Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Christine Hegerstrøm

Marine Operations in the Aquaculture Industry with focus on Safe Wellboat Operations

Marine operasjoner i havbruksindustrien med spesielt fokus på brønnbåtoperasjoner

Master's thesis in Marine Technology
Supervisor: Kjell Larsen and Pål Lader
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Norges teknisk-naturvitenskapelige universitet
Institutt for marin teknikk

MASTER THESIS SPRING 2019

for

Stud. tech. Christine Hegerstrøm

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Background

Fabrication, transport, assembly and final operation of the different components of a floating fish farm are phases exposed to risk. Risk management is a challenging task. In the oil and gas industry the requirements to risk management is well defined through development of rules and regulations, several decades of experiences and improvement due to competence development.

The aquaculture industry has also become increasingly competence driven. The planning and execution of marine operations is, however, challenging the limit of what personnel, fish and equipment can handle. It is a significant risk for personnel and fish escapes. Fish welfare is regularly compromised, and marine operations are becoming more complex and must be performed in more exposed areas. Therefore, there is a need to assess if the existing requirements to planning and execution of marine operations in the aquaculture industry need improvements.

Scope of Work

1) Review relevant literature and describe briefly the main requirements and the main steps in the planning process of a marine operation for the oil and gas industry. Describe the present Norwegian rules and regulation regime for the aquaculture industry. Identify gaps and propose improvements and revisions related to marine operations.

2) Describe briefly state-of-art concepts and some of the new concepts for aquaculture structures. Typical marine operations related to installation and operation of the facilities shall also be described.

3) Familiarize with the numerical simulation suite SIMA/SIMO/RIFLEX and describe the theory that is relevant for determining operational limits for a typical wellboat operation.

4) Specify and describe a relevant concept for an operation with a wellboat and an aquaculture structure. Establish a numerical simulation model of the concept in SIMA/SIMO/RIFLEX. Concept to be decided in co-operation with the supervisors.

5) Propose design parameters that may determine the operational limits of the operation, perform numerical simulations of a selected parameter and propose limits based on simulation results. The variability and sensitivities of changes in weather parameters and other system parameters (e.g. mooring system) on operational limits to be discussed.

6) Conclusions and recommendations for further work.

General information

The work scope may change or prove to be larger than initially anticipated. Subject to approval from the supervisor, topics may be changed or reduced in extent.
In the project the candidate shall present her personal contribution to the resolution of problems within the scope of work.
Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.
The candidates should utilise the existing possibilities for obtaining relevant literature.

Report/Delivery
The thesis report should be organised in a rational manner to give a clear exposition of results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.
The report shall be written in English and edited as a research report including literature survey, description of relevant mathematical models together with numerical simulation results, discussion, conclusions and proposal for further work. List of symbols and acronyms, references and (optional) appendices shall also be included. All figures, tables and equations shall be numerated.
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.

The report shall be submitted in Inspera, as specified by the department of Marine Technology.
In addition, an electronic copy (pdf) to be sent to the supervisors.

Ownership
NTNU has according to the present rules the ownership of the project results. Any use of the project results has to be approved by NTNU (or external partner when this applies). The department has the right to use the results as if the work was carried out by a NTNU employee, if nothing else has been agreed in advance.

Thesis supervisors**:**
Main supervisor: Prof. II Kjell Larsen, NTNU/Equinor ASA
Co-supervisor: Prof. Pål Lader, NTNU

Industry Contact:
Martin Søreide, Aqualine AS

Deadline: June 11th, 2019

Trondheim, January 20th, 2019

Kjell Larsen (sign.)

Christine Hegerstrøm (sign.)

Preface

This master thesis is written during the second semester of the final 5^{th} year of M.Sc degree in Marine Technology at the Department of Marine Technology, Norwegian University of Science and Technology (NTNU). The thesis comprises the study of *Marine Operations in the Aquaculture Industry with focus on Safe Wellboat Operations* and the workload corresponds to 30 ECTS.

Firstly, I would like to thank my main supervisor Kjell Larsen and co-supervisor Pål Lader for regularly and structured guidance during the year. Kjell Larsen is employed as Advisor in Equinor within Marine Structures and Hydrodynamics, in addition to a professor II position at NTNU, where he lectures the course Marine Operations. Professor Pål Lader is employed at the Department of Marine Technology, NTNU and he has previously worked at SINTEF in the Fisheries and Aquaculture department. Their knowledge and experience on different disciplines, marine operations and aquaculture industry have given me valuable perspective throughout this process. Their constructive feedback and enthusiasm for the topic considered in this thesis are highly appreciated.

I would also like to thank industry contact Martin Søreide, CTO in Aqualine AS. He has contributed to this thesis with valuable information about the aquaculture industry, discussions and been a key person to provide information from several sources within the industry. Among these sources are Henrik Hareide, Director Government Relations and Compliance at Sølvtrans, who has provided useful information about their practice and fleet.

PhD candidate Carlos Eduardo Silva de Souza deserves a special thanks for guidance and good help with the software SIMA. SINTEF Ocean deserves acknowledgement for providing the essential wellboat model. In addition, I would like to thank Torgeir Strand Fjelnset, Operational manager at SalMar, for providing information about the wellboat operation.

Christine Hegerstrøm

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06.06.2019

Date

Summary

The thesis highlights how planning and execution of marine operations in the aquaculture industry are implemented in Norwegian regulations and standards. The study identifies a lack of regulations, thus proposals for improvements are emphasized. As an example, specifications for the overall duration of the operation including a time buffer that considers unforeseen events is one of the measures that should be included in the regulations. Furthermore, operational limits must be determined for what is acceptable levels of significant wave height, wind and current strength without compromising on the safety of personnel, fish and equipment. With the stipulated total duration of the operation and the required operational limits, a sufficient weather window can be defined for the operation to take place within safe limits. DNV-OS-H101 "Marine Operations, General" can be used as a basis for adopting the principles of the petroleum industry and a supervisory authority will be necessary to ensure that the industry complies with the legislation.

Based on the lack of regulations and standards for planning and execution of marine operations in the aquaculture industry, the objective of this thesis is to show a methodology for how operational limits can be established for a typical operation in the industry. When determining operational limits, the uncertainty of the weather forecast should be accounted for by using alpha factors. As alpha factors are not established for the aquaculture industry, this uncertainty is not accounted for in this thesis. In cooperation with the supervisors, the operation was decided to be a wellboat operation, where the vessel is moored to a single cage system with the use of four mooring lines. To determine the operational limits, the axial force in the vessel's mooring lines was chosen to be the design parameter of interest. The maximum allowed axial force was set to be the breaking strength of the mooring line with a safety factor of three.

A coupled SIMO-RIFLEX model was established to simulate the operation. The sensitivities of the operational limits to changes in weather exposure was examined by varying the following parameters; weather directions, wave amplitude and period, with and without applied current and wind. Three directions were examined, 180, 225 and 270 degrees relative to the wellboat's coordinate system. Since the industry has no specified procedures for how much pre-tension the mooring lines should have, other than tightening the lines sufficiently, the sensitivities of the operational limits to the degree of pre-tension was examined.

The operational limits are sensitive to short wave periods due to the influence of large wave drift forces. The wave drift force is a function of the wave amplitude squared, which means

that an increase in the amplitude will result in a significant increase in the contribution from the wave drift forces. To maintain sufficient safety when the amplitude is large, the wave period must be long, as the wave drift forces approach zero for long periods. The results from the simulations also showed that the system is sensitive to changes in the incoming load direction from waves, wind and current. For the three directions analysed in this thesis, bow sea (270 degrees) is the most exposed, while head sea (180 degrees) is the least exposed. This is because the wave drift forces are greater for 270 degrees, in addition to the wind and current coefficients which gives a significantly greater contribution in this direction compared to 180 degrees. When wind and current act on the system in addition to waves, the total mean forces acting on the system will increase, thus the operational limit will be reduced. Assessment of the system's natural periods is necessary, as corresponding wave periods may cause a significant increase in the axial forces in the vessel's mooring lines. Results from the sensitivity analysis of pre-tension suggest that the system is not particularly sensitive to the amount of pre-tension applied.

Sammendrag

Oppgaven belyser hvordan planlegging og utførelse av marine operasjoner i havbruksnæringen er implementert i norske reguleringer og standarder. Studien identifiserer et manglende fastsatt regelverk, og derfor vektlegges forslag til forbedringer. Som et eksempel, er spesifikasjoner i forhold til total varighet av operasjonen medregnet en tidsbuffer som tar hensyn til uforutsette hendelser et av tiltakene som bør nedfelles i reguleringene. Videre må operasjonsgrenser fastsettes for hva som er akseptabelt nivå av signifikant bølgehøyde, vind- og strømstyrke uten at det går på bekostning av sikkerheten for personell, fisk og utstyr. Med en fastsatt total varighet av operasjonen og nødvendige operasjonsgrenser, kan et tilstrekkelig værvindu defineres slik at operasjonen kan finne sted innenfor sikre rammer. DNV-OS-H101 "Marine Operations, General" kan benyttes som utgangspunkt for å adoptere prinsippene fra petroleumsnæringen, og utnevnelse av en tilsynsmyndighet vil være nødvendig for å sikre at næringen følger lovverket.

Med bakgrunn i manglende regelverk og standarder for planlegging og utførelse av marine operasjoner i havbruksnæringen, er formålet med oppgaven å vise en metodikk for hvordan operasjonsgrenser kan etableres for en typisk operasjon i næringen. Ved fastsettelse av operasjonsgrenser skal usikkerheten knyttet til værvarslingen medregnes gjennom bruk av alfa-faktorer. Ettersom alfa-faktorer ikke er etablert for havbruksnæringen, blir ikke denne usikkerheten tatt hensyn til i denne oppgaven. Operasjonen ble i samarbeid med veilederne bestemt til å være en brønnbåtoperasjon, hvor båten er fortøyd til et enkelt merdesystem ved bruk av fire tau. For fastsettelse av operasjonsgrensene ble aksialkraften i fortøyningstauene til brønnbåten valgt som design parameter. Maksimal tillat aksialkraft ble satt til å være tauets bruddstyrke med en sikkerhetsfaktor på tre.

En koblet SIMO-RIFLEX modell ble etablert for å simulere operasjonen. Operasjonsgrensenes sensitivitet for endringer i véreksponering ble undersøkt ved å studere variasjoner av følgende parametere; værretninger, bølgeamplitude og periode, med og uten strøm og vind. Tre retninger ble totalt undersøkt, 180, 225 og 270 grader i forhold til brønnbåtens koordinatsystem. Siden industrien ikke har noen spesifiserte prosedyrer på hvor mye forspenning fortøyningslinene skal ha, annet enn at tauene skal strammes tilstrekkelig, ble operasjonsgrensenes sensitivitet i forhold til grad av forspenning undersøkt.

Operasjonsgrensene er sensitive for korte bølgeperioder på grunn av påvirkningen fra store bølgedriftskrefter. Bølgedriftskraften er en funksjon av bølgens amplitude kvadrert, som betyr at en økning i amplituden vil medføre en betraktelig økning i bidraget fra bølgedrift-

skreftene. For å opprettholde tilstrekkelig sikkerhet når amplituden er stor må perioden til bølgen være lang, da bølgedriftskreftene nærmer seg null for lange perioder. Resultatene fra simuleringene viste også at systemet er sensitivt for endringer i innkommende lastretning fra bølger, vind og strøm. For de tre retningene analysert i denne oppgaven vil tilfellet hvor været kommer rett inn mot siden av båten (270 grader) være det mest eksponerte, mens tilfellet hvor bølger kommer rett inn mot baugen (180 grader) vil være minst usatt. Dette er fordi bølgedriftskreftene er større for 270 grader, i tillegg til at vind- og strømkoeffisientene gir et betydelig større bidrag i denne retningen i forhold til 180 grader. Når vind og strøm virker på systemet i tillegg til bølger, vil de totale middelkreftene som virker på systemet øke, slik at operasjonsgrensen reduseres. Vurderinger av systemets egenperioder er nødvendig, da korresponderende bølgeperioder kan medføre en betraktelig økning i de aksielle kreftene i tauene, som medfører en reduksjon av operasjonsgrensene. Resultatet fra sensitivitetsanalysen indikerer at grad av forspenning ikke er av stor betydning for etablering av operasjongrenser.

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Nomenclature

The most commonly used nomenclature through this thesis is presented here. Those which are not specified here is explained in the text.

Abbreviations

$ALARP$	As low as reasonably practicable
DLF	Dynamic load factor
FFT	Fast Fourier Transform
$HAZID$	Hazard identification analysis
$HDPE$	High-density polyethylene
$HEAR$	Human environment assets and reputation
HF	High frequency
HSE	Health Safety and Environment
IMO	International Maritime Organization
$JONSWAP$	Joint North Sea Wave Project
LF	Low frequency
MAB	Maximum allowed biomass
NDP	The Norwegian Petroleum Directorate
NPD	Norwegian Petroleum Directorate
OP_{LIM}	Design criterion

OP_{WF}	Operation criterion
PM	Pierson-Moskowitz
PNR	Point of no return
RAO	Response amplitude operator
RMP	Risk managment plan
SJA	Safe job analysis
$SQRA$	Semi quantitative risk analysis
T_C	Contingency time
T_R	Operation reference period
T_{POP}	Planned operation period
TDP	Touch down point
VMO	Veritas marine operation rules
WF	Wave frequency

Symbols

β	Frequency ratio
η_A	Wave amplitude
Λ	Logarithmic decrement
ω_0	Natural frequency
ω_p	Peak frequency
$\overline{q_{wa}}(\omega)$	Mean wave drift force
ρ_{air}	Density of air
ρ_{water}	Density of water
ξ	Damping ratio
$A(\omega)$	Frequency- dependent added mass matrix
$C(\omega)$	Frequency-dependent potential damping matrix
C_D	Drag coefficient

C_{cr}	Critical damping
C_{wa}	Mean wave drift force coefficients
D_q	Quadratic damping matrix
D_t	Linear damping matrix
E	Young's modulus
F_1^M	Mooring system's total surge force
F_2^M	Mooring system's total sway force
F_6^M	Mooring system's total yaw moment
F_D	Drag force
H	Wave height
$H(\omega, \theta)$	Transfer function
$h(\tau)$	Retardation function
H_s	Significant wave height
$K(r)$	Non-linear stiffness matrix
K_E	Elastic stiffness
K_G	Geometric stiffness
K_{TOT}	Total system stiffness
M	Mass matrix
$Q(t, r, \dot{r})$	Excitation force vector
q_{cu}	Current force
q_{wi}	Wind force
$r, \dot{r}, \ddot{r}$	Position, velocity and acceleration vectors respectively
$S(\omega)$	Wave spectrum
T_0	Natural period
T_p	Peak period
$T_x = T_H$	Horizontal top tension

Chapter 1

Introduction

The introduction contains the background of the research and objectives for this master thesis. To guide the reader, a structure of the thesis is presented at the end.

1.1 Background

Over the past 40 years, the aquaculture industry has become one of Norway's most important industries dominated by the production and export of Atlantic salmon. With an expected increase in the world's population, it is an inevitable challenge that food production must increase, which inter alia requires better utilization of marine raw materials. This implies that Norway's salmon production must increase significantly from today's production level. Furthermore, this will require more space and better production sites where the environmental footprint becomes less concentrated in one area and where the density of salmon lice is within acceptable limits. Thus, exposed areas must be utilized and the industry must meet new challenges related to operations, equipment and structure due to rougher weather conditions.

Structures designed for exposed aquaculture are of greater complexity than conventional cages, which leads to a correspondingly increased complexity for the related marine operations. Today, the marine operations associated with conventional HDPE-cages are on the limit of what humans, fish and equipment can handle. Fish welfare and escapes are in the media's spotlight and the aquaculture industry is struggling to maintain the reputation of the industry.

To operate a justifiable industry it is essential that sufficient requirements for planning and execution of marine operations are established. Thus, there is a need to assess if the existing requirements for planning and execution of a marine operation are sufficient or need to be improved.

Through several decades the offshore petroleum industry has developed rules and regulations which ensure that marine operations are carried out with use of high competence and with the lowest possible associated risk for personnel, equipment and the environment. Lessons from accidents have been used to continuously improve their rules and regulations. Thus, it is of high relevance to assess in what extent the aquaculture industry can adopt principles from the petroleum industry's handling of marine operations and how operational limits could be established.

1.2 Objective

In the following the main objectives of this master thesis are listed:

1. Describe the main requirements and the main steps in the planning process of a marine operation for the oil and gas industry. Describe the present Norwegian rules and regulation regime for the aquaculture industry. Identify gaps and propose improvements and revisions related to marine operations.
2. Describe aquaculture structures, both new and conventional. Typical marine operations related to installation and operation of the facilities shall also be described.
3. Describe the theory that is relevant for determining operational limits for a typical wellboat operation.
4. Specify and describe a relevant concept for an operation with a wellboat and an aquaculture structure. Establish a numerical simulation model of the concept in SIMA/SIMO/RIFLEX.
5. Propose design parameters that may determine the operational limits of the operation, perform numerical simulations of a selected parameter and propose limits based on simulation results. The variability and sensitivities of changes in weather parameters and other system parameters (e.g. mooring system) on operational limits to be discussed.

1.3 Limitations

The simulations study was limited to investigate the operational limits associated with a wellboat operation, where the wellboat is moored to a single cage system by using four mooring lines. These lines are subjected to a high level of dynamic response and was therefore chosen as the main parameter of interest. The environmental loads consist of waves, wind and current. The approach angles of these loads were limited to 180, 225 and 270 degrees relative to the vessel's coordinate system. For each case, the loads were applied in the same direction. Due to a limitation in the software, only regular waves were applied, as the floating collar was established by using partially submerged RIFLEX elements. A sea state with irregularity is therefore not examined.

The main focus of this thesis is to show a methodology for how operational limits can be established for a typical operation in the aquaculture industry. When the operational limits were determined for the system, some aspects which are important if a real operation were executed, was not considered. Some of these will be presented in the following:

- With respect to computational time consumption, the fish net was neglected from the model. In a wellboat operation, it is of high importance to moor the wellboat in a position where the net is unable to drift into the hull. If the net comes in contact with the thrusters, a significant probability for fish escapes arises.
- When the wellboat is moored next to the floating collar, contact forces will arise. These forces have not been accounted for in the simulations and would have contributed to lowering the axial forces in the mooring lines. Hence, neglecting these forces is a conservative approach. The floating collar is assumed to have high strength, thus be able to withstand larger forces compared to the vessel's mooring lines.
- The presence of a wellboat moored to a cage system introduces larger forces to the entire system. It has been assumed that these increased forces have been taken into consideration when the mooring analysis described in NS 9415 was conducted for the cage system.

The operational limits presented at the end of this master thesis are only valid for the specific system configuration and the applied weather loads in the given directions.

1.4 Previous Work

This master thesis is a continuation of the work from the project thesis entitled "Marine Operations in the Aquaculture Industry" written by the same author during the fall of 2018. The focus of the project thesis was to address the requirements and guidance related to planning and execution of marine operations, which the aquaculture industry must relate to. In addition, improvements to the rules and regulations were discussed and emphasized.

1.5 Structure of the Report

Chapter 2: Theory related to marine operations is elaborated. The planning process implemented in the petroleum regulations is described through seven steps.

Chapter 3: Structures and components used in the aquaculture industry are described, in addition to new innovative concepts.

Chapter 4: An overview of the rules and regulation regime for the aquaculture industry in Norway is elaborated. If any requirements related to marine operations are found, these are emphasized.

Chapter 5: General marine operations in the aquaculture industry are described. Thereafter, a wellboat operation is used to illustrate how the planning process from chapter 2 can be implemented in the industry. Improvements and revisions to the rules and regulation regime, outlined in chapter 4 are discussed and the motivation for performing simulations is presented.

Chapter 6: Theory relevant for the simulation model of the cage and wellboat configuration is presented.

Chapter 7: The SIMA software with the numerical tools, SIMO and RIFLEX is described as well as the simulation model established.

Chapter 8: The numerical model is verified through tests, and coefficients for wave drift, wind and current along with the RAOs are plotted for analysis.

Chapter 9: The results from the numerical simulations are presented. The variability and sensitivities in terms of changes in the weather parameters and the degree of pre-tension on operational limits are discussed.

Chapter 10: Concluding remarks and recommendations for further work are given.

Chapter 2

Marine Operations

In the following sections, essential marine operation terms are presented. DNV-OS-H101 "Marine Operations, General" which gives general recommendations and requirements for planning, preparations and performance is used as a basis (DNVGL, 2011), as well as Kjell Larsen's marine operation lectures from spring 2017 (Larsen, 2018a).

A *Marine operation* is defined as a non-routine operation of limited defined duration in the marine environment, which is associated with quay areas, subsea, offshore/inshore waters and construction sites (Larsen, 2018a). The operation is related to handling of vessel(s) and/or object(s) during temporary phases. A marine operation should be designed with the principle, to bring an object from one safe condition to another. The definition of a safe condition is related to the condition where the object is exposed to normal risk for loss and damage. Normal risk is the similar risk which is assumed during in-place condition. The main task for a marine operation aims for minimizing cost at an acceptable operability and risk level. The overall design acceptance criteria are set to ensure a probability of less than 10^{-4} for structural failures. This criterion is used when load-, safety- and material factors are established in the design phase and considers only structural capacity. Human errors and operational errors may lead to an increase in the probability of total failure.

In some cases, it may be necessary to halt an operation, or reverse it. The point where it is no longer possible to halt or reverse the operation is called the *point of no return (PNR)*, and should be clarified and taken into account in the planning process. The first safe point after PNR shall also be clarified.

Operations are further divided into sub-operations that can either be qualified as weather *restricted* or *unrestricted*. Which category the operation is classified as depends on the duration and if the operation can take place within the limits of weather forecast that is favourable. The latter describes a weather restricted operation and shall normally be less than 72 hours for a planned operation. These types of operations can be designed and planned with substantially lower environmental conditions than for a weather unrestricted operation. A weather unrestricted operation should be planned in such a way that it can take place safely within any weather condition that can occur during the current period. These operations are therefore associated with high design criteria, which is determined by the statistical extremes for the season and area. To select an operational limit for these operations, both DNV-OS-H101 and ISO 19901-6 could be used where the duration of the operation defines the return period that should be considered in further calculations. The duration is normally longer than 72 hours.

Time is expensive in a marine operation, therefore a well-planned schedule is essential. The duration is defined by the operation reference period (T_R), where the start and end points are clearly indicated. The start point is always after an acceptable weather forecast and the end point is when the object is considered in a safe condition. T_R is calculated from the planned operation period (T_{POP}) and the contingency time (T_C). T_C should cover both uncertainties in T_{POP} and operations where weather sensitivity or contingency time could affect the time spent. The relation between T_R, T_{POP} and T_C is presented by equation 2.1 and in figure 2.1. If T_C is not properly assessed, twice of the planned operation period should be used to estimate the reference period, equation 2.2. Normally a T_C less than 6 hours is not permitted.

$$T_R = T_{POP} + T_C \tag{2.1}$$

$$T_R \geq 2 * T_{POP} \tag{2.2}$$

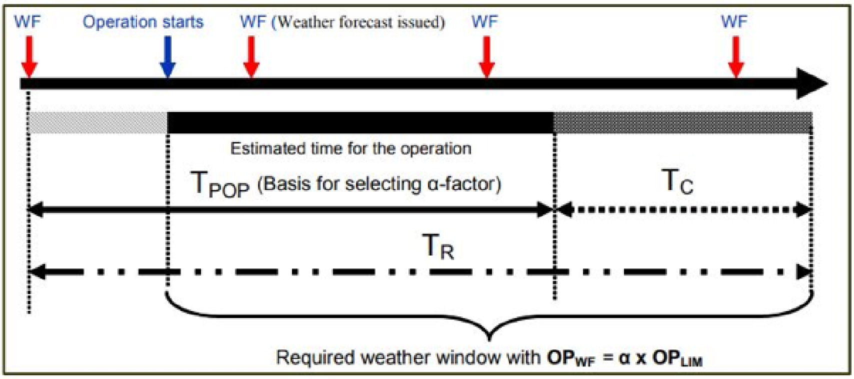


Figure 2.1: Presents the relation between T_R, T_C and T_{POP} (DNVGL, 2011)

As mentioned, weather restricted operations are dependent to take place within the limits of a certain weather forecast. Therefore, the uncertainty of the weather forecast should be accounted for in the calculations by using an alpha factor. Alpha factors are in the range between 0 and 1 having the effect of reducing the operation criterion (OP_{WF}) to a more conservative level, equation 2.2.

$$OP_{WF} = \alpha * OP_{LIM} \tag{2.3}$$

Where OP_{LIM} is the design criterion. This limit shall never exceed the maximum environmental criteria, safe working principles for crew, restrictions for equipment, diving systems and position keeping systems.

In order to find the correct alpha factor for a certain sub-operation, DNV-OS-H101 section 4 is required to use (DNVGL, 2011). In this standard, there are tabulated values of the alpha factor that could be found by knowing the weather forecast level, design criteria for H_s or wind speed and the planned operation period (T_{pop}). The weather forecast levels can be found in table 2.1 and is based on the considered operational sensitivity to weather and the operation reference period (T_R) (DNVGL, 2011).

Table 2.1: Weather forecast level A, B and C

Level	
A	Includes marine operations that are characterized as major and sensitive to weather. In order to use the table values associated with level A, a meteorologist is required on site. The meteorologist is required to use at least two independent weather forecast sources. Maximum allowed forecast interval is 12 hours, but could be smaller due to high weather condition sensitivity.
B	Includes marine operations of significant value and consequences, which are sensitive to environmental conditions. Meteorologist is not required on site, but in the event of an unstable weather situation and/or close to the defined weather limit, a meteorologist should be conferred. Two independent weather forecast sources should be used and the most severe forecast shall be applied. Maximum allowed forecast interval is 12 hours.
C	In contrasts to level A and B, these marine operations are less sensitive to weather conditions and performed on a more regular basis. Meteorologist is not required on site and only one weather forecast is required. As with level A and B, the maximum weather forecast interval is defined to be 12 hours.

Another frequently used term in this context is weather window, which implies a time period of sufficient length where the marine operation can be carried out. For this period, the operation criterion shall remain larger than the weather forecasted values. A long weather window is therefore preferred in terms of increasing flexibility of starting/ending the operation and the ability to handle contingency events.

Whether a sub-operation is defined as restricted or unrestricted has a great influence on weather windows, safety and cost. For this reason, the type of operation should be pointed out early in the planning process. Unrestricted categorized operations are often associated with high costs due to strict safety factors necessary for conducting a safe and sound practice. In the case of restricted operations, the cost due to waiting-on-weather could be high.

High operational limits are desirable because they have a large impact on the weather window. If the operational limits are high, it is possible to allow higher threshold on critical weather parameters, such as wave height and wind speeds. The costs related to an increase in the operational limit can reach a maximum of what is expedient.

Minimizing risk associated with humans, environment and assets should always be the main priority in marine operations. Therefore, it is always preferable to maintain a short duration of the operation itself, high operational limits and long weather windows. This combination will enhance the safety margin, thus these factors should be maximized within reasonable costs. Figure 2.2 illustrates the importance of these factors, and how they correlate.

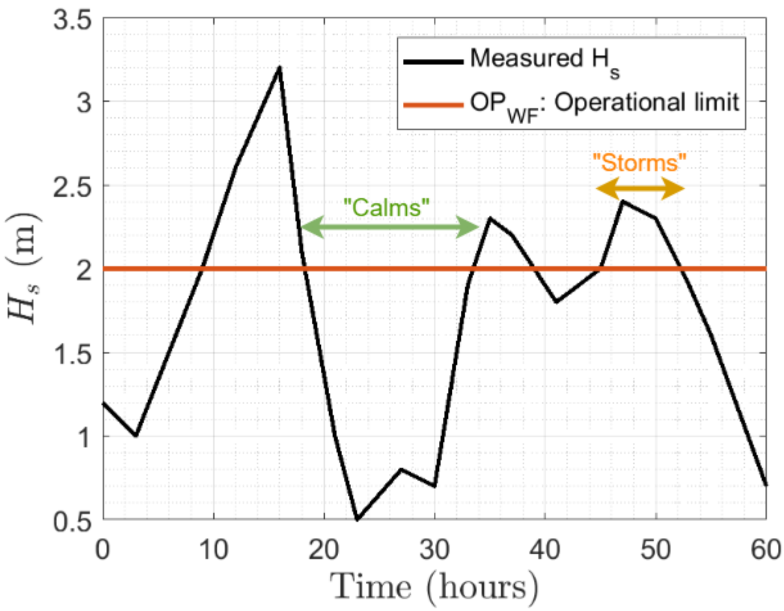


Figure 2.2: Example of measured significant wave height as a function of time. The "storms" and the weather window indicated as "calms" is given by the operational limit and indicates whether an operation could take place

2.1 The Planning Process

When the Ekofisk field was declared for commercial production in 1969, it was the start of a new chapter in the Norwegian history. Subsequently, more discoveries have been done, several fields have been established and several fields have been put into production. The petroleum industry has given major advances in technology, legislation and regulations and has created the foundation for the Norwegian economy. Lessons have been learned from accidents and mistakes, and processed the regulations to prevent such incidents to repeat (Smith-Solbakken and Ryggvik, 2018).

Planning and design sequence should be conducted before a marine operation is carried out. According to DNV-OS-H101, the following sequence shall be performed (DNVGL, 2011):

1. Identify relevant and applicable regulations, rules, company specifications, codes and standards, both statutory and self-elected.
2. Identify physical limitations. This may involve pre-surveys of structures, local conditions and soil parameters.
3. Overall planning of operation i.e. evaluate operational concepts, available equipment, limitations, economic consequences, etc.
4. Develop a design basis describing environmental conditions and physical limitations applicable for the operation.
5. Develop design briefs describing activities planned in order to verify the operation, i.e. available tools, planned analysis including method and particulars, applicable codes, acceptance criteria, etc.
6. Carry out engineering and design analyses.
7. Develop operation procedures.

2.1.1 Identify Rules

"Identify relevant and applicable regulations, rules, company specifications, codes and standards, both statutory and self-elected."(DNVGL, 2011)

To plan an operation, the framework consisting of requirements and rules must be defined. This is necessary in order to handle petroleum activities on the Norwegian continental shelf within legal and safe limits.

The rules and regulations, which deal with marine operations, consist of acts, regulations, guidelines and standards. The intent of this is to give the industry a clear and common framework to ensure high quality and safety of operations performed. The Acts are defined by The Norwegian Petroleum Directorate (NPD), where act 29 number 72 is central in relation to petroleum activity. The Norwegian Petroleum Safety Authority defines the regulations, which the industry has to follow. These regulations cover management, facilities, activities, working environment and both technical and operational regulations. In addition to this, the regulation also includes a framework regarding HSE. This is to ensure a high level of safety and secure a systematic implementation of measures to meet the requirements and intentions specified (The Petroleum Safety Authority, 2019).

Guidelines and standards help engineers to plan, analyze and perform marine operations. International standards as ISO 19901-6 and NORSOK, which is developed by the Norwegian petroleum industry, is often applied. NORSOK N-001 refers to Veritas Marine Operation Rules (VMO) and implies that this shall be the basis for planning, preparation and execution of marine operations. In 2016, the VMO standards were merged into one and named DNVGL-ST-N001. Guidelines on how the offshore standards shall be used are found in the recommended practices (Larsen, 2018a).

For sea transport and pipelaying, the vessel will be regulated by the Maritime Safety Authority and the Flag State Rules. The standards which apply for these vessels are given by the International Maritime Organization (IMO) (Larsen, 2018a).

2.1.2 Identify Physical Limitations

"Identify physical limitations. This may involve pre-surveys of structures, local conditions and soil parameters."(DNVGL, 2011)

Physical limitations shall be considered relative to the operation and the local conditions. The structures and equipment involved should be adapted for the operation. Within these pre-surveys of structures, geographical inspections and light conditions i.e. polar night phenomena should be considered.

For example, in a tow operation manoeuvrability is of high importance to operate safe in-shore. This could be accomplished by the use of a short towline, low speeds and a favourable tow configuration. Another example is load-out operations, which considers activities where an object is moved from land onto a vessel or barge. For these cases, the strength and capability of the quay are two of the measures that need to be taken into account.

2.1.3 Overall Planning

“Overall planning of operation i.e. evaluate operational concepts, available equipment, limitations, economical consequences, risk assessment etc.”(DNVGL, 2011)

The purpose of overall planning is to clarify material and economic needs, as well as the necessary employment and knowledge. Based on the regulations and physical limitations considered, concepts for the specific marine operation can be evaluated. The concepts are seen in connection with available equipment and vessels, constraints, financial consequences and associated risks. According to DNVGL-RP-N101 "Risk Management in Marine and Subsea Operations", risk is defined as the product of probability of occurrence and consequence. It is crucial to keep in mind the principles to understand and manage risk through all of the stages associated in an operation (Larsen, 2018a).

Design concepts must be specified and elaborated in relation to the same description criteria so that it is possible to evaluate the concepts against each other. The chosen concept depends on the criteria that the company values as the highest in addition to the requirements specified in the rules. A common denominator for these criteria is efficiency, economic profitability and low risk.

A sufficient weather window for the operation should be established in an early phase, in addition to categorize the operation as weather restricted or unrestricted. If the operation is weather restricted, the weather window will affect the feasibility of the operation. The reason is that a long operation needs an even longer weather window, where the operation criterion (OP_{WF}) is satisfied. This implicates that OP_{WF} should be larger than the forecasted level for the whole period. A longer operation period is related to a higher probability of waiting on weather, which is undesirable in relation to costs.

Risk assessment is an important part of the planning process and shall be assessed in relation to the *HEAR*-principle, which covers Humans (H), Environment (E), Assets (A) and Reputation (R). During all phases of the marine operations, hazards must be identified and ranked. After the ranking, the risk associated with each hazard shall be set to as low as reasonably practicable (*ALARP*). The purpose of performing a risk assessment is to aim for zero accidents, incidents and losses. This principle is also the basis for DNVGL-RP-N101. This recommended practice contains both recommendations and guidelines for establishing risk management in marine- and subsea operations. One of these recommendations is to make use of a risk management plan (*RMP*). This is a method for documenting and manage risk to an acceptable low level through all project phases within a marine operation (Larsen, 2018a).

The risk can be classified as high, medium or low. There are several techniques and methods for identifying and assessing the risks involved in a marine operation. An acknowledged method is the hazard identification analysis (*HAZID*), which is one of the listed techniques recommended in DNVGL-RP-N101. *HAZID* should be applied in an early stage of a project, making it possible to reveal potential hazards and weaknesses. Associated with *HAZID* is a typical worksheet in combination with Semi-Quantitative Risk Analysis (*SQRA*), which provides structured documentation. Any identified potential hazard should be ranked according to the risk acceptance criteria form, which is an efficient method to evaluate their consequence and probability. *HAZID* could also help the engineers in the decision process, by eliminating concepts associated with unaccepted risk levels and introduce risk reducing activities (DNVGL, 2017a).

For all sub-operations, risk reducing activities are required. In accordance with (Larsen, 2018a) the following risk reducing activities should be conducted.

- Operation feasibility assessment
- Document verification where all main operational procedures are verified.
- Familiarization of all personnel involved, which could be done with use of a Safe Job Analysis (*SJA*).
- Familiarization of safety plans for the involved personnel, which includes escape routes and safe access in every situation.
- Preparedness for emergency situations.
- Inspections, maintenance and testing of equipment. It is crucial that all involved equipment are reliable at all times and that the personnel is familiarized with it.

- Survey of the involved vessels if they are suitable for the intended use.
- Survey of the operation, where the procedures should be approved.

According to (Larsen, 2018a), there are some risks that should be assessed before a marine operation can start. These events will be presented in the following.

- Position loss: This could be a failure in the mooring line, anchor drag or DP system.
- Capsize or heeling: Stability and ballasting capacity could be insufficient.
- Collisions: Between passing vessels and structures. This could happen during transit, load transfer, supply or in a standby position.
- Grounding: During transport.
- Lost tow: During transport.
- Icing: Could be an important factor for artic operations.
- Dropped objects: During crane operations, construction or transfer of cargo.
- Structural failures: Fatigue, design failure or unacceptable quality of components involved.
- Extreme weather: Design limits increases.
- Transfer of personnel between vessels is associated with high risk
- Lack of competence of personnel.
- Insufficient preparatory work with design documentation, procedures and personnel familiarisation.

Redundancy, backup philosophies and other measures taken to reach an acceptable risk level should be specified, along with mitigation actions.

Barrier management should be established to reduce risk related to failure, hazards and accidents by employing preventive and limiting barriers. There can be several hazards leading to an undesirable event. Preventive barriers should be implemented in order to prevent these to arise and develop further into serious events. The aim with limiting barriers is to minimize the consequences related to the undesirable event. An overview of these principles can be illustrated in a bow tie model figure 2.3, where the preventive barriers are found to the left of the considered event and the limiting barriers are found to the right (The Petroleum Safety Authority, 2017).

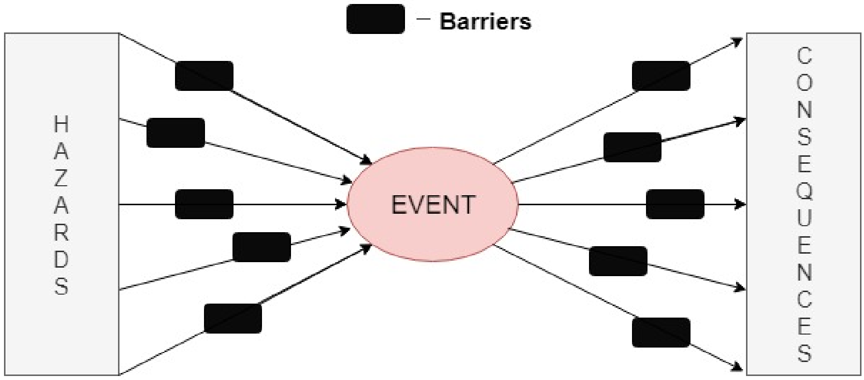


Figure 2.3: Illustration of the bowtie principle

2.1.4 Design Basis

"Develop a design basis describing environmental conditions and physical limitations applicable for the operation."(DNVGL, 2011)

The design basis should describe the environmental conditions and physical limitations, which are associated with the marine operation. Environmental conditions are natural phenomena that can lead to structural stress and strain over time, of general importance is wind, waves/swell, currents and tide. Other phenomena that could be considered are soil conditions, temperature, ice and snow, visibility/fog, heavy rain, earthquake and fouling. Local conditions should also be considered, within these are tide variations, wind and current variations, strong winds due to polar lows and squalls, tsunami and swell and wave conditions. The possible combinations of swell and wind should be assessed (DNVGL, 2011).

To establish characteristic environmental conditions, statistical data should be used. Extremes, short- and long-term variations should be revealed in the statistical description. If characteristic environmental criteria should be established, statistical data for a sufficiently long period is required to use. According to DNV-OS-H101, meteorological and oceanographic data is recommended to be a minimum of three to four years of data collection. Longer periods are required when using seasonal data (DNVGL, 2011).

Marine operations categorized as unrestricted should be based upon extreme value statistics. If the reference period associated with the operation is more than 30 days, wind velocities with a return period of 100 years should be used. For durations less than 30 days, a return period of 10 years should be considered. Long term statistical data shall be used as a basis for selecting characteristic wave conditions (DNVGL, 2011).

The design wind, wave heights and periods should be selected independent of statistical data for a weather restricted operation. The significant wave height may be based upon weather forecast. Selection of significant heights and periods considers several factors, among these are operation period, typical weather conditions associated with the site, feasibility and safety of the operation. As mentioned, alpha factor accounts for the uncertainty in the weather forecast and shall therefore be applied to the considered design limits (DNVGL, 2011).

2.1.5 Design Briefs

"Develop design briefs describing activities planned in order to verify the operation, i.e. available tools, planned analysis including method and particulars, applicable codes, acceptance criteria, etc."(DNVGL, 2011)

To verify operations, design briefs describing the sub-operations related should be conducted. The design brief should be formulated as a document reflecting upon the previous phases of the planning process. The sub-operations which are defined as weather unrestricted or restricted will affect the acceptance criteria, recommendations and requirements that are needed to apply. These are found in the standards identified in section 2.1.1 as ISO 19901-6, NORSOK and VMO standards.

In this section, a planned analysis should be established. This analysis should facilitate guidance for further engineering and design analyses. Methods on how the operation should be managed and particulars related are necessary to assess and implement into further analyses. All involved elements, structures and equipment should also be included.

2.1.6 Engineering and Design Analyses

"Carry out engineering and design analyses."(DNVGL, 2011)

The engineering and design analysis shall be carried out and verified for the specified sub-operations in accordance with section 2.1.5. The intent for this is to clarify that the sub-operations satisfies the operational criteria. In the earlier stages of the planning process, environmental and physical limitations have been established. This information must be used as input along with loads associated with the operation itself.

2.1.7 Operation Procedures

"Develop operation procedures."(DNVGL, 2011)

The operations procedures should include instructions on how the operations shall be performed. This should be done in accordance with the previously mentioned steps in the planning process. There may be several involved in the marine operation with different backgrounds who will follow the procedures. For this reason, it is of high importance that the procedures do not leave any room for misunderstandings. To ensure that the risk is understood and managed by everyone involved in the entire operation, it is crucial to connect the risks to procedures, which could be done with a safe job analysis (*SJA*). With use of *SJA* the hazards could be clearly understood and a recommendation for the safest way to do the job can be carried out (DNVGL, 2011).

Occasionally, disagreement arises between those developing the procedures, and the people carrying out the engineering and design analysis. Therefore, an iterative process is necessary in order to get to an agreement and find the most optimal procedures.

Chapter 3

Aquaculture Structures

The conceptual choice of a fish farm's design and shape is based on the desired amount of fish which is in accordance with the law. The density of fish allowed in one production unit can not exceed 25 kg/m^3 or an amount of 200 000. This is required in the "Aquaculture Operation Regulation" (Akvakulturdriftsforskriften) given by the Norwegian Government (Akvakulturdriftsforskriften, 2018). In addition to this, it is also a limit of producing more than 780 tons per licence, except Troms and Finnmark where the limit is 945 tons (The Directorate of Fisheries, 2016).

Another important design factor is the structure's capacity to withstand the environmental conditions associated at a site. The conditions vary with the degree of exposure. Sheltered sites are often located in inner parts of the fjords or protected by a collection of islands from harsh environmental conditions. At exposed sites, the duration of storms and the distance from the shore are both longer. This makes the environmental conditions rougher, which may lead to higher risks in relation to the operation of the aquaculture installation, with regards to employees, fish escapes and structural damage (Fredheim, 2017a).

3.1 Concepts

In the following sections are three different fish farm concepts presented; flexible systems, hinged connected bridges and rigid structures. They are categorized after structural properties in environmental conditions (Fredheim and Langan, 2009).

Flexible Systems

Circular collar fish farm is an example of a flexible system, shown in figure 3.1. It consists of welded high-density polyethylene (*HDPE*), in preferred lengths to form the diameter of the structure. To ensure sufficient buoyancy, one to three rings can be connected with clamps. Railings and walkways are attached to the structure to form an operation platform and make the farm easier and safer to be operated by the workers. *HDPE* generate high flexibility, and together with the mooring system, this fish farm concept can withstand a high degree of environmental conditions in semi-exposed locations. In these locations, access to water flow with sufficient oxygen level is achieved. In addition, an optimal distance between the cages generates good conditions for acceptable fish welfare (Fredheim and Langan, 2009).

In relation to working conditions, flexibility is related to large movements of the fish farm. According to this, the fish farm has a low freeboard, which makes the working conditions tough (Fredheim and Langan, 2009).

Figure 3.1: HDPE collar fish farm (NDLA, 2015)

Hinged Connected Bridges

The interconnected hinged fish farm consists of square cages made of bridged steel with flotation connected, shown in figure 3.2. The flotation is usually made of expanded polyester and attached underneath the steel bridges. The hinges do not allow rotation in the vertical direction, only rotation of one axis in the horizontal plane may occur. Due to low flexibility, currents and waves can cause undesired stresses, which over time may lead to fatigue. For this reason, sheltered areas are the only suitable locations for this cage solution. An advantage of this concept is the large areas for walkaways and operational equipment, which makes the operations associated with the fish farm safer and easier (Fredheim and Langan, 2009).

Figure 3.2: Hinged steel fish farm (AKVA group, 2018b)

Another similar concept is the Catamaran steel fish farm, see figure 3.3. It consists of steel hulls for flotation, which is connected together with hinges and bridges. The advantages and disadvantages of this concept are much the same as for the interconnected hinged fish farm. There is a significant difference in the flotation between these two concepts, the catamaran fish farm has only flotation around one axis. This is because the bridges that connect the hulls are not in contact with water, which provides better resistance to displacement forces in contrast to the interconnected steel fish farm (Fredheim and Langan, 2009).

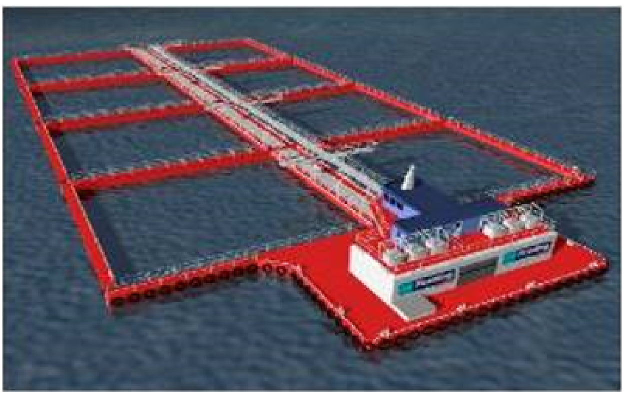


Figure 3.3: Catamaran fish farm (Fredheim, 2017a)

Rigid Steel Fish Farm

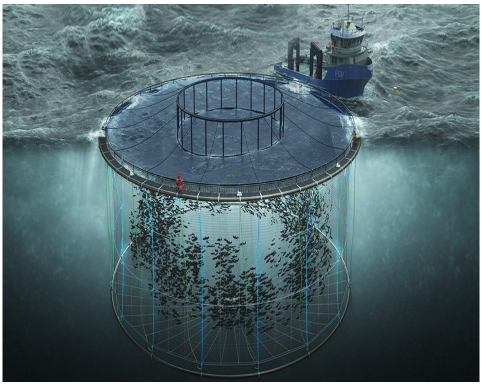
The rigid steel fish farms category consists of several different designs. Steel pipes welded together into square collars and fish farms made of truss work are the most common types, where the latter is shown in figure 3.4. In contrast to the circular collar fish farm, the rigid fish farms are more stable and the working platforms are larger. An important aspect is that wave loads that are induced to a rigid or less flexible structure, will have larger forces introduced than similar flexible structures. In relation to this reasoning, rigid steel fish farms are not suited for exposed sites (Fredheim and Langan, 2009).

Figure 3.4: Fish farm made of truss work (Fredheim, 2017a)

3.2 Components of the Fish Farm

In the Norwegian aquaculture industry, flexible circular collar is a commonly used concept. Hence, an elaboration of this concept with its associated components will be presented.

A production plant often ranges between 6 to 12 cages, depending on the intended biomass production, the size of the location and the dimensions of the cages. In accordance with NS 9415, which is a Norwegian standard for floating fish farms, the main components are stated to be the net cage, floating collar, feed barge and the mooring system. These components will be presented in the following sub-sections and seen in figure 3.5a and 3.5b (Standard Norway, 2009).



(a) Aqualine Midgard System

(b) AKVAgroup feed barge

Figure 3.5: (Left) Illustration of the main components within a fish farm (Aqualine, 2018a) and (Right) (AKVA group, 2018a)

Net Cage

The main purpose of the net is to keep the farmed fish from escaping and protect it from the surrounding environment. The net structure needs to resist environmental forces such as currents and waves, and forces induced by handling. Various factors need to be considered when the net design shall be established for a site. Among these factors are the volume of the cage, shape of the floating collar, bottom depth, possibilities to attach weight systems and the net design.

The net is both flexible and non-solid so that a continuous flow can pass through it and add and replace water, to achieve good water quality with a sufficient content of oxygen. Considering the flexibility of the net, deformations may occur when forces are applied. To reduce this effect a weight system is used. Hence, individual weights or a sinker tube with a weight range between 15-140 [kg/m] is placed at the lower parts of the net (Aqualine, 2018b).

There are different designs of net shapes, each with their own characteristics. According to Aqualine, a supplier of equipment to the industry, there are mainly six net shapes, cylindrical, square, cylindrical with individual weights, cone, spaghetti and combination net. Both cone and spaghetti shapes require great depths. To collect dead fish, all the designs have a cone shape at the bottom of the net (Aqualine, 2018c).

A net cage is designed with both ropes and netting with the intent of carrying and transferring forces through the ropes. The netting materials can either be produced of knitted bundles of nylon multifilaments, called knotless netting, or twines of twisted multifilament bundles connected by knots, called knotted netting. In the Norwegian aquaculture, the knotless square mesh nylon material is the most dominating (Moe, 2009).

Other elements to consider are the mesh strength, mesh length and the solidity. The definition of mesh length is described in NS 9415 as the distance between the centre of two opposite nodes in the same mesh when it is fully stretched out. To decide the required mesh length it is important that the fish is not able to escape nor get stuck in the mesh. During a production cycle, the fish will vary in size. Due to this, it is necessary to change the net to desired mesh lengths over time. Solidity is the relation between the projected area and the total area of the net panel and varies between 0 (no net) and 1 (completely closed). A range in solidity between 0.2-0.3 is commonly used, which is optimal regarding the intensity of the acting forces, escape security and water quality (Føre, 2017).

The lifetime of a net is normally considered three years, but it depends on the degree of exposure and usage. Over years, net shrink could result in reduced volume and wear. A good strategy for the replacement of net should therefore be implemented in the production plan (Føre, 2017).

Floating Collar

The floating collar has two main functions, to ensure system buoyancy and maintain the volume of the net along with the sinker tube. *HDPE* provides sufficient buoyancy and at the same time, it is flexible enough to let the construction adapt to the environmental effects. Other important functions for the floating collar is to be an attachment point for the net cage, an operational platform for workers and it should distribute forces to the mooring system (Fredheim and Langan, 2009).

Ropes are attached between the collar and the net, and the collar and the sinker tube. Winch systems could be installed to operate the lifting of the ropes when maintenance or other operations are needed. A crane installed on a service vessel could also be used for the same purpose (Aqualine, 2018c).

Feed Barge

Several functions are associated with the feed barge, among these are control rooms, recreation areas, feed storage, feed managing systems, equipment and spare parts storage, generators for the pump units, waste separators and storage tanks. In accordance with NS

9415, the barge should not be moored directly to the floating collar. However, if the barge is moored to the floating collar, this should be the weakest link (Standard Norway, 2009).

Another aspect is that the barge should be located in a way providing easy access to the feed boats. This means that the depth should be sufficient to prevent grounding during entry and exit.

Mooring System

Mooring systems are required with the purpose of keeping the fish farm in a desired three – dimensional position at all times, figure 3.6. The floating collar has low horizontal stiffness, thus a grid mooring system is required to reduce the risk of fish escapes and technical failures. It consists of ropes, chain, floaters, connection plates, shackles, rings and anchors or/and rock pins (Fredheim and Langan, 2009).

Bridles connect the floating collar and the mooring frame. This configuration makes the collar freely floating inside the frame. The upper part of the bridle is made of chains to avoid propellers from cutting it. To minimize the risk of wear between the mooring and the net cage, the rest of the bridle is made of synthetic fibre (Fredheim, 2017b). These materials are lighter than chains, but have lower strength in the transverse direction. To ensure easier access for the operation vessels, the mooring frame and the coupling plate are kept at a depth of 5-7 meters. The coupling plate connects the frame, bridles and mooring line, and a buoy is attached to ensure buoyancy (Fredheim and Langan, 2009).

The mooring line is a combination of chains and synthetic fibre rope, to achieve the most optimal solution with high abrasion and easy handling characteristics. According to NS 9415, it is required that a site survey is performed regarding the level of exposure and bathymetry (Standard Norway, 2009). If the survey finds that the bottom consists of rocks, pins are used as bottom attachment. If a clay and sand bottom is found, anchors are the preferred attachment tool (Fredheim, 2017b).

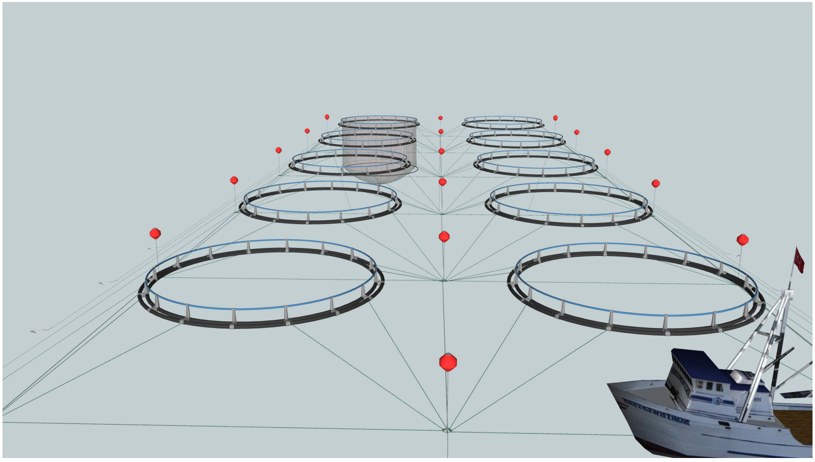


Figure 3.6: Mooring system for a typical fish farm (Akuakare, 2018)

3.3 State of the Art

In the recent years, there has been a high focus on how challenges related to the industry should be solved. This has encouraged companies to come up with new innovative solutions. In the following sections, some of these concepts will be elaborated.

Innovation Licenses

The aquaculture industry is regulated by licenses, where each license allows a site to produce the maximum allowed biomass (MAB), described in detail in section 4.1. Licences can be assigned by The Norwegian Directorate of Fisheries, described in the Aquaculture Act. These licenses have been limited by the directorate due to a high demand, to preserve the environment and the market. In order to obtain a licence, a developer could either buy a licence from an auction organized by the Directorate of Fisheries, or apply for an extraordinary license e.g. an innovation licence (The Directorate of Fisheries, 2017b).

From November 2015 to 2017 developers could apply for innovation licenses with concepts that had potential for solving one or more challenges concerning the environment and area limitations the industry is facing. The arrangement has contributed to significant investments to develop new technology. Developers can apply for several licenses for one concept and could be granted permission to produce more biomass than the MAB limitation (The Directorate of Fisheries, 2018c).

As long as the criterion for the concept is met by the end of the project period, the Directorate of Fisheries can offer the developer to convert the innovation license into a regular production license for a price of 10 MNOK (The Directorate of Fisheries, 2018c).

Three concepts which have been approved for building and operating are the following, Ocean farm 1, Havfarm and Egget. These are elaborated in the following sections (The Directorate of Fisheries, 2018b).

Ocean Farm 1

Ocean Farm 1 is the first built offshore cage and it is a full-scale pilot facility, figure 3.7. Its purpose is to produce fish in new areas with less influence from salmon lice. These areas are exposed to harsh weather conditions and have therefore not been used earlier. Ocean Farm 1 is designed by Ocean Farming AS, which is a subsidiary of the SalMar Group. In addition to this, Innovation Norway has contributed with grants through the development phase (SalMar, 2018).

The offshore fish farm is constructed to contain 6240 tons of fish with a volume of 250 000 cubic meter (The Directorate of Fisheries, 2018b). Its key dimensions are a height of 68 meters and a diameter of 110 m. The technical solution positioned in Frohavet is a slack moored semi-submersible production plant intended for water depths of 100 to 300 meters. Fish handling is performed internally in the plant without any needed vessels or equipment. In addition to this, the plant can be operated autonomously, involving fewer heavy marine operations (Ocean farming, 2018).

Ocean Farm 1 is equipped with three bulkheads that enable the possibility of dividing the plant into three sections which make the fish handling less complicated. It is planned to operate with three to four workers on a daily basis to ensure thoroughly monitoring and management of the operations (Ocean farming, 2018).

Figure 3.7: Ocean Farm 1 (Haugaland Vekst, 2017)

The Egg

Hauge Aqua has signed a contract with Marine Harvest for developing a fully enclosed fish cage solution named The Egg, which is allowed to produce more than MAB. The Egg will have a total volume of 22000 cubic meters and can contain 3120 tons of fish, figure 3.8 (The Directorate of Fisheries, 2018b).

The water inlet is located at the bottom of the structure where seawater from below 20 meters is sucked in by the use of two pumps. The purpose of this solution is related to salmon lice and less environmental variations for improved growth. Lice larvae's natural habitat is primarily in the upper water layers. Hence, water pumped from deeper layers will have a lower probability of containing lice. The Egg can consequently be placed where the density of salmon lice is high without being affected. Hauge Aqua claims that the water inlet and outlet are double secured so that fish escape is not possible (Hauge Aqua, 2018).

The water quality is continuously monitored to ensure a steady oxygen and carbon dioxide level, in accordance with good fish welfare. Feed is supplied automatically at various levels within the structure, and both waste and feed will be controlled and handled without affecting the surrounding environment. Harvesting, catching and emptying the tank for fish is performed with use of an expandable fish grid, which harvests only fish bigger than a predetermined size (Hauge Aqua, 2018).

Regarding marine operations, most of the operations are performed autonomously, which provides fewer heavy operations with humans involved. On daily basis, personnel may arrive by vessels through a docking area, where they can enter the inside of the unit. The inside is sheltered from harsh weather conditions and can thus handle higher operational limits (Hauge Aqua, 2018).

From a hydrodynamic perspective, there are significant differences in the design between the enclosed and open cage. According to Newton's second law, a structure with high mass will induce large forces. As the Egg is a closed structure, the internal water must be incorporated in the total mass of the structure. Hence, the total mass of a closed structure becomes larger compared to an open structure. Another element is the effect of external waves that can generate waves inside the structure, called sloshing. A consequence of sloshing and larger forces may be that the operations and the fish welfare are affected in a negative manner. The optimal location for this design is therefore in fjords or other sheltered areas with limited harsh weather conditions (Lader, 2018).

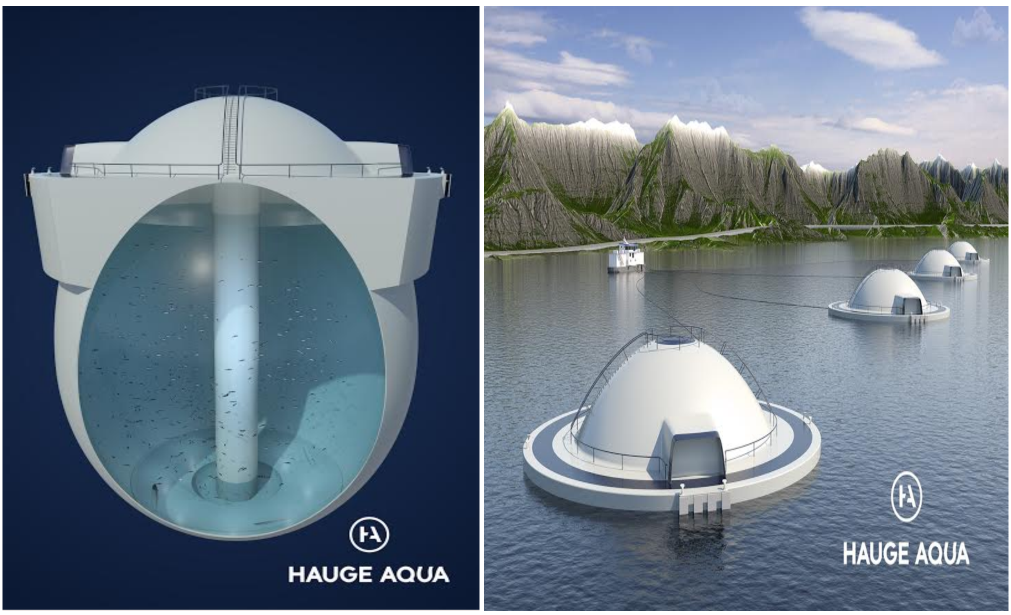


Figure 3.8: The Egg (Berge, 2016)

The Dynamic and Stationary Havfarm

Nordlaks is a Norwegian company that has been granted permission to start fish production in two units, the dynamic Havfarm and the stationary Havfarm, figure 3.9. The total biomass permission given by The Norwegian Directorate of Fisheries is
16 380 tons and the designs are developed in cooperation with NSK Ship Design (The Directorate of Fisheries, 2018b).

The dynamic and stationary Havfarm are designed with a length of 430 meters and a width of 54 meters, consisting of six framed cages with a depth of 60 meters and a surface area of 2500 square meters. The structures shall resist a significant wave height of ten meters and during harsh weather, they can be deballasted, and raised by four meters. To avoid salmon lice, the structures will be equipped with a ten meters lice skirt made of steel (NSK, 2018).

Stationary Havfarm shall have a permanent mooring solution in the bow section. At locations where mooring is impossible to use, e.g. extreme depth, geotechnical or topographical conditions, Dynamic Havfarm is suited. It is designed with dynamic positioning and propulsion systems, but simple mooring systems could be used if needed (Nordlaks, 2018).

When considering the environmental footprints, the Dynamic Havfarm shall be able to spread waste over larger areas. Both design concepts promote wider use of the Norwegian coast and surrounding sea (Nordlaks, 2018).

Figure 3.9: Havfarm (Ilaks, 2017)

Chapter 4

The Norwegian Regime

The Norwegian aquaculture industry must relate to a set of rules and regulations. They can be divided into disciplines, which are controlled by different authorities. The disciplines are presented in figure 4.1 and will be further elaborated (Holmen, 2018).

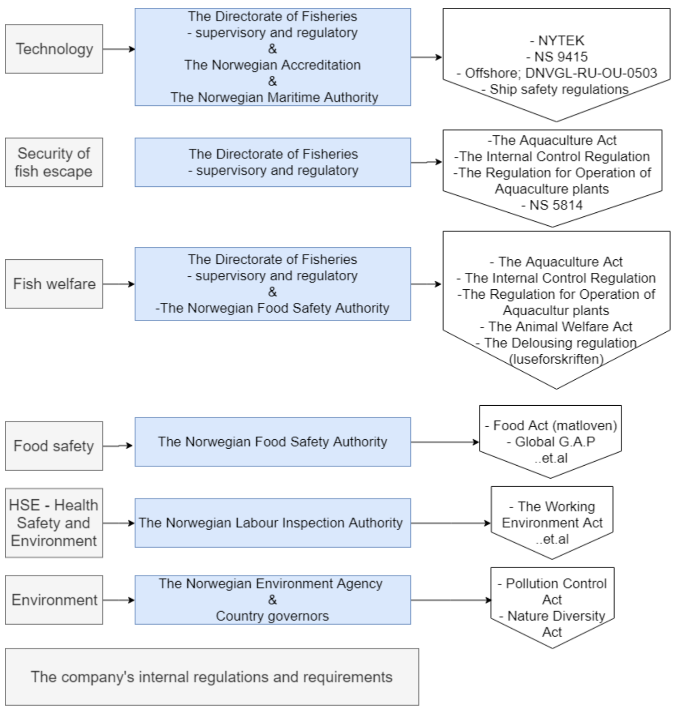


Figure 4.1: Disciplines, associated authorities and regulations and rules

4.1 Authorities

To be allowed to operate an aquaculture facility on the Norwegian continental shelf, enterprises must relate to the regulations set by the authorities. In the following sections, these will be presented.

The Directorate of Fisheries

The Ministry of Trade, Industry and Fisheries is responsible for the aquaculture industry, trade and seafood policy. This includes further development of regulations and requirements, which the industry must relate to. The Directorate of Fisheries is the executive body and aim to promote a profitable and sustainable use of the marine resources in the marine environment. Their authority could be divided into supervisory and regulatory (Regjeringen, 2018).

Supervisory authority means that the Directorate controls that the individual enterprises follow the regulations and requirements defined by the ministry (The Directorate of Fisheries, 2015). This includes the NYTEK-regulation, biomass, monitoring of environmental impact, fish escapes, land-based production sites, approval of production plan in accordance with the aquaculture production regulation (Akvakulturdriftsforskriften) paragraph 40 and sanctioning in the case of regulatory violations (The Directorate of Fisheries, 2018a).

The regulatory authority is responsible for the distribution of licenses, which is required to allow aquaculture production in Norway. In addition to this, the Directorate is enforcing the limit of produced biomass per licence. The limit is 780 tons per licence, except Troms and Finnmark where the limit is 945 tons (The Directorate of Fisheries, 2016). Companies could until 2017 apply for innovation licences. These aimed to encourage development of new technology that could solve one or more challenges associated with the industry. The Directorate has the authority to approve such innovation licences (The Directorate of Fisheries, 2017b).

In operations where wellboats are involved the Directorate of Fisheries is focusing on preventing, handling and limiting the risk for fish escapes (The Directorate of Fisheries, 2017a).

The Norwegian Maritime Authority

The Norwegian Maritime Authority is the administrative and supervisory authority related to the safety of life, health, environment and material values on vessels with Norwegian flag and foreign vessels in Norwegian waters. Their authority associated with the aquaculture industry involves supervision of the vessels that is used, issuing certificates and following up regulations. These regulations are mainly related to technical design and issuance of certificates (The Norwegian Maritime Authority, 2018).

The Norwegian Food Safety Authority

The Norwegian Food Safety Authority is responsible for ensuring good fish health within the aquaculture industry. They ensure vaccination of the fish, good treatment of cleaner fish, fish feed with high nutrition values, alive fish transportation, slaughtering, low amounts of sea lice and disease cases. The requirements for maximum allowed salmon lice is set to 0.5 sexually mature female lice on average per fish producing unit (The Norwegian Food Safety Authority, 2018). The fish farmers are required to send in documentation of the level of salmon lice on their facilities and react if the legal amount is exceeded. If the amount of salmon lice is noted as unacceptable even though delousing methods have been adapted, the Food Safety Authority is obligated to require slaughtering. The same is required if undesirable diseases are detected (The Norwegian Food Safety Authority, 2013).

The Norwegian Labour Inspection Authority

The Norwegian Labour Inspection Authority focus on occupational health and safety by administrative, supervisory and informational work. Regulations and laws are the foundation, which the authority implement in their work. The work associated with the aquaculture industry is both land and sea related and this can result in conflicts on which regulations regarding human safety to use. For this reason, the Supreme Court has decided that the aquaculture industry shall use The Working Environment Act for any human safety consideration. Activities using vessels are also included in this act (Arbeidstilsynet, Fellesforbundet og Fiskeri- og havbruksnæringens landsforening , 2011). The Labour Inspection Authority requires a risk clarification and evaluation of potential hazards and accidents (The Norwegian Labour Inspection Authority, 2018).

The Norwegian Environment Agency

The Norwegian Environment Agency and the various Country Governors perform supervision of the marine environment in relation to the Environmental Acts. The acts, which apply for the aquaculture industry, are mainly the Nature Diversity Act and Pollution Control Act (The Norwegian Environment Agency, 2018a). ISO 14001 "Environmental management", is a standard that also could be applied. If the Environment Agency reveals deviations from the mentioned acts, the enterprises will be imposed deadlines for rectifying the matter. Fines or police reports could be the consequences if the regulations do not comply (The Norwegian Environment Agency, 2018b).

The Norwegian Accreditation

The Norwegian Accreditation is designated by the Ministry of Trade, Industry and Fisheries to conduct technical accreditation to private companies. Accreditation is defined by The Norwegian Accreditation as "…a means of assessing, in the public interest, the technical competence and integrity of conformity assessment bodies" (The Norwegian Accreditation, 2014).

Accredited private companies can perform technical inspection and certification. Certification shall be performed to ensure that all equipment involved in the fish production is in accordance with NYTEK and NS 9415. Technical inspections shall include a site classification where wind, waves and current levels are determined on the certain site. In addition to this, a mooring analysis shall be performed. The Accredited Inspection Company issues an aquaculture facility certificate if the technical inspection is approved (Fredheim, 2017c).

4.2 Regulations and Rules

There are several regulations, standards and laws that the Aquaculture industry must relate to. To achieve an understanding for this system the governing rules and regulations will be presented in this section.

The Aquaculture Act

The Aquaculture Act is issued by the Ministry of Trade, Industry and Fisheries and applies for production of all aquatic organisms. The purpose of this act is to ensure profitability and competitiveness while maintaining a sustainable development and wealth creation for the nation (Akvakulturloven, 2015).

The Act states that the Ministry grant permission to operate aquaculture production facilities of certain species at certain locations. All aquaculture facilities shall be registered. Another important aspect of the Aquaculture Act is the interaction between the aquaculture and the environment, which should be investigated properly during the entire production period (Akvakulturloven, 2015).

The Ministry of Trade, Industry and Fisheries can impose the enterprises operating aquaculture production to catch the escaped individuals (Akvakulturloven, 2015).

To ensure that the Aquaculture Act is followed as intended, the Internal Control Regulation has been created. This regulation aims to fulfil the Aquaculture Act by stating actions that companies shall conduct (IK-Akvakultur, 2004).

The Regulation for Operation of Aquaculture Plants (Akvakulturdriftsforskriften)

The Regulation for Operation of Aquaculture Plants concerns how fish welfare shall be taken care of in production to ensure profitability and competitiveness within the aquaculture industry. Fish welfare in relation to operations, slaughtering and transport are elaborated in the regulation. In addition, the regulation describes several measures to minimize mortality, infections, fish escapes and insufficient treatment (Akvakulturdriftsforskriften, 2018).

One important aspect in relation to fish welfare is the fish density within a cage, this shall not exceed 25 kg/m^3 or 200 000 fish. Counting and other measurements for controlling the biomass can be carried out while the Directorate of Fisheries is present. If fish escape occurs during the production cycle, it must be reported and the cause shall be investigated (Akvakulturdriftsforskriften, 2018).

To achieve good fish welfare, oxygen saturation, temperature and other water parameters essential for fish welfare must be measured systematically and adapted to the natural environment of the fish (Akvakulturdriftsforskriften, 2018).

A minimum requirement is to fallow a location for two months, which shall be repeated for every production cycle. If an environmental analysis considers it necessary, the fallow period may be extended by the Directorate of Fisheries. Environmental monitoring of the site shall be carried out regularly (Akvakulturdriftsforskriften, 2018).

NYTEK

NYTEK is issued by the Ministry of Trade, Industry and Fisheries and is valid within the Norwegian territory, the continental shelf and the Norwegian economic zone. This regulation was made with the intent to prevent fish escapes from floating aquaculture production plants. NYTEK sets requirements for all involved in the industry, which means manufacturers, suppliers and farmers (NYTEK, 2015).

As mentioned in section 4.1, private companies are accredited by the Norwegian Accreditation to conduct inspection and product certification according to the requirements specified in NS 9415 (NYTEK, 2015).

Before an aquaculture facility can be put into operation a locality survey must be carried out by an accredited inspection company. The outcome of the survey must be documented in a rapport satisfying the certain requirements in NS 9415. A mooring analysis shall be conducted after a locality survey and summarized in a report (NYTEK, 2015).

The accredited product certification company has the responsibility to control that the net cage, floating collar, feed barge and structural parts for mooring are product certified in accordance with NS 9415. When the product certification is accepted, a certificate shall be issued to the supplier (NYTEK, 2015).

To operate a fish farm, a certificate is needed which is issued by an accredited inspection body described in NYTEK. It states that the certificate is valid in five years from the date of issue and shall document that the main components withstand the environmental loads associated with a certain site (NYTEK, 2015).

Another aspect outlined in NYTEK is requirements for mounting, usage and maintenance of the involved equipment to ensure proper technical condition. In any case where infringement of NYTEK is revealed, reactions will be executed depending on the severity (NYTEK, 2015).

NS 9415

The technical standard NS 9415 specifies the requirements stated in NYTEK in relation to site survey, risk analysis, design, dimensioning, production, installation and operation. NS 9415 aims to reduce fish escapes due to technical failure and misuse of floating fish farms. The standard does not include requirements or operational tasks, which is not relevant for fish escapes. To ensure safe interaction between components within the fish farm, installation and operation manuals are required in the standard (Standard Norway, 2009).

NS 9415 describes how a site survey should be conducted, and defines a classification of local environmental conditions such as current, wind speeds, influence from ice, wave heights and periods. In addition to this, water depth, bottom condition and topography shall be included in the locality report. The parameters stated in the report will be used as a basis to calculate the environmental loads that act on the production units. These loads will be considered when dimensioning the main structural parts; net cage, floating collar, feed barge, mooring (Standard Norway, 2009).

As stated in NS 9415, a risk assessment in accordance with NS 5814 or equivalent shall be carried out to minimize the risk of fish escapes (Standard Norway, 2009).

NS 5814

As NS 9415 outline, the risk assessment shall be carried out in accordance with NS 5814. With use of NS 5814, risk in relation to planning, execution, delivery, mounting and operation will be identified (Standard Norway, 2009).

DNVGL-RU-OU-0503; Rules for Classification

DNV GL aims to safeguard life, property and the environment and has been involved in the aquaculture industry by classification of offshore fish farming units, such as Ocean farm 1 (DNVGL, 2018). The rules applied for these cases are described in DNVGL-RU-OU-0503 and its objective is to present technical and procedural requirements which are needed to obtain and retain a class certificate (DNVGL, 2017c).

The Working Environment Act (Arbeidsmiljøloven)

As mentioned, the Supreme Court has decided that the aquaculture industry shall use The Working Environment Act for any human safety considerations. This also includes activities where vessels are operated (Arbeidstilsynet, Fellesforbundet og Fiskeri- og havbruksnæringens landsforening , 2011). Safety shall be related to physical and mental harmful effects, in addition to work environment and equality (Arbeidsmiljøloven, 2005).

Internal Regulations

In addition to the regulations given by the authorities, the enterprises usually define their own rules and requirements. This could help them stay within limits given by the authorities. As an example, an enterprise could set an internal limit of the amount of salmon lice within a cage. Thus, the enterprises can be sure they are below the limits set by the authorities at all times.

4.3 Requirements in relation to Marine Operations

Planning and execution of a marine operation are partially covered in the current aquaculture regulations and laws. Two important aspects that should have been assessed are the duration and which operational limits that is acceptable for the certain operation and its location. After reviewing the current regulations and laws, risk management was the only concept mentioned which is important when planning a marine operation.

In the Internal Control Regulation (IK-Akvakultur), it is stated that hazards should be identified to assess the risk related. Based on this, plans and measures should be conducted to reduce risks. It is important to highlight that the regulation in general cover everyday activities and does not identify which standards to apply. Marine operations are defined as "...non-routine operations of a limited duration related to handling of object(s) and/or vessel(s) in the marine environment" (Larsen, 2018a). Hence, it is not sufficient to use the Internal Control Regulation (IK-Akvakultur) in marine operation situations. Due to the rarity of marine operations, it is more likely that the employees are not familiar with the routines and the risk involved. This, in combination with the fact that marine operations tend to be longer in duration and more complex, increases the need for managing and understanding risks (IK-Akvakultur, 2004).

The technical standard NS 9415 is also considering risk management and refers to NS 5814 for instructions on how it should be conducted. NS 9415 is only considering the risk for fish escapes. Hence, when it refers to risk management in NS 5814, it is related to minimizing the risk of fish escapes in any operation (Standard Norway, 2009).

Although NS 5814 is not referred to frequently by the aquaculture regulations, the standard provides procedures for how to manage risk. The risk analysis methods considered are not described in detail, but referred to as examples of methods one can choose from, such as FTA, ETA, FMEA and HAZOP (Standard Norway, 2008).

Chapter 5

Aquaculture Operations

Marine operations in the aquaculture industry can be divided into non-fish involved operations and fish involved operations. The latter must take fish welfare into account and be conducted in a way that prevents fish escapes. Examples of such operations are delousing, fish transport, sorting, cleaning and maintenance. Some of these operations include crowding and pumping of fish, which may lead to undesired stress and weakening of the fish health (Lader, 2018).

Delousing can be carried out in several different ways, both by using mechanical treatment such as brushes, fresh water, hot water and chemical treatment with hydrogen peroxide. Chemical treatment with use of tarpaulin is a demanding operation that requires a high number of workers, assisting vessels and crane use (Lader, 2018).

Fish transport includes transport of smolt to the production sites, moving fish within the site and delivery of fish to the slaughterers. Maintenance and cleaning of the cages are essential to prevent a high concentration of biofouling. This phenomena impair the water quality within the cage and increases the mass of the construction. By Newton's second law it can be shown that the increase in mass leads to higher forces acting on the cage. In addition, increased biofouling implicates higher solidity which results in an increased drag force. For the cleaning and maintenance operations, cranes, robot washers and workboats are usually used. ROV and divers are used to control the condition of the net cage after the cleaning operation (Lader, 2018).

Weighing of a representative sample of the fish to check that the biomass inside the plant does not exceed the maximum permitted biomass, is done with regular intervals. A similar operation is lice counting (Lader, 2018).

Operations that do not involve fish can for instance be feed delivery, installation and re-configurations. Feed delivering ships arrive at the fish production site and holds its position by DP-systems during the delivery. This reduces the relative motions between the feed barge and the ship while the feed is pumped into silos through pipes. When a production facility is established or decommissioned, towing of the feed barge and floating collars are performed (Lader, 2018).

5.1 Wellboat Operation

The wellboat operation, elaborated in this section, deals with harvestable fish which is pumped into wells on a wellboat. Since a marine operation is designed to bring an object from one safe condition to another safe condition, the operation will be defined from the phase where the cage is prepared for the arrival of the wellboat until the wellboat leaves the facility. To prevent unhygienic conditions in the wellboat, and to simplify the slaughter process, the feeding of the fish is stopped a few days prior to the operation (Sjømat Norge, 2013).

After correspondence with the operation manager Torgeir Strand Fjelnset at the SalMar facility, Storskjæret (appendix A.1), procedures for the wellboat operations are defined in table 5.1 and 5.2. Note that the procedures for a wellboat operation may diverge between different enterprises and locations. The procedures described here are based on one source, and may not give a representative picture of how the operation is performed. The wellboat operation is a relatively extensive operation, which involves a minimum of two workers from the facility, but three to four are more preferable. The crew on the wellboat consists of two workers on the deck along with the captain and machinist.

The capacity of wellboats vary, but they rarely have a capacity that can handle more than 500 tons of fish. If it is estimated that the cage contains around 650 tons when the fish is considered harvestable, it means that the emptying operation will be conducted in two sequences (appendix A.1).

In modern vessels, dynamic positioning (DP) is commonly used to control the movements of the ship to hold its position. As Fjelnset states, it is not used in a wide range in the aquaculture industry, but the use of technology is under development (appendix A.1). Thrusters and propellers should be used with care to avoid conflicts with the net cage and mooring, which may lead to fish escapes.

Table 5.1: Wellboat procedures, when harvestable fish is pumped into the wells (I)

Step	Description	Estimated duration
1	Prepare the cage before the wellboat arrives. This include removal of cleaner fish and its hideouts, feeding machine and pipes, camera and other types of equipment placed in the cage. This is performed by the workers at the fish farm location and workboats. If the draft of the wellboat is deeper than the frame mooring (5-7 m), the buoys must be removed to lower the mooring.	3-4 hours
2	Crowding: Raising the bottom weight and net to crowd the fish from underneath the cage. This should be done gradually to ensure that the forces are evenly distributed. Once the bottom weight is lifted, a ball chain (Norwegian: kulerekke) is entered at the outside/underneath the net to crowd the fish near the surface. Performed by using a crane installed on the working boat. This operation starts when it is confirmed that the wellboat is on its way.	2-3 hours
3	Arrival of the wellboat: Prior to its arrival the wellboat needs to clarify which cage it shall operate, the facility configuration with respect to mooring systems and the topography to avoid collisions.	less than 15 min
4	Rigging the wellboat mooring configuration: The wellboat will be moored directly to the floating collar and the two nearby buoys see figur 5.1. In each case the weather data should be taken into account, to consider if it is necessary to use extra mooring. This could be carried out in three different ways, dependent on the level and direction of the waves, wind and current: 1. Use extra mooring between the wellboat and the cage. 2. In the case where the wellboat is drifting away from the cage, extra mooring could be mounted from the wellboat bow and stern to the neighbour cages.	30 min

Table 5.2: Wellboat procedures, when harvestable fish is pumped into the wells (II)

Step	Description	Estimated duration
4	3. If the boat is drifting towards the cage, mooring between the wellboat bow and stern, and the shackles connected to the two nearby buoys are mounted. All of the mooring equipment is installed at the wellboat, but the mounting is done by use of workboats from the facility.	30 min
5	Start of the pumping operation: The pumping pipes are placed in the cage with use of the crane installed on the wellboat. By the time the fish density reaches the maximum capacity of the wells, the pumping is stopped.	2-3 hours
6	Dismantling and removal of mooring: The pumping pipes and mooring are removed from the cage(s). The complexity of this is related to the need for configuration 1,2 or 3, see 4).	30 - 40 min
7	The wellboat leaves the locality	less than 15min
8	Lowering the bottom weight: Situation dependent operation. If the net cage is empty of fish, the net is removed before the bottom weight is lowered to a storage position 3 meters below the floating collar. If the wellboat must return once more to empty the cage, the bottom weight stays in its position until the wellboat returns.	2 - 4 hours

Figure 5.1: Mooring configuration of a wellboat directly moored to the floating collar, (appendix B.2)

The following sections will consider how the planning process for marine operations related to the oil and gas sector can be used in the aquaculture industry. It should be mentioned that this does not describe how the process is implemented today, but may be a suggestion of how it could be used.

5.1.1 Identify Rules

The rules that the aquaculture industry must relate to was described in section 4.2. In addition to these, regulations regarding ship safety, safety management and design are also applicable, but in this thesis the focus will be on the regulations specifically related to aquaculture operations.

In a document issued by the Marine Directorate of Fisheries, titled "Hvordan vurdere risiko for rømming knyttet til brønnbåtoperasjoner", the following requirements are emphasized to reduce the risk of fish escapes during operations including wellboats (The Directorate of Fisheries, 2017a):

- The Aquaculture Act §12 requires that suppliers of service and equipment for the aquaculture industry perform their tasks and services in an environmentally proper manner. In addition, installations and equipment shall be properly designed, have proper structural characteristics and be used with care (Akvakulturloven, 2015).
- The Aquaculture Act §22 requires that anyone participating in activities covered by the Aquaculture Act shall have the necessary professional competence for such activity (Akvakulturloven, 2015).
- Internal Control Regulation (IK-Akvakultur) requires that service providers covered by the Aquaculture Act shall have a functioning internal control to ensure compliance with aquaculture legislation (IK-Akvakultur, 2004).
- NYTEK § 23 requires that in case of deviation of products or services that may lead to fish escapes, the supplier is obliged to notify the Directorate of Fisheries and recipients of the product or service (NYTEK, 2015).

5.1.2 Identify Physical Limitations

A survey of the local conditions must be carried out. In a wellboat operation, it is important to consider the conditions that are expected around the cages. Local conditions mean flow direction and strength, as well as bottom conditions and topography. In addition, lighting conditions must be determined and, if necessary, compensated for by external light.

Some of the sub-operations include handling of live fish. To maintain good fish welfare and avoid fatalities, care must be taken. Strong individuals can endure a higher number of operations before they are significantly impaired, while for weak individuals the same handling can be fatal. Hence, the effect of crowding and handling must be taken into account during the planning process.

5.1.3 Overall Planning

The fundamentals of the operation must be determined, such as the size of the cage to be emptied, with associated conditions such as the number of tons of fish. This will contribute in defining the capacity of the wellboat, and if the emptying of the cage must take place in several operations. In addition, the length/width ratio of the vessel must correspond to the available mooring configuration at the site.

Selection of anchoring method depends on the local weather conditions as mentioned in table 5.1, step 4 "Rigging of the wellboat mooring configuration". Also, the draft of the wellboat must be taken into consideration. If it is deeper than the frame mooring (5-7 m), the buoys must be removed, so that the mooring could be lowered. This requires sufficient crane capacity on the workboat.

The choice of wellboat has a major impact on the costs, which makes it important to optimize the vessel with regards to the specified needs. In addition, the required labour and number of assisting workboats need to be determined. It is common that the aquaculture enterprises rent wellboats on a long term basis. This gives more flexibility when deciding which wellboat that is most suited for the overall needs.

Risk assessment shall be carried out according to the HEAR-principle, table 5.3, to ensure that all aspects are taken into account. Adapting the principle to the aquaculture industry means more focus on fish welfare and set the risk for fish escapes to ALARP.

Table 5.3: HEAR-principle in relation to the aquaculture industry

H	- Humans involved in the operation, this includes both the crew on the wellboat and the crew at the aquaculture facility.
E	- In this context environment is considered to include fish escapes as a pollution to the natural ecosystem.
A	- Assets includes the fish, cages with its associated equipment, work-boat and wellboat.
R	- The reputation for the aquaculture enterprises would be affected in the case of accidents where humans have been injured or fish have escaped or been mistreated. Such incidents may lead to reduced willingness from the community to realize new projects and operations.

In order to manage and understand the risks involved, related hazards will be assessed for the wellboat operation in the following. As these are identified, associated mitigation measures are established. In a real-life situation, these measures should finally be implemented in the operation. Firstly, the hazards and associated mitigation measures for the overall operation are established, before each step is further elaborated.

- The overall operation:
    - H : Fall overboard or crush and cut injury, due to snap loads, crane or capstan use, or ropes in tension are possible hazards. Drowning can occur and in worst case lead to fatalities.
    - E : Fish escapes may lead to interbreeding between farmed and wild fish. Diseases can be transmitted and the natural ecosystem can be affected.
    - A : Construction damage, this is a hazard itself and can also lead to fish escapes. In addition, fish may be harmed with morality as an outcome. Reparation and purchase of new equipment can lead to undesirable costs.
    - R : Fish escapes, injuries or accidental death(s) on humans or the fish may occur. This can harm the reputation of the enterprise owning the facility and the whole industry. A bad reputation is often related to difficulties in landing new contracts, unpopularity among the local community and undesired attention by the media.

- Mitigation measures:
  - Sufficient on the job training for new workers. This training must be conducted by experienced workers.
  - Crane certificate is required for the one operating the crane and a boating license is required for operating the workboat.
  - Safety zones on deck when the crane and capstan is in use.
  - Mandatory with wearing a helmet, safety shoes and life vest.
  - Training by use of simulation.
  - Easy access to lifebuoys and emergency stop for the capstan.
  - Safe Job Analysis (*SJA*) as a practice before operation start, to make sure that everyone involved is familiar with the associated risks.
  - Operational limits (wind, wave and current) must be established before the operation takes place. To make sure that the operation is performed within these limits, sensors could be placed at strategic locations.
  - Safety factors should be applied to the involved constructions and equipment in the design phase.

1. The preparation phase
   - H : Transfer of crew between cage and workboat can lead to fall overboard and in worst case drowning. Serious injury or death may be the consequence of workers getting hit by falling objects.
   - E :Fish escapes may be the consequence of collision between the workboat and the cage. Thrusters that are used near the net or mooring structure may also lead to fish escapes due to construction damage.
   - A : Same as mentioned above. The aquaculture structure or the workboat may also get hit by lifted objects which can lead to damage.
   - R : Same as mentioned in reputation under the overall operation.
   - Mitigation measures:
     - Care must be taken when transferring workers between cage and workboat. This applies to the transferring worker and the operator of the boat. The risk due to transferring must be familiarized for everyone involved.

2. The crowding phase

    - H : Lifting chains and ropes connected to the bottom weight could be a potential hazard for workers located underneath the crane. The operation takes place at a small area, if a failure occurs to the crane during the operation, workers could get hit by objects falling from the crane. This may lead to injuries and/or fatalities.
    - E : Lack of knowledge when raising the bottom weight may lead to uneven distribution of loads on the cage. This in turn, can damage the construction which may lead to fish escapes.
    - A : Same as mentioned above in E).
    - R : Same as mentioned in reputation under the overall operation.
    - Mitigation measures :
        - Automatize the operation related to the use of crane, to minimize the risk exposure on the workers. Could be conducted by a remote controlled winch system stationed on the cage.

3. Arrival of the wellboat

    - H : The wellboat may collide with the surroundings at the facility, this can happen due to loss of power delivered to the propulsion system, loss of GPS signals, or in the case of reduced visibility due to fog, darkness or heavy rain. The wellboat may also collide with the workboat. These incidents can be a great risk for the crew involved, which may suffer from injuries, or in worst case drowning.
    - E : Fish escapes can happen if the wellboat or workboat collide/drift into the fish farm facility. Oil and fuel leak can occur if the wellboat grounds. This may harm the surrounded ecosystem and the farmed fish.
    - A : Same as mentioned above in E) - the wellboat, workboat, the farmed fish and the constructions at site may be subjected to serious damage and loss, in the case of collision or grounding.
    - R : Harmed reputation for the wellboat enterprise if they are responsible for the event of collision or grounding. Leaked oil and fuel may lead to a low willingness for starting new projects within the industry.

- Mitigation measures:
  - Redundancy in systems delivering power to the propulsion system, and backup solution for the GPS, i.e. printed maps.
  - Make sure the wellboat is equipped with powerful floodlights.
  - Wellboat crew familiarization of the production facility configurations prior to the arrival.

4. Rigging the wellboat configuration

- H : The wellboat can be improperly moored, which may cause large forces acting on the cage. Improper mooring can be a result of lack of experience of the crew members, or a miscalculation of the predicted weather. The workers standing on the floating collar may not be used to such high forces and large movement on the cage. Hence, workers may fall into the water and drown or get injured.
- E : As a result of the above mentioned hazard, the cage can get damaged, leading to fish escapes.
- A : Same as mentioned above in E). In addition to this, the hull of the wellboat could get seriously damaged.
- R: Same as mentioned in reputation under the overall operation.
- Mitigation measures:
  - The cage should be designed to withstand forces from the wellboat.
  - Knowledge and understanding of the distribution of forces. This is crucial because it is important to know how the forces from the wellboat act on the cage through the mooring. On the job training should therefore be required.

5. Start of the pumping operation

- H : Human injuries due to crane operation.
- E : Fish escape due to pipe failure during pumping.

- A : Damage on assets due to crane failure or pipe failure. In addition to this, the fish can get injured if the pipe contains sharp edges. If the density of fish inside the well is exceeded due to failure on the counting mechanism, there is a greater risk of fish mortality due to an increased stress level. Malfunction of the pumping system could make it impossible to pump the fish. This could lead to unnecessary stress of the fish, and the crowding period may be exceeded.
- R : The reputation of the wellboat enterprise may be harmed in the case of human injuries, or high fish mortality.
- Mitigation measures
  - Periodically maintenance of the pumping equipment.
  - Periodically inspection of the internal of the pipes.
  - Conduct a test of the pumping equipment before leaving the port.

6. Dismantling and removal of mooring : This step is similar to step four, but reversed. This means that the hazards and mitigation measure are almost the same. The exception is the sequence the mooring is dismantled and removed. This is important to get a desired force distribution.
7. Wellboat leaves the locality : This step is similar to step three, including the hazards and mitigation measures.
8. Lowering the bottom weight : This step is similar to step two, including the hazards and mitigation measures.

Figure 5.2 presents the main hazards which are relevant for the wellboat operation, along with a ranking of their associated consequence. The ranking is done in relation to each other. This means that even though "damage on wellboat" is a serious hazard which could have a major impact on the enterprise, it is not as serious as "fatality of humans". To get a complete risk matrix, each hazard should be evaluated in terms of both probability and consequence. The result of this may be that some of the hazards evaluated to "moderate" or "significant" could be "severe" if they have a high probability of occurring. For the hazards that are scored "severe" or "significant" in the matrix accounting for probability, the risk is required to be set to ALARP.

Consequence / Hazard	Minor	Moderate	Significant	Severe
1 - Fatality of humans				
2 - Serious injuries of humans				
3 - Escape of fish				
4 - Oil and fuel leakage				
5 - Fish mortality				
6 - Damage on well boat				
7 - Damage on cage and mooring system				
8 - Minor injuries of humans				
9 - Fish injuries				
10 - Damage on equipment				

Figure 5.2: Consequence/Hazard ranking

5.1.4 Design Basis and Briefs

Environmental conditions such as influence from wind, current, wave height and period must be established for the current site. These conditions must be taken into account when the operational limits are set. In addition, the planned operation period and contingency time should be determined to establish the operation reference period. Planned operation time in combination with the design operational limit forms the basis when choosing the alpha factor. This factor includes the uncertainties in the weather forecast for both wind strength and significant wave heights. With use of alpha factors the operation criteria could be established, which reflects the maximum weather condition allowing the operation to be performed. Based on the predicted operation time, a required weather window could be defined (Larsen, 2018a).

The different sub-operations are categorized as either weather restricted or unrestricted. For a typical wellboat operation, all the sub-operations are weather restricted. Humans, fish and equipment are highly exposed to the external conditions, which complicates the work.

An overall document summarizing the planning process's findings and regulations should be established. The relevant sub-operations categorized as weather restricted will be linked to the rules that must be followed and which acceptable criteria that should be set. A sufficient operation criterion must ensure that the operation takes place within acceptable limits, where hazards have a low probability to occur.

5.1.5 Engineering and Design Analysis

Estimation of the effects from wind, wave and current must be used to decide the structural resistance. In this way, the design of the wellboat and equipment is adapted to the required strength to ensure that the operation is performed within safe conditions at all time.

5.1.6 Operation Procedures

Based on the previously established steps in the planning process the operation procedures could be specified according to duration, required weather window, operation criteria and associated risk. Wellboat operations must be designed in a way that makes it possible to halt the operation and bring the fish back to a safe condition. For parts of the operation where this is not possible, a point of no return (*PNR*) shall be defined. Theoretically, there are no steps in the wellboat operation table 5.1 and 5.2, which can be categorized as *PNR*. However, it is highly undesired to stop the pumping operation of the fish, because of the already high amount of stress the fish has been exposed to from crowding. Hence, this operation could be considered *PNR*. If the operation is exposed to an event which sets humans, environment, assets and/or reputation to significant danger, the operation could be stopped.

Employees both from the land organization, wellboat and fish production site should be aware of the execution of the wellboat operation. Improvements of the procedures should be made in accordance with their preferences. The procedures shall prevent misunderstandings and conflicts during the operation. The involved should be made aware of the risk exposure associated with the operations by the use of *SJA*, for instance fish escapes during net cage handling and snap loads when the bottom weight is lifted.

5.2 Improvements to the Aquaculture Rules and Regulations

The significance of marine operations and how this is implemented in the petroleum regulations has been elaborated earlier in the thesis. With an understanding of how the petroleum industry acts when a marine operation is planned and carried out, the strengths and weaknesses of the aquaculture industry's legislation will be discussed in order to raise awareness of the need for improvements.

Essential in the aquaculture regulations are NYTEK, which refers to NS 9415. The latter explicitly states that technical requirements or operational tasks that are not related to fish escapes are not included. In addition to the technical standards, the regulations considering the operation of an aquaculture facility are central. In these regulations, fish welfare and fish escapes stand strong, which is an important aspect of justifiable fish farming. The reason why fish escapes are undesired can be divided in two. From a social perspective, there is a negative effect on the wild salmon's gene material if it mates with farmed fish. From an economic point of view, a financial loss is associated with fish escapes for the enterprises involved.

In the article «Occupational safety in aquaculture» (Holen et al., 2018), it is specified that from 1992 to 2015 the main reason for fatalities has been related to work operations, involving eight fatalities. These incidents have happened due to blow from an object/crushing, man overboard and one major loss of vessel incident. Figure 5.3 is from the above mentioned article and illustrates fatalities in different operations in Norwegian aquaculture. This may imply that today's regulations involving marine operations are not sufficient, as the aim is zero injuries and fatalities (Holen et al., 2018).

It is important to point out that even if the safety for the personnel is not the main focus in NS 9415, the technical requirements to the structure established to prevent fish escapes has indirectly made a great contribution to the worker's safety with a reduction in occupational hazards (Holen et al., 2018).

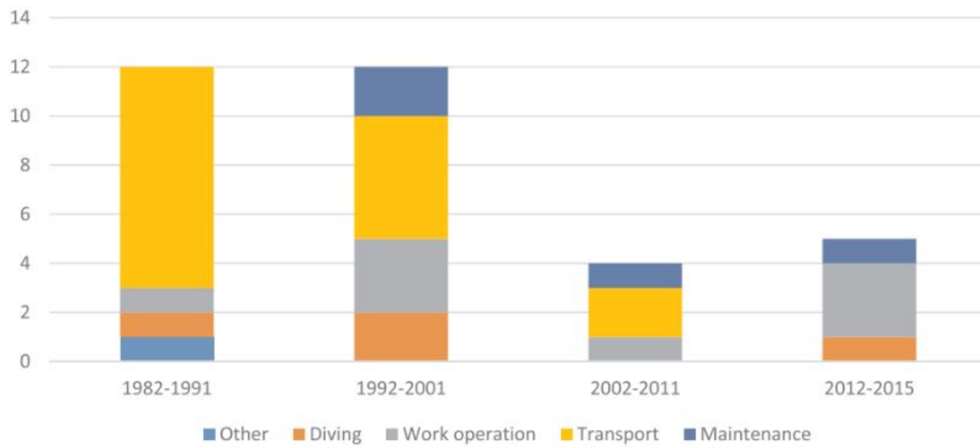


Figure 5.3: Fatalities in Norwegian aquaculture (1982-2015) categorized by types of operations (Holen et al., 2018)

New innovation projects designed for more exposed areas, causes a higher risk associated with the operations regarding personnel, environment and equipment due to increased complexity. As today's regulations are not sufficient for planning and execution of marine operations, they will definitely not be sufficient for operations in exposed areas.

If a new set of regulations are to be implemented in the aquaculture industry, it is of high importance that they are implemented in the regulation. Without such an arrangement, the enterprises will not necessarily obey the regulations, because they are associated with increased costs and use of resources. To make sure the regulations are followed at all times, a corresponding supervisory body should be designated to perform verification and control. In the petroleum industry, the Petroleum Safety Authority has been granted regulatory responsibility for controlling that the safety levels are within acceptable limits. A similar authority could be established for the aquaculture industry.

To set requirements for planning and execution of marine operations in the aquaculture industry, DNV-OS-H101 "Marine Operations, General" could have been used as a basis for further development and modification towards the aquaculture industry. An important aspect which needs to be taken into account is the handling of live fish, and how this affects the operations. In DNV-OS-H101 it is being emphasized that a planning process as mentioned in section 2.1 must be performed. The aquaculture industry could take lessons of the importance of defining a proper weather window where the operation could take place within safe limits, and the uncertainty in the weather forecast is included by the use of an alpha factor. If the wellboat operation described in section 5.1 were exposed to a sudden weather change not accounted for, it could have resulted in damage on the facility, fish escapes, injuries to personnel and in worst case fatalities.

In DNV-OS-H101 it is referred to DNVGL-RP-N101 "Risk Management in Marine and Subsea Operations", which includes risk management with the purpose of making systematic evaluations and handling of risk for humans, assets and environment. In NS 9415 it is stated that risk assessment of operations should be done to minimize the risk associated with escapes. For this, NS 5814 could be used. The Norwegian Labor Inspection Authority on the other hand, sets requirements to how risk assessments for personnel with regards to injuries, working loads and work environment are performed. Instead of today's partially cover of risk assessment, a full cover could be achieved by the use of DNVGL-RP-N101. This would have simplified risk assessment for the enterprises regarding humans, assets and environment, as they would only have to relate to one document. Having only one document to relate to, would also have simplified the verification job for the supervisory body.

One of the limitations for this thesis is that the author does not possess the individual aquaculture enterprise's guidelines for how to plan and conduct marine operations. Nevertheless, enterprises perform several preventative measures to ensure good practice. This is being done because it is of the enterprise's own interest to make sure that materiel, fish and personnel are treated in a justifiable way, and to prevent a bad reputation. Between the different actors, the way of implementation and how extensive the requirements are may differ, because it is up to the enterprise itself.

5.3 Motivation for Simulation

As presented in section 5.2 'Improvements to the Aquaculture Rules and Regulations', a more precise set of rules and guidelines should be established to regulate how operations are planned and executed in the aquaculture industry. The main priority when determining operational limits is how to safeguard the safety of human lives, escape of fish and fish welfare, and assets. This thesis focus on a wellboat operation, where simulations will be conducted to suggest a methodology for how operational limits can be established. These are determined by analyzing the axial forces acting in the mooring lines between the vessel and the cage system. To perform the analysis, the software SIMO-RIFLEX will be used. Wave, wind and current conditions will be applied to the model, while the corresponding responses in the mooring lines will be monitored. A detailed description of the simulation model is elaborated in chapter 7.

As mentioned in chapter 2, the operational limits shall account for uncertainties in the weather forecast through the use of alpha factors. These factors depend on both the duration of the operation and the topography at the location. Alpha factors have not been developed for the aquaculture industry yet, thus not considered in this thesis. For a relatively short duration, the uncertainty in the weather forecast could be considered low, thus the applied alpha factor could be set to one. If the aquaculture production site is sheltered by islands, the exact weather forecast could be difficult to report, thus alpha factors are needed. The sites which are found along the Norwegian coast has different weather exposure, the development of a common set of alpha factors could therefore demand for a high use of resources.

Chapter 6

Theory of Moored Floating Structures

A wellboat operation will be subjected to environmental loads from waves, wind and current in addition to functional loads from operating equipment. Waves will have a significant influence on the establishment of operational limits, wave theory will therefore be outlined. In addition, the essential equation of motion and mooring line theory will be presented.

6.1 Linear Wave Potential Theory

Linear wave potential theory is assumed through this thesis. Three important assumptions for potential theory are that the water is *incompressible, inviscid* and the fluid motion is *irrotational*. A velocity potential ϕ can be used to describe the fluid velocity vector **V** at a time *t* at a point *x* in a Cartesian coordinate system fixed in space. Equation 6.1 expresses this relationship, where **i**, **j** and **k** are the unit vectors along the x, y and z-axes, respectively (Faltinsen, 1990).

$$\mathbf{V} = \nabla\phi \equiv \mathbf{i}\frac{\partial\phi}{\partial x} + \mathbf{j}\frac{\partial\phi}{\partial y} + \mathbf{k}\frac{\partial\phi}{\partial z} \tag{6.1}$$

When the vorticity vector $\boldsymbol{\omega}$ is zero everywhere in the fluid, it follows that the fluid is irrotational, equation 6.2. Water is incompressible, hence the velocity potential has to satisfy the Laplace equation, equation 6.3 (Faltinsen, 1990).

$$\boldsymbol{\omega} = \nabla \times \mathbf{V} \tag{6.2}$$

$$\nabla^2 \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \tag{6.3}$$

To establish an expression for ϕ, the Laplace equation with relevant boundary conditions on the fluid must be applied. By assuming an infinite horizontal free-surface and horizontal sea bottom, linear wave theory for propagating waves can be derived. The expression for ϕ for linear propagating waves could be obtained by using the free-surface condition (equation 6.4) and the bottom condition (equation 6.5) together with the Laplace equation (equation 6.3). The free-surface condition defined in equation 6.4 is found by combining the kinematic (equation 6.6) and the dynamic condition (equation 6.7). The kinematic boundary condition expresses that a fluid particle on the free-surface is assumed to stay on the free-surface and the dynamic condition is simply that the water pressure is equal to the constant atmospheric pressure on the free-surface. The sea bottom condition expresses impermeability, which means that no fluid can enter or leave the body surface (Faltinsen, 1990).

$$\frac{\partial \phi^2}{\partial t^2} + g\frac{\partial \phi}{\partial z} = 0 \quad z = 0 \tag{6.4}$$

$$\frac{\partial \phi}{\partial z} = 0 \quad on \quad z = -h \tag{6.5}$$

$$\frac{\partial \zeta}{\partial t} = \frac{\partial \phi}{\partial z} \quad (kinematic\ condition) \tag{6.6}$$

$$g\zeta + \frac{\partial \phi}{\partial z} = 0 \quad (dynamic\ condition) \tag{6.7}$$

The surface elevation ζ for a single regular wave propagating in the horizontal x-direction can be expressed by equation 6.8 (Faltinsen, 1990).

$$\zeta = \zeta_a sin(\omega t - kx) \tag{6.8}$$

where,
ζ_a = Wave amplitude
k = $\frac{2\pi}{\lambda}$, Wave number
λ = Wave length
ω = $\frac{2\pi}{T}$, Angular frequency

The velocity potential can be expressed by equation 6.9 for a linear wave at a finite water depth (Faltinsen, 1990).

$$\phi = \frac{\zeta_a g}{\omega} \frac{cosh(k(z+d))}{cosh(kd)} cos(\omega t - kx) \tag{6.9}$$

where,
g = Acceleration due to gravity
d = Water depth

6.2 Irregular Waves and Wave Spectra

The theory presented in the following sections (6.2 and 6.3) is collected from the compendium (Myrhaug and Lian, 2009). If a real sea where observed, it is obvious that the sea state cannot be described by a single regular wave. The waves behave both chaotic and random, thus they could be categorized as irregular. To describe an irregular sea state, superposition of N number of regular long crested waves could be performed, as shown in equation 6.10.

$$\zeta(x,t) = \sum_{n=1}^{N} \zeta_{An} \sin(\omega_n t - k_n x + \epsilon_n) \tag{6.10}$$

Where,
ζ_{An} = Wave amplitude of the linear wave component with frequency ω_n
ω_n = Circular frequency , k_n = Wave number
ϵ_n = Phase angle, uniformly distributed between 0 and 2π.

Short crested waves can be described by modifying equation 6.10 to take into account the angle θ, which the wave propagates with relative to the horizontal axis.

The wave process is assumed to be:

- Stationary - The mean value and variance are constant within a short time interval (20 min - 3 hours).
- Normal distributed with variance σ^2 and zero mean.
- Ergodic, which means that one single time series can represent the wave process.

The total energy in a sea state where long crested waves are present, could be described by summing N linear waves components as shown in equation 6.11.

$$\frac{E}{\rho g} = \sum_{n=1}^{N} \frac{1}{2} \zeta_{An}^2(\omega_n) \tag{6.11}$$

By introducing the wave spectrum, the area of a small frequency interval $\Delta\omega$ (figure 6.1) is equal to the energy of all wave components within this particular interval. By summing the areas for all frequency intervals, the total energy is obtained, shown in equation 6.12.

$$\frac{E}{\rho g} = \sum_{n=1}^{N} \frac{1}{2} \zeta_{An}^2 = \sum_{n=1}^{N} S(\omega_n)\Delta\omega \tag{6.12}$$

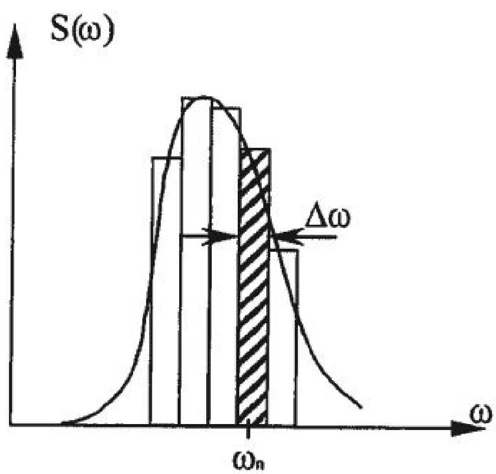


Figure 6.1: Principle sketch of a wave spectrum (Myrhaug and Lian, 2009)

Significant wave height (H_s) and the peak period (T_p) are two important parameters which are of considerable interest. H_s is defined as the average of the one third highest waves in a time series. When the significant wave height is calculated from the wave spectrum, the notation H_{m0} is often used, where m denotes the moments of the spectrum, presented in equation 6.13.

$$m_n = \int_0^{\infty} \omega^n S(\omega) d\omega \; ; n = 0, 1, 2, 3.. \tag{6.13}$$

By using the previously mentioned assumptions for the wave process (stationary, normal distributed and ergodic) the significant wave height can be described as in equation 6.14.

$$H_s = H_{m0} = 4\sqrt{m_0} \tag{6.14}$$

The peak period, T_p is defined from the frequency in a wave spectrum where the spectrum has its maximum value (DNVGL, 2017b).

The maximum wave height in a sea state is approximated by equation 6.15.

$$H_{max} = H_{m0}\sqrt{\frac{ln\,N}{2}} \quad \text{where,} \quad N = \frac{D}{T_z} \tag{6.15}$$

Where,
D = Duration of the sea state (normally between 1 to 4 hours)
T_z = Zero-crossing period

6.3 Standardized Wave Spectra

In a design phase it is convenient to use a standardized wave spectra. Some of the commonly used wave spectra are JONSWAP (*Joint North Sea Wave Project*), PM (*Pierson Moskowits*), ITTC (*International Towing Tank Conference*) and ISSC (*International Ship Structures Congress*) (Myrhaug and Lian, 2009).

The PM spectrum is defined by equation 6.16 and is valid for fully developed sea states and unlimited fetch, where fetch is defined as the undisturbed distance the wind has blown (Myrhaug and Lian, 2009).

$$S_{PM}(\omega) = \frac{5}{16} \cdot H_s^2 \omega_p^4 \cdot \omega^{-5} \, exp(-\frac{5}{4}(\frac{\omega}{\omega_p})^{-4}) \tag{6.16}$$

Where,
ω_p = Angular spectral peak frequency

The JONSWAP spectrum is based on the PM spectrum, but also accounts for the limited wind fetch. The formulation of the spectrum is given by equation 6.17 (DNVGL, 2017b).

$$S_J(\omega) = A_\gamma S_{PM}(\omega) \gamma^{exp(-0.5(\frac{\omega - \omega_p}{\sigma \, \omega_p})^2)} \tag{6.17}$$

Where,
γ = Non-dimensional peak shape parameter, typically = 3.3 for the JONSWAP spectrum
σ = Spectral width parameter
A_γ = 1-0.287 ln (γ)

If the JONSWAP spectrum is compared to the PM spectrum for the same sea state, the total energy i.e. the area under the spectrum curve would be the same. The difference between the two spectra is how the energy is distributed around the peak frequency. The JONSWAP spectrum has a higher energy density near the peak frequency compared to the PM spectrum. Hence the graph for the JONSWAP spectrum would appear taller and narrower in comparison to the PM spectrum, illustrated by figure 6.2 (Myrhaug and Lian, 2009).

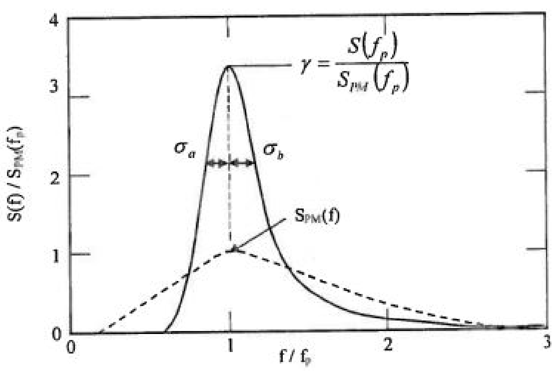


Figure 6.2: Principle sketch of a JONSWAP spectrum and a PM spectrum plotted for the same sea state (Myrhaug and Lian, 2009)

6.4 Classification of Wave Loads and Morison's Equation

When structural analysis are performed on floating structures, it is convenient to distinguish between large-volume structures and small-volume structures, illustrated by figure 6.3. To determine if a structure is either large- or small-volume, the structure is considered as a vertical cylinder with diameter D, and the waves are considered as regular sinus waves with height H and wavelength λ. If the ratio $\frac{\lambda}{D} < 5$ the structure is defined large-volume, while for $\frac{\lambda}{D} > 5$ the structure is considered small-volume (Greco, 2012).

Large-volume structures are characterized by diffraction loads. Diffraction loads are induced when incident waves are modified as a result of the interaction with the structure. For a small-volume structure, the incident waves are not affected by the structures present and long-wave approximation can then be applied. This approximation implies that the wave loads are analysed as if the structure was not present in the fluid. The loads acting on the small-volume structures could be divided into drag- and inertia loads. The load that dominates could be determined by the ratio $\frac{H}{D}$, indicated by figure 6.3. If $\frac{H}{D} > 4\pi$, drag is considered as the most significant load and is induced due to viscous forces. For $\frac{H}{D} < 4\pi$ the inertia loads are dominating (Greco, 2012).

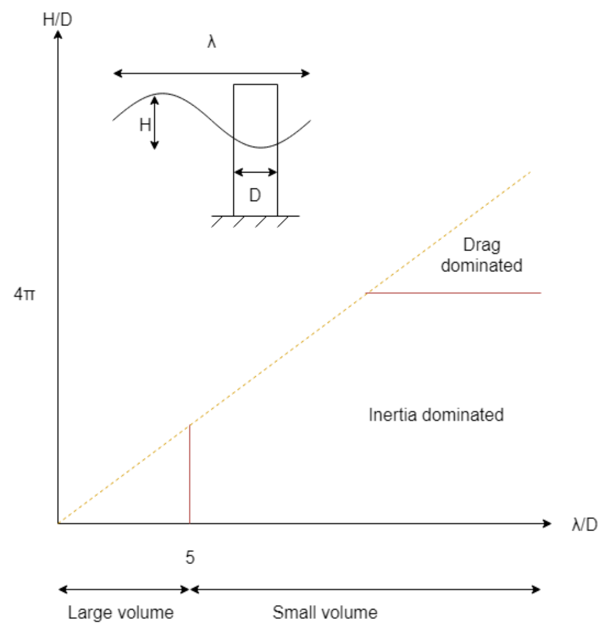


Figure 6.3: Classification of wave forces

Morison's equation is often used to determine wave loads on cylindrical structures, which is presented by equation 6.18. This equation states the horizontal force acting on a strip with length dz on a vertical cylinder. The first term represents the inertia force, while the second term describes the drag force (Pettersen, 2007).

$$dF = \rho_{water}\pi\frac{D^2}{4}C_M a_1 + \frac{\rho_{water}}{2}C_D D|u|u \tag{6.18}$$

Where,
ρ_{water} = Mass density of water
D = Cylinder diameter
u = Horizontal undisturbed fluid velocity
a_1 = Acceleration at the mid-point of the strip
C_M = Mass coefficient
C_D = Drag coefficient

A typical fish farm consists of multiple bodies, both large- and small-volume. The parts which are small-volume are typically mooring lines and the net, where Morison's equation could be applied.

6.5 Definitions of Motions

For floating structures, the motions that could affect the body can be divided into mean drift, high-frequency (HF), wave frequency (WF) and low-frequency (LF) motion. The rigid body motion is defined by three translational modes (surge, sway and heave) and three rotational modes (roll, pitch and yaw). This is presented in figure 6.4.

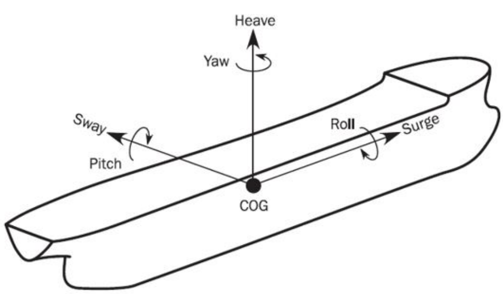


Figure 6.4: Coordinate system and rigid body motion modes (TheNavalArch, 2019)

The motion of any point on the wellboat is given by equation 6.19 (Faltinsen, 1990).

$$\mathbf{s} = \eta_1\,\mathbf{i} + \eta_2\,\mathbf{j} + \eta_3\,\mathbf{k} + \boldsymbol{\omega} \times \mathbf{r} \tag{6.19}$$

Where,
η_1 = Surge motion
η_2 = Sway motion
η_3 = Heave motion
$\boldsymbol{\omega}$ = Rotation vector
$\mathbf{r}$ = Position vector

$$\boldsymbol{\omega} = \eta_4\,\mathbf{i} + \eta_5\,\mathbf{j} + \eta_6\,\mathbf{k} \quad \text{and} \quad \mathbf{r} = x\,\mathbf{i} + y\,\mathbf{j} + z\,\mathbf{k} \tag{6.20}$$

When inserting the equations in 6.20 into equation 6.19, the complete expression for the motion of an arbitrary point located on the wellboat is obtained. This is presented in equation 6.21 (Faltinsen, 1990).

$$\mathbf{s} = (\eta_1 + z\eta_5 - y\eta_6)\,\mathbf{i} + (\eta_2 - z\eta_4 + x\eta_6)\,\mathbf{j} + (\eta_3 + y\eta_4 - x\eta_5)\,\mathbf{k} \tag{6.21}$$

6.6 Equation of Motion

Aquaculture installations consist of coupled flexible components which affect one another when current, waves and wind acts on the system. The system is composed of both stiff and flexible components, causing challenges when the system is treated as a uniform coupled system. The response of such a system will differ from an equivalent stiff system.

The equation of motion (*EOM*) is used to find the motion of a rigid body as a function of time and could be expressed for all six degrees of freedom, shown by equation 6.22 (Larsen, 2019). Thus, the equation of motion applies to the wellboat. For other parts of the cage system e.g. floating collar and fish net, other equations must be considered. The terms that the EOM is composed of will be described in the following sections.

$$(M + A(\omega)) \cdot \ddot{r} + C(\omega) \cdot \dot{r} + D_l \cdot \dot{r} + D_q \cdot \dot{r}|\dot{r}| + K(r) \cdot r = Q(t, r, \dot{r}) \tag{6.22}$$

Where,
M = Mass matrix
A(ω) = Frequency-dependent added mass matrix
r , $\dot{r}$, $\ddot{r}$ = Position, velocity and acceleration vectors respectively
C(ω) = Frequency-dependent potential damping matrix
D_l = Linear damping matrix
D_q = Quadratic damping matrix
K(r) = Non-linear stiffness matrix
$Q(t, r, \dot{r})$ = Excitation force vector

The natural frequency and period for an undamped system are defined by equation 6.23. Although the system in this thesis is affected by damping, this expression could be used to indicate where the natural frequencies for the system may be found.

$$\omega_0 = \sqrt{\frac{K}{(M + A(\omega))}} \quad \text{and} \quad T_0 = \frac{2\pi}{\omega_0} \tag{6.23}$$

The dynamic load factor (*DLF*), states the ratio between the dynamic and static response of a system for a given load. DLF is a dimensionless number and could be less than or larger than one, depending on the frequency ratio β and the damping ratio ξ, figure 6.5.

The expression of DLF is given by equation 6.24. The DLF gives valuable information about which term (inertia, stiffness or damping) in the equation of motion that is of high importance for balancing the excitation loads for different frequency ratios (Larsen, 2015).

$$DLF = |\frac{U_{dyn}}{U_{st}}| = \frac{1}{\sqrt{(1-\beta^2)^2 + (2\xi\beta)^2}} \tag{6.24}$$

Where,
$\beta = \frac{\omega}{\omega_0}$, ω = Load frequency
$\xi = \frac{c}{c_{cr}}$, C = Damping, C_{cr} = Critical damping

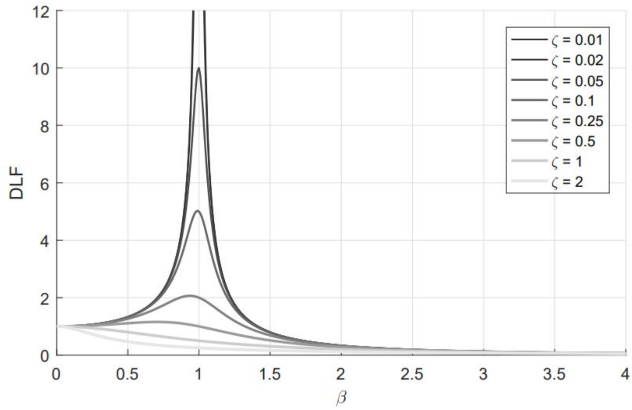


Figure 6.5: Dynamic load factor as a function of the frequency ratio for given values of damping ratio (Larsen, 2015)

6.6.1 Inertia

The mass term in the equation of motion contains both the mass of the structure and the hydrodynamic mass, known as added mass. Added mass is not a property associated with the vessel as mass is, but represents the mass of the fluid that the vessel must displace when accelerating. By multiplying the added mass term with the acceleration of the vessel, the added mass could be expressed as a force (Pettersen, 2007).

The inertia forces dominate when the load frequency is larger than the natural frequency of the system, highlighted by the bold line in figure 6.6. This means that the inertia forces balance the excitation forces in the equation of motion.

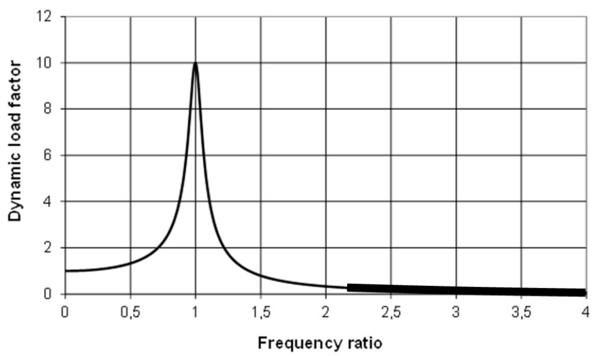


Figure 6.6: Inertia dominated system (Larsen, 2015)

6.6.2 Damping

Damping is a structure's ability to reduce oscillations, by converting kinetic energy to other types of energy. Like added mass, damping is also dependent on frequency. Damping could be divided into over, under and critical damping. If a system is overcritically damped, it will not oscillate, but gradually decrease towards a constant value. An underdamped system will oscillate about a constant value, with decreasing amplitude until the system has reached equilibrium. Critical damping represents the fastest way a system could come into equilibrium without oscillating (Langen and Sigbjörnsson, 1979).

As further described in chapter 8.5, the wellboat has large natural periods in surge, sway and yaw. It is therefore of high importance to provide sufficient damping to these degrees of freedom in order to prevent resonance due to LF forces originating from wind and waves. The main contributors to damping are the following:

- Viscous effects can be divided into skin friction effects and viscous effects due to the pressure distribution around the vessel often referred to as eddy-making damping in the literature. The damping provided by skin friction is quite small in comparison to the eddy-making damping (Faltinsen, 1990).
- Wave drift damping is caused by body interactions with the incident waves. By comparing free-decay model tests for a vessel in calm water and regular waves, this damping term can be obtained (Greco, 2012).
- Drag forces on the mooring lines originate from the horizontal top end motions of the wellboat and the floating collar. These top end motions are excited by WF loads and contribute to dynamic motions in the mooring lines. The drag forces induced by the dynamic motions act in the opposite direction of the top end motions and provides damping to the system (Larsen, 2019).
- Wave radiation damping is created as a result of WF wave loads which excites motions on the system, which in turn generate waves. These waves contribute to damping of the WF motions of the system. For long waves with a low frequency, the wave radiation damping will be very small (Greco, 2012).
- Low-frequency current and wind damping - When wind and current interact with the vessel, drag forces occur which provides damping to the system (Larsen, 2019).
- Thruster damping - Vessel motions can be damped by the use of thrusters. This damping term is not relevant for this thesis, because the wellboat shall not use

thrusters to provide station-keeping near the cage. The use of thrusters could contribute to an unacceptably high risk for impairing the net cage.

As shown by figure 6.7 the damping forces are dominating in the resonance region where the motion response has its largest magnitude. Thus, it is the damping forces that balance the excitation forces in the region of the natural frequencies of the system.

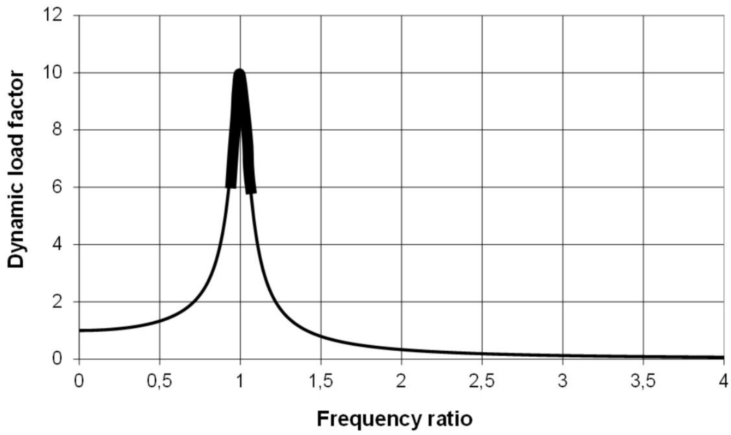


Figure 6.7: The resonance region (Larsen, 2015)

6.6.3 Stiffness

The stiffness of the wellboat in surge, sway and yaw is given by the mooring system of the facility. When the system is exposed to external forces, the mooring system must provide enough stiffness to prevent large displacements in the aforementioned degrees of freedom. Figure 6.8 presents a simplified model of the vessel moored to the cage system and illustrates its system stiffness when a force Q is applied. The relation between the applied force Q and the spring forces from the mooring lines are presented by equation 6.25.

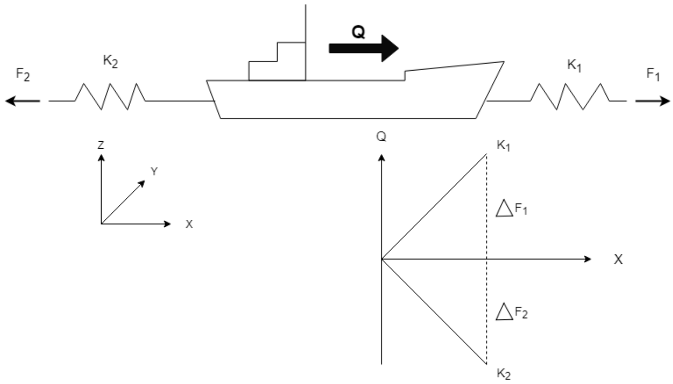


Figure 6.8: Principle of system stiffness for the wellboat with mooring lines

$$\Delta Q = \Delta F_1 + \Delta F_2 \tag{6.25}$$

The stiffness of the system has mainly two contributors; elastic and geometric stiffness. Elastic stiffness is the mooring line's ability to withstand axial deformation and is given by the material properties of the line, cross-sectional area and length. The most significant contributor to elastic stiffness is given by the fibre rope and equation 6.26 shows how the elastic stiffness coefficient could be derived. Figure 6.9 illustrates how the elasticity of the line provides stiffness to the system. In the figure, point 1 and 2 indicates the location of the object before and after offset, respectively. ΔL gives the length which the line is stretched with when the object is displaced by a ΔX (Larsen, 2019).

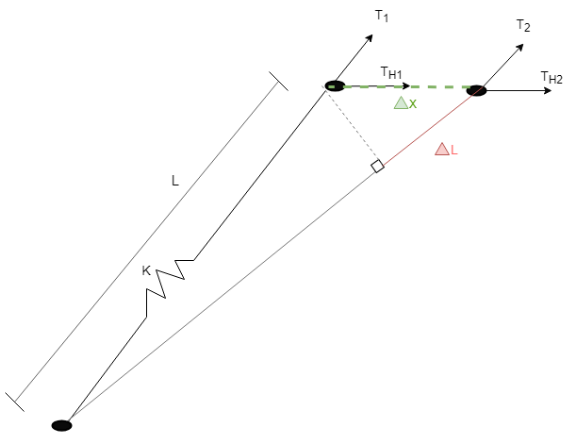


Figure 6.9: Principle of elastic stiffness

$$\Delta T = T_2 - T_2 = \frac{EA}{L} \cdot \Delta L \Rightarrow K_E = \frac{EA}{L} \tag{6.26}$$

Geometric stiffness is provided due to the weight of the line and for this case, it is the chain which provides the largest contribution. Figure 6.10 illustrates how the weight of the line provides geometric stiffness to the system, where point 1 and 2 represents the initial and final position, respectively. W1 and W2 indicate the weight of the line at position 1 and 2. Likewise is T_{H1} and T_{H2} representing the horizontal tension in the line. A1 and A2 is the distance from the line's centre of gravity to the object's position in the x-direction, while d is the water depth. To obtain the horizontal tension T_H, moment equilibrium about the object's position 1 or 2 is used, as presented by equation 6.27. If this equation is solved for T_H, the horizontal tension is obtained, as shown in equation 6.28. Furthermore, the geometric stiffness coefficient K_G could be found from equation 6.29, where the difference between horizontal tension in position 1 and 2 is divided by the difference in the object's offset in the x-direction (Larsen, 2019).

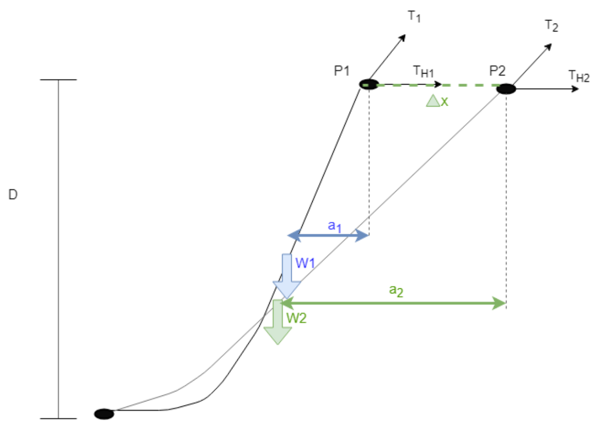


Figure 6.10: Principle of geometric stiffness

$$T_H \cdot D = W \cdot a \tag{6.27}$$

$$T_{H1} = \frac{W_1 \cdot a_1}{D} \quad and \quad T_{H2} = \frac{W_2 \cdot a_2}{D} \tag{6.28}$$

$$K_G = \frac{T_{H2} - T_{H1}}{\Delta X} \tag{6.29}$$

The stiffness of the system controls the low-frequent motions and mean offset. In addition, the stiffness of the mooring system must absorb the forces excited by WF motions. For a line consisting of two different segments, chain and fibre rope, both the elastic and geometric stiffness will contribute to the total stiffness. This could be expressed as two springs in series, seen in equation 6.30 (Larsen, 2019).

$$\frac{1}{K_{TOT}} = \frac{1}{K_E} \cdot \frac{1}{K_G} \tag{6.30}$$

Where,
K_E = Elastic stiffness , K_G = Geometric stiffness
K_{TOT} = Total stiffness

When load frequencies are less than the natural frequency, the stiffness forces are dominating for balancing the excitation forces in the equation of motion. The bold line on figure 6.11 illustrates this region.

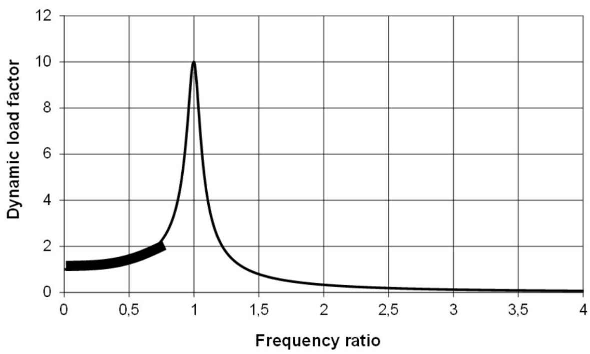


Figure 6.11: Stiffness dominated system region (Larsen, 2015)

A more thorough description of the stiffness provided by the anchor lines will be presented in section 6.7.

6.6.4 Excitation forces

The excitation forces acting on the system are mainly created by wind, current and waves, and is defined in equation 6.31. The wind forces act on the parts of the cage structure above the sea surface, in addition to the area above the waterline of the vessel. The current forces act on the mooring lines, the floating collar, the buoys and the area below the waterline of the vessel. The model does not include the net structure, which would have been highly affected by current forces.

$$Q(t, x, \dot{x}) = q_{wa} + q_{cu} + q_{wi} \tag{6.31}$$

Where,
q_{wa} = wave forces
q_{cu} = current forces
q_{wi} = wind forces

The following table 6.1 presents the different contributors to the excitation force and the individual factors that characterize them.

Table 6.1: Excitation regimes for wave, current and wind forces obtained from (Larsen, 2019)

	Mean	**5-30s : WF (wave -frequency)**	**>30s: LF (low-frequency)**
Waves	Mean wave drift force (2nd order)	1st order wave forces, proportional to the wave amplitude	Wave drift forces (2nd order)
Current	Mean current velocity		
Wind	Mean wind velocity		Wind gusts

The natural frequencies of a moored wellboat are relatively large, thus HF wave forces do not excite any considerable motions to the system, and are therefore neglected in this thesis.

Wave forces

Wave forces could be divided into first and second-order forces.

First order wave forces
Wave frequency forces are 1^{st} order wave forces which are proportional to the wave amplitude and could be divided into excitation and radiation loads. The excitation loads are composed of Froude-Kriloff and diffraction forces and moments, while the radiation loads are identified as added mass, damping and restoring terms (Faltinsen, 1990).

Second order wave forces

The second order non-linear forces consist of mean wave drift forces, high-frequency forces and low-frequency forces. For the wellboat moored to the cage-system, low-frequency and mean wave drift forces are the only second-order forces, which are of interest. These forces are of high importance due to load frequencies near the natural frequencies of the system (Larsen, 2019).

Current forces

Current forces consist of forces from mean current velocity. The current turbulence is neglected. The formula for the current force is given by equation 6.32 and the current coefficient is found by equation 6.33.

If the current velocity $\overline{V}$ is larger than the floater LF velocity $\dot{x}$, equation 6.32 can be re-written to equation 6.34. The first term in equation 6.34 is the constant force and the second term is the low-frequency damping force (Larsen, 2019).

$$q_{cu} = \frac{1}{2}\rho_{water} \cdot C_D \cdot A \cdot |\overline{V} - \dot{x}| \cdot (\overline{V} - \dot{x}) \tag{6.32}$$

$$c_{cu} = \frac{1}{2}\rho_{water} \cdot C_D \cdot A \tag{6.33}$$

$$q_{cu} \approx \frac{1}{2}\rho_{water} \cdot C_D \cdot A \cdot \overline{V}^2 - \rho_{water} \cdot C_D \cdot A \cdot \overline{V} \cdot \dot{x} \tag{6.34}$$

where,
ρ_{water} = Mass density of water
C_D = Global drag coefficient
A = Area projected to current

Wind forces

Wind forces consist of forces from mean wind velocity and wind gusts as figure 6.12 illustrates. The formula for wind force is given by equation 6.35 and the wind coefficient is found by equation 6.36. The LF velocity of the structure $\dot{x}$ and the dynamic wind gust u(t) can be assumed to be relatively small in comparison to the mean wind velocity $\overline{U}$, thus equation 6.35 can be re-written to equation 6.37. In the SIMA model, the dynamic wind gust u(t) is implemented by the use of the Norwegian Petroleum Directorate (*NPD*) spectrum.

The first term in equation 6.37 is the constant force, the second term is the low-frequency excitation force and the last term is the low-frequency damping force (Larsen, 2019).

$$q_{wi} = \frac{1}{2}\rho_{air} \cdot C_D \cdot A \cdot (\overline{U} + u(t) - \dot{x})^2 \tag{6.35}$$

$$C_{wi} = \frac{1}{2}\rho_{air} \cdot C_D \cdot A \tag{6.36}$$

$$q_{wi} \approx \frac{1}{2}\rho_{air} \cdot C_D \cdot A \cdot \overline{U}^2 + \rho_{air} \cdot C_D \cdot A \cdot \overline{U} \cdot u(t) - \rho_{air} \cdot C_D \cdot A \cdot \overline{U} \cdot \dot{x} \tag{6.37}$$

where,
ρ_{air} = Density of air
C_D = Global drag coefficient
A = Area projected to wind

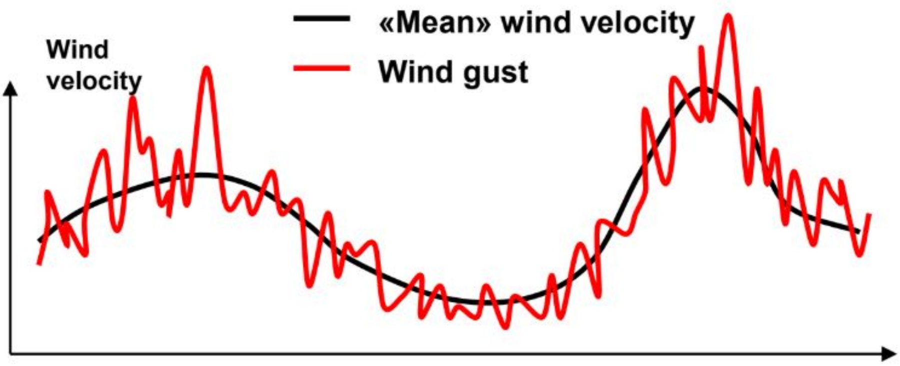


Figure 6.12: Wind gusts and mean wind velocity (Larsen, 2019)

6.6.5 Solution of Equation of Motion

Equation of motion can be solved in two ways to find the top end motions, in frequency-domain or in time-domain. When time-domain analysis is used, non-linearities may be considered, unlike frequency-domain analysis where the system is linearized (Min, 2018). When frequency-domain analysis is employed, LF and WF loads are calculated separately, while for time-domain analysis the loads are calculated simultaneously for each time step (Larsen, 2019).

For a time-domain analysis where both *A(w)* and *C(w)* are frequency dependent, they have to be inverse Fourier transformed before further implementation. Equation 6.38 presents the time-dependent equation of motion, where the frequency dependent variables have been transformed by the use of the retardation functions, $h(\tau)$ (Yuan et al., 2017).

$$(M + A_{\infty})\ddot{x} + \int_0^t h(t-\tau)\dot{x}(\tau)d\tau + D_l\dot{x} + D_q\dot{x}\,|\dot{x}| + K(x)x = Q(t, x, \dot{x}) \quad (6.38)$$

$$h(\tau) = \frac{2}{\pi}\int_0^{\infty} C(\omega)cos(\omega\tau)d\omega = -\frac{2}{\pi}\int_0^{\infty} \omega A(\omega)cos(\omega\tau)d\omega \quad (6.39)$$

The system studied in this thesis is analysed in SIMA, which uses time-domain analysis. However, the wellboat given by SINTEF Ocean was developed in the frequency-domain software WAMIT, before it was implemented in the SIMO-RIFLEX model.

Time Domain Analysis

When calculating the forces and response in the time domain of a wellboat moored to a fish cage, there are mainly two different approaches - the coupled and de-coupled analysis, figure 6.13. The system elaborated in this thesis is analysed using a coupled SIMO-RIFLEX analysis.

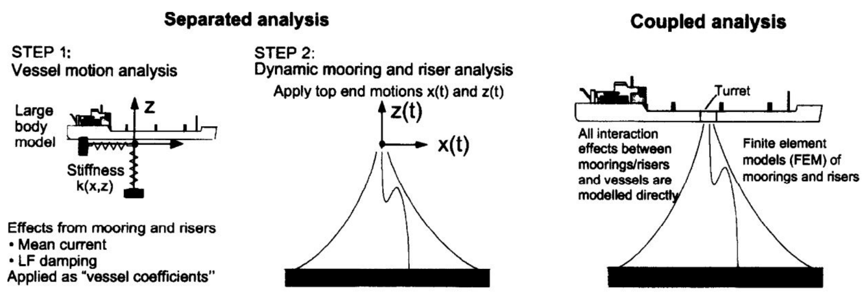


Figure 6.13: Separated and coupled analysis (Ormberg and Larsen, 1998)

In the de-coupled approach, the wellboat and mooring system is considered individually. First, the motion of the wellboat is calculated, which is dependent on the excitation forces from wind, current and waves. These results are then used as input for the top end motions when the reaction forces in the mooring lines are calculated. The main shortcomings of this approach are (a) The mean current loads on the mooring lines are normally not accounted for, particularly in deep water, (b) The damping effect from the mooring lines on the LF motion needs to be included in a simplified way (Ormberg and Larsen, 1998).

In the coupled analysis, the motions and forces on the complete system including both the wellboat and the mooring system are calculated simultaneously. The forces from the wellboat are defined as nodal forces at the top end of the mooring lines, which are represented by finite elements. The hydrodynamic loads acting on these slender structures are calculated by the use of Morison's equation. By using a coupled approach, the limitations from the de-coupled analysis will be avoided and the important coupling effects will be taken into account. The main disadvantage associated with this analysis is that it is expensive in terms of computational time (Ormberg and Larsen, 1998).

6.7 Mooring Lines

Static Equilibrium of a Mooring Line

A mooring line could be considered as a two-dimensional line as illustrated in figure 6.14, where the forces acting on the line are included. F and D are the hydrodynamic forces in the tangential and normal direction, respectively. T is considered as the line tension, while A is the cross-sectional area of the line and E is the elastic modulus. The dynamic effects on the line are neglected, as well as the bending stiffness as the radius of curvature is assumed large (Faltinsen, 1990).

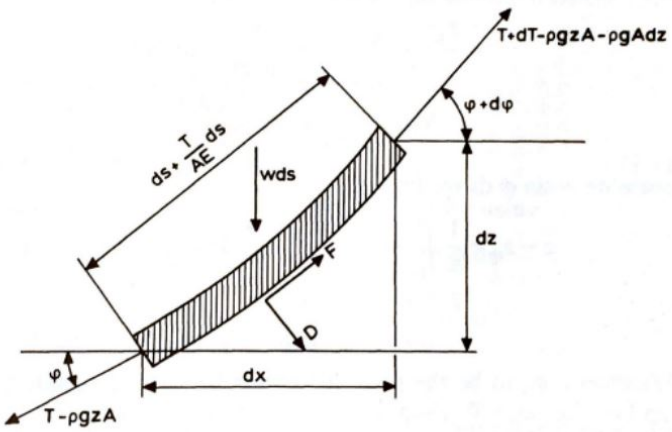


Figure 6.14: Illustration of the forces acting on a two-dimensional mooring line (Faltinsen, 1990)

The forces acting in the tangential and normal direction of the mooring line are described by equation 6.40 and 6.41 respectively.

$$dT - \rho g A\, dz = [w\, sin\phi - F(1 + T/(AE))]ds \tag{6.40}$$

$$T\, d\phi - \rho g A z\, d\phi = [w\, cos\phi + D(1 + T/(AE))]ds \tag{6.41}$$

These equations are nonlinear, and thus difficult to solve. In some cases, the current forces F and D are small, and could therefore be neglected. To further simplify the analysis, the elasticity may also be neglected. However, for some extreme cases, the elasticity provides a significant contribution and can thus not be ignored (Faltinsen, 1990).

Line Characteristics for an Inelastic Mooring Line

The relation between the pre-tension and the horizontal offset of the wellboat is called the line characteristic. The notation used to define the line characteristic is given by figure 6.15.

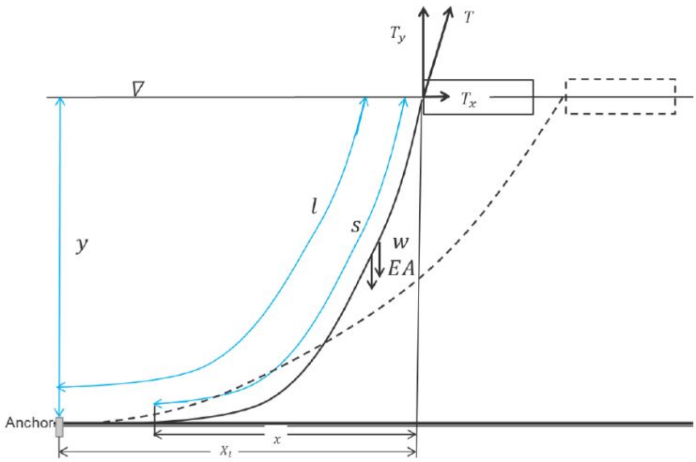


Figure 6.15: The notation that defines the line characteristics (Larsen, 2018b)

Usually, the horizontal distance between the anchor and vessel is known, but not the corresponding tension in the mooring line. Equation 6.42 states the horizontal offset of the wellboat as a function of the horizontal tension in the mooring line (Larsen, 2018b).

$$X_l = l + \frac{T_x}{w} \cdot \cosh^{-1}(1 + \frac{w \cdot y}{T_x}) - \sqrt{y \cdot (y + \frac{2T_x}{w})} \tag{6.42}$$

Where,
X_l = Distance from the vessel to the anchor
l = Length of the line
y = Water depth
T_x = Horizontal top tension

The point where the anchor line touches the ground is called the touchdown point (*TDP*). The horizontal distance between this point and the vessel is given by equation 6.43 (Larsen, 2018b).

$$x = \frac{T_x}{w} \cdot ln[1 + \frac{y \cdot w}{T_x} + \sqrt{(1 + \frac{y \cdot w}{T_x})^2 - 1}] \tag{6.43}$$

Line Characteristics for an Elastic Mooring Line

The previous equations defined for line characteristics assumed an inelastic line. A typical anchor line for the fish cage described in this thesis consists of chain at the bottom end of the line, and polypropylene on the remaining line. The part which is chain is often assumed inelastic, thus the previously defined equations apply. The part which is polypropylene is elastic, and thus an equation that accounts for this needs to be considered. Equation 6.44 presents the expression for TDP of an elastic mooring line (Larsen, 2018b).

$$x = \frac{T_x}{w} \cdot \sinh^{-1}(\frac{T_y}{T_x}) + \frac{T_x \cdot T_y}{w \cdot EA} \tag{6.44}$$

Where,
T_y = Vertical tension

The corresponding line characteristic is given by the following equation 6.45.

$$X_l = (l_0 - \frac{T_y}{w}) \cdot (1 + \frac{T_x}{EA}) + x \tag{6.45}$$

Where,
l_0 = Unstretched length

Finally, the horizontal tension in the mooring line is given by equation 6.46.

$$T_x = EA\,[\sqrt{(\frac{T}{EA} + 1)^2 - \frac{2wy}{EA}} - 1] \tag{6.46}$$

Restoring Forces

The restoring forces of a system are divided into horizontal forces and a yaw moment. The total restoring force of the system is the sum of the restoring forces and moment of the individual mooring lines. Equation 6.47, 6.48 and 6.49 defines the restoring forces and moment in surge, sway and yaw motion from the mooring lines respectively (Faltinsen, 1990). The terms in these equations are illustrated in figure 6.16.

$$F_1^M = \sum_{i=1}^{n} T_{Hi}\, cos\, \psi_i \tag{6.47}$$

$$F_2^M = \sum_{i=1}^{n} T_{Hi}\, sin\, \psi_i \tag{6.48}$$

$$F_6^M = \sum_{i=1}^{n} T_{Hi}\, [x_i\, sin\, \psi_i - y_i\, cos\, \psi_i] \tag{6.49}$$

Where,
T_{Hi} = Horizontal force from anchor line i
x_i = x-coordinate of the attachment point of the anchor line to the floating system
y_i = y-coordinate of the attachment point of the anchor line to the floating system
ψ_i = Angle between the x-axis and the anchor line

In order to ensure equilibrium of the moored system, the restoring forces and moments have to balance the mean forces acting from waves, wind and current (Faltinsen, 1990).

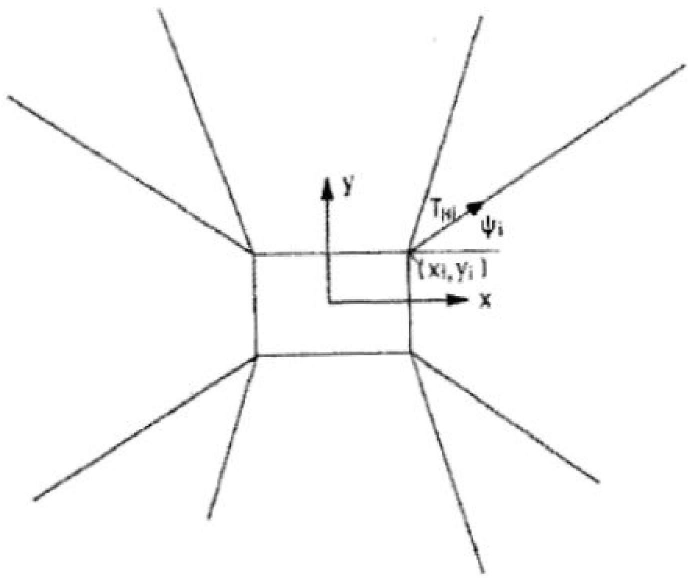


Figure 6.16: Horizontal restoring force (Faltinsen, 1990)

Chapter 7

The Simulation Model

The marine operation analyzed in this master thesis is a wellboat operation. The wellboat is moored with four mooring lines to the cage-system and is exposed to external environmental impacts from waves, wind and current.

This chapter will give a brief introduction to the software SIMA with the numerical tools used for this thesis, SIMO and RIFLEX. These tools were used to model the wellboat and the cage system. A coupled analysis was used to simulate the two systems together. The wellboat model, the cage system and the coupled model are elaborated.

7.1 SIMA

SIMA is a simulation workbench for marine applications, which perform time domain analyses. The software is developed by SINTEF Ocean and contains several numerical tools, such as SIMO and RIFLEX. A 3D graphical representation of the modelled objects is provided by the software (Reinholdtsen et al., 2018).

7.1.1 Coordinate Systems

SIMA utilizes right-handed Cartesian coordinate systems and defines positive rotations counter-clockwise. The global earth-fixed coordinate system, XG is presented in figure 7.1. The xy-plane coincides with the calm water surface, while the z-axis points upwards.

All user specified propagation directions of the environmental parameters refer to this coordinate system (SIMO Project Team, 2018).

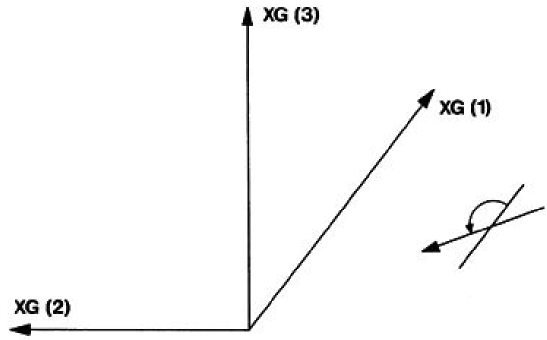


Figure 7.1: The global earth-fixed coordinate system (SIMO Project Team, 2018)

The local coordinate system XB, follows the body motions. It is used to describe the coordinates of positioning elements and coupling elements. The body-related coordinate system denoted XR, follows the body's horizontal motion for floating vessels. The xy-plane is located at the calm water surface and the z-axis is pointing upwards. Most motion transfer functions and forces refer to XR. All three coordinate systems are defined in figure 7.2 (SIMO Project Team, 2018).

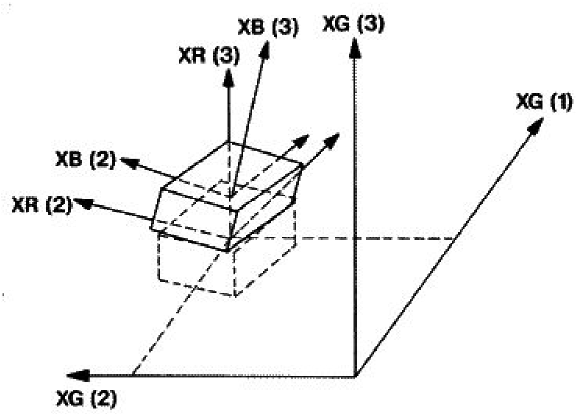


Figure 7.2: Illustrates the global, local and body-related coordinate systems (SIMO Project Team, 2018)

7.1.2 SIMO

According to (SIMO Project Team, 2018) "SIMO is a computer program for simulation of motions and station-keeping behaviour of complex systems of floating vessels and suspended loads". Essential features are listed in the following also obtained from (SIMO Project Team, 2018):

- Flexible modelling of multibody systems.
- Nonlinear time-domain simulation of wave frequency as well as low frequency forces.
- Environmental forces due to wind, waves and current.
- Passive and active control forces.
- Interactive or batch simulation.

SIMO is based on linear wave potential theory, which is outlined in section 6.1.

7.1.3 RIFLEX

RIFLEX performs non-linear time domain FEM analysis of slender structures. The hydrodynamic forces acting on the slender structures are calculated according to Morison's equation, described in section 6.4. The cage system including the floating collar, buoys and the mooring lines were modelled in RIFLEX, in addition to the mooring lines between the wellboat and the cage system (RIFLEX Project Team, 2018).

7.1.4 SIMO-RIFLEX Coupled

SIMO-RIFLEX coupled is according to (Reinholdtsen et al., 2018) described as "simulation of multi-body systems with flexible couplings and/or slender marine structures". This feature was used to simulate the wellboat with the cage system. The coupled-approach was outlined in section 6.6.5.

7.2 The Wellboat

The wellboat MachoShip4500, used in the simulations was developed in the software WAMIT by SINTEF Ocean. The WAMIT- file was imported into SIMO with a visualization of the underwater hull and information about the kinematic properties of the vessel. The coordinate system is located in the middle of the vessel, with the x-axis pointing ahead of the ship, the y-axis pointing in the port direction, and the z-axis pointing upwards. When the model was received from SINTEF, information about the quadratic current- and wind coefficients were not available.

To sustain realistic simulations, it was important to verify that the dimensions of MachoShip4500 were realistic compared to the dimensions of the wellboats used by the aquaculture industry. Based on this, a comparison was conducted between MachoShip4500 and Ronja Polaris, which is a wellboat in operation, belonging to the Sølvtrans' fleet. The dimensions of these two wellboats are presented in table 7.1. The dimensions of MachoShip4500 were obtained from SINTEF, presented in appendix C.3, while Ronja Polaris' dimensions were obtained from the website 'skipsrevyen' (Skipsrevyen, 2018). Figure 7.1 shows a picture of Ronja Polaris and MachoShip4500 taken from SIMA.

Table 7.1: Vessel specifications for Ronja Polaris and MachoShip4500

	Ronja Polaris	**MachoShip4500**
Length over all (LOA) [m]	75.8	85.4
Length between P.P (LPP) [m]	73.4	79.8
Breadth [m]	16	20
Design draught [m]	6.8	7.57
Cargo hold capacity [m^3]	3200	4500

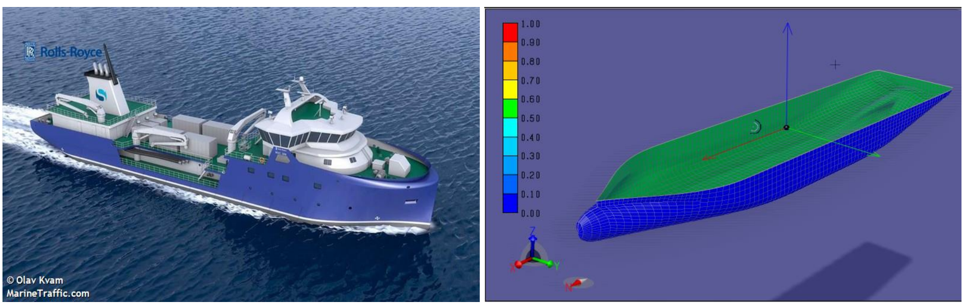


Figure 7.3: (Left) Ronja Polaris (Marine Traffic, 2019)
(Right) MachoShip4500

7.3 The Cage Model

The model used to simulate the cage system was created in RIFLEX, and consists of the following main components; floating collar, bridles, frame mooring, anchor lines and buoys, presented in figure 7.4 and 7.5. The net is not included in this thesis, as the interaction between the wellboat and the net is not the main focus. The net would have a significant impact on the simulation time, as the number of elements would have increased considerably. All relevant data of the RIFLEX model is provided in appendix F.6. To maintain realistic simulations, it was of high importance to use the same components as the industry are using with similar dimensions. The supplier of aquaculture equipment Aqualine, contributed with guidance in terms of system setup and choice of components in accordance with the industry practice, appendix G.7.

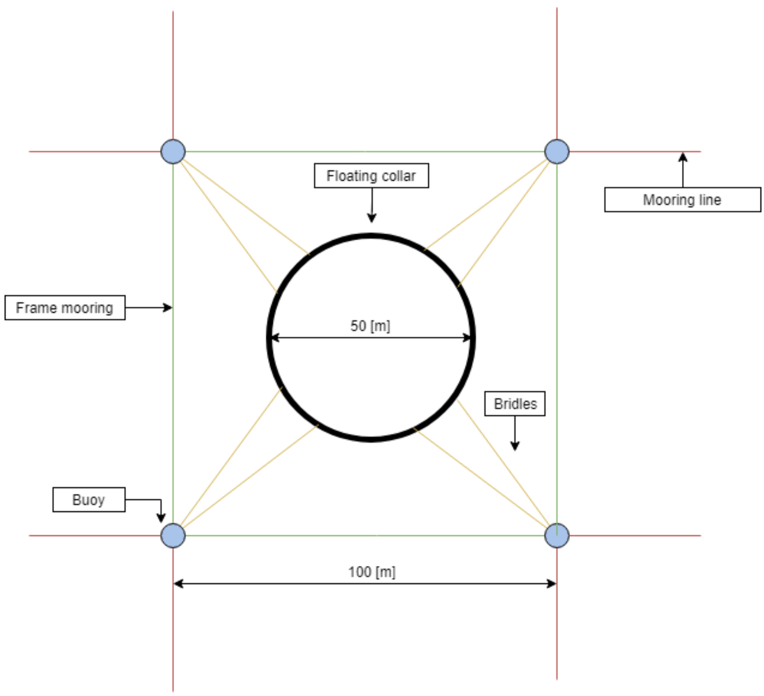


Figure 7.4: Bird's-eye view of the simplified cage system with main components.

The diameter of the floating collar was set to 50 meters, giving a circumference of 157 meters. The floater is moored to the frame mooring with a total of eight bridles shown in figure 7.4. To facilitate operational vessels to moor to the floating collar, the frame mooring is submerged eight meters below the sea surface. To provide sufficient buoyancy, four buoys are attached to the frame mooring, one in each corner. These buoys are attached to the bridles and anchor lines with the use of a coupling plate. Figure 7.5 shows that the projected length of the anchor line to the sea bottom is 272 meters. This length is approximately three times the vertical distance between the sea bottom and the coupling plate. Hence, the ratio becomes 3:1 which is in accordance with the industry's best practice. The ratio was used as a basis when the anchor lines were designed. The anchor lines consist of two segments, an upper part of polypropylene rope and a lower part made of studless chain. This combination of an elastic fibre rope and a heavy chain provides a desired behaviour when the system opposes the combined effect from waves, wind and current.

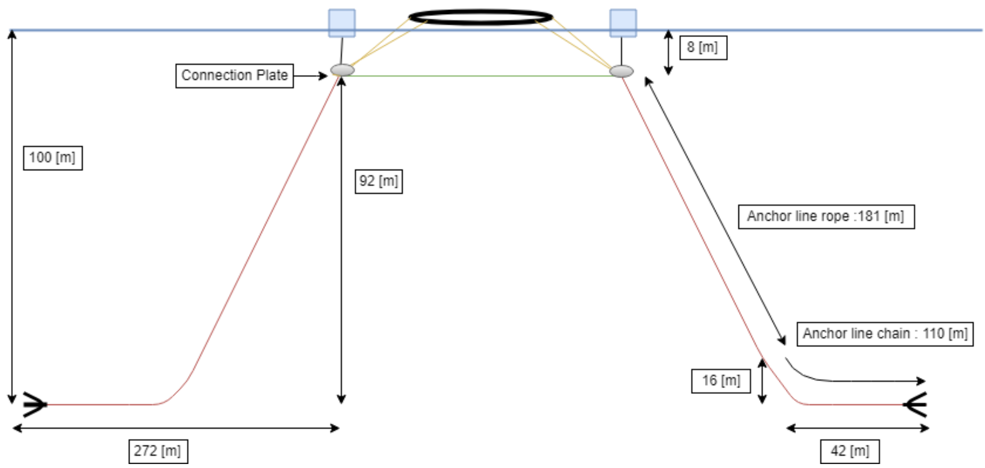


Figure 7.5: Side view of the simplified cage system with main components.

The anchor lines were pre-tensioned to a value of 4.2 tons. Pre-tension is important to prevent the leeward anchor lines from getting slack, which may lead to wear in the fibre rope due to seabed contact. This pretension will propagate into the frame mooring and the bridles. Table 7.2 summarize the pre-tension for the individual lines.

Table 7.2: Pre-tension for the lines in the cage system

	Pre-tension [tons]
Anchor line	4.2
Frame mooring	2.2
Bridles	1.2

7.4 The SIMO-RIFLEX Coupled model

A bird's eye view of the SIMO-RIFLEX coupled model is shown in figure 7.6, where the wellboat is lying in position next to the floating collar. The red mooring lines are numbered from 1-4, which will be used later in simulations, to distinguish between the axial forces in the individual mooring lines. Two of the mooring lines are connected to the floating collar (1 and 3) and two lines are connected to the nearest coupling plate (2 and 4). The specifications of the mooring line characteristics were based on advice from Martin Søreide at Aqualine AS, and the line configuration was decided in co-operation with the supervisors. The fibre rope chosen was "New SuperTec 8-Strand Rope" with properties summarized in table 7.3 (DSR, 2019b).

Table 7.3: Data for mooring lines between wellboat and cage system

Mooring lines	Value	Unit
Diameter	50	mm
Breaking strength	5.1e+05	N
Axial stiffness	3.9e+06	N

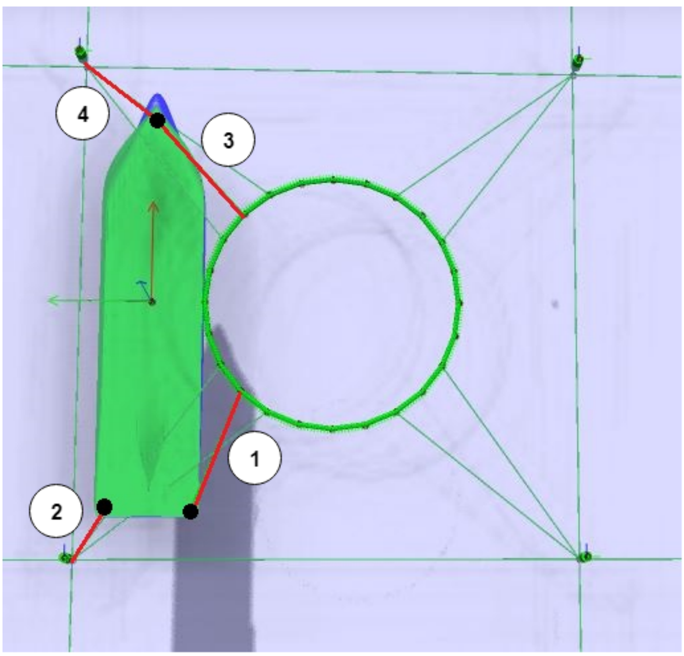


Figure 7.6: Bird's-eye view of the SIMO-RIFLEX coupled model

Each mooring line between the wellboat and the cage was pre-tensioned and it was assumed that the vessel is equipped with a capstan at each attachment point. After correspondence with Henrik Hareide in Sølvtrans, it was confirmed that they do not have any specific pre-tension procedures, other than tension the system sufficiently. Hence, a specific pre-tension had to be determined. This decision was based on that the pre-tension should be within the capacity of the capstan. The capacity of a capstan has a wide range, thus a capstan in the middle of the range was chosen, with a capacity of 3 tons (LORENTZEN HYDRAULIKK, 2019). To stay well within this capacity, a pre-tension of roughly 1 ton was applied to the model. An overview of the precise pre-tension in the individual lines is presented in table 7.4.

Table 7.4: Pre-tension of mooring lines between wellboat and cage-system

	Pre-tension [N]
Line 1	9904
Line 2	10380
Line 3	7830
Line 4	7803

7.4.1 Floating Collar

The floater is modelled with beam elements, which are assembled into a circular ring. In reality, the floating collar consists of two parallel pipes that are connected with a walkway in between. When the floating collar was defined in RIFLEX, it was simplified as one single pipe, with the properties of two pipes in parallel. The beam element accounts for axial forces, shear forces and torsion (RIFLEX Project Team, 2018).

7.4.2 Rope, chain and buoys

Rope, chain and buoys are modelled with bar elements with specified properties. Unlike the beam elements, bar elements only account for axial forces. The axial stiffness for the rope and the chain was determined by multiplying the E-modulus with the cross-section area. The buoys were assumed to not deform in the axial direction, thus the axial stiffness was set to a large value.

7.4.3 Design parameter

When the system is subjected to environmental loads, the vessel will have larger dynamic responses compared to the cage. These dynamic motions are transferred as axial forces in the mooring lines and eventually spread out to the mooring lines of the cage. Thus, the top end line motions on the vessel are of great interest as they are highly exposed to dynamic motions, and will therefore be the design parameter when deciding the operational limits.

The maximum allowed force in these mooring lines was set to one-third of their breaking strength, which corresponds to 170 [kN]. This criterion was decided in co-operation with supervisor Kjell Larsen. It is assumed that the design capacity of the attachment points is higher than the lines, thus these will not be any further discussed in this thesis.

In addition to the chosen design parameter, other parameters should also be taken into consideration when the operational limits are to be established, although these are not examined in this thesis. Among these parameters are:

- The axial forces in the bridles, anchor lines and frame mooring.
- Forces in the anchor lines. If the anchor line is subjected to large forces, the entire chain segment could be raised above the seabed. This would exert vertical forces on the anchor, which could drag the anchor out of its position. As a consequence, the leeward anchor lines would get correspondingly slacked and the risk for wear of the fibre rope segment due to seabed contact arises.
- Forces acting in the connection points between the wellboat and cage system. These include the coupling plate, mooring points on the vessel and the connection points on the floating collar.
- Snap loads may lead to wear in the vessel's mooring lines and hazard for the workers involved in the operation.
- Displacement of the wellboat relative to the cage. If the displacement becomes too large, the fish pumping pipes could be damaged and fish escapes and fatalities may be the outcome.
- Contact between the fish net and the hull of the vessel, as this increases the risk for impairing the net.
- Contact forces between the vessel and the floating collar, and associated deformations of the collar.

7.4.4 Environment

Waves, wind and current were implemented in the model with the purpose of finding operational limits based on the responses in the mooring lines between the wellboat and cage system. Although the fish net was not implemented in the simulation model, it was important to take into account how the current will affect the net. Following the industry's practice on how to moor such that the net is unable to drift into the thrusters of the wellboat, environmental loads in the following directions was applied; head sea (180 degrees), beam sea (270 degrees) and 225 degrees. Figure 7.7 presents the incoming wind, waves and current relative to the coordinate system of the vessel.

This thesis considers only conditions where incoming waves, wind and current approach from the same direction. In reality, these environmental loads often occur from different directions simultaneously. There will also be a correlation between the measured wind velocity and the wave data, which is not considered.

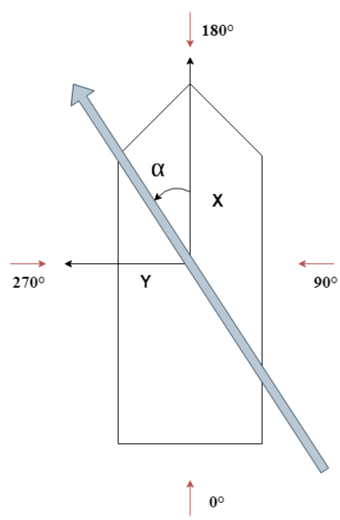


Figure 7.7: Coordinate system on the vessel relative to wave, wind and current directions (blue arrow)

Waves
The cross section of the floating collar must be defined as a partially submerged cross section by the software. This leads to a limitation in the software, which means that only regular waves could be applied to the model (RIFLEX Project Team, 2018). The regular waves applied are the extremes observed in irregular sea states. To obtain the

extremes, equation 6.15 found in section 6.2 could be used, with a duration of three hours. Consequently, this will lead to a more conservative approach of assessing the operational limits for the operation. The amplitude and period of the waves was applied in a range of 0.5-2 meters and 5-14 seconds, respectively.

Wind
The wind gust is described by using the NPD spectrum with a reference height of 10 meters and a height coefficient of 0.11. The wind was set to a velocity of 10 [m/s] which refers to fresh breeze according to Beaufort scale (NOAA, 2019).

Current
A uniform distributed current profile with a velocity of 0.5 and 1 [m/s] was applied. For the current directions, 270 and 225 degrees a velocity of 1 [m/s] caused too high axial forces in the mooring lines. Hence, a velocity of 0.5 [m/s] was applied in these directions to determine the operational limits, while a current velocity of 1 [m/s] was used for 180 degrees.

7.4.5 Simulation Runs

Simulations was performed to examine the system's sensitivities and variability of changes in the weather parameters by varying the following parameters; weather directions, wave amplitude and period, and with or without wind and current. Initially, a certain weather direction and wave amplitude was held constant, while wave periods were varied. When all wave periods in the range was performed, a new wave amplitude was set, and the same procedure with varying periods was carried out. When all periods for all the amplitudes in the range was simulated, wind and current was applied for a wave amplitude in the range of 0.5-2 meters. To determine which periods to use, the previously obtained results for wave amplitude of 1 meter was used. The periods showing the highest axial force without crossing the limit was chosen. This procedure was then repeated for the remaining weather directions. As previously mentioned, the industry does not have any specific procedures on how to pre-tension the lines, other than providing sufficient tightening. The system's sensitivity with respect to pre-tension was examined by comparing the effect of applying a low amount of pre-tension, with an estimated normal amount.

The results from the simulation was extracted from a range where the transients had been damped out, and steady state was obtained. The number of integration time steps per period was set to 1500.

Chapter 8

Verification of Numerical Model

To verify that the wellboat used in the simulations is within reasonable values, tests were performed, and coefficients for wind, current along with wave drift forces and RAOs were plotted for analysis. The tests include a free-decay test and a static pull-out test which will be further elaborated. The mooring system imposes stiffness to the vessel in surge, sway and yaw motion, thus these motions are of special interest.

8.1 Quadratic Wind and Current Coefficients

The current and wind forces acting on the vessel are extracted from appendix D.4 and E.5 for 1 knot and 20 m/s, respectively. These values were extracted from Ronja Polaris as similar values were not available for MachoShip4500. The quadratic coefficients were calculated by equation 8.1, and inserted into the kinematic properties of MachoShip4500 in SIMA. Since these values originate from Ronja Polaris, they constitute as an inaccuracy during simulations.

$$F_D = \frac{1}{2}\rho C_D A u^2 \quad \rightarrow F = C\,u^2 \tag{8.1}$$

Where,

ρ = Density of water/air

F_D = Environmental drag force

C_D = Drag coefficient

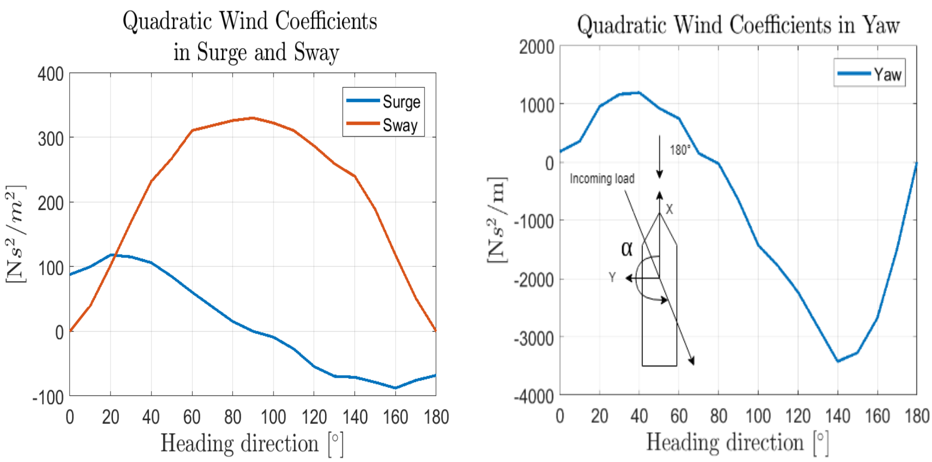
A = Reference area

u = Flow velocity relative to the object

The quadratic wind coefficients for surge and sway are plotted in figure 8.1a. The vessel is assumed to be symmetric about the x-axis and therefore the coefficients are plotted from 0-180 degrees. As indicated by the figure, the quadratic wind coefficient for sway motion has a value of zero at 0 and 180 degrees. The reason is that the wind in these directions will only have a positive or negative x-component and the y-component will be zero, hence there will be no response in the y-direction. The largest quadratic wind coefficient in sway is found at 90 degrees, as the x-component is zero. When wind is approaching at 90 degrees, the associated area of the vessel is at its maximum, resulting in a large quadratic wind coefficient.

In surge motion, the quadratic wind coefficient will have its maximum value at roughly 20 and 160 degrees. At these angles, the incoming wind will have its greatest impact, possibly due to a combination of the angle and the shape of the topside and superstructure. At 90 degrees, the wind vector has zero x-component, resulting in a quadratic wind coefficient in surge of zero.

Figure 8.1b presents the quadratic wind coefficients in yaw for angles ranging from 0 to 180 degrees. The sign of the coefficient change at 80 degrees and the highest negative value is approximately three times greater than the highest positive value. This may result from the shape and the area distribution of the topside and superstructure. Figure 8.1b indicates that the coefficient value is not zero at 0 degrees, while at 180 degrees, the value is zero. This may be a result of asymmetry about the vessel's x-axis if viewed from the rear.

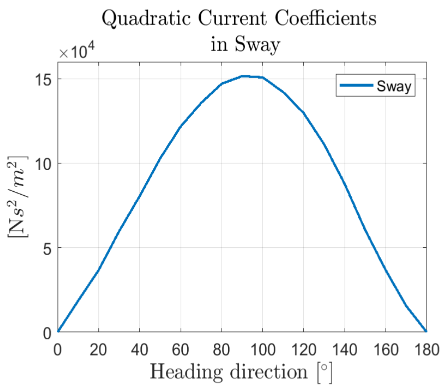


(a) **(b)**

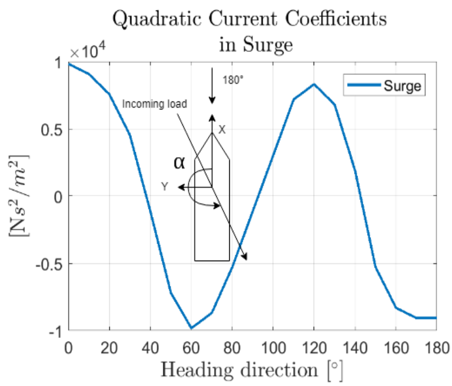
Figure 8.1: Quadratic wind coefficients

For the quadratic current coefficients presented in figure 8.2a, it could be found that the shape of the sway coefficient is similar to the quadratic wind coefficient in sway, with values of zero at 0 and 180 and a maximum value at 90 degrees. The figure also indicates that the magnitude of the current coefficients is higher than the wind coefficients. If equation 8.1 is studied, it is shown that the magnitude of the quadratic coefficient is proportional to the density of the medium. Since water has a significantly higher density than air, the quadratic current coefficients are correspondingly higher.

As presented in figure 8.2b, the quadratic current coefficient in surge is somewhat different from the corresponding wind coefficient. For a heading direction of 0, 60, 120 and 180 degrees, the quadratic current coefficient is at its largest. Following the same argumentation as for the quadratic wind coefficient in surge, a heading direction of 0 and 180 degrees should be among the highest values. The peaks at 60 and 120 degrees could be a result of vortex shedding around the hull which affects the inflow and reaction pattern. At 90 degrees the coefficient has a value of zero due to zero x-component.



(a) Sway



(b) Surge

Figure 8.2: Quadratic current coefficients in sway and surge

Figure 8.3 shows the quadratic current coefficient in yaw. Compared to the figure illustrating the quadratic wind coefficient in yaw, the current coefficient is similar in shape but mirrored. Both figures are zero at 0 and 180 degrees. For incoming current between 0 and roughly 80 degrees, the yaw moment is negative, hence clockwise. Whether the slope is positive or negative depends on the geometry of the hull.

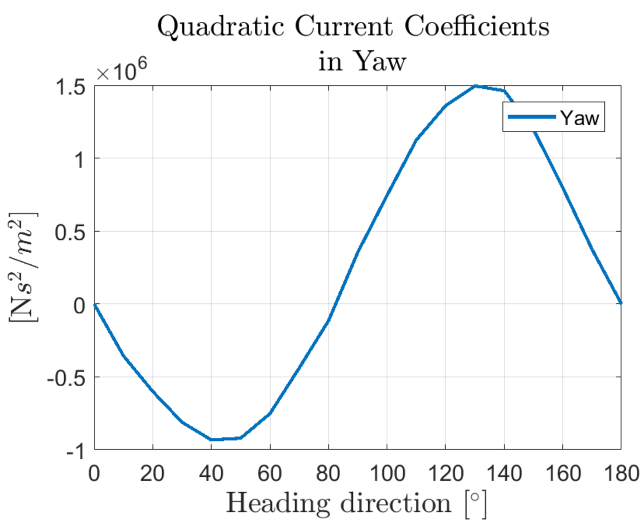


Figure 8.3: Quadratic current coefficient in yaw

8.2 Wave Drift Force Coefficient

Wave drift forces are slowly varying second order forces that occur on difference frequencies (ω_i-ω_j). The mean wave drift force and coefficient could be written as presented in equation 8.2.

$$\overline{q}_{wa}(\omega) = c_{wa}(\omega) \cdot \eta_a^2 \quad \Rightarrow \quad c_{wa}(\omega) = \frac{\overline{q}_{wa}(\omega)}{\eta_a^2} \tag{8.2}$$

Where,
$\overline{q}_{wa}(\omega)$ = Mean wave drift force
$c_{wa}(\omega)$ = Mean wave drift force coefficient
η_a = Wave amplitude

In the following figure 8.4 the wave drift coefficients are plotted for surge, sway and yaw for 180, 225 and 270 degrees. A common feature for all the three figures is that for large periods, the wave drift force is approaching zero. At such large periods, the vessel follows the motion of the waves, thus the waves do not have any impact on the vessel. For short periods, the vessel will appear as a solid wall inducing large forces to the system.

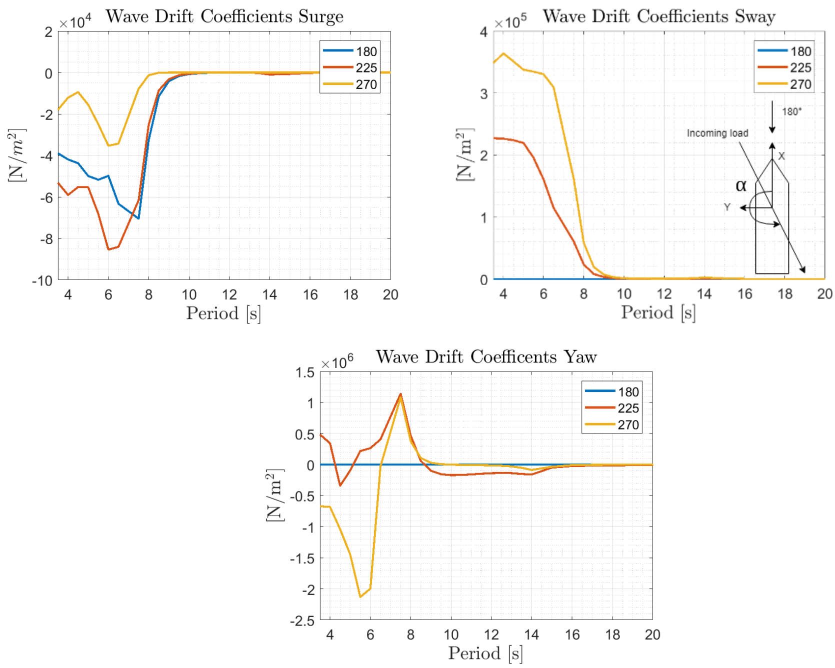


Figure 8.4: Wave drift forces

It is also observable in figure 8.4, that the wave drift force in sway and yaw is zero for incoming waves at 180 degrees. This is due to the symmetry of the vessel about the xz-plane, which means that an incoming force at 180 degrees will have no contribution in the y-direction nor be able to create a moment about the z-axis. The wave drift coefficients for heave, roll and pitch are zero for all degrees, thus these are not plotted.

8.3 Response Amplitude Operator (RAO)

A Response Amplitude Operator (*RAO*) is the transfer function of the body motions amplitude and could be defined as presented in equation 8.3 (Greco, 2012). The RAO's for all six degrees of freedom are plotted as a function of period with a range from 0-30 seconds for 180, 225 and 270 degrees.

$$|H(\omega, \theta)| = \frac{\eta_a}{\zeta_a} \tag{8.3}$$

Where,
η_a = Dynamic motion of vessel
ζ_a = Wave amplitude

The RAOs for the vessel in surge motion is presented in figure 8.5. It is observable that the RAO in head sea approach 1 [m/m] for periods larger than 20 seconds. This means that the vessel's motion amplitude in surge is equal to the wave amplitude. For wave periods shorter than 7 seconds the RAOs are small. Thus, the waves pass the vessel without the vessel managing to react.

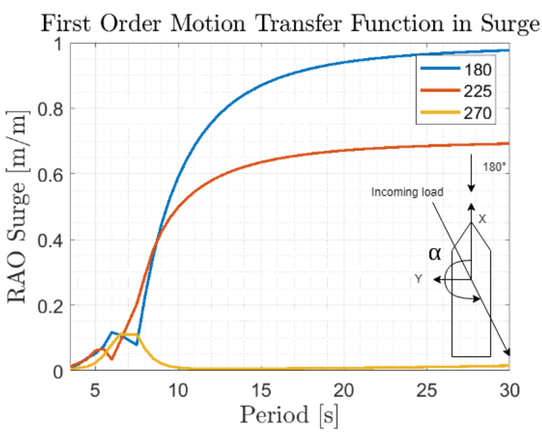


Figure 8.5: First order motion transfer function in surge

Figure 8.6 displays the RAOs for sway motion. As the graph indicates, the highest RAO is found for incoming waves at 270 degrees, where the value is approaching 1 [m/m]. For head sea the vessel's motion is unaffected, thus the RAO is zero. The remaining degrees for incoming waves have amplitudes between these two extremes.

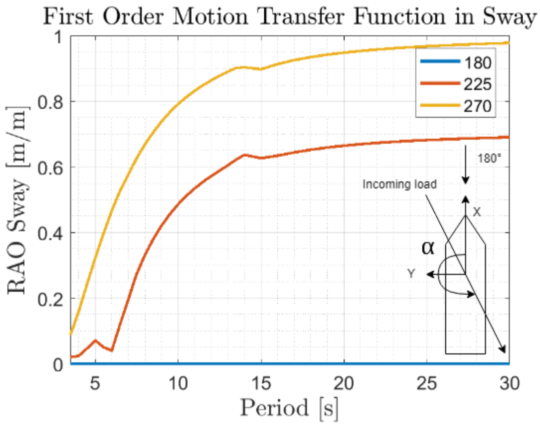


Figure 8.6: First order motion transfer function in sway

The RAOs for heave motion of the vessel are presented in figure 8.7. The peak at approximately 7.5 seconds indicates resonance, which means that the vessel has a natural period at this point. The highest RAO is 1.6 [m/m] at 270 degrees, hence the vessel's response is 60% larger than the incoming wave amplitude. For higher periods, the vessel's motion in heave relative to the wave amplitude for all incoming wave directions approach 1 [m/m].

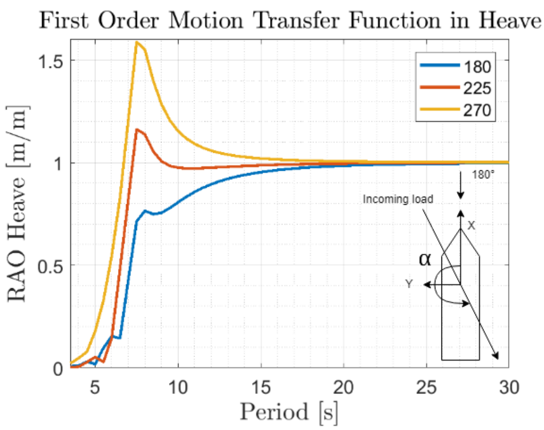


Figure 8.7: First order motion transfer function in heave

Figure 8.8 displays the RAOs for roll motion. As observed, there is a peak for roll that indicates a natural period at 14 seconds. The largest RAO is found for an incoming wave at 225 degrees with a value of 8.8 [deg/m]. For incoming waves at 180 degrees, the response amplitude is zero, because the vessel will not initiate roll motion for these waves.

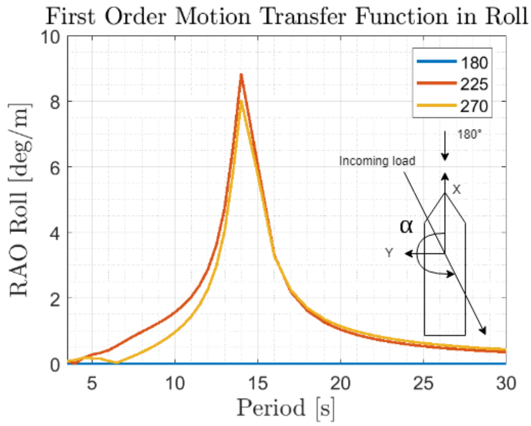


Figure 8.8: First order motion transfer function in roll

The RAOs for pitch motion are presented in figure 8.9. Large RAOs are observed at periods of roughly 8 seconds. At this period the wavelength is approximately equal to the length of the vessel, which will induce large pitch motions. The largest RAO is 2.8 [deg/m], for incoming waves at 180 degrees. For long wave periods, the response amplitude approaches a negligibly small value.

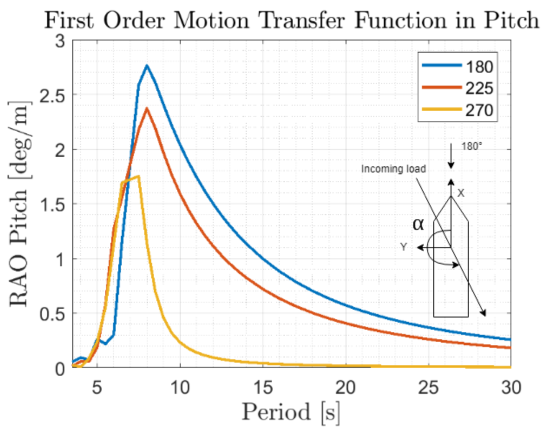


Figure 8.9: First order motion transfer function in pitch

Figure 8.10 presents the RAOs for yaw motion. A prominent peak could be observed at 8 seconds for an incoming wave direction of 225 degrees, where the RAO is roughly 1 [deg/m]. As the period increase, the response amplitudes are approaching 0.1 [deg/m], except for incoming waves at 180 degrees, where the response is zero for all periods.

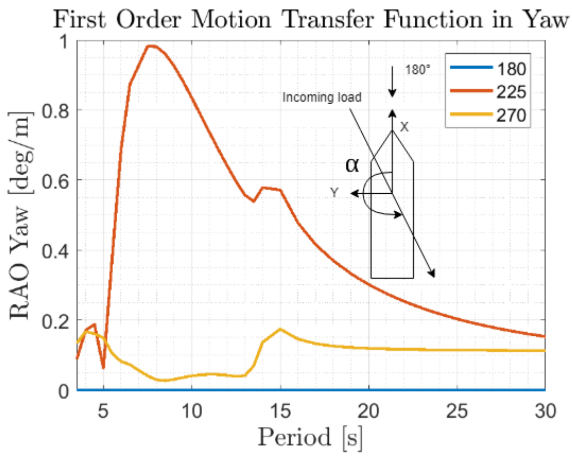
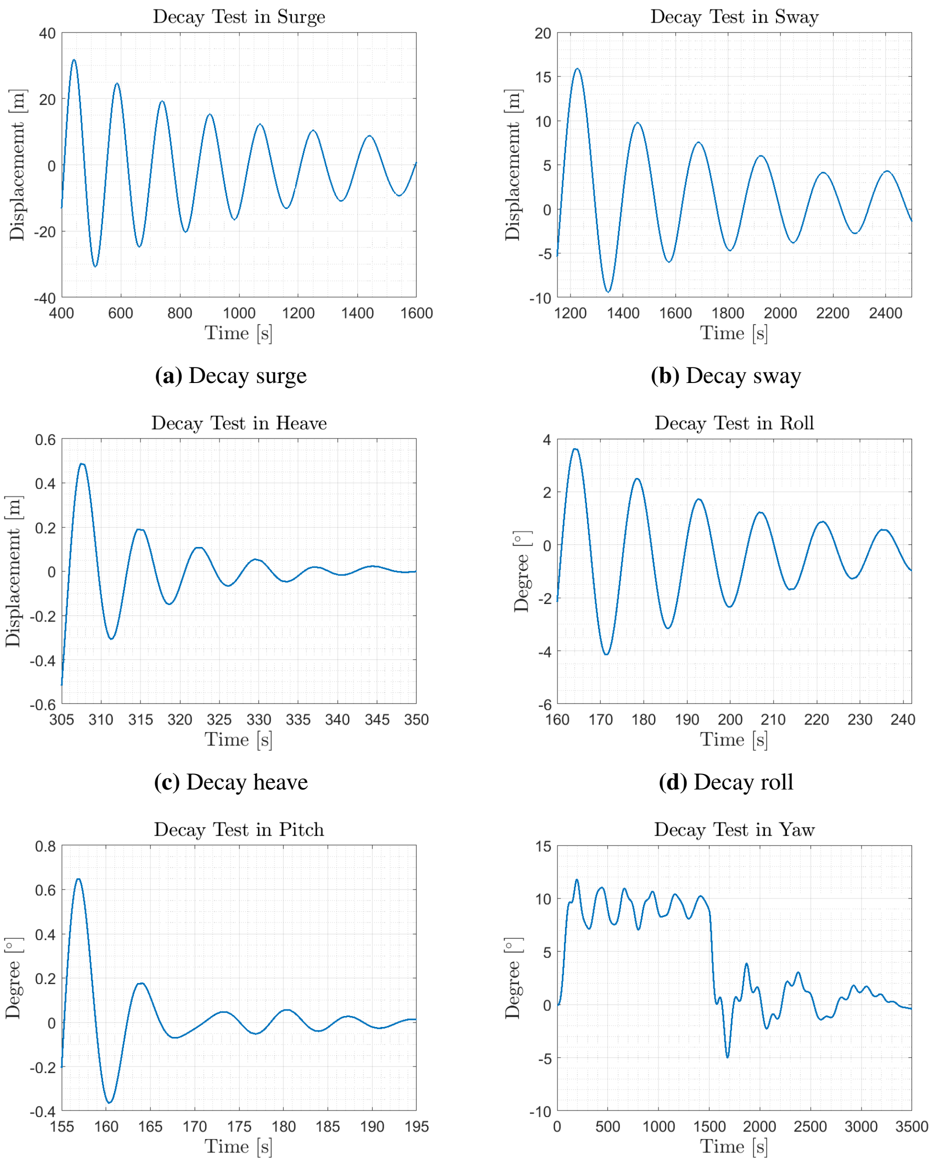


Figure 8.10: First order motion transfer function in yaw

8.4 Free-Decay Test

A decay test was performed to find the natural periods of the system in all six degrees of freedom. By performing these tests, the damping, damping ratio and the critical damping of the system were found. For a decay test, a force or a moment is applied to the vessel in a desired direction. The tests are performed in SIMO-RIFLEX, and the force or moment is applied stepwise through a ramp force for a preset time until the system is loaded by a desired amount. This force or moment is held for a given amount of time before the vessel is released, and the system oscillates freely until it finds its equilibrium. The results from the test were extracted from SIMO-RIFLEX and processed in MATLAB. These results are presented for all six degrees of freedom in figure 8.11.



(a) Decay surge

(b) Decay sway

(c) Decay heave

(d) Decay roll

(e) Decay pitch

(f) Decay yaw

Figure 8.11: Decay tests in all six degree of freedom

The natural periods were found from the graphs as the distance between two peaks on the decay graph. An average from a selection of peaks was used to find the natural period for the different degrees of freedom. The critical damping of the system was found by equation 8.4, which contains the natural period of the system.

$$C_{cr} = 2 \cdot m \cdot \omega_0 = 2 \cdot (M + A) \cdot \frac{2\pi}{T_n} \tag{8.4}$$

where,
C_{cr} = Critical damping
m = Total mass
M = Structural mass
A = Added mass
ω_0 = Natural frequency
T_n = Natural period

To find the damping and the damping ratio, the logarithmic decrement Λ must be found from equation 8.5. The logarithmic decrement describes a relation between the amplitude at time t_i and t_i+t_d. If the damping ratio ξ is less than 0.2, the logarithmic decrement may be written as equation 8.6, and with this as a basis, ξ could be found. Because the damping ratio states the relation between the damping and the critical damping, it could be solved for the damping, as shown in equation 8.7 (Steen, 2014).

$$\Lambda = ln\frac{x_i}{x_{i+1}} \tag{8.5}$$

$$\Lambda \simeq 2\pi\xi \Rightarrow \ \xi = \frac{\Lambda}{2\pi} \tag{8.6}$$

$$\xi = \frac{c}{c_{cr}} \Rightarrow \ c = c_{cr} \cdot \xi \tag{8.7}$$

The natural periods, the damping, the critical damping and the damping ratio is presented in table 8.1 for all degrees of freedom. The decay graph for yaw (figure 8.11f) was studied and several peaks having different amplitudes were observed in the time range 1500-3500 seconds. To identify the periods within this range, a Fast Fourier Transform (*FFT*) was performed by using the post-processing tool in SIMA. The result from the FFT is presented in figure 8.12, showing periods at 126 and 546 seconds. These periods may result from coupling forces between different degrees of freedom. The time range of 0-1500 seconds in figure 8.11f illustrates the system being ramped up and held at a constant force. Within this range, a period of roughly 243 seconds is observable, which could be considered to be the natural period of the system in yaw.

Table 8.1: Results from the decay test

	Natural period [s]	**Damping, c [kN/m]**	**Critical Damping, c_{cr} [kN/m]**	**Damping ratio [-]**
Surge	185	26.5	744	0.036
Sway	235	52	961	0.054
Heave	7.4	3858	33416	0.115
Roll	14.3	37097	581181	0.064
Pitch	7.4	2991987	1.44e+07	0.21
Yaw	243	1541	338743	0.00455

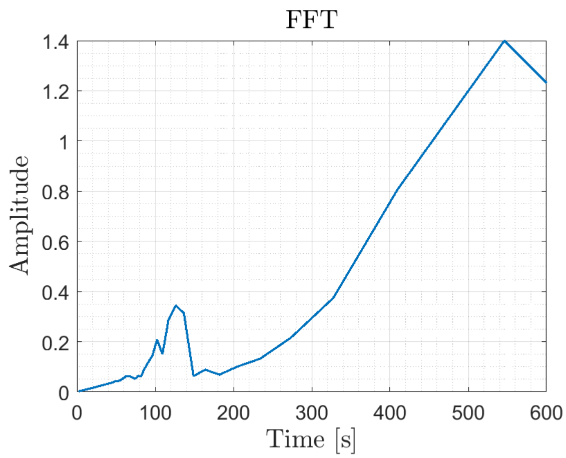


Figure 8.12: Fast Fourier Transform of yaw decay

Linear damping was added to the model in surge, sway, roll and yaw.

- Surge ≈ 2 % of critical damping.
- Sway ≈ 1.5 % of critical damping.
- Roll ≈ 5 % of critical damping.
- Yaw ≈ 6 % of critical damping.

Quadratic damping are in addition to the linear damping added in yaw as 2.95e+09 [Ns^2m]. This was calculated by the use of equation 8.8.

$$D_{q_{yaw}} = \frac{1}{32} \cdot C_2^{90} \cdot L^3 \tag{8.8}$$

Where,
C_2^{90} = Current coefficient for yaw 90 degrees
L^3 = Length of the wellboat

As shown by the decay test in yaw, the period is large when the system is oscillating freely, thus the yaw-velocity is small. As the quadratic damping is a function of the velocity in the power of two, the quadratic damping term will have a very small contribution to the total damping compared to the linear damping for small velocities.

To check whether the natural periods found in the decay tests were correct, hand calculations were performed in accordance with equation 8.9. These calculations were done for heave, roll and pitch, as the mass, added mass and stiffness K was known from SIMA. To perform hand calculations for the remaining degrees of freedom, K had to be found by conducting a pull-out test, which is further described in section 8.5. The results from the hand calculations for heave, roll and pitch are presented in table 8.2 along with the result from the decay tests. As presented, the results from the decay tests are slightly larger than the natural periods obtained from hand calculations. This may be because equation 8.9 used for the hand calculations does not include any damping in the system, which in reality is present. It should also be noted that the values presented in table 8.2 correlates well with the natural periods found from the RAO analysis, where the natural periods for heave, roll and pitch was found to be approximately 7.5, 14 and 8 seconds respectively. A natural period of 14 seconds in roll indicates that the vessel is soft (low stiffness) about the x-axis, which imply that the metacentric height (GM) is relatively low.

$$T_0 = 2\pi\sqrt{\frac{M+A}{K}} \tag{8.9}$$

Table 8.2: Natural periods both from hand-calculations and decay-tests

	T_0 **from hand calculations [s]**	T_0 **from decay-test [s]**
Heave	7.2	7.4
Roll	14.1	14.3
Pitch	6.9	7.4

8.5 Pull-Out Test

A pull-out test has been conducted to find the system characteristics, by assigning a force or a moment in a given direction for a certain amount of time. Thus, it is possible to observe which restoring force that corresponds to a given offset in meters or degrees. The test was performed in surge, sway and yaw to find the stiffness which later was used to calculate the natural periods by hand. These results could then be used to verify if the natural periods found from the decay-tests corresponds. The force in surge was applied in the positive x-direction, sway in the positive y-direction and the yaw moment was applied in the counter-clockwise direction.

The results from the pull-out tests are plotted in figure 8.13 and 8.14. All three graphs are relatively linear, indicating that the system is characterized by elastic stiffness. As illustrated by figure 8.13, the stiffness in surge and sway are similar. This is expected as it is the same mooring lines that are constraining the wellboat in both surge and sway motion.

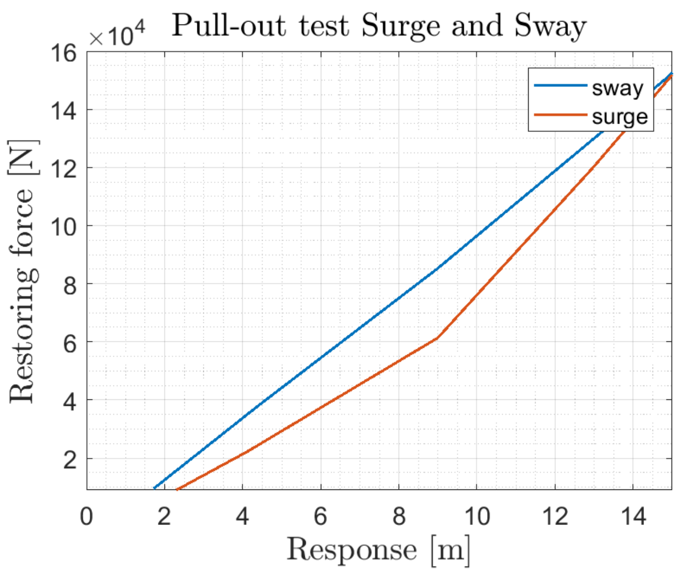


Figure 8.13: Pull-out test in surge and sway

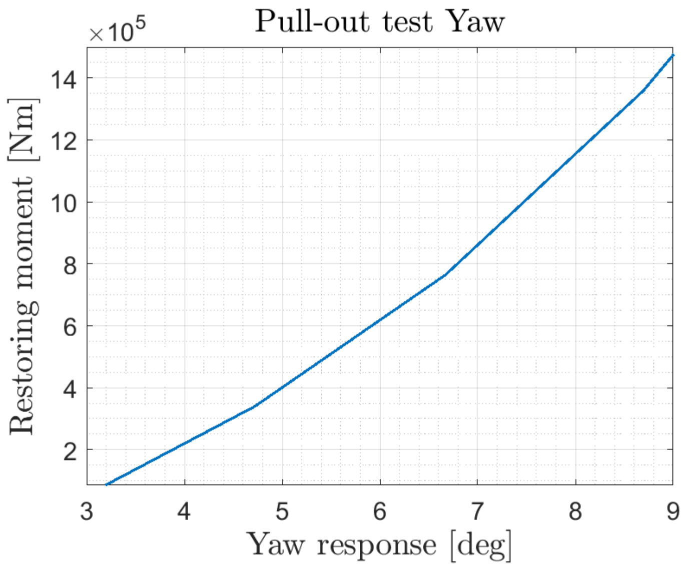


Figure 8.14: Pull-out test in yaw

The stiffness in surge, sway and yaw were obtained by calculating the slope of the pull-out test curve at a selected point. To compare the natural periods obtained from the pull-out test with those obtained from the decay-test, the stiffness must be calculated from approximately the same offset applied to the vessel in the decay-test. The natural periods calculated by equation 8.9 is presented by table 8.3, where the stiffness obtained from the pull-out test is applied.

As presented by table 8.3, the natural periods obtained by hand calculations correspond well with the natural periods obtained from the decay-tests in surge, sway and yaw.

Table 8.3: Presents the natural periods found from the decay tests and the hand-calculations, where the stiffness is obtained from the pull-out tests.

	T_0 **hand-calculation [s]**	T_0 **from decay-test [s]**
Surge	182	185
Sway	234	235
Yaw	180	126, 243, 546

The wellboat analysed in this thesis is moored using two lines connected to the floating collar and two lines connected to their nearest coupling plate. In this way, the system is not fixed, but rather connected to other components with individual mass contributions, shown in figure 8.15. As a consequence of this, the system has a higher mass than the wellboat itself. This could lead to higher natural periods for the system compared to the natural periods calculated by hand, as the hand calculations only included the mass of the vessel. This may be the case for yaw, as the natural period calculated by hand (180 seconds) was considerably lower than the natural period of 243 seconds found from the decay test.

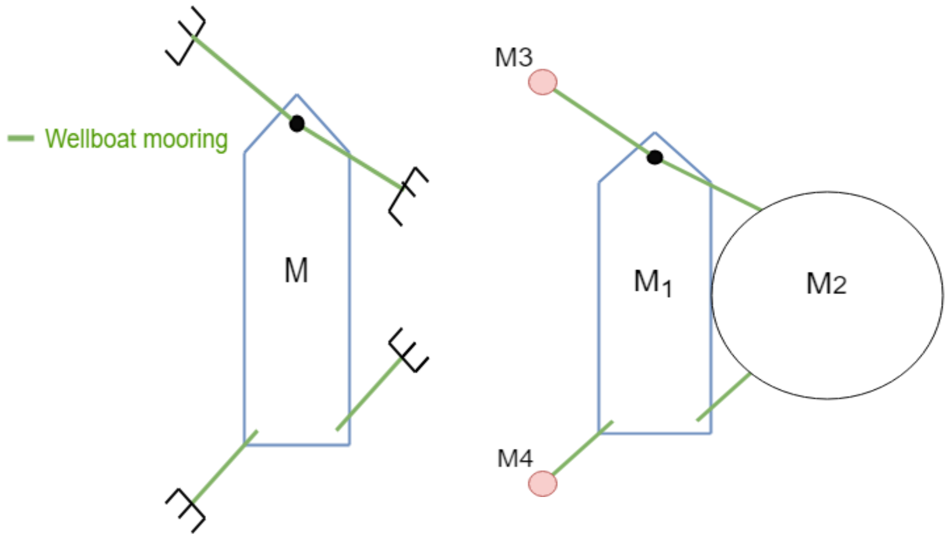


Figure 8.15: (Left) Illustrates a simplified model of the wellboat mooring if the attachment points were fixed (Right) Illustrates a simplified model of the wellboat mooring.

Chapter 9

Results and Discussion

The results obtained from the simulation study has been used to establish operational limits for a wellboat operation in the aquaculture industry. The variability and sensitivities in terms of changes in the weather parameters and the degree of pre-tension are presented and discussed. Eventually, essential remarks are emphasized.

9.1 Verification of Simulation Results

External weather with exposure from waves, wind and current was applied to the model. To verify whether the results of the simulations are realistic, an investigation was carried out with focus on the RAOs, forces and responses. This was done for all simulation results, but only one of them is presented here to show the procedure. The result investigated is exposed to head sea. The wave period was set to 8 seconds and the wave amplitude was 1 meter, while the current velocity was set to 1 [m/s].

Response Amplitude Operator

The RAOs of the wellboat shall match the responses found from the dynamic analysis. Figure 9.1 illustrates the response in surge, heave and pitch respectively, obtained from SIMA. As explained in section 8.3, the remaining degrees of freedom give an RAO for 180 degrees equal to zero.

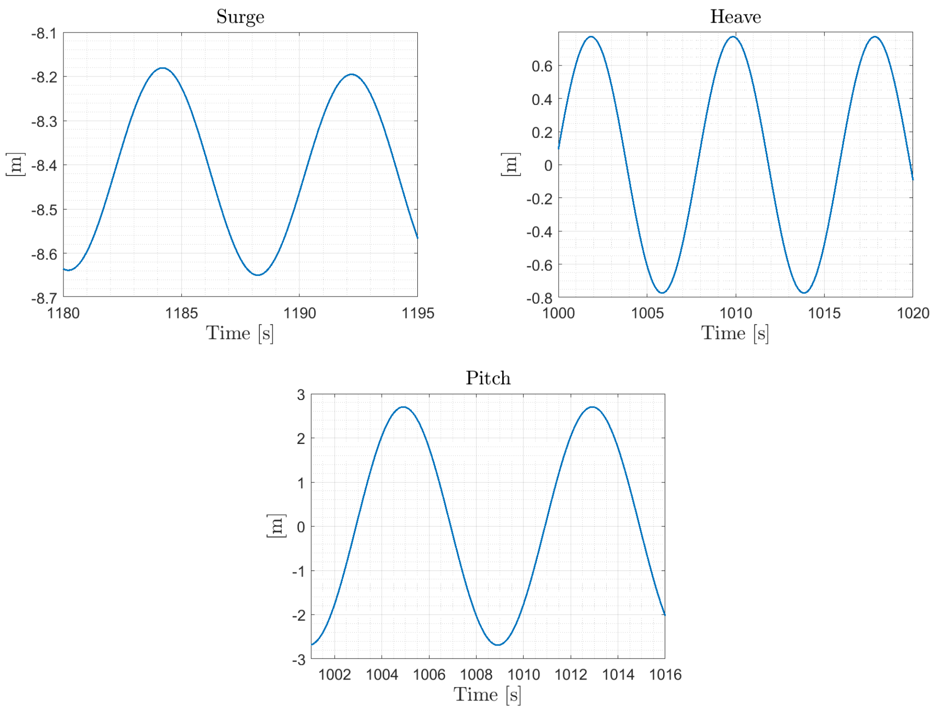


Figure 9.1: Dynamic response from simulations in surge, heave and pitch for a wave period of 8 seconds

As the RAO and wave amplitude was known, equation 8.3 could be used to solve for the dynamic response of the vessel. This calculated response shall correspond to the response of the vessel obtained in the dynamic simulation. By extracting the RAOs at 8 seconds from the figures 8.5, 8.7 and 8.9 in surge, heave and pitch, the values 0.2, 0.75 and 2.9 are found. With an amplitude of 1 meter, the response of the vessel shall be equal to the respective RAO value. This was confirmed by comparing the aforementioned values by the plots shown in figure 9.1.

Forces

The forces acting on the system from waves, current and wind could be estimated and used to find the forces which the mooring lines must absorb to keep the system stationary. In this case, both wave drift forces and current forces are present. From figure 8.4 presenting the wave drift forces in surge at 180 degrees, this force should be roughly 35 [kN] for a wave amplitude of 1 meter. From figure 8.2b the quadratic current coefficient in surge at 180 degrees is approximately 9 [kN]. Hence, the forces acting on the vessel from current with a velocity of 1 [m/s] is 9 [kN]. The total force acting is then estimated to be 44 [kN].

From the dynamic simulation, the forces acting in the mooring lines could be analyzed. An estimate of the mean forces acting in each line is presented in figure 9.2. As illustrated by the figure, the forces in the mooring lines seem reasonable compared to the environmental forces. For incoming waves at 180 degrees, the vessel will move in the negative x-direction, providing tension to mooring line 1 and 4. Intuitively, mooring line 2 and 3 should get less tensioned compared to mooring line 1 and 4. This is the case for mooring line 2, but not for 3. The reason may be that the vessel is subjected to some yaw moment due to asymmetry in the mooring line configuration.

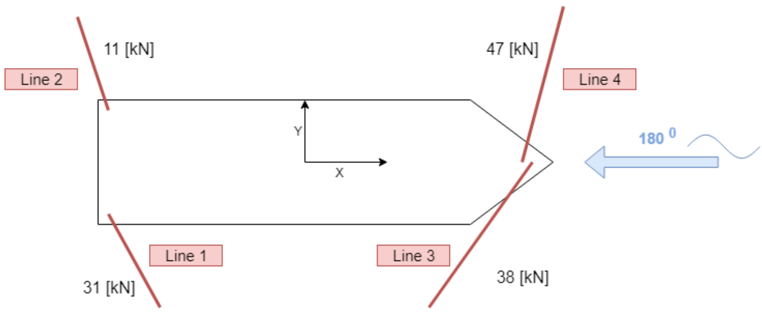


Figure 9.2: Illustration of the mean forces in the mooring lines when the wave amplitude is 1 meter, the wave period is 8 seconds and the current velocity is 1 [m/s]

The dynamic analysis shows that the vessel obtains a yaw-angle of roughly 8 degrees after 600 seconds, seen in figure 9.3. This means that when there is head sea, a part of the vessel's side will be subjected to forces. As the current force coefficients in sway and yaw will become nonzero, the total magnitude of the forces acting on the wellboat will increase. The quadratic current coefficients in sway and yaw were obtained from figure 8.2a and 8.3. While studying figure 9.3, it is observable that the vessel has an initial yaw angle of -1.7 degrees. This indicates that a small rotation of the vessel is necessary to obtain equilibrium between the mooring lines connecting the vessel to the cage system.

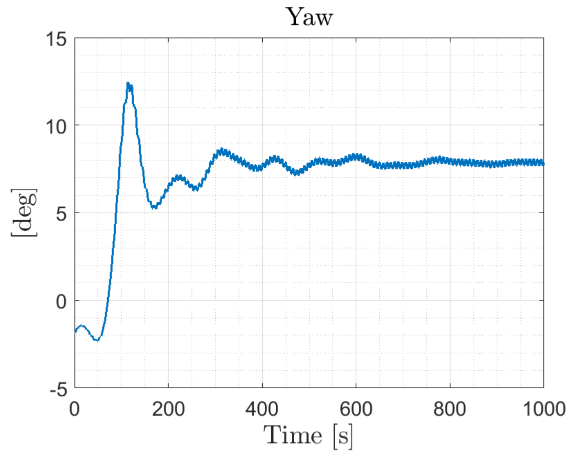


Figure 9.3: Yaw response for head sea, when the wave amplitude is 1 meter, the wave period is 8 seconds and the current velocity is 1 [m/s]

Responses

When head sea is approaching, it is interesting to study the surge motion of the vessel, plotted in figure 9.4. For environmental forces of 44 [kN] acting from current and waves, the vessel has an average displacement of eight meters in the negative x-direction. To verify this result, the pull-out test in surge (figure 8.13) could be used, which confirms that these results correspond. From the response of the wellboat illustrated by figure 9.4, the system seems to be influenced by both low-frequency- and wave-frequency motions.

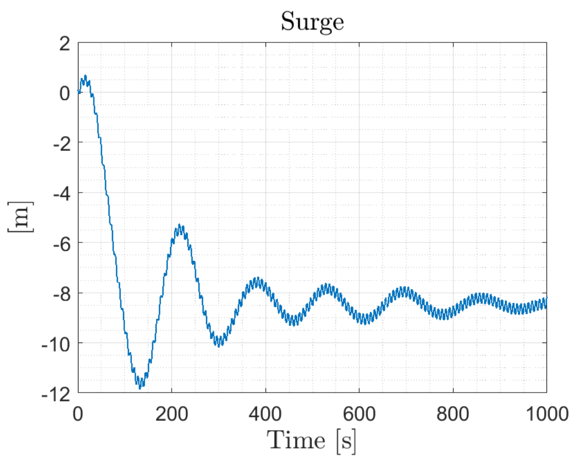


Figure 9.4: The surge response as a function of time when the system is subjected by current- and wave drift forces

In addition to the constant force provided by the current force, the current force also contributes to a low-frequency damping force. Figure 9.5 shows the motion of a system where the wave amplitude is defined as 1 meter, the wave period is 8 seconds and no current forces are applied. In figure 9.4 the current forces damp out the low-frequency wave motions which is more prominent in figure 9.5.

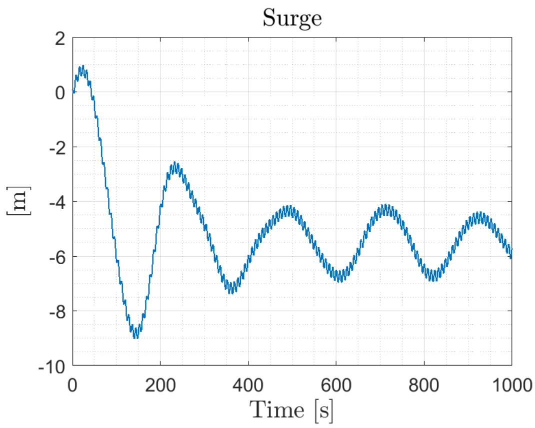


Figure 9.5: The surge response as a function of time when the system is only subjected to wave drift forces

As mentioned above, the vessel is subjected to an initial yaw angle. Consequently, the current and wave forces exert a force component in the y-direction providing a displacement of 0.9 meters in sway-direction. The response plot in sway direction is presented in figure 9.6. In addition, a rotational displacement in roll occurs, due to a moment created by the environmental forces and the forces provided by the mooring lines. This could be observed in figure 9.6, as well as an initial roll angle of 1.9 degrees, originating from the static equilibrium.

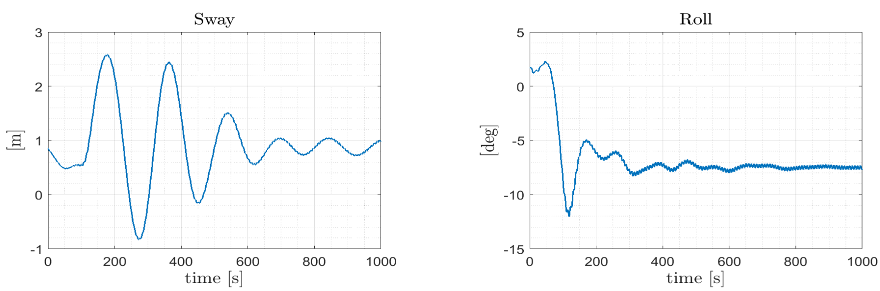


Figure 9.6: Sway and roll response for a wave amplitude of 1 meter, wave period of 8 seconds and a current velocity of 1 [m/s]

9.2 Axial Forces in the Mooring Lines

The figures 9.8, 9.11 and 9.13 represents the results for the simulations with incoming waves at 180, 225 and 270 degrees respectively, where waves are the only applied loads. The wave amplitude was held constant while the period, represented by the x-axis, was varied between 5-14 seconds. The y-axis represents the axial force in newton and was extracted from the mooring line's top end. The maximum allowed axial force in the mooring lines were plotted as a constant line with a value of 170 [kN]. Only a selection of the mooring lines was plotted on each figure. These lines have the highest observed axial forces for the given load case. Thus, these forces will be decisive when the operational limits are to be established.

The figures 9.9, 9.12 and 9.14 represents the mooring line tension when wind and current loads were applied, in addition to waves. In this case, the wave period was held constant, while the amplitude was varied between 0.5 and 2 meters. The decision of which wave period to choose was based on the plots where only waves were applied, with an amplitude of 1 meter. The period where the graph was close to the force limit without crossing it, was the one used when current and wind loads were applied.

The industry does not have any specific pre-tension procedures, other than tightening the mooring lines sufficiently. Therefore, it is interesting to evaluate the system's sensitivity to the degree of pre-tension in these lines. At the end of this section, these results will be presented and discussed.

9.2.1 Environmental Load Direction 180°

Figure 9.7 presents the time series for waves approaching from 180 degrees with an amplitude of 1 meter and a period of 7 seconds. The time series shows the response when transient effects have been sufficiently damped. The red line indicating the mean force acting in the mooring line represents the applied pre-tension and the forces from the mean wave drift forces. If wind and current were applied in addition to waves, these forces would also have contributed to the mean force. The blue oscillating curve represents the mean force added with the dynamic loads acting in the mooring line. The figures 9.8-9.14 (except figure 9.10) are based on data collected from the time series.

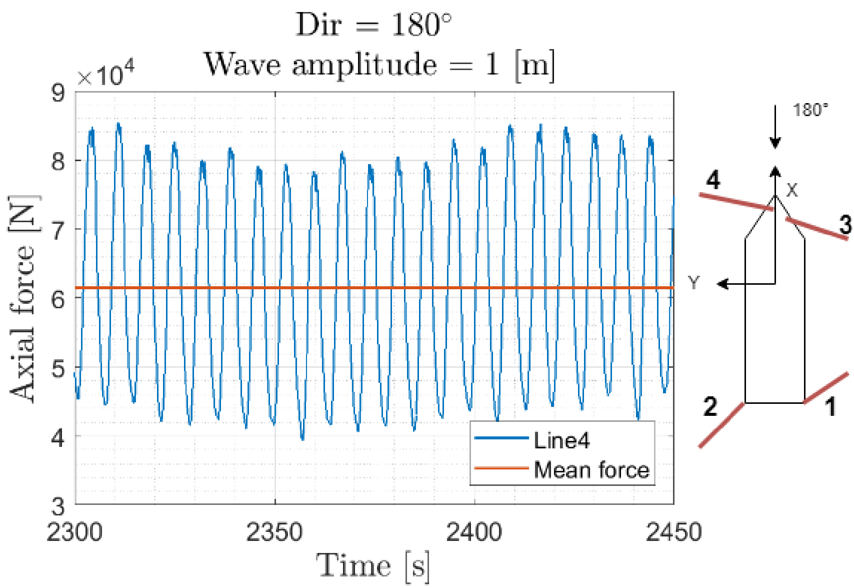


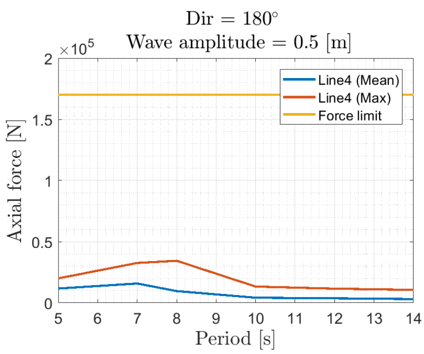
Figure 9.7: Time series for the axial force in mooring line four, with wave direction of 180 degrees, amplitude of 1 meter and a wave period of 7 seconds

Figure 9.8a presents how the axial force in mooring line number four varies as a function of wave period for an amplitude of 0.5 meters. As illustrated, the axial forces are well below the force limit, thus an operation could safely take place. This is also the case for a wave amplitude of 1 meter, presented by figure 9.8b. However, the forces acting at wave amplitudes of 1 meter are higher than those for an amplitude of 0.5 meters. This is due to a larger contribution from the wave drift forces, which are proportional to the wave amplitude squared, described in section 8.2. Figure 9.8 also illustrates that the wave drift forces are prominent for periods below 9 seconds. For higher periods, the graphs tend to flat out, which is in accordance with the magnitude of the wave drift force, which approach zero for high periods. This observation applies for all wave directions.

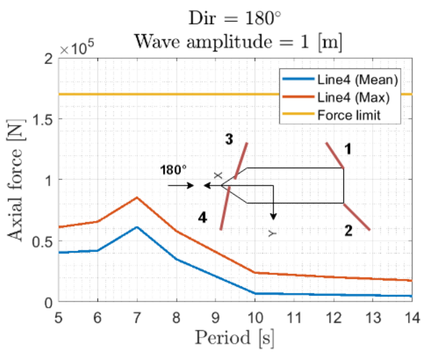
For a wave amplitude of 1.5 meters, the maximum axial force in line four exceeds the force limit for wave periods between 6.2-7.7 seconds, illustrated by figure 9.8c. Thus, the operational limit for this load case is at a period of 6.2 and 7.7 seconds. It is observable that for periods below 6.2 seconds, the axial force in the mooring line is close to the force limit, while for periods higher than 7.7 seconds, the forces decrease more rapidly. Figure 9.8d illustrates the forces acting in line four when a wave amplitude of 2 meters is applied. For this load case, the operational limit is at a period of 7.7 seconds, thus an operation should not take place below this period.

For a period of 7 seconds a peak is observed, most prominent on figure 9.8b and 9.8c presenting wave amplitudes of 1 meter and 1.5 meters. The period for this peak corresponds well with the period giving the highest wave drift force for an incoming wave at 180 degrees, presented by figure 8.4 in section 8.2. Also, as presented in section 8.4 both pitch and heave have a natural period at approximately 7 seconds. The RAOs for these degrees of freedom are given in section 8.3. When comparing the RAOs for heave and pitch, it is observable that pitch has the greatest contribution to system response when incoming waves at 180 degrees with a period of 7 seconds are considered.

The importance of including the dynamic response in the lines is illustrated by the figures. If only the mean axial force had been studied, an operation could take place for all wave periods when the wave amplitude is 1.5 meters. Thus, it will be expedient to consider the operational limit based on the maximum measured force in the lines.



(a)



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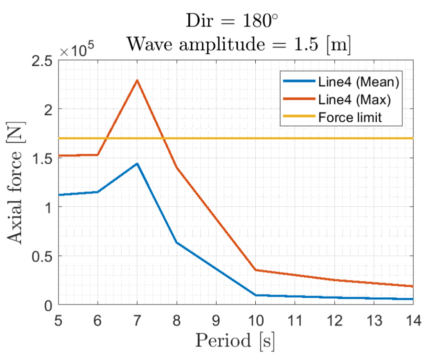
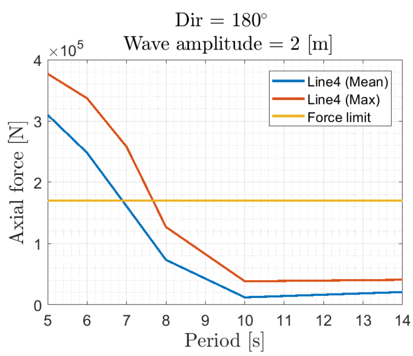


(c)



(d)

Figure 9.8: Mooring line axial force response for environmental load direction 180°, when only waves are applied

For a wave period of 7 seconds, the operational limit was re-studied by adding current and wind with a velocity of 1 and 10 [m/s] respectively, as presented in figure 9.9. In this case, an operational limit where the wave amplitude is 1.2 meters could be defined. Current and wind provide a constant force contribution in addition to the wave drift force, which the mooring lines have to absorb. This can be observed by comparing the forces acting at a wave amplitude of 1 meter in figure 9.9 with the forces acting in figure 9.8b when the period is 7 seconds.

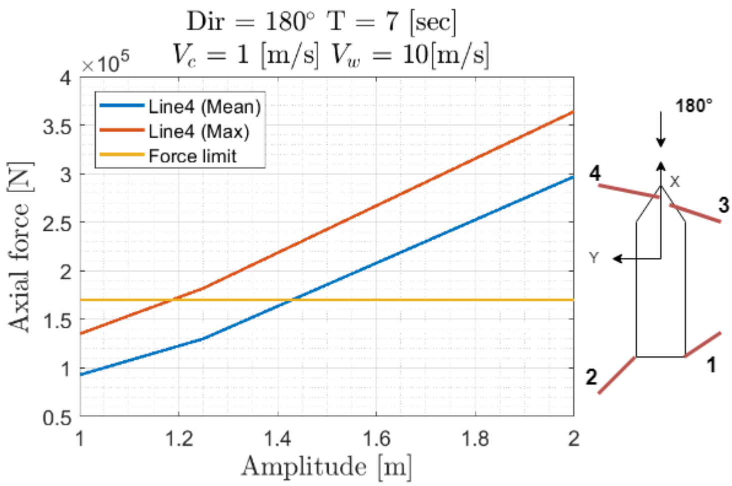


Figure 9.9: Mooring line axial force response for environmental load direction 180°, when waves, wind and current are applied

Figure 9.10 presents the time series for the axial force in mooring line four with an amplitude of 1.2 meters, for both with and without influence from wind and current. As expected, the presence of wind and current increase the amount of force acting on the system, thus lowering the operational limit. From the figure, it could also be observed that the force range is larger when wind and current are present. The elevated forces acting on the vessel will provide an increased displacement on the system, causing higher axial forces in the mooring lines. The increased stretch in the mooring lines will propagate into the anchor lines, which will raise the chain segment from the sea bottom, providing a higher contribution from the geometric stiffness. The additional geometric stiffness provides a nonlinear contribution to the total stiffness, hence the axial force range is larger when wind and current are present.

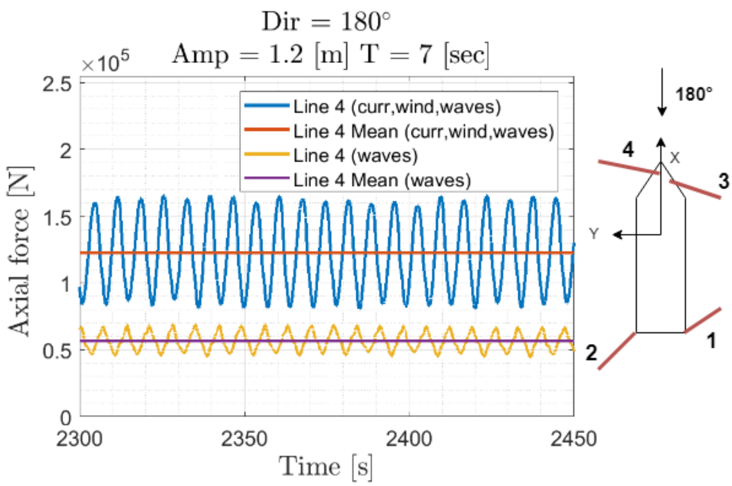


Figure 9.10: Mooring line axial force response for an environmental load direction of 180°, when the influence from wind and current is included and excluded

9.2.2 Environmental Load Direction 225°

In figure 9.11 incoming waves at 225 degrees are present and the responses in the mooring lines which are most exposed to the external loads are the ones plotted. With a wave amplitude of 0.5 meters, the force limit is not reached and the operation could safely take place under these conditions, seen by figure 9.11a. By doubling the wave amplitude to 1 meter, the force limit of 170 [kN] is reached for periods below 5.6 seconds. If the wave amplitude is further increased to 1.5 meters and 2 meters, the period where an operation could safely take place must be greater than 7.7 and 8.4 seconds, respectively. The operational limit tends to move towards larger periods when the amplitude increases. In comparison to the graphs representing incoming waves at 180 degrees, the axial force for incoming waves at 225 degrees is larger. This is due to a greater contribution from the wave drift force.

In section 8.4 the natural period in roll was found to be 14 seconds. If incoming waves with this period interact with the system, resonance is initiated. Thus, large responses in the mooring lines occur. This is observed when the period is approaching 14 seconds, as the axial force is slightly increasing. It was also observed relatively large RAO values in pitch and yaw for incoming waves at 225 degrees, with a period of 7-8 seconds. This would influence the response of the vessel, and increase the axial forces in the mooring lines.

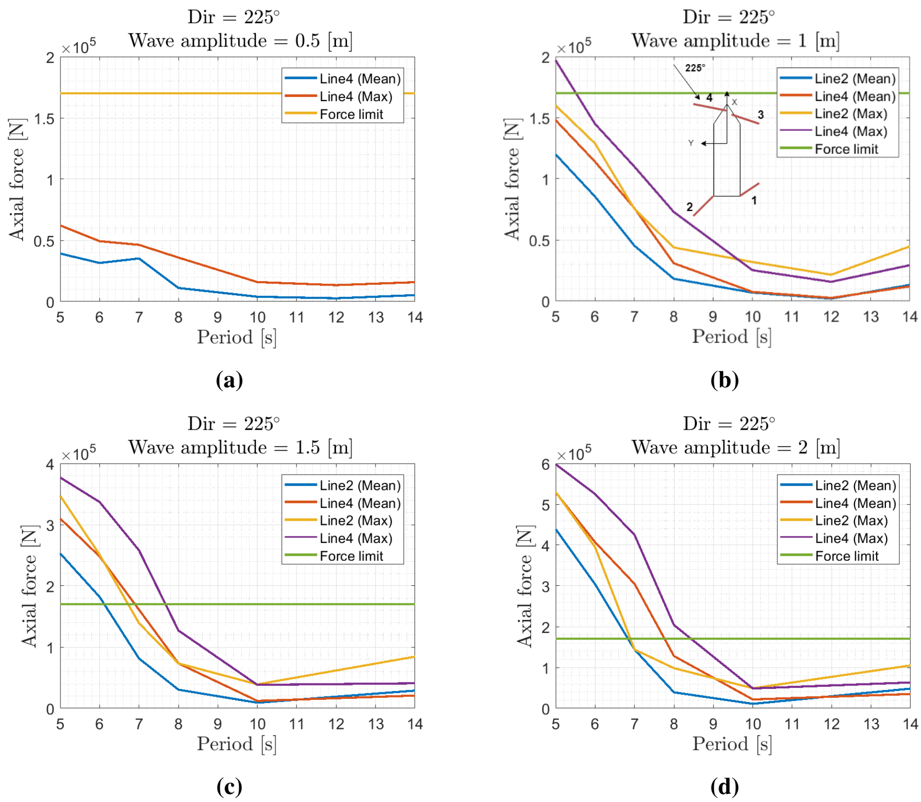


Figure 9.11: Mooring line axial force response for environmental load direction 225°, when only waves are applied

Figure 9.12 shows the axial force response in the mooring lines with applied wind and current velocities of 0.5 [m/s] and 10 [m/s] respectively, in addition to waves with a period of 6 seconds. As illustrated by the intersection point between the maximum force in line four and the force limit, an operation could safely be executed if the wave amplitude is below 0.95 meters. By comparing these values with figure 9.11b, it is observable that the presence of wind and current lower the operational limit, due to greater forces acting on the system.

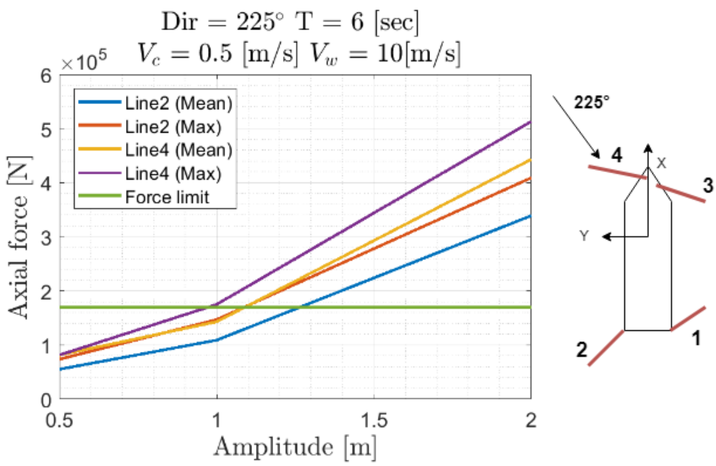


Figure 9.12: Mooring line axial force response for an environmental load direction of 225°, when waves, wind and current are applied

9.2.3 Environmental Load Direction 270°

In figure 9.13, incoming waves at 270 degrees are present. If the wave amplitude is 0.5 meters, the operation could be executed for all the plotted wave periods. With wave amplitudes equal to 1, 1.5 and 2 meters, the operational limits could be set to wave periods of 7.2, 7.9 and 8.8 seconds, respectively. As mentioned in section 9.2.2, the operational limit tends to move towards larger periods when the amplitude increases. It was also pointed out that the axial force slightly increased for periods approaching 14 seconds, due to the natural period in roll. For a load direction of 270 degrees, this was also observed. Figure 9.13d shows that the maximum force in line two has reached the force limit at this period.

The axial force is large for small periods and decreases rapidly for periods larger than 7 seconds. This corresponds to the wave drift force for incoming waves at 270 degrees. It is also observed that the RAO for heave and pitch has a considerable value for incoming waves at 270 degrees at approximately 7 seconds.

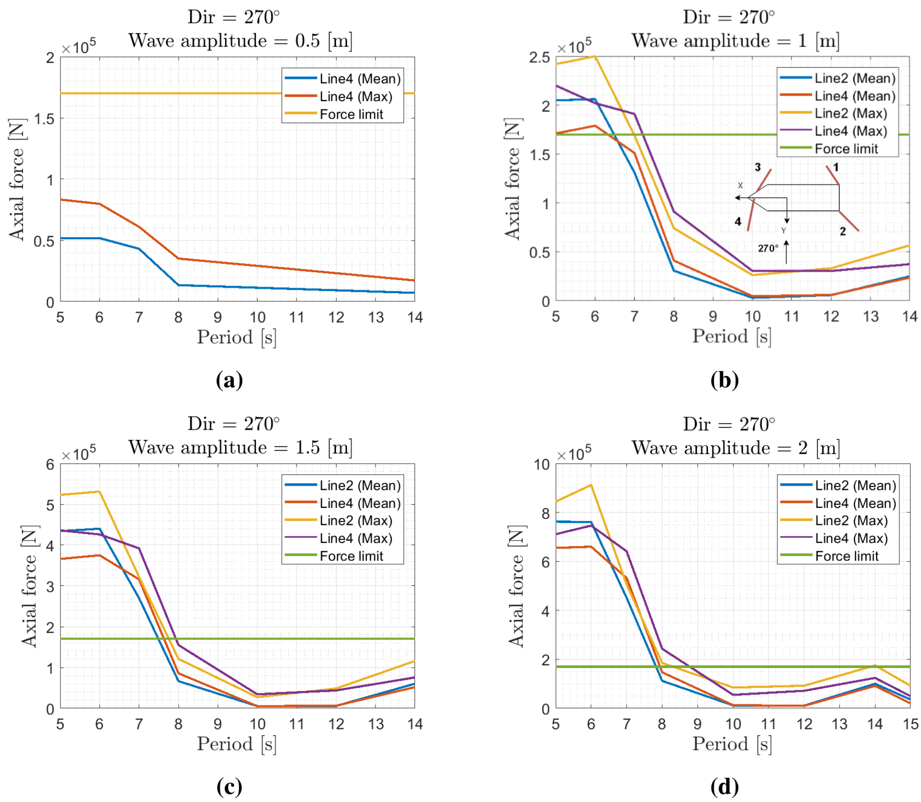


Figure 9.13: Mooring line axial force response for an environmental load direction of 270°, when only waves are applied

Figure 9.14 presents the axial force response for waves with a period of 8 seconds, wind velocity of 10 [m/s] and current with a velocity of 0.5 [m/s]. For wave amplitudes greater than 0.9 meters, the force limit is exceeded by the axial forces in line two and four. Hence, the operation cannot be executed for these conditions.

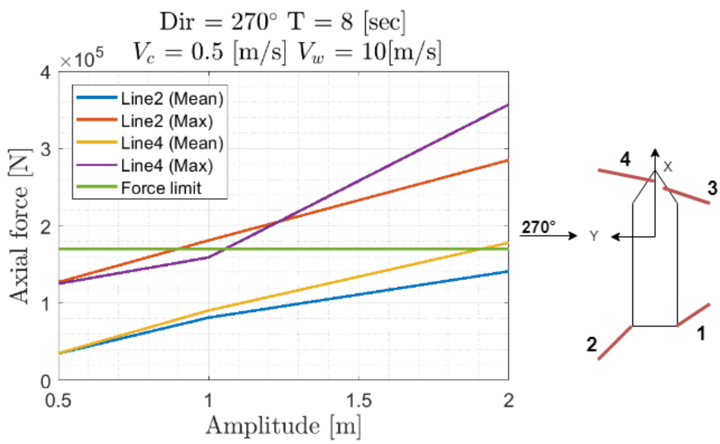


Figure 9.14: Mooring line axial force response for an environmental load direction of 270°, when waves, wind and current are applied

9.2.4 Pre-tension

A part of the sensitivity analysis of the system was to compare the effect of applying low pre-tension with an estimated normal amount of pre-tension. The pre-tension in each line is presented in table 9.1.

Table 9.1: Pre-tenison in mooring line, showing both low and normal configuration

	Pre-tension Low [N]	Pre-tension Normal [N]
Line 1	175	9904
Line 2	160	10380
Line 3	350	7830
Line 4	330	7803

The analysis was performed using a load case with incoming waves at 180 degrees, with a period of 7 seconds and an amplitude of 1 meter. Figure 9.15 shows the axial force as a function of time for the different mooring lines, with low and normal pre-tension. The mean value of the axial force for both cases is also plotted as horizontal lines. The difference in axial force between low and normal pre-tension in the individual mooring lines is relatively small. This may indicate that the amount of pre-tension does not have any significant impact on the axial forces in the lines. Hence, the pre-tension procedures used today seem to be safe to use. However, simulations where other design parameters are considered, are needed in order to corroborate the results. If a low amount of pre-tension is applied, it could be of importance to examine the displacement of the wellboat relative to the cage. If the displacement becomes too large, the pumping pipe transferring fish between the vessel and cage might get damaged.

As shown on the figure, the axial forces are varying periodically with some larger and smaller peaks occurring with a period of roughly 7 seconds. This period corresponds to the maximum value of the wave drift force and the RAO in pitch at incoming waves at 180 degrees. As the vessel moves, some of the lines get tightened while others get slacked, due to the mooring configuration. This is observed by the figure, as the peaks in the different lines have a phase shift relative to each other. On figure 9.15a it is observable that the range in axial force is somewhat larger for the case with low pre-tension. The lowest axial force is observed in mooring line two, as this line will provide the smallest contribution in keeping the vessel stationary. In line four, the opposite is observed, as this line absorbs the largest axial forces.

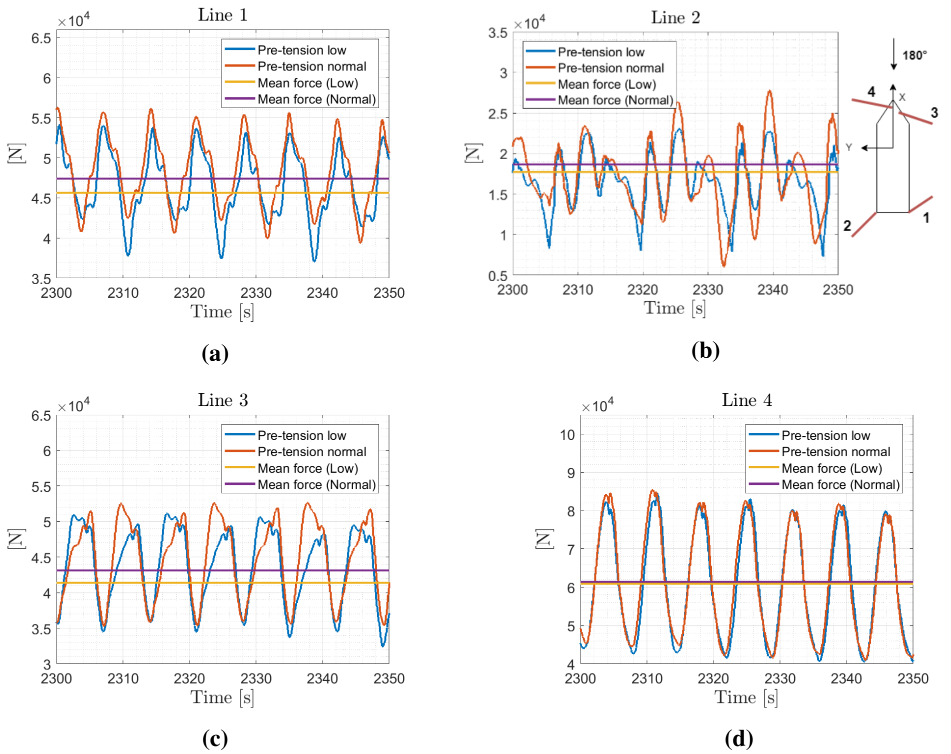


Figure 9.15: Axial force as a function of time plotted for the four mooring lines, when low and normal pre-tension is applied

9.3 Remarks

Through simulations, it has been investigated how the system handles weather loads of different magnitudes and from different directions. The system is sensitive to short wave periods due to large wave drift forces. For wave amplitudes below 0.5 meters, an operation can safely be executed. If the wave amplitude increases, the contribution from the wave drift force will also increase, since the wave drift force is a function of the amplitude squared. To carry out safe operations at high amplitudes, the period must be large, because the wave drift forces approach zero for increased periods. The system is sensitive to changes in the incoming load direction. For the three directions analysed in this thesis, the results indicate that the system is most exposed to incoming environmental loads at 270 degrees. The system has its lowest exposure from a direction of 180 degrees, but if an operation is subjected to a sudden weather change where the load direction changes, the forces acting on the system will increase. If the system is exposed to wind and current in addition to waves, the total mean forces acting on the system will increase, thus the operational limit will be reduced. The wind and current coefficients depend on the vessel's projected area. Hence, these forces obtain their largest contribution at 270 degrees, and their lowest contribution at 180 degrees. Nevertheless, the results show that the wave forces are prominent for the establishment of the operational limits. Besides the aforementioned remarks, the system's natural periods need to be considered. Incoming waves corresponding to these periods contribute to an increased system response, which is observed in the mooring line's axial forces.

In a real wellboat operation, contact forces between the floating collar and the hull of the wellboat would arise. These forces would be distributed through the bridles to the connection plates and the anchor lines, thus contributing to lowering the axial forces in the mooring lines between the wellboat and the cage system, illustrated in figure 9.16. The approach in this thesis is therefore conservative regarding axial forces in the mooring lines, as the aforementioned contact forces are neglected.

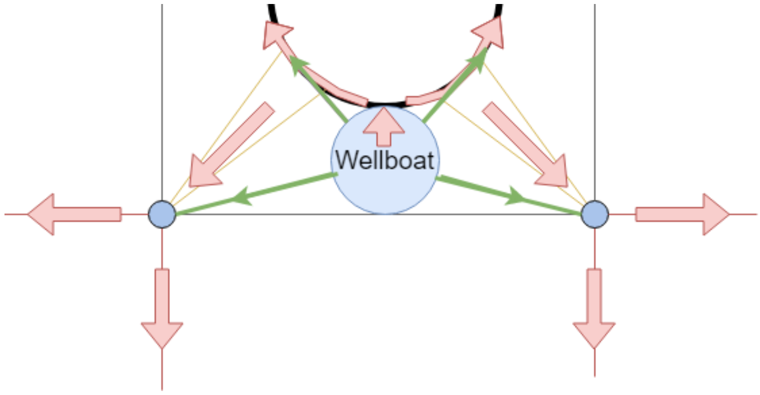


Figure 9.16: Force distribution in the system when contact forces are present

In the oil and gas industry, a report referred to as "Metocean design basis" is required, documenting all environmental conditions associated to a particular production site. NS 9415 refers to a similar site survey report, which all aquaculture sites are obliged to possess. Data from this site survey report could be used as environmental inputs for a particular location analysis in SIMA. When the operational limits are determined, the wellboat company and the operation manager at the facility should familiarize themselves with the limits. The limits for different scenarios that take the sensitivities of weather parameters and system parameters into account should be gathered into a catalog. The wellboat crew and the operation manager should use this catalog to find the limits for a given condition. A sample of this catalog should be found at the bridge on the wellboat and another at the control room at the facility. If this shall be practiced by the industry, requirements need to be implemented in the regulations and a supervisory authority must be assigned the responsibility of following up.

Today, most of the production facilities are not equipped with instruments to measure current velocity and wave data. The decision of whether an operation can be carried out or not is often based on the operator's estimate of the environmental conditions. This estimate can contribute to an uncertainty when operation decisions are made. Therefore a requirement could be necessary, expressing that the facilities must be equipped with sufficient measurement instruments. To ensure reliable measurements from the instruments, the regulations should require calibration regularly.

Chapter 10

Conclusion

This chapter will present the results from the simulation study and summarize the identified gaps, improvements and revisions related to planning and execution of marine operations in the aquaculture industry. At the end, recommendations for further work will be presented.

10.1 Concluding Remarks

A coupled SIMO-RIFLEX simulation model was established to simulate a wellboat operation. The objective was to provide a methodology for how operational limits could be determined. The axial force in the mooring lines between the wellboat and the cage was set as the design parameter to determine the operational limits. The simulations were performed by varying the environmental load direction, wave amplitude and period, and with and without wind and current loads. This was done to uncover the sensitivities and variability of the operational limits. In addition, the system's sensitivity was examined with regards to the amount of applied pre-tension.

One major contributor to the axial forces in the mooring lines is the wave drift forces, which are affected by the wave period, the amplitude and the environmental load direction. The wave drift forces are large for short periods and approach a negligible value for long periods. By studying the results, the system is found to be prone to wave periods below 9 seconds as the axial force in the mooring lines have a considerably high value. As the wave drift force is a function of the wave amplitude squared, increasing amplitudes will cause a reduction in the operational limits. The sensitivities of the operational limits were also investigated for environmental loads from wind and current. The presence of wind and current has the effect of lowering the operational limits, compared to when only wave loads are applied. The results indicate that the system is more robust against wind and current forces approaching from 180 degrees compared to 225 and 270 degrees. This is related to the wind and current coefficient's dependence on the vessel's projected area. The projected area is larger at 225 and 270 degrees compared to 180 degrees. Consequently, the coefficient is also larger for these angles. Hence, at a direction of 270 degrees the vessel experience its highest exposure from wind and current loads. By adding wave drift forces, this direction is the most vulnerable direction regarding environmental load effects.

Assessment of the system's natural periods are necessary, as corresponding wave periods may cause a significant increase in the axial forces in the vessel's mooring lines. For an environmental direction of 180 degrees, a peak is observed at a wave period of 7 seconds, most prominent for amplitudes of 1 and 1.5 meters. Especially two factors contribute to this peak, the wave drift force in surge at 180 degrees has its maximum value at 7 seconds, and pitch has a natural period of roughly 7 seconds. At the environmental directions 225 and 270 degrees and for wave amplitudes of 1, 1.5 and 2 meters, another peak is observed at a period of 14 seconds. At this wave period, the wave drift force is negligible, but it corresponds with the natural period in roll.

As mentioned, the system's sensitivity regarding the degree of pre-tension in the mooring lines was analysed. A pre-tension considered low and normal was applied to the system, and the results showed no significant difference in the axial force acting in the mooring lines. Hence, the pre-tension procedures used today seem to be safe to use. However, simulations where other design parameters are considered are needed in order to corroborate the results. If a low pre-tension is applied, it is important to monitor the displacement of the wellboat relative to the cage, to prevent it from becoming considerably large.

Currently, the aquaculture industry lack a governmental regulation concerning marine operations. Given that the industry will continue growing, exploitation of new areas with a higher degree of exposure is required. To maintain a justifiable operation at these locations and the sites currently used, regulations are essential to maintain the safety for humans, fish and assets. The regulations should include how to plan and execute marine operations, and a comprehensive instruction on how risk assessment should be performed. DNV-OS-H101 “Marine operations, General” is a regulation, which is central in the petroleum industry, and could be used as a basis for developing a similar regulation for the aquaculture industry. To establish operational limits, the methodology outlined in this thesis could be used.

Operational limits should account for uncertainties in the weather forecast, through the use of alpha factors. These factors are not established for the aquaculture industry, thus not accounted for in this thesis.

DNV-OS-H101 refers to DNVGL-RP-N101 "Risk Management in Marine and Subsea Operations", which could have been used to manage risk in a proper way. A central aspect relevant for the aquaculture industry, which is not covered by the aforementioned standard by DNVGL is to maintain good fish welfare for operations involving live fish. A supervisory body should be appointed to control and verify that the regulations are being obeyed.

10.2 Recommendations for Further Work

In addition to the axial force in the mooring lines between the wellboat and cage system, other system components should also be taken into consideration when the operational limits are to be established. These system components includes the floating collar, bridles, anchor lines, connection plates and frame mooring. As mentioned earlier, if the entire chain segment of the anchor line is lifted from the sea bed, the anchor may be subjected to vertical loads and in worst case be pulled out from its position. The fish net could also be included, to validate how it respond when subjected to current forces. This would be important in order to analyse whether the net may come in contact with the wellboat for different mooring configurations and weather directions.

The choice of mooring configuration for the wellboat presented in this thesis is one of many possible solutions. The wellboat companies use different practice for mooring configurations, based on weather conditions and the size of the vessel and the cage. In some cases, the two nearby cages are used as mooring points in addition to the lines connected to the operated cage. By considering the variability of mooring configurations in SIMA, it is possible to find optimal configurations for different weather conditions, for instance when current, wind and waves have three different approach angles.

As mentioned earlier, contact forces between the hull and floating collar are present in reality, but not considered in this thesis. These forces should be quantified, in order to determine in what extent they will influence the operational limits.

The operational limits determined in this thesis have been found without considering alpha factors. Unforeseen weather changes could have undesirable consequences in terms of fish escapes, construction failure and in worst case injuries to humans. Thus, alpha factors need to be included if the duration of the operation is of a sufficient length or if the production site is associated with uncertain weather forecasts.

If weather data for previously performed wellboat operations were available, this information could be compared to the operational limits provided from simulations. This could emphasize the importance of establishing a well formulated legislation for marine operations in the aquaculture industry, where operational limits are essential. During the thesis work, the author had not access to the internal regulations of the enterprises. For further work, these internal regulations could have been used to gain a better understanding of how the enterprises work to ensure safe and sound operations.

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Appendices

A.1 Mail: Torgeir Strand Fjelnset

Mail sendt av Christine Hegerstrøm:

Jeg konsentrer meg om en operasjon hvor brønnbåten skal ankomme lokaliteten for å ta med seg slakteklar fisk. Vedlagt ligger prosedyrer (excel) om hvordan jeg tror dere gjennomfører en slik type operasjon, men den inneholder sikkert feil og mangler. Kunne du kommentert litt?

Jeg er heller ikke sikker på forankringen, men jeg tror brønnbåten har to valg. Enten å koble seg direkte til flytekragen eller koble seg til rammen via koblingsplatene. Jeg har tegnet en skisse på hvordan jeg tror dette ser ut, men ønsker gjerne kommentarer. Benyttes DP eller bunnforankring? Om man kobler seg opp til koblingsplatene er det mulig for arbeiderne på brønnbåten å entre flytekragen uten båt? Hvor mange er egentlig involvert i en slik operasjon? Både fra anlegget og brønnbåten?

Om man estimerer at det er 650 tonn fisk i merden som skal sendes til slakt. Kan dette gjøres i en operasjon eller er man avhengig av å dele dette opp i to operasjoner? Jeg forstår at dette avhenger av kapasiteten til brønnbåten, men hva er vanlig?

Svar fra Torgeir Strand Fjelnset:

Det brukes per i dag ikke DP på slike operasjoner, men er så vit jeg veit under utvikling i noen selskaper, men ikke i SalMar. Bunnforankring brukes ikke, men som beskrevet litt i rødt, brukes bøyer som er festet i rammefortøyning ved behov. Fra anlegg må vi minimum være 2 stk, men bør være 3-4. Fra BB er det stort sett 2 mann på dekk + BB-skipper og maskinist. Er det 650 tonn fisk i merder er dette som du sier opp til BB. Stort sett laster BB +/- 500 tonn.

Ste	Hva	Estimert tid	Andre kommentarer	
1	Gjøre klar merden før brønnbåten ankommer. Dette innebærer å fjerne rensefisk og deres skjul, fôringsautomaten med tilhørende rør, kamera, evt hamsterhjul og annet utsyr som er plassert i merden. Dette utføres av arbeiderne ved lokaliteten med tilhørene arbeidsbåter.	3-4 timer OK		Hamsethjul med taknett :) Stikker BB dypere enn rammefortøyninge må bøyer fjernes for å "senke" rammefortøyninger.
2	Reise opp bunnringen for å trenge fisken fra undersiden av merden. Dette innebærer bruk av kran på arbeidsbåten.	2 timer (2-3 timer)	starter når man vet at brønnbåten er på vei. Når man løfter opp bunnringen er det viktig å hindre store løft kun på en side av merden, dette kan medføre store konsentrerte laster som kan skade konstruksjonen (potensiell fare for rømming). Dermed viktig å løfte gradvis.	1. Vi heiser her bunnring også for å at det skal være mulig for arbeidsbåt å tre inn kulerekke som dras på utsiden/undersiden av nota for å få fisken om bord i båten. 2. Under løfing er det også viktig å passe på at notsider blir hengt opp (linet) for å unngå at denne kan komme i kontakt med båter eller klemt mellom bunnring og flytekrage.

3	Fortsette å trenge fisken her kan enten flexi-paneler brukes eller orkastnot. Arbeidsbåt med kran er nødvendig.	1-2 timer		Kulerekke brukes til tømming av not. Orkast, flexipaneler? Brukes hvis BB ikke kan ta all fisken i en last, eller overstiger MAX trengetid av fisk.
4	Brønnbåten ankommer lokaliteten. Før den ankommer må den vite hvilken merd som skal opereres, konfigurasjoen til anlegget (slik at den ikke kommer i konflik med fortøyning) og topografien i området.	Mindre enn 15 min OK		Ingen komentar, Helt etter boka :)
5	Forankring av brønnbåten. Kan enten legge seg til merden eller til rammefortøyningen (koblingsplatene).	Oppkobling til rammefortøyningen tar lengere tid enn direkte fortøyning til merden. (15 min for kobling til flytekragen og 30 min for kobling til rammen.	fartøyet som bestemmer oppkoblingen? Dvs. et mindre fartøy kobles direkte til flytekragen, mens et større er nødt til å kobles til rammefortøyningen ? Hvordan ser fortøyningskonfigurasjonen ut for de to tilfellene? Hvis man velger å legge seg til rammefortøyningen er det mulig for brønnbåt arbeiderene å entre flytekragen uten båt? Legger med skisser av hvordan jeg tror dette ser ut.	Det bli i hvert tilfelde vurdert om det er bebov for ekstra fortøyninger ut fra vannhastighet(strøm) og/eller vind. Da er det flere anternativer. 1. dra ut ekstra fortøyninger fra BB til den merden båten ligger på. 2. Dra ut ekstra fortøyninge til nabo merd bau/hekk brønnbåt. (oftes hvis BB presses BORT fra flytekrage) 3. Dra ut ekstra fortøyninger fra bau/hekk BB ut som festes i sjakkel på fortøyninges bøyene. Dett blir gjort for hvis BB blir presset MOT merd Alle disse fortøyningen tilhører BB, men det er lokalitet som kjører disse på plass med pram eller lokalitetsbåt. Fortøyningsanalysene er gjort med tanke på at det skal BB skal
6	Pumpeoperasjonen kan starte ved at pumperørene plasseres i merden ved bruk av kran lokalisert på brønnbåten. Pumpingen stopper når tettheten i tankene har nådd sitt maksimum.	2-3 timer ok	Klarer en brønnbåt og tømme en merd eller må den dele opp dette i flere operasjoner?	Se kommentar lit lengre opp
7	Nedrigg. Rørene tas ut av merden og fortøyningen fjernes.	30-40 min ok		
8	Brønnbåten : Utfart fra lokaliteten	15min		
9	til sin posisjon. Utføres av arbeiderne på lokaliteten med tilhørende arbeidsbåt.	2 timer. 2-4 timer (litt etter hva som velges mtp komentarer jeg har satt ved siden av		senkes, men not tas opp først, for så å senke ned bunnring til "lagrings posisjon" som er bunnring på 3 meter under

B.2 Mail: Martin Søreide - Aqualine

Martin Søreide Martin@aqualine.no via studntnu.onmicrosoft.com
til Christine

Hei Christine,

Brønnbåt fortøyes på mange måter. En måte er vist på illustrasjon nedenfor.

Viktig kriterie er at thrustere ikke berører not eller at brønnbåt påfører for store krefter på selve flytekragen.

C.3 MachoShip4500 Dimensions - SINTEF

MAIN PARTICULARS			
LENGTH OVER ALL (LOA)	APPR.	:	85,40 m
LENGTH BETWEEN P.P. (LPP)	APPR.	:	79,80 m
BREADTH MLD		:	20,00 m
DEPTH TO MAIN DECK		:	8,80/9,80 m
DEPTH TO SHELTER DECK		:	12,40 m
DESIGN DRAUGHT		:	7,57 m
		:	
CARGO HOLD CAPACITY	APPR.	:	4500 m^3
FUEL OIL	APPR.	:	350 m^3
FRESH WATER	APPR.	:	150 m^3
WATER BALLAST	APPR.	:	950 m^3
TECHN. F.W./WATER BALLAST	APPR.	:	1700 m^3
GROSS TONNAGE	APPR.	:	0 GT
EQUIPMENT NO. **NB!! to be adjusted**		:	abt. 847 letter U (DNV)

D.4 Ronja Polaris Current Forces at 1 kn - Sølvtrans

Ship: P11-6717
Run : Environmental forces
Ship Heading: 0.0 deg

Env. [deg]	Surge [kN]	Sway [kN]	Yaw [kNm]
0.0	2.4	0.0	0.0
10.0	2.4	4.1	-98.7
20.0	2.2	9.7	-210.5
30.0	1.4	16.0	-316.4
40.0	-0.5	23.2	-386.9
50.0	-1.8	29.4	-395.6
60.0	-2.2	34.3	-359.9
70.0	-1.9	37.6	-297.7
80.0	-0.8	39.9	-197.2
90.0	0.3	40.1	-93.7
100.0	1.4	38.9	30.5
110.0	2.3	35.9	116.2
120.0	2.6	32.2	199.1
130.0	1.9	27.2	243.6
140.0	0.3	21.3	246.8
150.0	-1.2	15.8	214.6
160.0	-2.0	9.7	158.8
170.0	-2.4	4.9	94.1
180.0	-2.6	-0.0	-0.0
190.0	-2.4	-4.9	-94.1
200.0	-2.0	-9.7	-158.8
210.0	-1.2	-15.8	-214.6
220.0	0.3	-21.3	-246.8
230.0	1.9	-27.2	-243.6
240.0	2.6	-32.2	-199.1
250.0	2.3	-35.9	-116.2
260.0	1.4	-38.9	-30.5
270.0	0.3	-40.1	93.7
280.0	-0.8	-39.9	197.2
290.0	-1.9	-37.6	297.7
300.0	-2.2	-34.3	359.9
310.0	-1.8	-29.4	395.6
320.0	-0.5	-23.2	386.9
330.0	1.4	-16.0	316.4
340.0	2.2	-9.7	210.5
350.0	2.4	-4.1	98.7

E.5 Ronja Polaris Wind Forces at 20 m/s - Sølvtrans

Ship: P11-6717
Run : Environmental forces
Ship Heading: 0.0 deg

Env. [deg]	Surge [kN]	Sway [kN]	Yaw [kNm]
0.0	27.2	0.0	0.0
10.0	30.3	20.4	595.2
20.0	35.1	47.1	1071.4
30.0	31.5	75.4	1309.4
40.0	28.4	95.8	1369.0
50.0	27.8	103.6	1130.9
60.0	21.8	114.6	892.8
70.0	10.9	124.1	714.2
80.0	3.6	128.8	571.4
90.0	0.0	131.9	261.9
100.0	-6.1	130.3	11.9
110.0	-15.1	127.2	-59.5
120.0	-24.2	124.1	-297.6
130.0	-33.9	106.8	-369.0
140.0	-42.4	92.7	-476.2
150.0	-46.0	67.5	-464.3
160.0	-47.2	40.8	-380.9
170.0	-39.9	15.7	-142.8
180.0	-35.1	-0.0	-0.0
190.0	-39.9	-15.7	142.8
200.0	-47.2	-40.8	380.9
210.0	-46.0	-67.5	464.3
220.0	-42.4	-92.7	476.2
230.0	-33.9	-106.8	369.0
240.0	-24.2	-124.1	297.6
250.0	-15.1	-127.2	59.5
260.0	-6.1	-130.3	-11.9
270.0	0.0	-131.9	-261.9
280.0	3.6	-128.8	-571.4
290.0	10.9	-124.1	-714.2
300.0	21.8	-114.6	-892.8
310.0	27.8	-103.6	-1130.9
320.0	28.4	-95.8	-1369.0
330.0	31.5	-75.4	-1309.4
340.0	35.1	-47.1	-1071.4
350.0	30.3	-20.4	-595.2

F.6 Simulation model

- The chain segment of the anchor line was chosen from: (Aqualine, 2019)
- The fibre segment of the anchor line was chosen as a SuperDan 8-strand rope from: (DSR, 2019c)
- The bridles was chosen as a New SuperFlex 8-strand rope from: (DSR, 2019a)
- The mooring frame was chosen as a SuperDan 8-strand rope from: (DSR, 2019c)
- The bouys was chosen as a AQUA 10000 APB from: (Polyform, 2019)
- The floating collar was chosen from the information provided from Aqualine in appendix G.7
- The mooring lines was chosen as a New SuperTec 8-strand rope from: (DSR, 2019b)

Table 1: Data for the mooring system I

Mooring System	Value	Unit
Anchor lines		
Number	8	#
Total length	291	m
Anchor lines - Chain		
Length	110	m
Diameter	40	mm
E-modulus	110	GPa
Tension capacity	8.3e+05	N
Mass coefficient	32	kg/m
Anchor lines - Fibre		
Length	181	m
Diameter	60	mm
E-modulus	2	GPa
Tension capacity	5.9e+05	N
Mass coefficient	1.79	kg/m

Table 2: Data for the mooring system II

Bridles		
Bridles at each corner	2	#
Length	48	m
Diameter	50	mm
E-modulus	2	GPa
Tension capacity	5.4e+05	N
Mass coefficient	1.43	kg/m
Mooring frame		
Number	4	#
Length	100	m
Depth	8	m
Diameter	50	mm
E-modulus	2	GPa
Tension capacity	4.2e+05	N
Mass coefficient	1.65	kg/m

Table 3: Data for buoys

Buoys		
Number (one in each corner)	4	#
Height	5.29	m
Depth	8	m
Mass coefficient	375.35	kg/m

Table 4: Data for the floating collar

Floating collar	Value	Unit
Inner circumference	157	m
Inner diameter	50	m
Tube diameter	500	mm
Tube thickness	36.8	mm
E-modulus	1	GPa
Tension capacity (2 tubes in parallel)	2.7e+06	N
Mass coefficient (2 tubes in parallel)	102.82	kg/m

Table 5: Data for the mooring lines between the wellboat and cage system

Mooring lines (wellboat-cage system)	Value	Unit
Number	4	#
Length of line (Starboard -Aft)	25.3	m
Length of line (Port - Aft)	13.8	m
Length of line (Starboard - Bow)	26.3	m
Length of line (Port - Bow)	21.4	m
Diameter	50	mm
E-modulus	2	GPa
Tension capacity	5.1e+05	N
Mass coefficient	1.245	kg/m

G.7 Mail: Mats Nåvik Hval - Aqualine

Hei,

Når vi beregner fortøyning benytter vi vanligvis en E-modul på tau i området 1.87-2.0 GPa. Hovedbestanddel i tauene er PP, så vi benytter elastisitetsmodulen i materialet direkte. Videre benytter vi som oftest nominelt tverrsnitt på tauene med diameter i området 48-80mm. Vekt på tau kan finnes under 3-strand eller 8-strand «SuperDan» eller «New SuperTec» på nettsiden https://www.dsr.com:5001/pages/?p=134&c=01

Angående kjetting benytter vi vanligvis 30, 36, 40 og 48mm stolpeløs svartkjetting med enhetsvekt 18.4, 27.6, 32 og 49.8kg/m og Elastisitetsmodul 110GPa. Tverrsnittsareal er antatt til samlet areal av to stolpe-legger.

Drag koeff er tatt fra tabeller i https://rules.dnvgl.com/docs/pdf/dnvgl/os/2015-07/DNVGL-OS-E301.pdf
Added mass er satt til 1. Bakgrunnen for denne vet jeg ikke.

Vi opererer vanligvis med 1-2 lås kjetting (1lås = 27.5m) og ønskelig for ankerlinene er en ratio for horisontal lengde/dybde = 3/1.

Dimensjonering gjøres ut fra hvert case, med last og materialfaktorer fra NS9415.

Bøyer ligger i område 1000-10000liter av typen Polyform APB https://polyform.no/hard-shell-pe-products/apb-series/

Bruk rør med ytre diameter 500mm, og tykkelse 36.8mm. E-modul 1000GPA. Da gir bøyestivheten seg selv med to rør i parallell. Flytespenning for disse rørene med PE100 er 25MPA.

Christine Hegerstrøm

Marine Operations in the Aquaculture Industry with focus on Safe Wellboat Operations

NTNU
Norwegian University of
Science and Technology