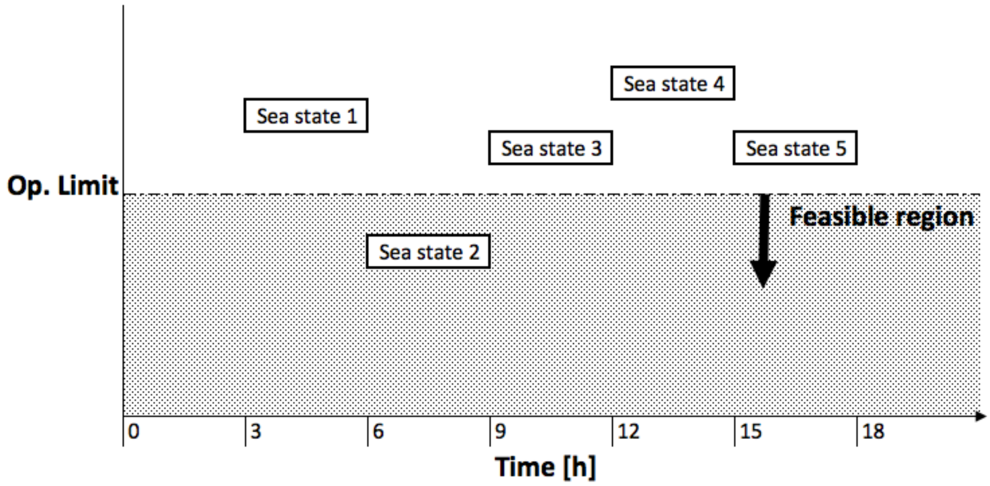


Figure 6.1: Illustration of how a single sea state within the operational limits (Sea state 2) is considered feasible. A real-life operation would most likely not be initiated due to the short weather window.

In reality, many wellboat and service vessel operations lasts for more than three hours, and so a weather window of more than three hours is in general required for an operation to be initiated. There will be a chance that a vessel must wait for a sufficiently long weather window, or that an on-going operation must be aborted due to sudden changes in weather conditions. A single feasible sea state in between two non-feasible sea states, as shown in Figure 6.1, would therefore most likely not be utilized in a real-world operation. As discussed in Section 5.3.3, there are no official rules and regulations for operational limits for wellboats. Thus, in some cases, the situation described above may be considered feasible for operation by the decision-making people.

The inability to study weather forecasts and predict the conditions ahead of an operation is a limitation of the method, which in most cases will result in an over-estimated operability. Combining the operational limits obtained from VERES with a stochastic simulation model could prove to be a better and more realistic way of approach. This can be done by excluding the long-term statistics calculations (scatter diagrams) and include metocean data and weather forecasting in the simulation model. The idea is presented as a flowchart in Figure 6.2.

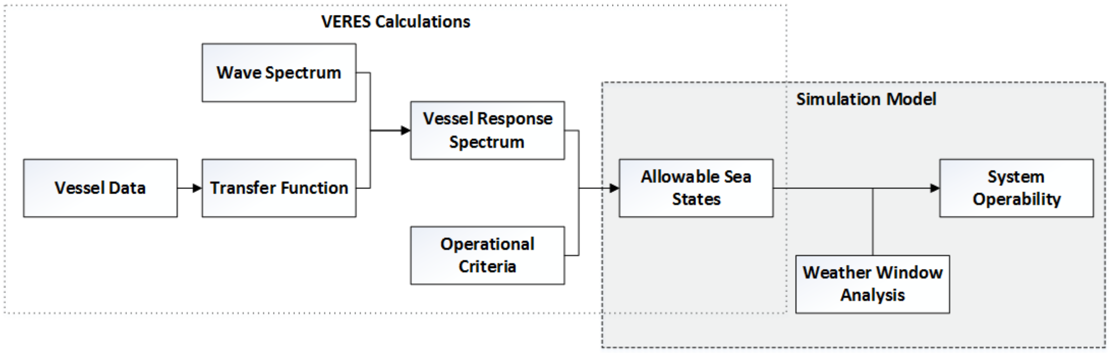


Figure 6.2: Combining vessel response and simulation to obtain operability for an entire system.

A combination of response calculations and a simulation model would also provide the opportunity to see how an entire system of operations would be affected by parameter variations, and not only the operability of an individual vessel. This means that the operability of an entire fleet of wellboats and/or service vessels can be estimated.

6.2 Developing the Model

When creating a simulation model, the goal is to imitate a real world system. Thus it is important that the output from the model is as realistic as possible. The reliability of the model depends on both the quality of the input data and the model assumptions implemented. Using wrong statistical distributions can lead to unreliable and non-realistic results. It is therefore important to be certain about the input reliability before any conclusions are drawn.

The basic idea in this case is to use the inputs from the response calculations in VERES as a tool in decision-making for vessel operations in exposed aquaculture. In order to do this, a simulation model representing an actual system of vessel operations must be developed. The flowchart in Figure 6.3 shows the sequence of events in the simulation model, leading to the decision of whether or not to carry out the operation. When an operation is needed at one of the farms, a signal is sent to the port. A weather window analysis is then performed and compared to the allowable sea states for the vessel. If the forecasted sea state(s) are within the operational limits, the operation is initiated. If not, the operation is postponed until the forecasting shows a sufficiently long weather window. Implementation of weather forecast and allowable sea states will be further discussed in Section 6.2.2 and 6.2.3, respectively.

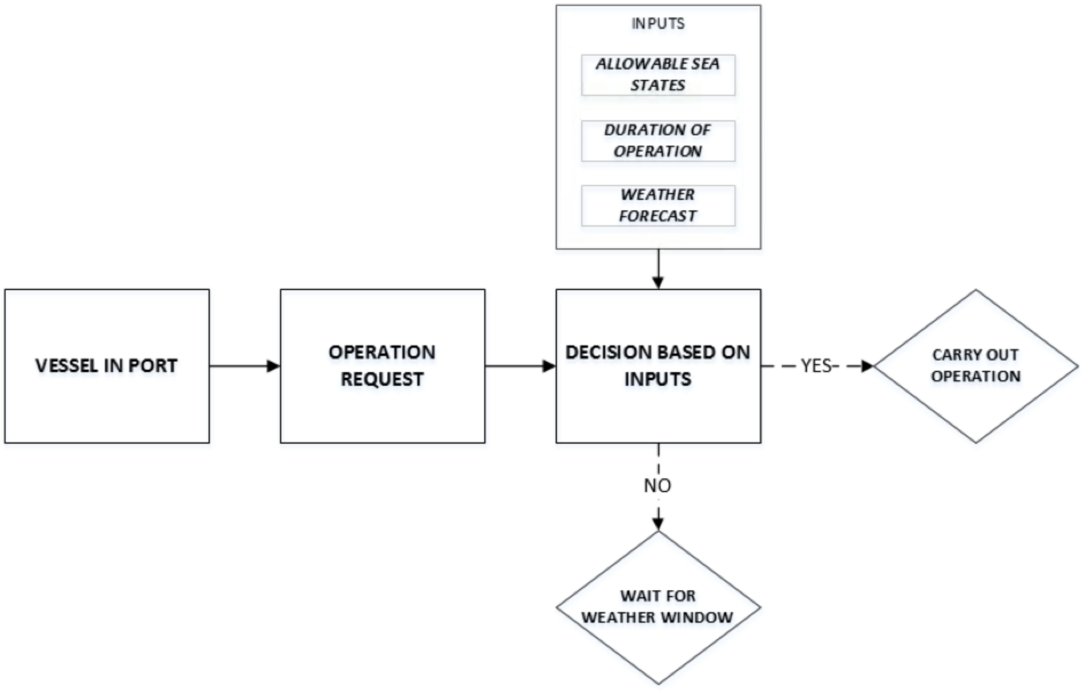


Figure 6.3: Flowchart showing the principle of the simulation model.

6.2.1 Basic Structure of the Model

Creating a simulation model for complex and dynamic systems like aquaculture operations is not an easy and quick process. Thus, the main focus in this part of the thesis is to understand how such a model can be created and how to implement the necessary inputs, rather than spending a lot of time making the model working. A simplified model is shown in Figure 6.4. This model is made to show how the basic layout of the model may look.

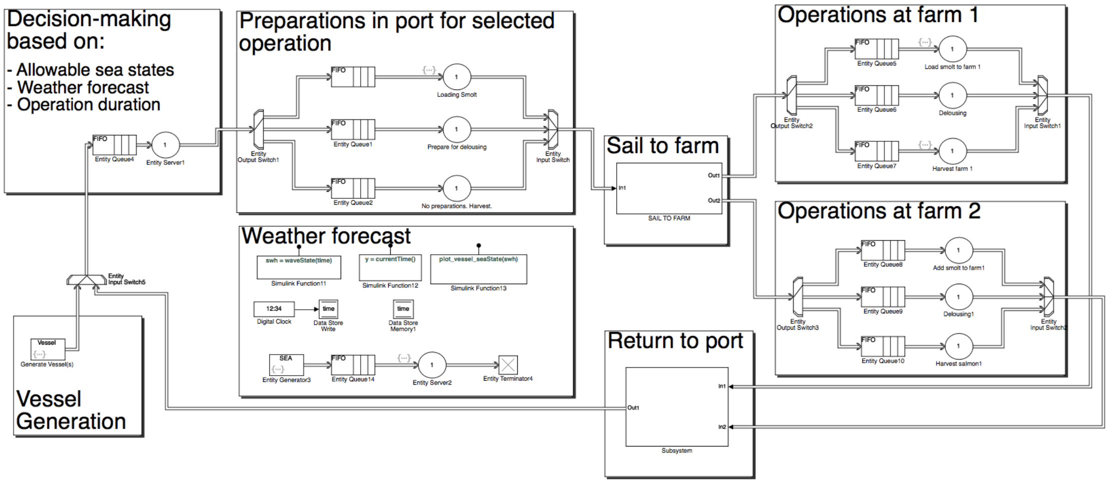


Figure 6.4: A simplified simulation model of an aquaculture operation system is created in the software Simulink.

The model in Figure 6.4 starts with a generation of a pre-defined number of vessels. They continue to the port, where each vessel waits until assigned an operation. Once an operation is requested at a farm, the weather window analysis is performed. If the conditions gets approved, the operation is initiated and the vessel continue to the next block where it makes the necessary preparations for the operation. Further, it will sail to the designated farm, where the sailing time will depend on forecasted sea states. Once at the farm, the operation is performed before sailing back to the port.

6.2.2 Weather Forecasting

Historical metocean data can be used to develop a forecasting model for a specific geographical area. A Markov chain is typically used for this purpose in simulation. Markov chains are stochastic processes describing a sequence of possible events. The possibility of each event is only based on the state of the previous event, i.e. the model is memoryless.

A number of sea states must be predefined in the forecasting model, and the historical data is categorised within these states. A transition matrix, P, is then created based on the number of transitions from one state to another.

$$P = \begin{array}{c} \\ S1 \\ S2 \\ S3 \end{array} \begin{array}{c} \begin{array}{ccc} S1 & S2 & S3 \end{array} \\ \begin{bmatrix} 0.5 & 0.4 & 0.1 \\ 0.4 & 0.5 & 0.1 \\ 0.1 & 0.6 & 0.3 \end{bmatrix} \end{array}$$

This matrix forms the basis for the forecasting, as it tells the probability of going from one sea state to any other. In the example matrix above, the probability of going from sea state 1 (S1) to sea state 2 (S2) is 0.4. The probability of remaining in S1 is 0.5, and so on. Random number sampling determines whether or not a transition will occur based on the probabilities in the transition matrix. Sea states are typically updated every three hours, thus a forecasting of the next nine hours can be done by sampling three subsequent sea states.

6.2.3 Allowable Sea States

Figure 6.5 shows the allowable sea states obtained for the wellboat operating at a fish cage in head seas. It can be seen that for wave periods of nine seconds, the maximum allowable wave height is about four metres. For each heading, and each vessel design there will be a similar curve showing the allowable sea states. The values will then be compared to the forecasted sea state and the conditions will be identified as feasible or non-feasible.

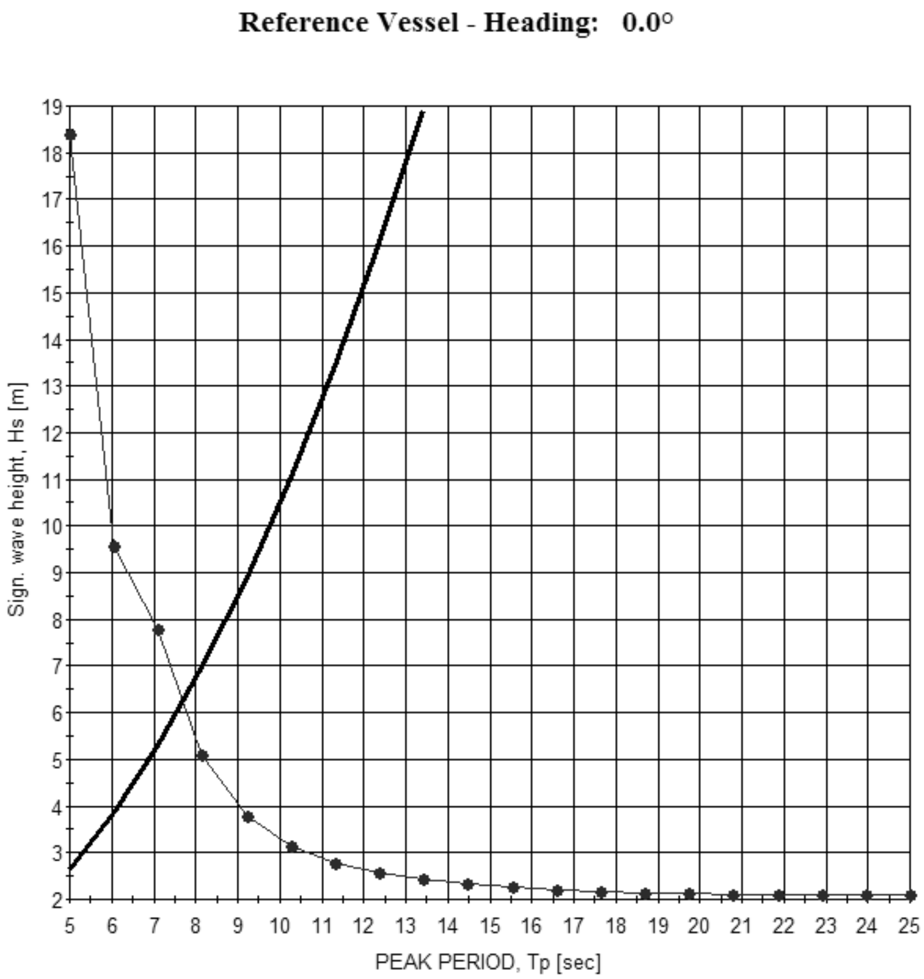


Figure 6.5: The operational limits for the wellboat in head seas. No waves above the bold line due to breaking.

There are probably several ways to implement the operational limits from VERES into the simulation model. One way would be to represent the curves as polynomial functions through curve fitting. The weather window analysis will then check whether the forecasted sea state is above or below the function value for the given wave period. An important aspect to consider in this case will be the uncertainty in weather forecasting. This issue will be discussed in more detail in Section 7.2.1.

Chapter 7

Discussion

This chapter will discuss the results and the methods applied through the work of this thesis. It will also aim to discuss the relation between vessel-structure interaction, vessel response and system simulation, and how the studies of these subjects have contributed to fulfil the objective of the thesis.

The development of the aquaculture industry has been characterised by incremental innovations and a focus on making profit rather than looking at the entire system as a whole and thinking long-term development. This has contributed to a lack of common operational procedures and regulations, making the industry vulnerable and dependent on human experience and expertise. As the industry is gradually moving the facilities further out from the shore, the challenges becomes even more apparent. With offshore aquaculture on the verge of realisation, this may be a good time to evaluate the industry as a whole and find common concept solutions which can thrive the industry towards expansion and further growth.

Vessel operations at exposed aquaculture locations introduce higher demands for vessels, equipment and systems involved in the operations. The interaction between vessels and installations can be critical during the operations, particularly during harsh weather conditions where the relative motions may become large. The fact that this is a problem for the operations becomes evident when studying the pilot projects for offshore aquaculture, where the systems are completely automated and the need for service vessels is absent. Increased automation will reduce the need of crane operations and the risk to personnel working at the facilities, which are two main challenges of the vessel-structure interaction today. Operations at exposed locations can to some extent be compared to open ocean operations in terms of harsh environmental conditions. The solutions applied in offshore farming could therefore be interesting to consider for exposed locations.

7.1 Reliability of Operability Results

The objective of performing a vessel response analysis was to assess whether or not the operability would change as a result of parameter variation. The results show that it depends on both vessel design, operational procedures and wave heading. The highest operability is obtained by increasing the draught and reducing the beam. Oppositely, the lowest operability is obtained when reducing the draught and increasing the beam. However, due to simplifications and assumptions in the analysis, the reliability of the results should be discussed.

In Section 5.4.1, the operability results from two different cases are presented. One where the vessel is moored to a fish cage during the operation, the other where it is freely floating on DP, some distance away from the cage. As expected, the operability was higher for the latter case, as the operability criteria allowed for larger vessel motions. When calculating the operability, an assumption was made to have an equal probability of all wave headings. In reality, wellboats are often moored in a position which will give the least probability of damaging the net structure. Thus, an investigation on this subject should be done, so that a more realistic distribution of wave headings can be implemented.

When a vessel is on DP some distance away from the facility structures, it is likely to lay with the bow towards the waves to reduce the roll motion. This was not accounted for in the analysis, and should be considered for more realistic results.

Independent Sea States
As discussed in Section 6.1, the inability to study weather forecasts and predict the conditions ahead of an operation is a limitation of the method, which in most cases will result in an over-estimated operability. Independent sea states means that each sea state is assessed without considering the conditions in the preceding and following sea states. For very short operations (< 3 hours) this can be accepted, but for operations with longer duration, this will not give provide realistic results.

Neglecting Parameter Coupling
When changing the design parameters, an assumption was made to neglect the coupling to other parameters. This means that a single parameter could be changed freely and independent of any other parameters. This assumption may not always be realistic, as the vessel designer must take into account the effect on rules and regulations, general arrangement (GA), metacentric height (GM) and so on. An example is the variation of beam dimensions, where a change will have a direct impact on the vessel stability. This

can be seen from Equation 7.1 (Amdahl et al., 2011), where the second moment of area $I \propto B^3$. The change in volume displacement, ∇, is accounted for in the analysis.

$$GM = KB + BM = KB + \frac{I}{\nabla} - KG \tag{7.1}$$

The vertical centre of buoyancy (KB) will not change as a result of beam variations, thus the change in GM can be accounted for by changing the vertical centre of gravity (VCG) and consequently the distance from keel to vertical centre of gravity (KG). The assumption of neglecting this coupling is likely to have influenced the results, and should be accounted for at a later stage. An advantage of the simplification is that the effect of each individual parameter variation becomes very clear. If several parameters are changed simultaneously, it can be hard to tell which parameter is having an impact and which is not.

Constant Point of Observation

When applying operational criteria, VERES provides the opportunity of defining a position of observation. This means that different criteria can be allocated to different locations on the vessel. For instance, the vertical motion of a crane positioned far out from the ship side will be a combination of the vessel's heave and roll motions, whilst at the transverse centre of flotation (TCF) it will only depend on the heave motion. Similar effects will occur at the bow and stern due to pitch motions. In this analysis, the point of observation was held constant at the Center of Gravity (COG) for all criteria. The COG is more or less coinciding with the centre of flotation (CF), which means the above-mentioned effects will not be accounted for. A sensitivity analysis was performed by Sandvik (2016) to see the effect of customizing the point of operation in roll. The results showed that the operability was over-estimated when assuming a constant point of observation. Thus, local criteria should be established in order to capture the true effect of parametric variations.

Natural Periods of the Vessel

The effect of natural periods can have a significant impact on the response calculations. If the wave spectrum density is peaking close to one of the vessel's natural periods, the vessel will experience resonance motions and probably obtain a lower operability. In this situation, parameter variations that will change the vessel's natural period is likely to increase the operability, as it will move the natural periods away from the most frequent wave periods.

If the distribution of wave periods is unfavourable with regards to natural frequency can be difficult to determine. If the vessel's natural periods are known, a direct comparison can tell whether or not the distribution is beneficial to avoid resonance motions. It is clear that the wave period distribution is an important factor to consider in operability assessments.

7.2 Considerations Regarding the Simulation Model

One of the main questions to be answered in this thesis, was to see how a generic simulation model can be developed to see the effect of design changes in a system perspective. This question is considered in Chapter 6, along with a description of how such a model can be developed. This section will discuss the opportunities within the simulation model and some key factors to consider when developing the model.

While a vessel response analysis provide detailed knowledge of how a specific vessel design behaves in the wave environment, a simulation model can imitate a whole system of operations. The combination can therefore prove to be a useful tool to evaluate the performance of an entire fleet of vessels, and to test and evaluate the performance of new designs or operational procedures before they are implemented.

One of the drawbacks of the operability analysis in VERES is the independent assessment of each sea state. This means that a sea state may be considered feasible for operation, even though the preceding and following sea states are exceeding the limits. Over time, this is likely to give over-estimated operability. By including a forecasting model in the simulation, a decision of whether or not to carry out an operation can be taken based on the expected environmental conditions throughout the duration of the operation.

The implementation of weather forecasting will also enable the possibility of estimating an expected number of feasible weather windows for different operations during a period of time. This can be useful in planning of future strategy and operations. For instance, if the expected number of weather windows in January-February is significantly lower than in March-April, it can be decided to postpone operations which are more exposed to environmental conditions to the period with better conditions.

An important consideration is to separate between allowable sea states for the sailing and the operation itself. Applying the same operational criteria will not be realistic, as the vessel is likely to be able to sail even though the sea state is exceeding the criteria for the operation. Thus, a way of separating these operations and make decisions based on the correct conditions will be necessary.

7.2.1 Uncertainty in Forecasted Environmental Conditions

Marine operations are often divided into two categories. Operations with a limited duration, typically less than 72 hours, are *weather-restricted*, while operations lasting more than this are *weather-unrestricted*. DNV (2011) define marine operations as

...a non-routine operation of a limited defined duration related to handling of object(s) and/or vessel(s) in the marine environment during temporary phases. In this context the marine environment is defined as construction sites, quay areas, inshore/offshore waters or sub-sea.

Due to the relatively short duration, wellboat operations can be identified as weather-restricted operations. In general, such operations may commence when the weather forecast predicts environmental conditions within the acceptable criteria for the entire duration of the operation. The degree of accuracy in the forecasts is therefore an important factor when it comes to planning, but also with respect to safety. DNV (2011) accounts for the uncertainty in weather forecasts by including a factor, α. It assures that the operational limit is less than the limit obtained in design. Values for the α-factor is obtained from designated tables in DNV-OS-H101, Section B 700. The operational limit for significant wave hight can thus be expressed as

$$H_{s,oper} = \alpha H_{s,design} \tag{7.2}$$

where α is less than one. A study of the uncertainty in weather forecasts for marine operations was done by Natskår, Moan, and Alvær (2015). They found that the uncertainty in the forecasts decrease with decreasing lead time. It was also pointed out that there is a lower correlation between forecasted and experienced data for wave periods than for significant wave heights. Hence, they suggested that it will be preferable to use a probability distribution for the wave period, while the wave height can be solely based on the forecasts.

Even though the correlation between forecasts and experienced data seems to be fairly good, not accounting for the uncertainty will in most cases give overestimated operability. As the duration of most aquaculture operations are significantly less than 72 hours, they depend a lot on the accuracy of weather forecasts. Hence, taking this uncertainty into account is important to obtain realistic results.

Chapter 8

Conclusion

Through the work of this thesis, an understanding of the challenges in the vessel-structure interaction in exposed aquaculture has been obtained. Relative motions between the vessel and structures and vessel navigation and approach has been identified as some of the main challenges during the operations. Based on assessments of alternative concepts, it seems clear that eliminating the direct interaction between the vessel and facility could contribute to solve many of the challenges. However, in order to do this, new concept designs are required to replace the current procedures.

The operability analysis show that the vessel operability depends on both hull design, operational procedures and wave heading. The highest operability was obtained from increasing the draught and reducing the beam, while the lowest was found by reducing the draught and increasing the beam. Changes to the vessel length seems to have less effect on the operability. Due to simplifications and assumptions during the analysis, the results should be taken as indications rather than exact calculations.

The inability to study weather forecasts and predict the conditions ahead of an operation is a limitation of the method applied in the operability analysis which in most cases will result in over-estimated operability. While a vessel response analysis provide detailed knowledge of how a specific vessel design behaves in the wave environment, a simulation model can imitate a whole system of operations. A generic simulation model can be developed by combining the allowable sea states obtained from VERES with a model for weather forecasting. This can prove to be a useful tool to evaluate the performance of an entire fleet of vessels, and to test and evaluate the performance of new designs or operational procedures before they are implemented.

Chapter 9

Further Work

The outcome from the work on this thesis has been an increased knowledge of the challenges in the vessel-structure interaction in exposed aquaculture. In addition, the study of vessel response and operability have provided insight and understanding which will be relevant for the development of a simulation model. It is clear that a more thorough study on the theory behind the vessel response is needed in order to obtain more realistic results, particularly if parameter variations is to be included. The hull design should also be given more attention to make it as authentic as possible.

Implementing weather forecasting in the simulation model has proven to be somewhat complicated, and has not been covered in great detail in this thesis. The process requires a combination of hydrodynamical, statistical and system design skills, and will be one of the key issues in the simulation model. To be able to make a model that gives a authentic representation of the real-world operations, it is necessary with a deeper understanding of the logistics and procedures in the industry. This includes duration of operations, typical sailing patterns, scheduled maintenance, smolt production and growth time in the sea, and so on. These aspects have not been considered in this thesis, as the development of the model did not reach a point where input data was considered relevant.

For further study in a master's thesis, it could be interesting to look more into the combination of vessel response, operability and system simulation, and try to develop a model which can provide useful information of the performance of an aquaculture system.

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Appendix A

Wellboat Database

Vessel Name	Type	Length [m]	Draught [m]	Main Engine [kW]	Bow thruster [kW]	Stern thruster [kW]	Well Capacity [m3]	Year built
Grip Transporter	Well boat	60,4	4,5	749	260	370	1250	1993
Ro Master	Well boat	71,9	5,6	2040	390		2600	2007
Ro Fjord	Well boat	72,2	6,2	1980			2800	2009
Øydrott	Well boat	62,1	5,1	1340	220	220	1200	2010
Bjørg Pauline	Well boat	70,0	6,1	2800	425	425	2870	2010
Frøystrand	Well boat	62,1					1200	2011
Viknatrans	Well boat	62,1	5,1	1340	300	300	1200	2011
Novatrans	Well boat	62,8	5,1	1340	300	300	1200	2011
Øylaks	Well boat	62,9	5,1	1325	300	300	1500	2012
Dønnland	Well boat	62,9	5,3	1325	300	300	1500	2012
Ro Fjell	Well boat	87,7	5,3	2999	770	770	4500	2013
Øysund	Well boat	69,9	5,3	1600	300	300	1800	2014
Øyfjord	Well boat	69,9	5,3	1600	300	300	1800	2014
Havtrans	Well boat	84,8	6,5	3000			3200	2014
Ro Arctic	Well boat	75,5	6	3000	650	650	3024	2014
Øytind	Well boat	69,9	5,3	1600	300	300	1800	2015
Gåsø Viking	Well boat	78,0		5780	600	600	3000	2015
Namsos	Well boat	84,8	6,5	3000			3200	2015
Ro Server	Well boat	82,1					3500	2016
FS Stormy	Well boat	84,6		3000			3250	
Seihav	Well boat			3000			3200	
Ronja Atlantic	Well boat	68,0	6,3	1920	300	300	1950	
Ronja Harvester	Well boat	68,0	6,3	1920	300	300	1950	
Ronja Polaris	Well boat	75,8	6,8	3840	630	630	3200	
Ronja Huon	Well boat	75,8	6,8	3840	630	630	3200	

Appendix B

Vessel Specification - MS Ro Fjell

Technical specifications (Aas Mek. Verksted, 2013):

- Length, OA: 87.7 m
- Length, BPP: 84.2 m
- Beam: 17.0 m
- Depth: 7.9 m
- Draught: 5.3 m
- Tonnage: 3893 GT
- Well capacity: 4,500 m^3
- Service speed: 14.6 $knots$

Figure B.1: The largest wellboat in the world, MS Ro Fjell, used as reference vessel in the vessel response analysis. (Rostein AS, 2016).

Appendix C

SustainFarmEx WP4 - Evaluated Concepts

The concepts presented in Figure C.1and C.2 are a selection of evaluated concepts from WP4 of the research project SustainFarmEx. The two concepts covered in Chapter 4.2, are the most relevant for this thesis, as they cover the transfer of fish between wellboat and fish farm. The concepts presented here consider transfer of feed, which is not part of the scope of this thesis. They are, however, included as they may provide useful and interesting aspects in terms of design.

Concept 1

The standard procedure for transferring feed from feeding vessel to the storage fleet is by mooring the vessel to the installation and transfer by the use of cranes, hoses and pumps. This concept aims to eliminate the direct interaction and transfer the feed through floating tubes. This method enables the vessel to use dynamic positioning which will increase its ability to handle harsh environmental conditions.

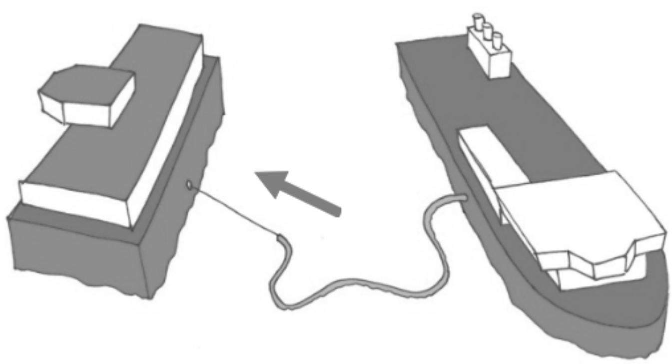


Figure C.1: Transfer of feed without the use of cranes(Lien, 2015).

Concept 2

This concept suggests utilizing the effect of heave-compensated systems. This will make the system more robust against large relative motions due to waves, but the connection is still quite rigid, and exposed to relative motions other than heave.

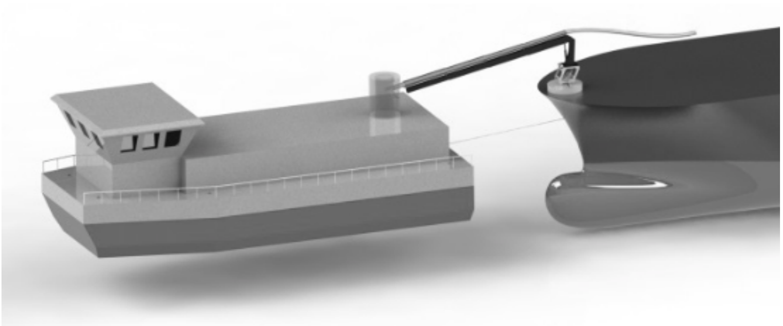


Figure C.2: Transfer of feed by the use of heave-compensated systems. (Lien, 2015).

Appendix D

Salmar - Ocean Farming

Technical information (SalMar, 2016):

- Height (overall): 68 m
- Diameter: 110 m
- Volume: 250,000 m^3
- Weight: 5,600 *tonnes*
- Automated operations

Figure D.1: Illustration of Salmar's pilot installation, to be launched in Frohavet. (SalMar, 2016).

Appendix E

Nordlaks - Havfarm

Technical information (Nordlaks, 2016a):

- Length: 431 m
- Beam: 54 m
- Draught (max): 10 m
- Depth of net: 60 m

Figure E.1: Illustration of Nordlaks' Havfarm project. (Nordlaks, 2016a).

Appendix F

Vessel Hydrostatics Report

Design hydrostatics report.

Designer			
Created by			
Comment		Wellboat	
Filename		Test_model2.fbm	
Design length	83,000 (m)	**Midship location**	41,500 (m)
Length over all	87,167 (m)	**Relative water density**	1,025
Design beam	16,999 (m)	**Mean shell thickness**	0,0000 (m)
Maximum beam	17,306 (m)	**Appendage coefficient**	1,0000
Design draught	5,300 (m)		

Volume properties		Waterplane properties	
Moulded volume	5763,0 (m^3)	Length on waterline	86,206 (m)
Total displaced volume	5763,0 (m^3)	Beam on waterline	17,001 (m)
Displacement	5907,1 (tonnes)	Entrance angle	40,212 (Degr.)
Block coefficient	0,7367	Waterplane area	1215,3 (m^2)
Prismatic coefficient	0,7436	Waterplane coefficient	0,8233
Vert. prismatic coefficient	0,8948	Waterplane center of floatation	40,912 (m)
Wetted surface area	1905,8 (m^2)	Transverse moment of inertia	24973 (m^4)
Longitudinal center of buoyancy	43,413 (m)	Longitudinal moment of inertia	559212 (m^4)
Longitudinal center of buoyancy	2,219 %		
Vertical center of buoyancy	2,768 (m)		
Total length of submerged body	86,820 (m)		
Total beam of submerged body	17,001 (m)		

Midship properties		Initial stability	
Midship section area	89,262 (m^2)	Transverse metacentric height	7,101 (m)
Midship coefficient	0,9906	Longitudinal metacentric height	99,802 (m)

Lateral plane	
Lateral area	436,43 (m^2)
Longitudinal center of effort	42,797 (m)
Vertical center of effort	2,687 (m)

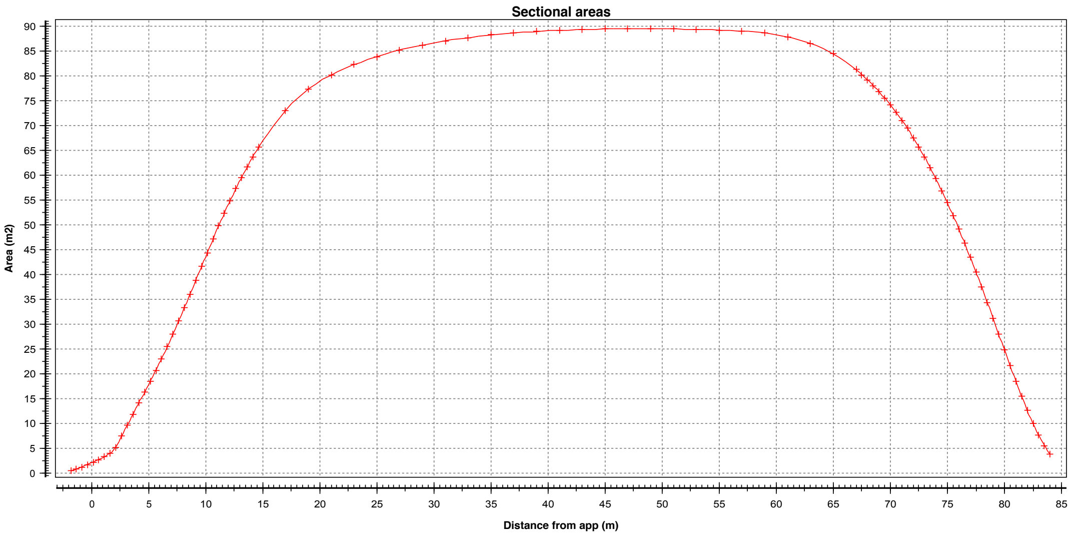
The following layer properties are calculated for both sides of the ship

Location	Area	Thickness	Weight	LCG	TCG	VCG
	(m^2)		(tonnes)	(m)	(m)	(m)
Hull	2612,6	0,000	0,000	41,414	0,000 (CL)	3,005

Sectional areas

Location	Area	Location	Area	Location	Area	Location	Area	Location	Area
(m)	(m^2)	(m)	(m^2)	(m)	(m^2)	(m)	(m^2)	(m)	(m^2)
-1,800	0,493	7,643	30,617	25,000	83,935	63,000	86,641	75,500	51,883
-1,357	0,815	8,143	33,311	27,000	85,305	65,000	84,488	76,000	49,202
-0,857	1,237	8,643	36,051	29,000	86,248	67,000	81,327	76,500	46,404
-0,357	1,702	9,143	38,831	31,000	87,139	67,500	80,303	77,000	43,526
0,143	2,185	9,643	41,621	33,000	87,743	68,000	79,253	77,500	40,579
0,643	2,702	10,143	44,397	35,000	88,336	68,500	78,101	78,000	37,514

Sectional areas									
Location	Area	Location	Area	Location	Area	Location	Area	Location	Area
(m)	*(m^2)*	*(m)*	*(m^2)*	*(m)*	*(m^2)*	*(m)*	*(m^2)*	*(m)*	*(m^2)*
1,143	3,294	10,643	47,133	37,000	88,677	69,000	76,866	78,500	34,409
1,643	3,976	11,143	49,821	39,000	89,015	69,500	75,584	79,000	31,235
2,143	5,232	11,643	52,424	41,000	89,222	70,000	74,164	79,500	28,031
2,643	7,446	12,143	54,894	43,000	89,381	70,500	72,722	80,000	24,823
3,143	9,619	12,643	57,294	45,000	89,496	71,000	71,097	80,500	21,641
3,643	11,872	13,143	59,555	47,000	89,532	71,500	69,467	81,000	18,522
4,143	14,110	13,643	61,684	49,000	89,561	72,000	67,626	81,500	15,517
4,643	16,283	14,143	63,751	51,000	89,505	72,500	65,765	82,000	12,636
5,143	18,470	14,643	65,635	53,000	89,436	73,000	63,708	82,500	9,984
5,643	20,707	17,000	73,097	55,000	89,296	73,500	61,597	83,000	7,606
6,143	23,034	19,000	77,386	57,000	89,069	74,000	59,330	83,500	5,525
6,643	25,471	21,000	80,275	59,000	88,676	74,500	56,951	84,000	3,759
7,143	27,999	23,000	82,320	61,000	87,940	75,000	54,484		



NOTE 1: Draught (and all other vertical heights) is measured above base Z=
NOTE 2: All calculated coefficients based on actual dimensions of submerged body.

Appendix G

Operational Criteria

Figure G.1 shows an overview of typical criteria included in operability analysis of different types of operations and subsystems. Figure G.2 shows typical criteria values included for different operations. The data is given in the VERES manual (Fathi, 2012).

Subsystem to be analysed	**Limiting criteria category**									
	Slam	**Deck wetn.**	**Vert. acc.**	**Lat. acc.**	**Roll**	**Motion Sickness**	**Pitch**	**Heave**	**Vert. velocity**	**Relative motion**
Ship hull										
Cargo										
Personell effectiveness										
Passenger comfort										
Lifting operations										

Figure G.1: Common limiting criteria included for vessel response analyses of different subsystems.

DESCRIPTION	CRITERIA (RMS)	COMMENT	REFERENCE
VERTICAL ACC.:			
Exposure ½ hour	0.10 g	10% motion sickness incidence ratio (MSI) (vomiting) among infrequent travelers of the general public. (One-third octave band frequency analysis is recommended.)	ISO 2631/3 1987 & 1982
1 hour	0.08 g		
2 hours	0.05 g		
8 hours	0.03 g		
Simple light work possible	0.275 g	Most of the attention devoted to keeping balance.	Conolly 1974
Light manual work possible	0.20 g	Causes fatigue quickly. Not tolerable for longer periods.	Mackay 1978
Heavy manual work	0.15 g	Limit in fishing vessels.	
Work of more demanding type	0.10 g	Long term tolerable for crew.	Payne 1976
Passenger on a ferry	0.05 g	Limit for persons unused to ship motions.	Goto 1983
Passenger on a cruise liner	0.02 g	Older people. Lower threshold for vomiting to take place.	Lawther 1985
ROLL:			
Light manual work	4.0°	Personnel effectiveness	Comstock 1980
Demanding work	3.0°	Personnel effectiveness	Hosoda 1985
Passengers on a ferry	3.0°	Short routes. Safe footing	Karppinen 1986
Passenger on a cruise liner	2.0°	Older people. Safe footing	Karppinen 1986
PITCH:			
Navy crew	3.0°	Personnel safety	Comstock 1980
Light manual work	2.0°	Personnel effectiveness	Hosoda 1985
Demanding work	1.5°	Personnel effectiveness	Hosoda 1985
HORIZONTAL ACC.:			
Passenger on a ferry	0.025 g	1-2 Hz frequency. General public	ISO 2631/1
Navy crew	0.050 g	Non-passenger and navy ships.	
Standing passenger	0.07 g (max.)	99 % will keep balance without need of holding.	Hoberock 1977
	0.08 g (max.)	Elderly person will keep balance when holding.	Hoberock 1977
Seated person	0.15 g (max.)	Average person will keep balance when holding.	Hoberock 1977
	0.25 g (max)	Average person max. load when holding	Hoberock 1977
	0.15 g (max.)	Nervous person will start holding.	
	0.45 g (max.)	Persons will fall out of seats.	

Figure G.2: Values for passenger/crew comfort due to vessel motions and accelerations. (Fathi, 2012).

Appendix H

ShipX Results - Operability

The following figures is the results from the vessel response and corresponding operability analysis of the reference vessel. These are used as basis to determine changes of operability due to parameter variations.

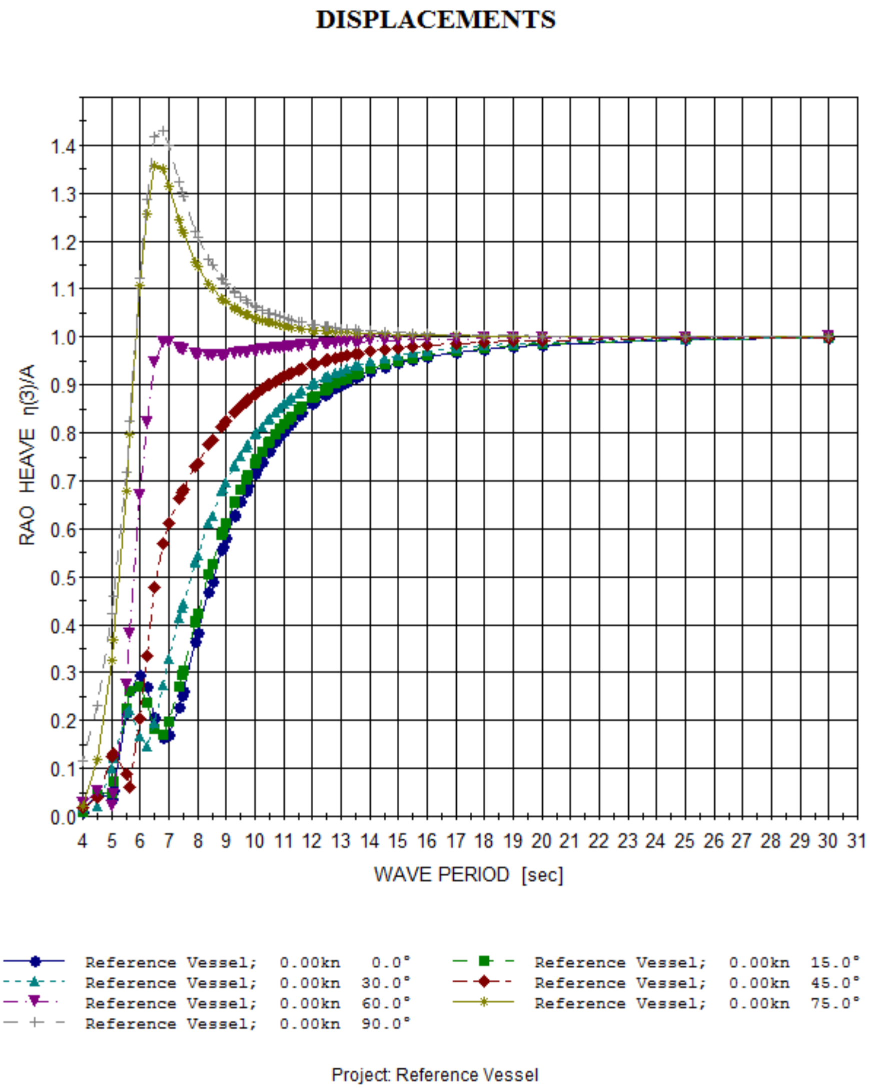


Figure H.1: Response Amplitude Operator in heave.

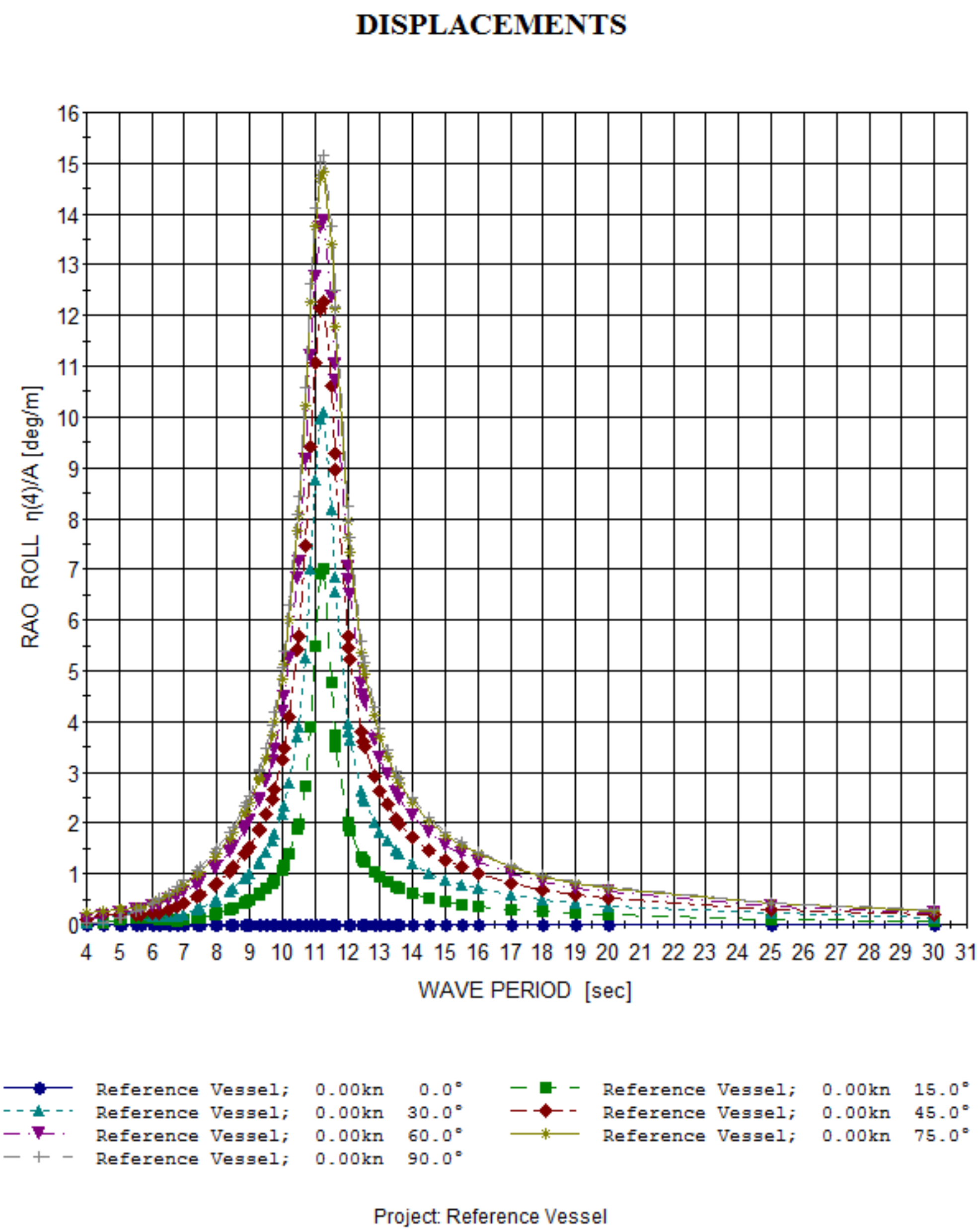


Figure H.2: Response Amplitude Operator in roll.

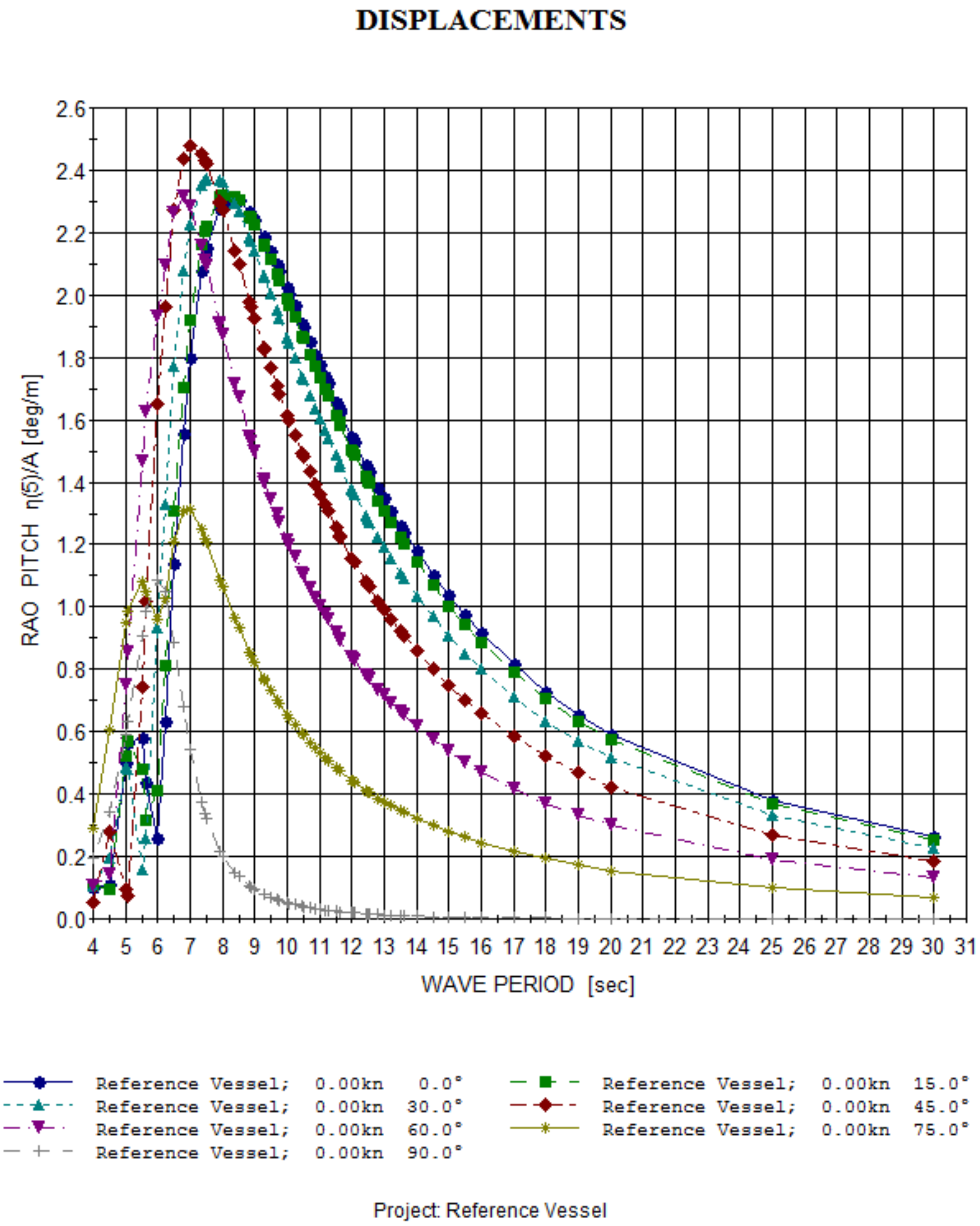


Figure H.3: Response Amplitude Operator in pitch.

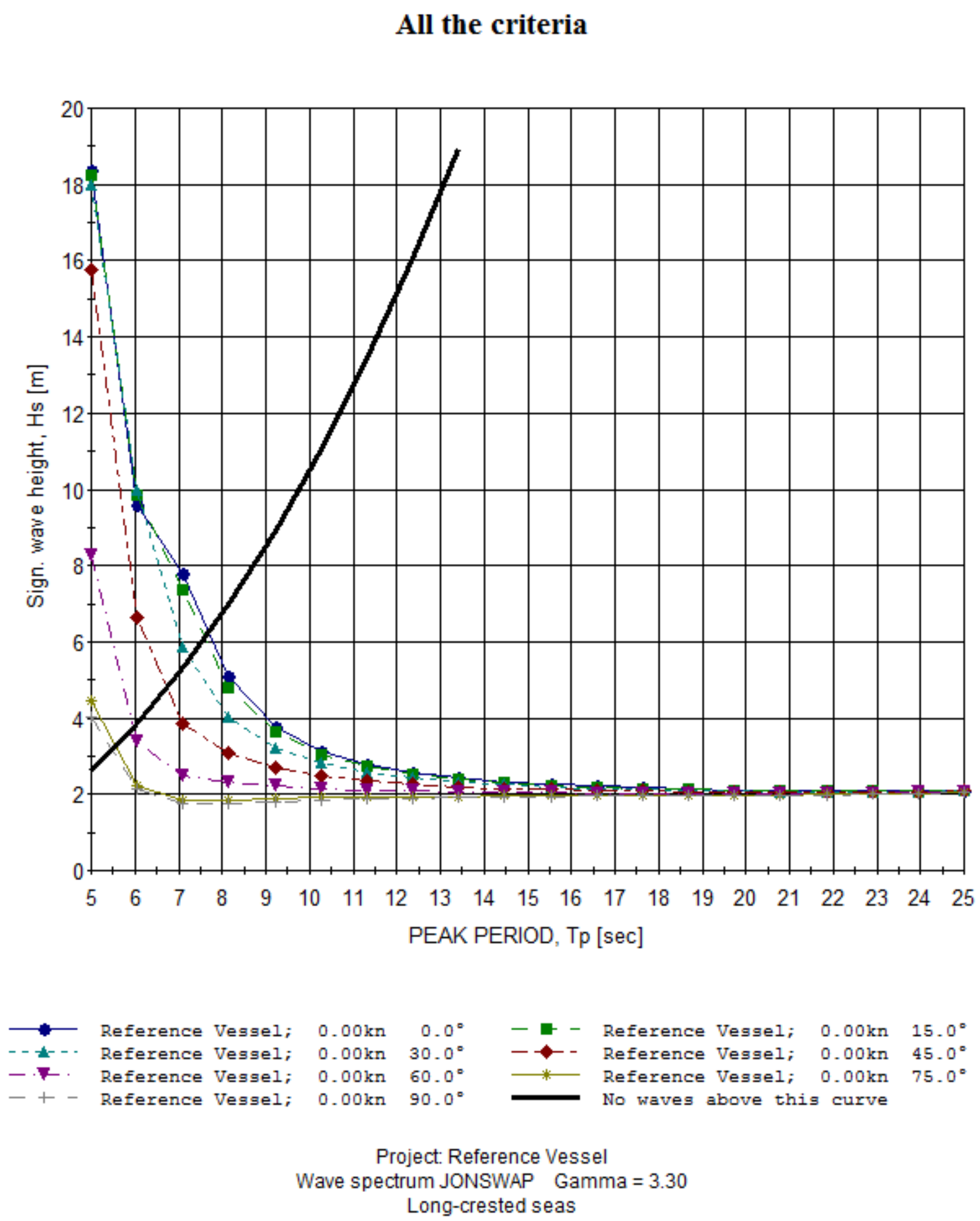


Figure H.4: Limiting sea states for Case 1 (moored to cage), all criteria.

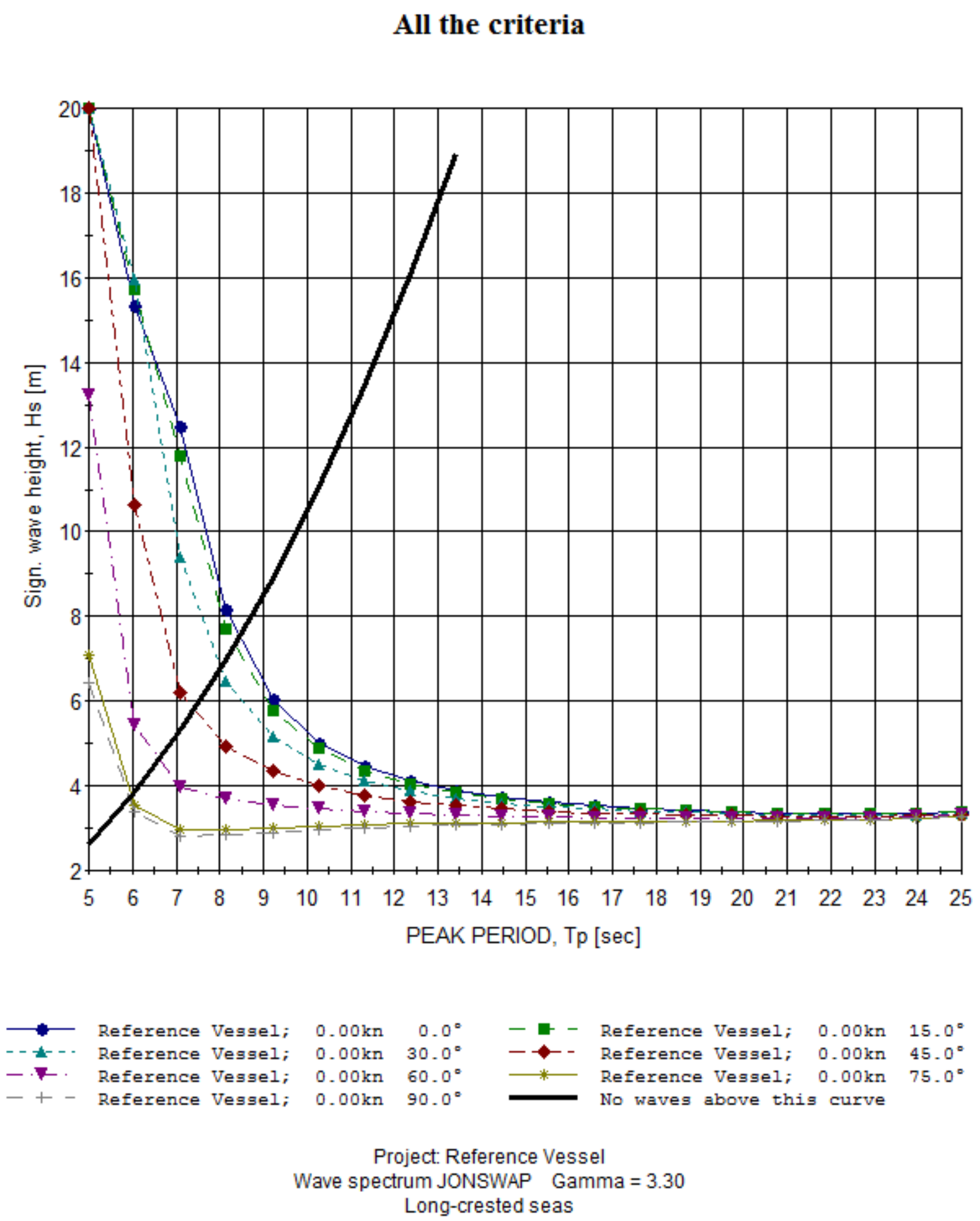


Figure H.5: Limiting sea states for Case 2 (on DP), all criteria.

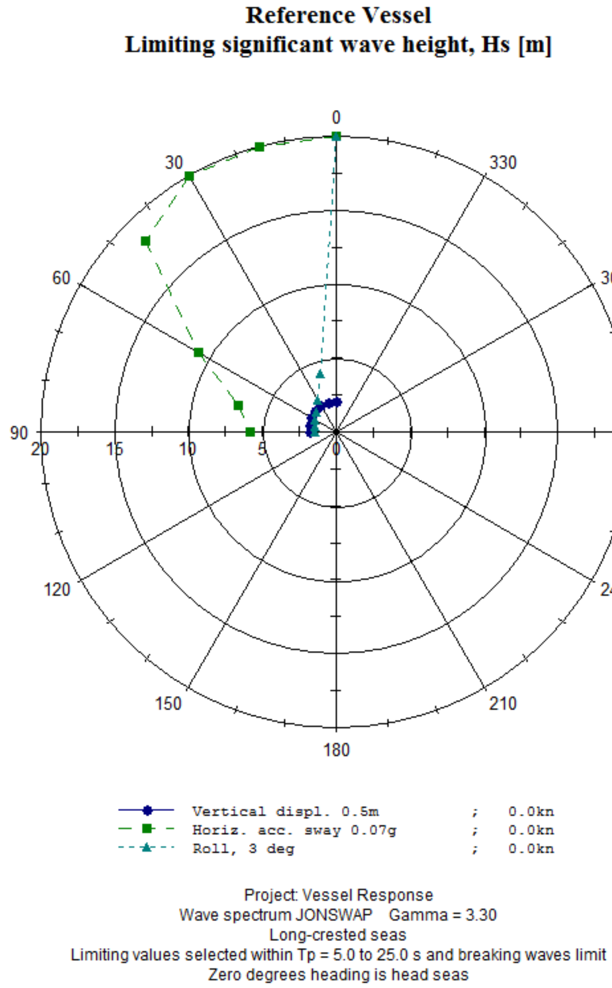


Figure H.6: Polar curves showing the limiting sea states for Case 1 (moored to cage), individual criteria.

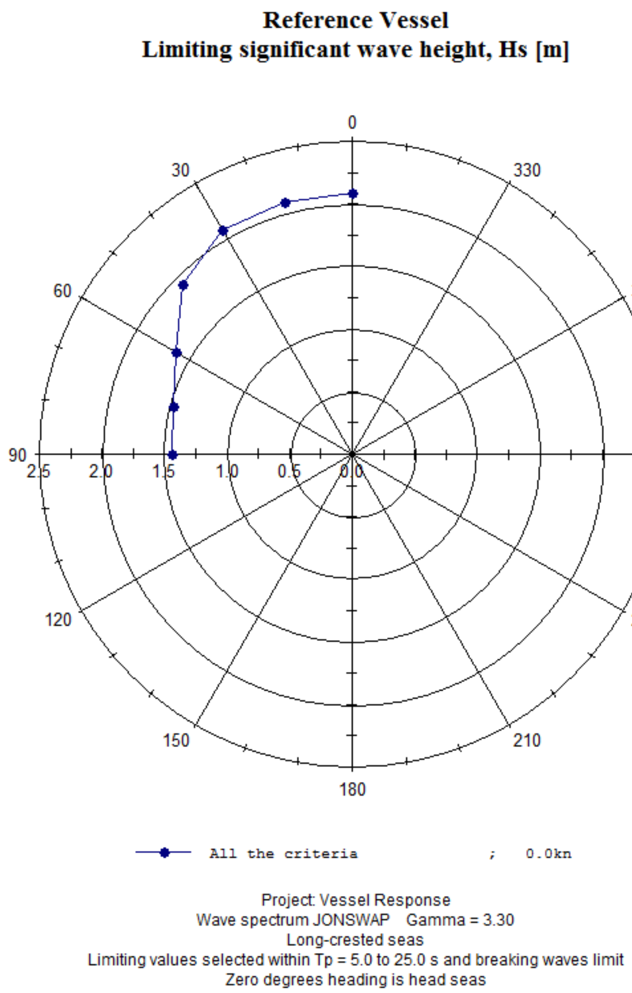


Figure H.7: Polar curves showing the limiting sea states for Case 1 (moored to cage), all criteria.

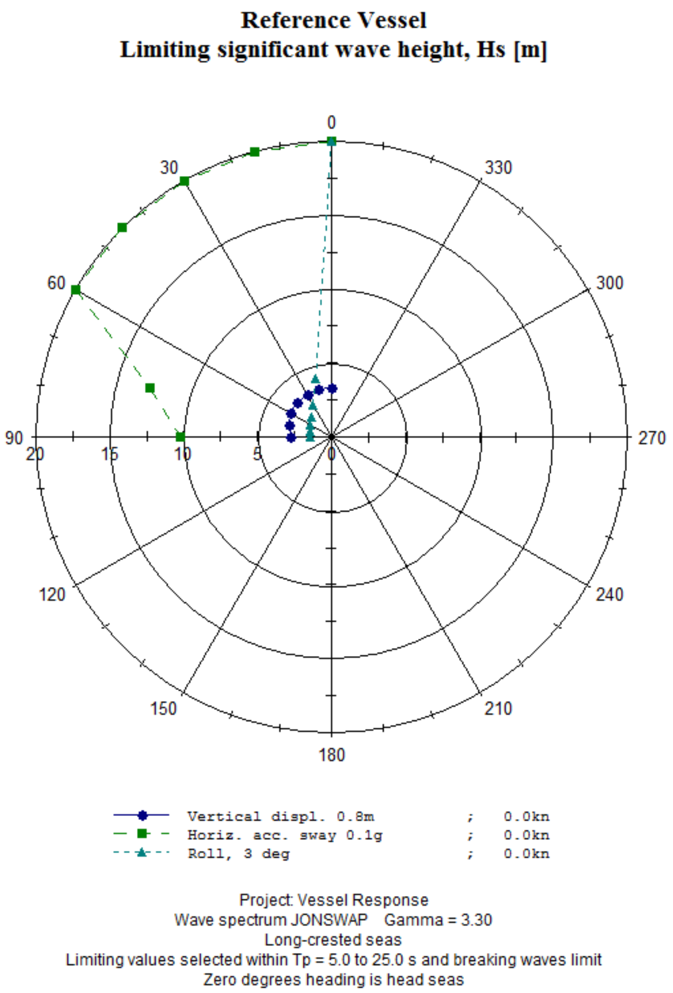


Figure H.8: Polar curves showing the limiting sea states for Case 2 (on DP), individual criteria.

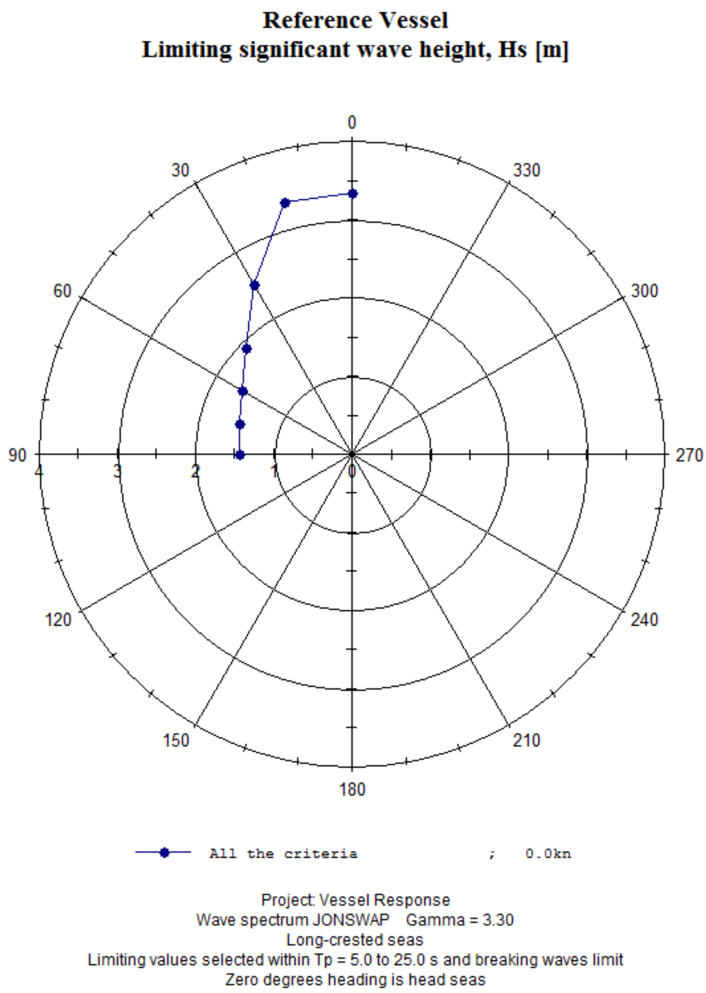


Figure H.9: Polar curves showing the limiting sea states for Case 2 (on DP), all criteria.