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Design criteria for offshore feed barges

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Designkrav for fòr plattformer for havbruk på utsatte lokaliteter

Background:

The aquaculture industry is an important and growing Norwegian industry. With an export value of 33.4 billion NOK fish from aquaculture constituted 62% of Norway's export of fish in 2010. Following the global population growth, food from the ocean is further expected to be of increased importance in the coming years. In is thus expected a future increase in seafood production from aquaculture both in Norway and globally, but this must take place in accordance with accepted requirements related to sustainability.

Today the main fish production in aquaculture takes place in fish farms located along the Norwegian coast. Each fish cage holds an amount of fish equivalent to about 2000 cows. These cages post a danger to the local environment through the escape of fish and fish lice. To deal with these problems one solution can be to move the fish farm further out in more exposed areas. Until now there has been strong focus on the fish and the cages the fish is held in, but what about the feed barges? These are large constructions designed to store fish feed, workshops and to house the workers. Well-functioning feed barges are fundamental for the functioning of the fish farms, and it may be questioned how they will function further out at sea. It may further be questioned whether there will be need for changes in the design criteria and the regulations and under what regulation system they will fall under.

So far, the candidate has in the project work, found that the minimum allowable freeboard demand may be too low. What will be important to study further are the motions at sea and the roll and pitch angle amplitudes tolerable for people to handle if a feed barge shall function as an efficient and safe working platform.

Work description

During his master thesis the candidate shall:

- Identify and describe rules and regulations relevant for feed barges. See preliminary list below.
- Identify and describe an exposed location for testing of rules and regulations.
- Identify and describe a typical feed barge design assumed to be fit for an exposed location.
- Make a model in GeniE.
- Perform analyses in the computer program; HydroD, in both hydrostatic and dynamic conditions.
- Check some of the regulations and design criteria versus computations. Verify the result from the pre-project.

The candidate shall strive to answer whether regulations cover moving the barges to more exposed locations.

Rules and regulations on feed barges

- NYTEK
- NS9415
- NORDFORSK
- DNV
- NMD - Norwegian Maritime Directorate

The work shall be carried out in accordance with guidelines, rules and regulations pertaining to the completion of a Master Thesis in engineering at NTNU.

The work shall be completed and delivered electronic by: June 10th, 2012.

Main advisor is Professor Harald Ellingsen, Department of Marin Technology, NTNU

Co-advisor is Research Director Arne Fredheim, SINTEF Fisheries and Aquaculture.

Trondheim, March 12th, 2010

Harald Ellingsen

Preface

This report is a master thesis in TMR4905 Marine Systems, spring 2012. The thesis counts 30 credits and is a part of the master study in Marine Technology at NTNU.

The subject in this report is design criteria for offshore feed barges. Moving a fish farm further offshore in the future could be a solution to some of the problems the fish farmers face today, as fish lice and the escaping of fish. If this is to be a viable solution the design criteria of the feed barge and the farm in general has to be sufficient.

The author would like to thank supervisor Harald Ellingsen and co-supervisor Arne Fredheim for guidance and discussions under the making of this report.

Trondheim 06.06.2012

Sindre Mathisen

Abstract

The fish farming industry faces some problems for the future as the escaping of fish and fish lice. One solution to these problems could be to move the farms further offshore. The main focus of the industry is on the cages the fish is held in, but the feed barge is the brain of a fish farm. Before offshore fish farming is an acceptable solution for the future the design criteria for the feed barge has to be sufficient for more exposed areas.

Some regulations both for fish farming and the oil industry have been evaluated. The conclusion from the evaluation of the regulations is that the regulation for floating fish farms is the least strict regulation. The purpose of this report is to enlighten the need for new thinking for design criteria for offshore feed barges by doing a hydrodynamic analysis in HydroD by using WADAM and potential theory applied to a panel model. The computer program is a recognized program developed by DNV. The model in this report is a design which is believed to be the best design for exposed areas. The model is analyzed in both hydrostatic and hydrodynamic conditions. The hydrostatic analyses conclude that the barge is stable and valid for operation in Norwegian waters. For the hydrodynamic analysis it as assumed two different locations with different wave data to enlighten the need to design a barge to a specific location. There is also assumed extra restoring as simulation of mooring. The result from the hydrodynamic analyses is used to evaluate the required freeboard for each location and the motions and accelerations of the barge. The results show that the barge in both locations will experience water on deck already for significant wave height of 2 meters, which actually is low even for the regulations today. The rotation and acceleration results are compared against limits for human tolerance and they show that there is a need for evaluating this in the design criteria.

The conclusion is that the regulation valid today for fish farming is insufficient for offshore fish farming and that it is possible to look towards the offshore industry for leads on how the regulations should be formed. For the future it would be appropriate to change the design criteria and design of the feed barge if the fish farming is to be moved further offshore.

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F_{min}	Minimum required freeboard
LOA	Length over all
k_1	Constant in the minimum freeboard requirement adjusting for the wave height
k_2	= 2000/B. Constant in the minimum freeboard requirement adjusting for cross-tie
B	Is the largest breadth of the barge
RMS	Root mean square
λ	Wave length
ζ	Wave elevation
A_j	Wave amplitude of wave number j
ω_j	Circular frequency of wave number j
k_j	Wave number of wave number j
ε_j	Random phase angle of wave number j
H_S	Significant wave height
T_Z	Zero up crossing period
T_1	Mean wave period
T_P	Wave peak period
β	Wave angle of attack relative to the barge
η_j	Motion in rigid body mode number j
M_{ij}	Structure mass
$A(\omega)_{ij}$	Frequency dependent added mass coefficient
$B(\omega)_{ij}$	Frequency dependent damping coefficient
C_{ij}	Restoring coefficient
F_i	Force in the i-th direction
T_{ni}	Natural period in the i-th rigid-body motion mode
B_{Ci}	Critical damping in rigid body motion mode i.
K	Stiffness coefficient of a mooring line
Ψ_i	Angle from mooring line number i to the x-axis in the horizontal plane
θ_i	Angle from mooring line number i to the x-axis in the vertical plane
ϕ_i	Angle from mooring line number i to the y-axis in the vertical plane
$\mathbf{s}_{3i}$	Vertical motion in point i on the barge
Rm_i	Relative motion between the vertical motion and the wave elevation in point i on the barge

1 Introduction

The aquaculture industry is an important and growing Norwegian industry. With an export value of 33.4 billion NOK, fish from aquaculture constituted 62% of Norway's export of fish in 2010. Following the global population growth, food from the ocean is further expected to be of increased importance in the coming years. It is thus expected a future increase in seafood production from aquaculture both in Norway and globally, but this must take place in accordance with accepted requirements related to sustainability.

Today the main fish production in aquaculture takes place in fish farms located along the Norwegian coast. Each fish cage holds an amount of fish equivalent to about 2000 cows. These cages post a danger to the local environment through, among others, the escape of fish and fish lice. To deal with these problems one solution can be to move the fish farm further out in more exposed areas. Until now there has been strong focus on the fish and the cages the fish is held in, but what about the feed barges? These are large constructions designed to store fish feed, workshops and to house the workers. Well-functioning feed barges are fundamental for the functioning of the fish farms, and it may be questioned how they will function further out at sea. It may further be questioned whether there will be need for changes in the design criteria and the regulations and under what regulation system they will fall under.

The work done in this report is:

- Identifying rules and regulations relevant for feed barges
- Design a model in GeniE according to present requirements
- Give two exposed locations with wave statistics
- Verify model with hydrostatic computations in HydroD
- Do a hydrodynamic analysis using HydroD and WADAM
- Check freeboard, motion and acceleration against the relevant regulations

The relevant regulations which will be reviewed are:

- NS9415
- NYTEK
- DNV
- NMD
- IMO
- NORDFORSK

In the end the need for new thinking both in the design of feed barges and the design criteria of feed barges will be enlightened.

2 Rules and regulations

As for all other maritime activity fish farming is regulated to ensure safe operation. Since the feed barge is the brain of the fish farm and also the storage area for the fish feed, it is very important that it is operational and functions as it is supposed to. Therefor it is important with a good set of regulations on how these barges are to be designed and operated. Today in Norway the Norwegian Standard(NS9415 2009) is followed and in addition the NYTEK(2011) guideline was taken into action in 2012. Other regulations that does not directly applies to marine fish farms will be looked into to see if they can apply to or be guidelines in how the technical design regulations of feed barges should look like in the future.

2.1 Location conditions

The location has to be classified to show that it is safe to set out a fish farm at the chosen location. This is mostly regarding the fish cages and the mooring of the cages, but the barge is also approved for conditions connected to a location.

A location where there is to be placed a fish farm has to be examined and classified according to its topography and degree of exposure. These parameters form the foundation for the calculations of the environmental loads on the fish farm. The measurements are to be done on an empty location before the fish farm is installed. In the cases where there already is a farm installed this is to be accounted for in the determination of the environmental parameters.

2.1.1 NS9415 – Requirements for location documentation

In NS9415 the data required for a location classification is listed and how they are gathered. And with support in NYTEK it has the intention to ensure that the location is charted thoroughly. These requirements are reproduced in this chapter.

Current

The current can be determined from 3 rules.

1. Current measuring over one year and using long time statistics
2. Current measuring in one month and using multiplication factors as result of return period, Table 1
3. Using earlier current data

The measuring depths for the current are 5 and 15 meters.

Return period [years]	Multiplication factor
10	1,65
50	1,85

Table 1 Multiplication factor from return period

Waves

The waves on a location is divided into two main types, wind generated waves and swell sea. The wind generated waves can be determined by the use of wave spectrum for irregular sea, by use of regular waves or by calculation of waves from fetch. In the case of calculating waves from fetch there is to be an evaluation whether there are other effects that could affect the wave spectrum. These effects could be:

- Waves generated by ships in the area.
- Wave reflection, e.g. from a steep rock wall.
- Effect from several wave trains, e.g. if two fjord systems meet.
- Wave-/current interaction, change in the wave spectrum due to current.

Swell sea can also be described by a wave spectrum. If swell sea is present on a location the period and wave height is to be determined from one of the following methods:

- Diffraction- and reflection analysis.
- Measuring to determine swell with return periods of 10 and 50 years.
- Other approved methods which can document safety, validity and accuracy.

When there is swell sea present the combined sea state should also be determined by combining the calculated swell sea with the calculated wind generated waves.

Wind

To determine the wind speed for calculating wind generated waves the Norwegian standard "NS-EN 1991-1-4 *Actions on structures - Part 1-4: General actions - Wind actions*" shall be used. To determine the wind conditions for calculating the wind loads on the fish farm either NS-EN 1991-1-4 or wind data from the two closest weather stations shall be used, with return periods of 10 and 50 years.

Ice

The risk of ice formation on floating fish farms and appurtenant equipment must be documented on the following meteorological observation on the location:

- Air temperature.
- Wind and wind exposure.
- Waves and wave exposure.
- Sea temperature.

In total this will give an icing potential which will give a dimensioning icing over a defined time interval. This time interval shall be evaluated from the possibility of ice removing or documented actions against icing. If nothing could be documented, 3 days shall be used. The methods used for determining of ice must be approved.

The risk of floating ice and ice enclosure on the location should also be evaluated and documented.

2.2 Rules and regulations relevant for the feed barge

The feed barge is a floating work station and storing area. This is where the cages are monitored from and the feeding is controlled, the crew is able to live on the barge and there is often a workshop and equipment storage on board. In one way a feed barge could be described as a floating office building, with possibilities for overnight stay. It is also interacting with ships carrying peoples and fish feed in bulk. In this chapter an overview of the relevant rules and regulations is given.

2.2.1 NS9415 - Feed barge design criteria

The focus of this report is the seaworthiness of a barge and the requirements set for this. In NS9415 it is set requirements for stability and freeboard.

Intact stability

These are the minimum requirements the barge has to meet.

- The area below the GZ-curve from 0 degrees to maximum righting arm shall not be less than 0,08 m-rad
- If the barge is unmanned or it is placed on a location with significant wave height equivalent to 2,0 m, the area shall not be less than 0,05 m-rad
- Static heeling angle caused by an evenly distributed load on 0.54 kPa (corresponding to a wind speed on 30 m/s), shall not exceed a heeling angle equivalent to half the freeboard in the current condition.
- The GZ shall be positive to a minimum of 15 degrees

Freeboard

The freeboard amidships is to be calculated from stability, trim and the strength of the hull. The minimum required freeboard (F_{min}) is given in equation (2.1).

$$F_{min} > LOA \times k_1 + k_2 \; [mm] \qquad (2.1)$$

Where:

LOA is the barges length in meters (Length over all)

k_1 is a constant decided by the wave height I accordance with Table 2

k_2 is an extra requirement when there is cross-tie = 2000/B

Table 2 Freeboard addition in relation to wave height

H_S [m]	k_1 [mm]	H_S [m]	k_1 [mm]
$H_S < 0.5$	300	$2.0 \le H_S < 3.0$	600
$0.5 \le H_S < 1.0$	400	$H_S \ge 3.0$	700
$1.0 \le H_S < 2.0$	500		

2.2.2 DNV

DNV is a classification agency. They work with the offshore industry and have throughout the years made a lot of rules and regulations for the oil industry. Therefore it is natural to look at their regulations when moving fish farms more exposed. In the case of feed barges it is not easy to see where they belong in the DNV regulations. The barge is a kind floating storage unit so it might fit in DNV (2012) for classification of floating production, storage and loading units. From these rules it is referred to DNV (2012) Stability and Watertight Integrity.

Intact stability

If the barge is ship shaped the rules for Stability and Watertight integrity refers to DNV (2012) Rules for Classification of Ships.

The general intact stability criteria from DNV (2012) is given for all ships as:

- The area under the righting lever curve (GZ curve) shall not be less than 0.055 metre-radians up to θ = 30° angle of heel and not less than 0.09 metre-radians up to θ = 40° or the angle of flooding θ_f if this angle is less than 40°. Additionally, the area under the righting lever curve between the angles of heel of 30° and 40° or between 30° and θ_f, if this angle is less than 40°, shall not be less than 0.03 metre-radians.
- The righting lever (GZ) shall be at least 0.20 m at an angle of heel equal to or greater than 30°.
- The maximum righting lever should occur at an angle of heel preferably exceeding 30° but not less than 25°.
- The initial metacentric height, GM_0 shall not be less than 0.15 m.

From part 5 chapter 7 section 14 I in DNV (2012) it is stated that barges of length over 24 m shall comply with the above mentioned criteria.

Freeboard

For ship shaped units in offshore standard C301 DNV (2012) in chapter 2, section 2, paragraph E, rule 201. It is stated that ship shaped units shall have sufficient freeboard.

DNV also refers to the International Maritime Organization (IMO) and the International Convention on Load Lines, 1966.

2.2.3 Norwegian Maritime Directorate (NMD)

NMD is a governmental agency. They have authority over ships registered in Norway and foreign ships calling Norwegian harbors. In NMD (2003) Regulations for Mobile Offshore Units, section VI-3, page 374-5 the intact stability requirements is listed. And in the same section, page 388-9 the requirements for freeboard is listed.

Intact stability

General requirements

- Static angle of inclination due to wind shall not exceed 17 degrees in any condition.
- The “second intercept” between the righting moment curve and the wind inclination moment curve shall occur at an angle of 30 or more. The “second intercept” is defined as the point where the righting moment curve, corrected for any progressive flooding, crosses the wind inclination moment curve for the second time.
- The righting moment curve shall be positive over the entire range of angles from upright to the second intercept.

Additional requirements for units of a ship design and self-elevating units.

- The metacentric height (GM) shall be 0.5 meters or higher.
- The area under the righting moment curve up to the “second intercept”, or alternatively to a smaller angle, shall be not less than 40% in excess of the area under the wind inclination moment curve to the same limit angle.

Freeboard

In general NMD (2003) states that the structure is to be designed to handle the environment it is exposed to, though no less than what is required in Load Lines (IMO 2002).

2.2.4 IMO – International Convention on Load Lines, 1966

In Load Lines (IMO 2002), which is the regulations from the International Convention on Load Lines (ICLL), it is set up some conditions of assignment of freeboard in chapter 2. In this chapter it is focused on the distance from different openings as doorways, hatchways and ventilators to the exposed freeboard deck. These requirements are meant to ensure safety against flooding. In chapter 3 is about the freeboard requirements. It divides ships into two types, type A and type B. Type A ships is designed to carry only liquid cargoes in bulk and is therefore not interesting for this report. Type B ships are ships which does not fit with the description of type A ships. A feed barge would fall in under type B ships. The freeboard of type B ships can be read out of table B in regulation 28 in IMO (2002). This freeboard is based on the length of the ship (Table 3).

Table 3 Excerpts from Table B, regulation 28 in (IMO 2002)

Length of ship [m]	Freeboard [mm]
24	200
25	208
26	217
27	225
28	233
29	242
30	250
31	258
32	267
33	275

The lengths in Table 3 should cover the lengths of feed barges. Regulation 31 in IMO (2002) is about correction of the freeboard where the hull depth D exceeds L/15. In this case the freeboard shall be increased with (2.2).

$$Freeboard\ increase = \left(D - \frac{L}{15}\right) R[mm] \qquad (2.2)$$

Where R is L/0.48 at lengths less than 120 m.

2.3 Motions

In NS9415 there are no requirements on how the barge should behave in waves. The motions of the barge affect the personnel working on board. They might get seasick from too much motion and acceleration. That would affect the safety of the fish farm and the ability to prevent serious accidents.

There is a Nordic co-operative project which has come up with some criteria for vertical and lateral acceleration and roll on ships (NORDFORSK 1987). These criteria are as shown in Table 4.

Table 4 Criteria with regard to acceleration and roll

RMS Criterion			Description
Vertical acc.	Lateral acc.	Roll	
0.20 g	0.10 g	6.0^{o}	Light manual work
0.15 g	0.07 g	4.0^{o}	Heavy manual work
0.10 g	0.05 g	3.0^{o}	Intellectual work
0.05 g	0.04 g	2.5^{o}	Transit passengers
0.02 g	0.03 g	2.0^{o}	Cruise liner
g = gravity = 9.81 m/s^2 ^{o} = degrees			

The work done on a feed barge is recognized as heavy manual work by Krokstad and Lønseth (2003). So the recommended requirements for a feed barge are 0.2g for vertical acceleration, 0.1g for lateral acceleration and 6.0^{o} for the roll amplitude. This means that for the barge the acceleration should not exceed 1.4715 [m/s^2] in vertical direction and 0.6867 [m/s^2] in lateral direction.

2.4 Summary of rules and regulations

The intention of this report is to see if the requirements today are sufficient and if there are other regulations which maybe are better to use for more exposed fish farming and design of feed barges.

2.4.1 Intact stability and freeboard

All of the mentioned regulating agencies have requirements for intact stability. They are somewhat similar, but the difference is that the regulations for offshore installations are more nuanced. Some of the regulations are compared in Table 5.

Table 5 Comparison of stability and freeboard regulations

	NS9415	DNV	NMD	IMO	NORDFORSK
Area below GZ	> 0.08 m-rad	> 0.055(30 deg), > 0.09(40 deg)	Not less than 40% in excess of the area under the wind inclination moment curve	-	-
Righting lever GZ	> 0 m	0.2 m (30 deg)	> Wind inclination lever	-	-
GM	> 0 m	> 0.15 m	> 0.5 m	-	-
Static wind heel angle	< Angle eqivalent to half the freeboard	-	< 17 degrees	-	-
Minimum angle for positive GZ	15 degrees	> 30 degrees	Angle of "second intercept"	-	-
Freeboard	Fmin = $LOA*k_1+k_2$ [mm]	Sufficient for environment and not less than Load Lines	Sufficient for environment and not less than Load Lines	Load Lines (Table 3)	-
Vertical acceleration	-	-	-	-	0.15g
Lateral acceleration	-	-	-	-	0.07g
Roll	-	-	-	-	4 [deg]

From Table 5 it can be seen that NS9415 is a little milder than the regulations for offshore units. This is understandable since the aquaculture industry is located near the shore and not so exposed, therefore the barge doesn't need the same amount of stability as an offshore unit. The most important factor to be investigated in this report is the freeboard requirement. NS9415 has a formula to calculate the minimum freeboard for a barge design and the offshore regulations requires sufficient freeboard and not less than stated in Load Lines. That is more reasonable, but that also means that each unit has to be designed according to the area it is supposed to operate in. The possibility to make a design for mass production is then lower since it will be very costly to make a design that covers every possible environment.

3 Method

It will be done hydrodynamic computations on a typical barge design to see how it behaves in larger waves than normal for operating conditions at present time. The selected design will be exposed to irregular waves from 3 different angles and the combined motions will be computed. It will be assumed an anchor system which only will be described as a restoring coefficient matrix added to the restoring coefficients of the model in the equation of motion. The computations will be carried out in the computer program HydroD(DNV) and WADAM. The model is designed in GeniE(DNV). They are both developed by DNV and are a part of the SESAM(DNV) package. The computations of WADAM are the input for the post processing program POSTRESP of the SESAM package.

3.1 Model

The selected design is a ship shaped barge which is assumed to be the best design for more exposure of the designs that exists, see Figure 1.

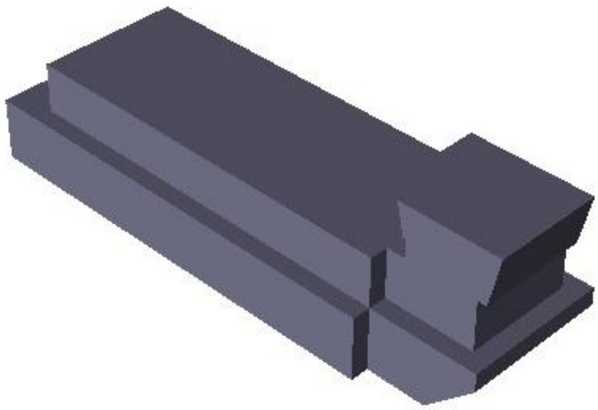


Figure 1 Ship shaped barge model

The barge is designed to match some of the largest barges that are in operation today.

3.1.1 Selected points

For freeboard estimates and acceleration estimates there has been selected some points on the barge (Centre of Buoyancy and Centre of Gravity is calculated in HydroD). They are presented along with the main dimensions in Figure 2.

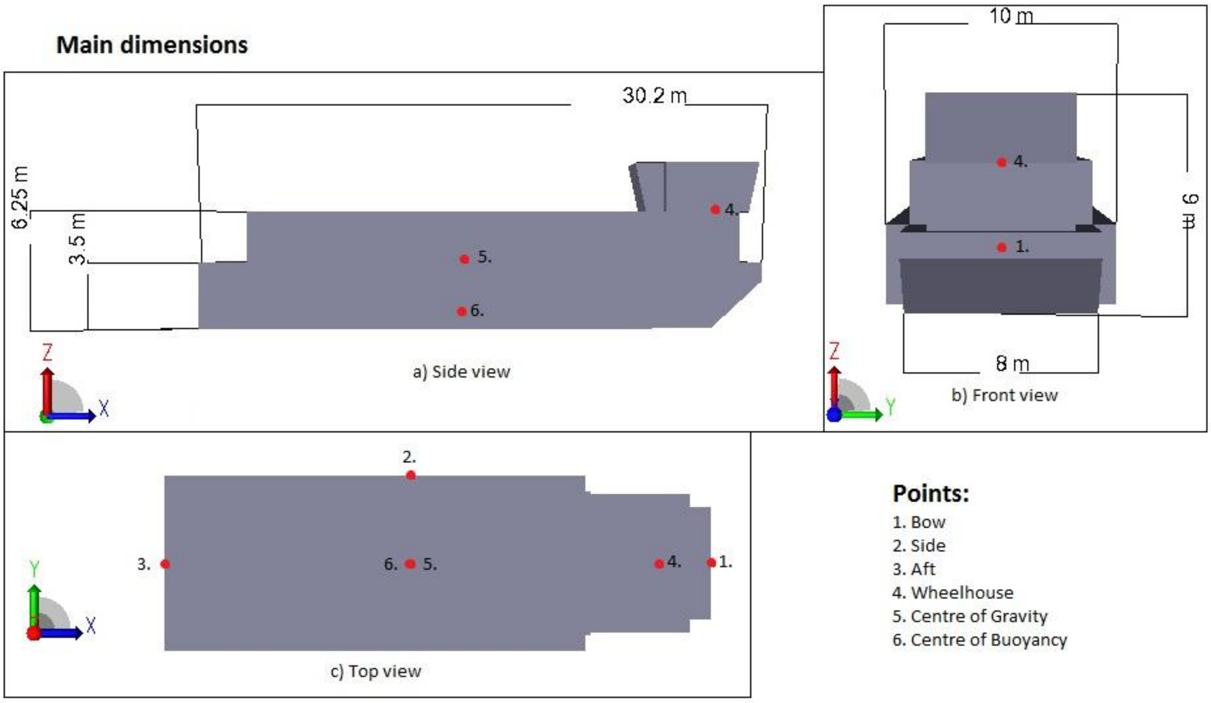


Figure 2 Main dimensions and selected points

The coordinates of the selected point, minus centre of gravity and centre of buoyancy which will be presented later, is given in Table 6.

Table 6 Coordinates of the selected points

Point	X [m]	Y [m]	Z [m]
BOW	27.5	0	3.5
SIDE	15.1	5	3.5
AFT	0	0	3.5
WHEELHOUSE	27.5	0	6.25

3.1.2 Reference coordinate system

The coordinate system corresponding to the model has its origin in the center of the stern at the keel of the barge, 3.5 meters below the AFT point. This coordinate system is also the reference system for Wadam when calculating the motions in the different points.

3.2 Exposed location

In the case in this report there are imagined two different locations, with finite fetch. One in the Northern North Sea (NNS), with wave statistics from page 30 in Faltinsen (1998), and one in the North Atlantic (NA) with wave statistics from DNV. They are presented as the probability of occurrence of combinations between significant wave heights (H_S) and zero up crossing period (T_Z), see Figure 3.

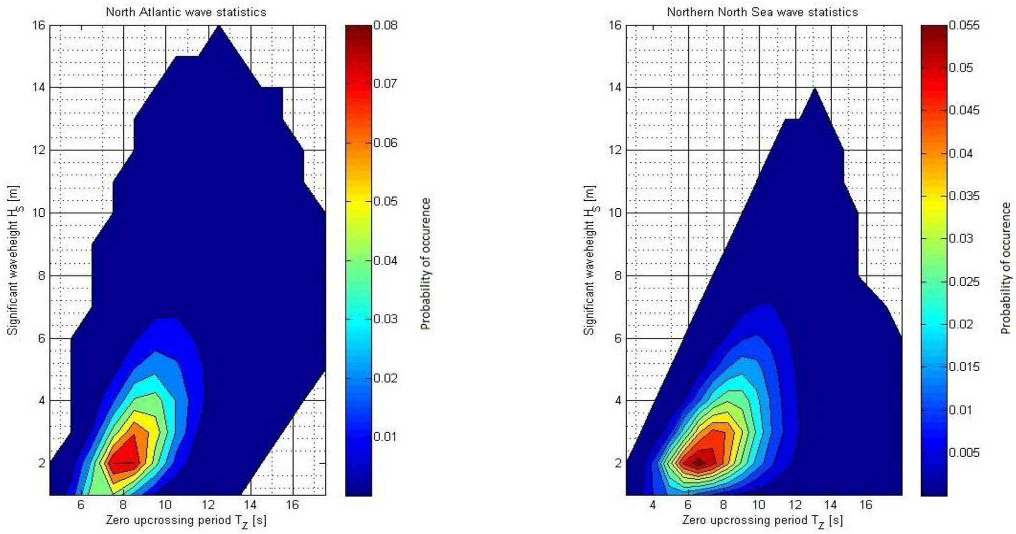


Figure 3 Joint frequency of significant wave height and zero up crossing period

From now these will be mentioned as different locations named accordingly NA and NNS. The wave period is an important factor when describing waves. The wave periods used in this report are the zero up crossing periods in Table 7.

Table 7 Wave zero up crossing periods

NNS T_Z [s]	NA T_Z [s]
2.45	4.5
3.27	5.5
4.09	6.5
4.91	7.5
5.73	8.5
6.55	9.5
7.37	10.5
8.19	11.5
9.01	12.5
9.83	13.5
10.65	14.5
11.47	15.5
12.29	16.5
13.11	17.5
13.93	
14.75	
15.57	
16.39	
17.21	
18.03	

The zero up crossing period is the time between each time the wave crosses the still water condition on the way up, see Figure 4.

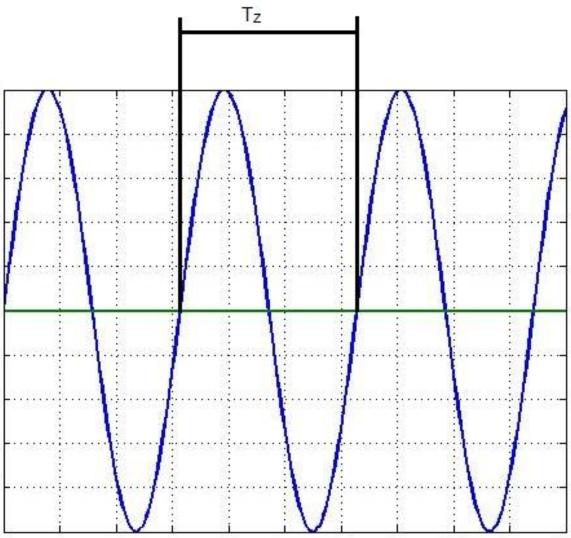


Figure 4 Description of zero up crossing period T_Z

The flat green line in Figure 4 is the still water level and the blue sinusoidal line represents the wave propagating towards the right.

Current, wind and ice

In this report current and ice will not be considered. Ice may be a problem for more exposed fish farming, but is too complicated to consider in this report. Current has little influence on the barge as it in this case not will have large enough draught to meet the constant measurable current. The wind has no direct influence on the hydrodynamic computation since the waves are assumed to be swelling sea and not wind generated. In the stability calculations there will be assumed a wind set according to the regulations for controlling purpose only and is not a result of location data.

3.2.1 Wave lengths

The wave lengths has an impact on the computation of the motions of the barge, in this report two different locations has been chosen and the wave lengths used in the report is calculated from the wave period inputs. The connection between the wave lengths and the period is show in equation (3.1).

$$\lambda = \frac{g}{2\pi} T_Z^2 \tag{3.1}$$

3.2.2 Irregular waves

Irregular waves are made up of many different regular waves in layers and it is stationary within a short term situation (Pettersen 2004). The sea state is therefore described with statistics, see equation (3.2) (Faltinsen 1998).

$$\zeta = \sum_{j=1}^{N} A_j \, sin(\omega_j t - k_j x + \varepsilon_j) \tag{3.2}$$

The wave amplitude A_j can be expressed by a wave spectrum S(ω), see equation (3.3).

$$\frac{1}{2} A_j^2 = S(\omega_j)\Delta\omega \tag{3.3}$$

For locations with finite fetch the 23rd ITTC recommends a JONSWAP (JOint North Sea WAve Project) spectrum (Stansberg, Contento et al. 2002), see equation (3.4 – 3.7).

$$S(\omega) = 155 \frac{H_S^2}{T_1^4 \omega^5} e^{\left(\frac{-944}{T_1^4 \omega^4}\right)} 3.3^{Y} \; [m^2 s] \tag{3.4}$$

$$Y = e^{\left(-\left(\frac{0.191\omega T_1 - 1}{\sqrt{2}\sigma}\right)^2\right)} \tag{3.5}$$

$$\sigma = 0.07 \; for \; \omega \leq \frac{5.24}{T_1} \tag{3.6}$$

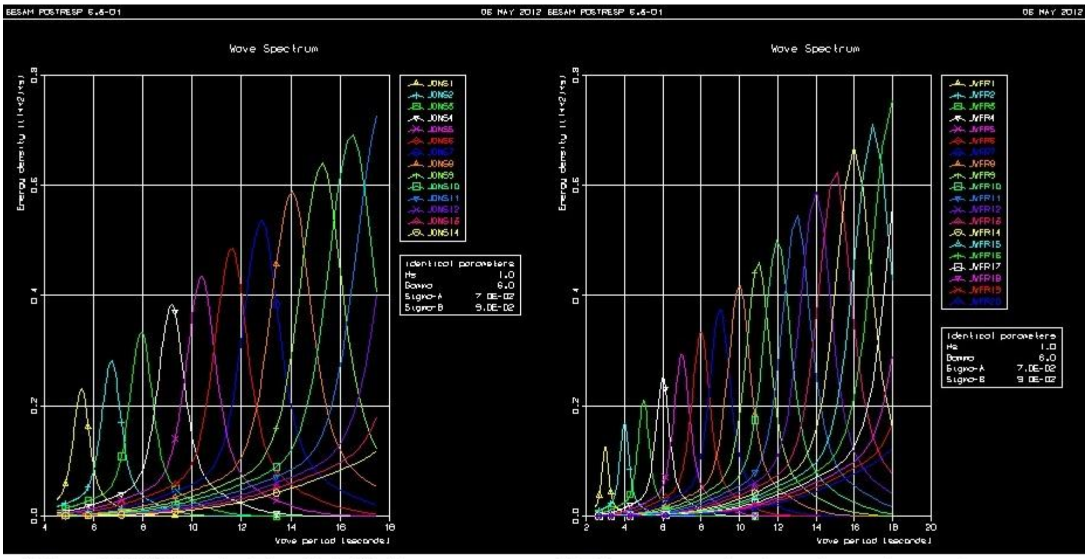
$$\sigma = 0.09 \; for \; \omega > \frac{5.24}{T_1} \tag{3.7}$$

In POSTRESP the JONSWAP spectrum is described with the zero up crossing period and γ. The connection between T_Z and T_1 is described in DNV-OS-E301(2010) as shown in equation (3.8 – 3.9)

$$\frac{T_1}{T_P} = 0.7303 + 0.0493\gamma - 0.006556\gamma^2 + 0.000361\gamma^3 \tag{3.8}$$

$$\frac{T_Z}{T_P} = 0.6673 + 0.05037\gamma - 0.00623\gamma^2 + 0.0003341\gamma^3 \quad (3.9)$$

In this report it is assumed fully developed swell sea and $\gamma = 6$ (NS9415 2009). As shown in Figure 3 the wave statistics cover an array of T_z which means that there has to be made two full range JONSWAP spectrums. One for NNS with T_z from 2.45 s to 18.03 s and one for NA with T_z from 4.5 s to 17.5 s, see Figure 5.



a)Full range JONSWAP based on T_Z from North Atlantic

b)Full range JONSWAP based on T_Z from Northern North Sea

Figure 5 Full range JONSWAP spectra illustration

As show in Figure 5 there are 14 spectra representing the data form NA and 20 spectra for the data from NNS. When using a wave spectrum it is normal to calculate the short term response as it is said that the wave spectrum is constant within 20 min – 3 hours. POSTRESP has the ability to do this computation with the input of wave spectra, response variable and wave directions. The wave directions used in the computation is given as an angle relative to the bow and the x-axis, see Figure 6

Figure 6 Definition of wave direction

The wave direction used in this report is given in Table 8.

Table 8 Wave directions

Angle nr.	Degrees
1	0
2	45
3	90

Since the barge is symmetric about the x- axis and is designed for dominating wave heading towards the bow, it is only taken angles up to 90 degrees into consideration.

3.3 Model hydrostatic and stability

The hydrostatics and stability computations done in HydroD is to verify that the design made in GeniE is valid. The model made in GeniE (Figure 1) with its tanks (Figure 7) and tank contents (Table 9) is the basis for the hydrostatic computation. The stability analysis is for intact stability to show that the model designed is stable and valid.

Table 9 Tank types, number and content density

Tank content	Number of tanks	Content density [kg/m³]	Volum per tank [m³]
Feed	10	650	69.79
Diesel	2	832	11.8
Water	1	1000	2.55
Grey water	1	1000	2.55

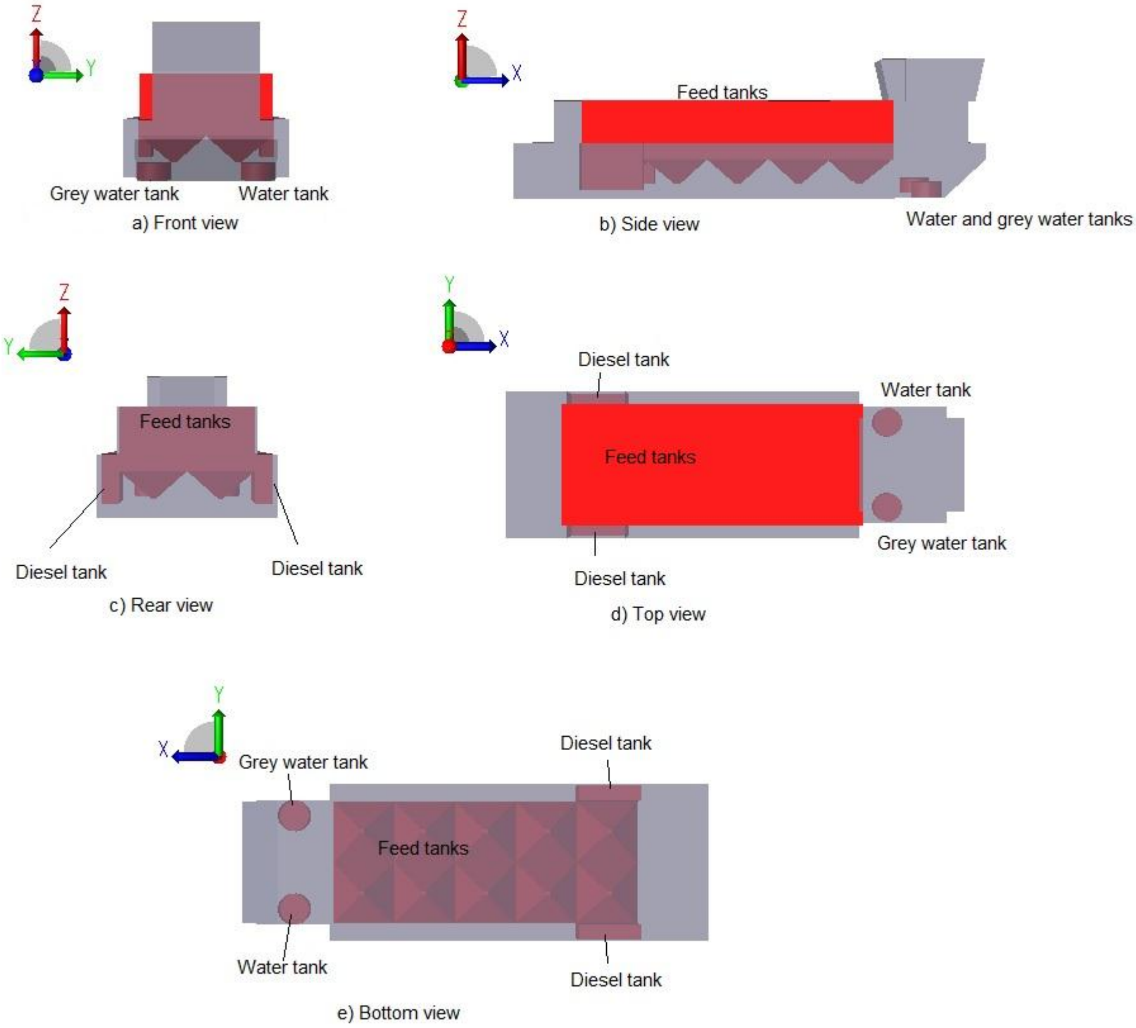


Figure 7 Tank arrangement

The loading condition used for the computations is with full tanks. The freeboard and other static values will be given from this condition. For the freeboard it will initially be considered according to the requirement set in NS9415 (2009). The minimum freeboard requirement (equation (2.1)) is calculated for the most extreme condition with $H_S > 3$ m and with cross-tie. The barges regulated freeboard and thus its maximum draught is given in Table 10.

Table 10 Freeboard requirements

LOA	30,2	m
Beam	10	m
Hull depth	3,5	m
Freeboard reg.	1,41	m
Draught reg	2,09	m

In Table 10 the regulated freeboard is calculated from NS9415. The results from the hydrodynamic computations will be compared with this freeboard.

For the hydrostatic analysis it is added a constant wind pressure caused by a wind on 30 m/s to make the static wind heeling moment. The analysis will give out the GZ-curve. It is a measure on how long the righting arm is at different heeling angles. It also gives a moment-curve, which compares the righting moment with the wind inclination moment. The GZ-Curve also tells how far the barge can heel before it reaches the angle of vanishing stability. Another property which is of interest is the area below the GZ-Curve. This area is also given from the analysis in HydroD. Other results and information given from the stability analysis is:

- The metacentric height (GM)
- The total mass with and without tank contents
- The center of gravity (COG)
- The buoyancy volume and mass
- The center of buoyancy (COB)
- The center of flotation (COF)
- The block coefficient
- Angle of deck immersion
- Tank information
    - Total volume
    - Content volume and mass

In HydroD it is possible to do rule checks on the stability, and in this case it will be done to intact stability rule checks, one check against IMO general regulations and one against NMD intact stability regulations.

3.4 Model hydrodynamic computation

From HydroD the frequency domain hydrodynamic analysis program WADAM (Wave Analysis by Diffraction And Morison theory) is executed (DNV). It calculates the interactions between waves and structure in the rigid-body motion modes shown in Figure 8.

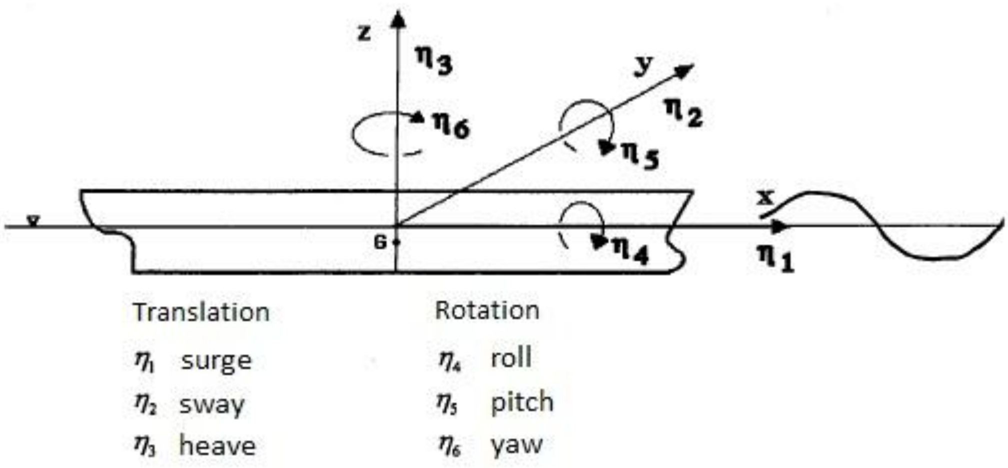


Figure 8 Definition of rigid-body motion modes in the axis system

3.4.1 WADAM

WADAM is a general analysis program of wave-structure interaction for fixed and floating structures. It is an integrated part of the SESAM suite programs (DNV 1994). The calculation method in WADAM used in this report for computation of wave loads is potential theory applied to a panel model. With this method it computes a global response analysis of which the result for wave excitation forces and moments, and motion response is used for analyzing the barge design.

Potential theory assumptions

When using potential theory there are some implicit assumptions. These assumptions are that the fluid is inviscid in irrotational motion and incompressible. That the fluid is inviscid means that it has zero viscosity; by irrotational it means that locally the fluid does not tend to rotate; and the assumption that the fluid is incompressible means that locally the fluid volume does not change. With these assumptions WADAM calculates first order radiation and diffraction effects on the barge model generated in GeniE. Thus find the wave induced forces on the barge from incident waves specified in this case by wave zero up crossing period (Table 7) and three wave directions (Table 8).

Equation of motion

By applying Newtons law and include the added mass, damping and excitation force contributions acting on the panel model of the barge the motion in each of the 6 rigid body motion modes can be found from the equation of motion (3.10).

$$\sum_{j=1}^{6}\left[\left(M_{ij}+A(\omega)_{ij}\right)\ddot{\eta}_j+B(\omega)_{ij}\dot{\eta}_j+C_{ij}\eta_j\right]=F(\omega,\beta)_i,\ \ (i=1,\ldots,6) \qquad (3.10)$$

Since the waves are described with period T_Z and wave heading β the rigid body modes values are given as response amplitude operators (RAO's) from WADAM. These are non-denominated values which is changed to response per meter H_S in SESAM's post processing program POSTRESP.

3.4.2 POSTRESP

The results from HydroD and WADAM are loaded into a post processing program called POSTRESP (DNV). In this report three of the features available in POSTRESP have been used:

- Display response variables
- Combine response variables
- Display short term response

The results are given as response amplitude operators (RAO) in POSTRESP, i.e. they are given as significant amplitude per significant wave height (H_S) and can be combined with irregular waves in the form of wave spectra. These RAO's are given in connection with the zero up crossing period (T_Z) and then via excel timed up with the significant wave height to be presentable and useful for this report. Also MATLAB has been used to present some of the results.

3.5 Natural periods of the model

The natural periods of the barge are important to find the resonance areas when exposed to waves of different periods. Relatively large motions are likely to occur if the structures are excited with oscillation periods in the vicinity of a resonance period. The uncoupled and undamped natural period can be written as (3.11), Faltinsen (1998).

$$T_{ni} = 2\pi\sqrt{\left(\frac{M_{ii}+A_{ii}}{C_{ii}}\right)} \tag{3.11}$$

This report will concentrate on the natural periods in heave (T_{n3}), roll (T_{n4}) and pitch (T_{n5}). As they are the modes connected to the vertical motion. The coefficients needed to calculate the natural periods can be found in the result file from WADAM or read out from POSTRESP. It will a iterative process as the natural period is first assumed from RAO graphs and then the coefficients is found from that period and then a new period is calculated from the coefficients and then the process is repeat until the input period is equal to the output period.

3.6 Compensation for viscous damping

In reality there is an effect called viscous damping which is a part of the damping in the equation of motion. To compute this effect the program needs a Morison model, such a model is not provided in this case. To account for this it will be added a fraction of the critical damping in some rigid-body motion mode where the result will show some irrationally large results. The critical damping is dependent on the natural period of the structure in a given rigid-body motion mode (3.12).

$$B_{Ci} = \frac{4\pi(M_{ij}+A(\omega)_{ij})}{T_{ni}}, (i = j = 1, \dots, 6) \tag{3.12}$$

The damping added is the assumed fraction between viscous damping and critical damping (3.13).

$$\xi = \frac{B_v}{B_c} \tag{3.13}$$

As a basic rule of thumb it is normal to add a fraction ξ between 3% - 7% of critical damping.

3.7 Mooring assumptions

To simulate the mooring of the barge it will be added a restoring matrix to the computations in WADAM. To estimate the restoring it is assumed that the barge is to be held stationary in the horizontal plane. Ergo the mooring has to withstand the horizontal forces acting on the barge from the waves. The mooring arrangement assumed in this report is shown in Figure 9.

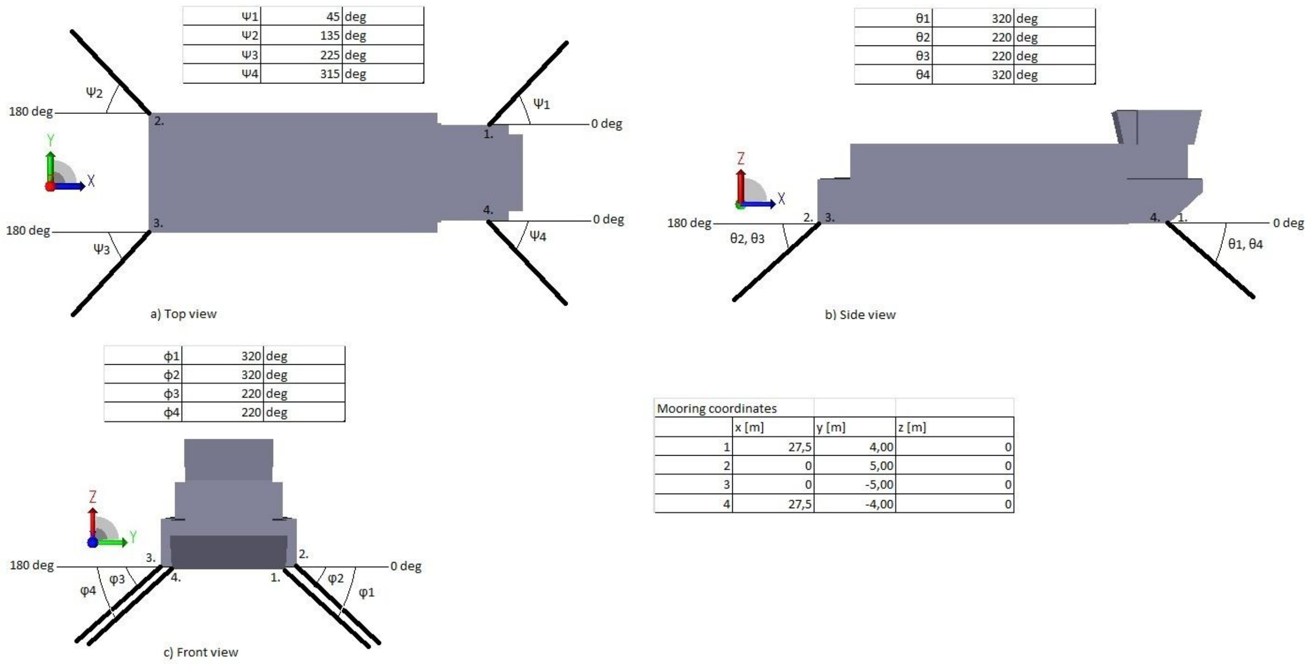


Figure 9 Mooring arrangement

The horizontal force from the waves acting the barge is computed in WADAM. From the force acting on the barge and the displacement in the same direction as the force acts the horizontal restoring is found, eq. (3.14-3.15).

$$C_{11} = \frac{F_1}{\eta_1} \quad (3.14)$$

$$C_{22} = \frac{F_2}{\eta_2} \quad (3.15)$$

And from the restoring and the mooring angle the stiffness coefficient of the mooring line can be found, eq. (3.16-3.17) (Faltinsen 1998:p266).

$$C_{11} = K \sum_{i=1}^{4} cos^2\Psi_i \rightarrow K = \frac{C_{11}}{\sum_{i=1}^{4} cos^2\Psi_i} \quad (3.16)$$

$$C_{22} = K \sum_{i=1}^{4} sin^2\Psi_i \rightarrow K = \frac{C_{22}}{\sum_{i=1}^{4} sin^2\Psi_i} \quad (3.17)$$

The K is assumed equal for every mooring line. The largest K from (3.16-3.17) is chosen and then from trigonometric properties used to calculate the rest of the restoring coefficients (Table 11), 36 in total, see Appendix 1.

Table 11 Restoring matrix

C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}
C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}
C_{41}	C_{42}	C_{43}	C_{44}	C_{45}	C_{46}
C_{51}	C_{52}	C_{53}	C_{54}	C_{55}	C_{56}
C_{61}	C_{62}	C_{63}	C_{64}	C_{65}	C_{66}

Since the mooring arrangement is symmetric about the x-z plane C_{16}, C_{61}, C_{12} and C_{21} are zero.

3.8 Relative motion between the barge and free surface elevation

The relative motion between the barge and the sea surface is important to know as it inflects the safety of people on board. The relative motion shows how much freeboard is needed to avoid water on deck. This relative motion is found as an absolute value of the difference between the barge vertical motions at point 1-3 in Figure 2 and the wave elevation on the free surface at the same point.

Vertical motion in a point i on the barge (3.18)

$$\boldsymbol{s}_{3i} = \eta_3 + y_i\eta_4 - x_i\eta_5,\ \ (i = 1, \dots, n) \tag{3.18}$$

The relative motion (Rm) is then described as (3.19).

$$Rm_i = |\boldsymbol{s}_{3i} - \zeta| \tag{3.19}$$

3.9 Acceleration and rotation

Acceleration is the double derived of the motion with regards to time. The point selected for the acceleration check is in point 4 in Figure 2 which corresponds to the wheel house. This is where the control center of the barge is located and it is from here the fish cages are monitored and the feed system is managed. The acceleration is calculated in surge, sway and heave (3.20 – 3.22)

$$\ddot{\boldsymbol{s}}_1 = \ddot{\eta}_1 + z\ddot{\eta}_5 - y\ddot{\eta}_6 \tag{3.20}$$

$$\ddot{\boldsymbol{s}}_2 = \ddot{\eta}_2 + x\ddot{\eta}_6 - z\ddot{\eta}_4 \tag{3.21}$$

$$\ddot{\boldsymbol{s}}_3 = \ddot{\eta}_3 + y\ddot{\eta}_4 - x\ddot{\eta}_5 \tag{3.22}$$

Where x, y, z is the coordinates to the WHEELHOUSE point (point 4 in Figure 2).

3.9.1 Root mean square

In NORDFORSK (1987) the criteria is given as a root mean square, which is the square root of the arithmetic mean of the squares of the original values. These values are a response as a function of wave height. The RMS is given as (3.23).

$$x_{RMS} = \sqrt{\frac{1}{n}({x_1}^2 + {x_2}^2 + \dots + {x_n}^2)} \tag{3.23}$$

Where x_1, x_2,…, x_n is response values as a function of wave height. This means that the total values for the NNS location is up to 19 responses for each of the 14 wave heights.

4 Results

In this chapter the results from HydroD, excel and matlab will be presented.

4.1 Hydrostatics and stability

When the model from GeniE is imported to HydroD and from the definitions of weights and volume of the structure and tank contents the draught, trim and heel is given from the program (Table 12).

Table 12 Hydrostatic data

LOA	30.2	m
Beam	10	m
Hull depth	3.5	m
Draught AP	1.79	m
Draught FP	2.06	m
Trim	0.52	Deg
Heel	0.00	Deg
Amidship draught	1.92	m
Freeboard	1.58	m

From the values in Table 12 it is run a stability analysis and two rule checks.

4.1.1 Stability analysis

In Table 13 the results from the stability analysis is presented.

Table 13 Stability analysis results

Result variable	**Value**	**X [m]**	**Y [m]**	**Z [m]**
Metacentric Height GM [m]	1.42			
Total mass (including compartment contents) [kg]	544014.92			
Total mass (without compartment contents) [kg]	89517.80			
Center of gravity (wet)		14.21	7.09E-05	3.80
Center of gravity (without compartment contents)		15.27	-1.21E-05	3.13
Center of gravity (with compartment contents in metacenter)		14.21	7.09E-05	3.80
Buoyancy volume [m^3]	530.75			
Buoyancy mass [kg]	544014.74			
Center of buoyancy		14.24	3.38E-05	0.97
Center of flotation		14.39	1.43E-06	1.92
Trim moment [Nm]	202800654.30			
Panel model block coefficient [-]	0.88			
Projected XZ area above waterline [m^2]	138.60			
Center projected XZ area above waterline		16.77	-	2.52
Projected XZ area below waterline [m^2]	54.92			
Center projected XZ area below waterline		14.64	-	-0.95
Deck immersion heel angle [deg]	16.69			

4.1.2 GZ- and Moment-Curve

In Figure 10 the GZ-Curve is presented and in Figure 11 the moment is presented. The values of interest read out of them in HydroD are presented in Table 14.

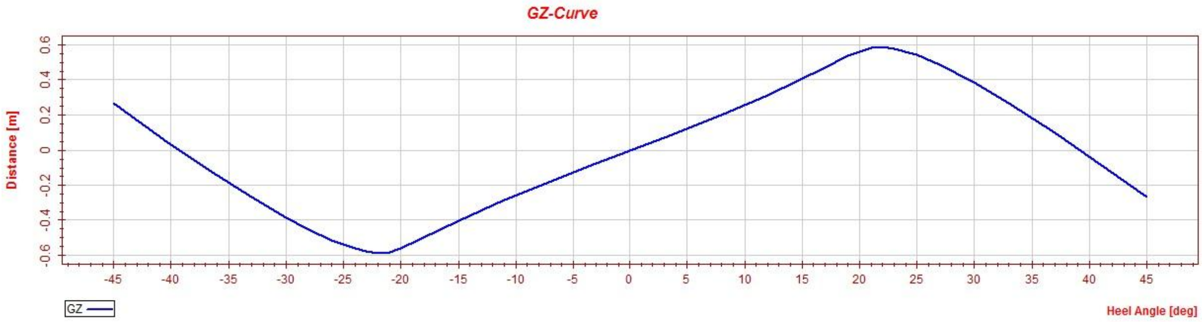


Figure 10 GZ-Curve

The GZ-curve (Figure 10) has to be positive for positive inclination angles. Since the barge is symmetric about the XZ-plane the GZ-curve also is symmetric about 0 degrees inclination, but with opposite sign.

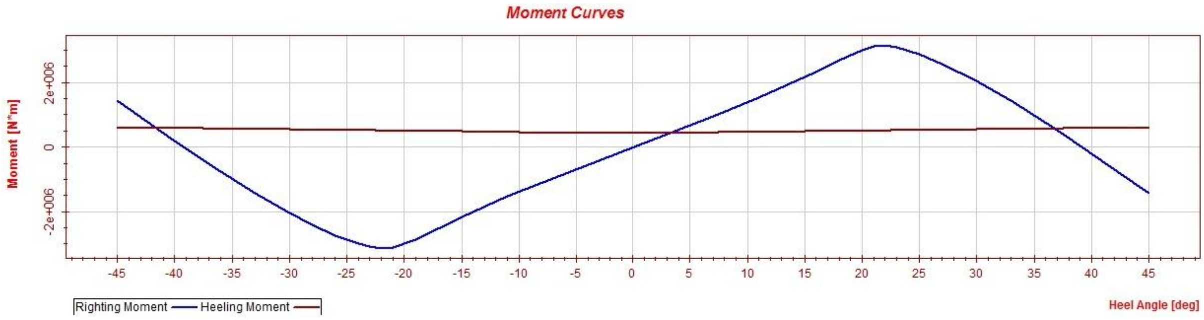


Figure 11 Moment curve

The moment curves in Figure 11 are a comparison of the wind heeling moment and the righting moment. On the right side of 0 degrees inclination the “first-“ and “second intercept” point can be found as the two points where the heeling moment and the righting moment curves cross each other on the positive side.

Table 14 Stability report

Angle of vanishing stability	39.26	deg
Max GZ	0.59	m
GZ at 30 deg	0.38	m
Angle of max GZ	22	deg
Area up to max GZ	0.11	m-rad
Area up to 30 deg	0.18	m-rad
Area up to 40 deg	0.22	m-rad
Righting moment integral up to 40 deg	1151205.68	Nm
Heeling moment integral up to 40 deg	367807.48	Nm
Area between heeling and righting moment up to 40 deg	783398.19	Nm

Table 14 shows some values of interest when it comes to see if the barge is floating in an upright position and how far it can heel before it has no more righting arm.

4.1.2 Rule checks

The rule checks and the results are being presented below.

NS9415 stability rule check

The NS9415 stability rule check (Table 15) is done manually since it is not implemented in HydroD.

Table 15 NS9415 Stability rule check

Analysis variables	Analysis	Requirements	Result
Area below GZ-curve from 0 deg to maximum righting arm	0.11 [m-rad]	0.08 [m-rad]	OK
Static heel angle due to wind	3.33 deg	8.98 deg	OK
Last angle of positive GZ	39.26 deg	15 deg	OK

Table 15 shows that the barge is within the requirements of NS9415.

IMO stability rule check

Based on the requirements set in the IMO regulations a stability check has been done in HydroD (Table 16).

Table 16 IMO stability rule check

Check	Value	Unit
Waterline Z	1.78794	m
Waterline length	29.7233	m
Angle flooding	Not encountered	deg
Mean moulded draught	1.9257	m
KG	3.79587	m
Projected area above waterline	138.6	m^2
Mass displacement	544015	Kg
Cb	0.875993	
Cw	0.962841	
Z	3.4626	m
OG	1.87894	m
GZ-area 30deg	0.183865	m
GZ-area 30deg required (and satisfied)	0.055	m
GZ-area 40deg/angle flooding	0.215785	m
GZ-area 40deg/angle flooding required (and satisfied)	0.09	m
GZ-area 30deg-40deg/angle flooding	0.0319207	m
GZ-area 30deg-40deg/angle flooding required (and satisfied)	0.03	m
Max GZ above 30deg	0.383692	m
Max GZ above 30deg required (and satisfied)	0.2	m
Angle of max GZ	22	deg
Warning: Angle of max GZ required (but not satisfied)	25	deg
Initial metacentric height	1.41803	m
Initial metacentric height required (and satisfied)	0.15	m
Wind and rolling criteria (area_b-area_a)	0.0590342	m
Wind and rolling criteria (area_b-area_a) required (and satisfied)	0	m

It appears from Table 16 that the barge will not be acknowledged by the IMO rules, but only concerning the angle of max GZ.

NMD intact stability check

Based on the requirements set in the NMD regulations a stability check has been done in HydroD (Table 17).

Table 17 NMD intact stability check

Check	Value	Unit
Waterline Z	1.78794	m
Waterline length	29.7233	m
Angle flooding	Not encountered	deg
Mean moulded draught	1.9257	m
KG	3.79587	m
Projected area above waterline	138.6	m^2
Mass displacement	544015	Kg
First intercept righting/heeling moment	3.32879	deg
Static wind inclination angle	3.32879	deg
Static wind inclination angle required (and satisfied)	17	deg
Second intercept angle righting/heeling moment	36.7235	deg
Second intercept angle righting/heeling moment required (and satisfied)	30	deg
Righting moment zero crossing angle	39.2598	deg
Righting moment zero crossing angle required (and satisfied)	36.7235	deg
Metacentric height	1.41803	m
Metacentric height required (and satisfied)	0.5	m
Righting moment area excess %	241.785	%
Righting moment area excess % required (and satisfied)	40	%

It appears from Table 17 that the barge passes the NMD stability rule check, and therefore is stable enough for the Norwegian government.

4.1.3 Weights and loading condition

From the model it is also defined size and capacities of the tanks and the total weight of the barge with its tank contents is given in Table 18.

Table 18 Weight capacities and structure weight

Feed	431	ton
Diesel	18.65	ton
Water	2.42	ton
Grey water	2.42	ton
Equipment	50.31*	ton
Total cargo	504.8	ton
Structure	89.52	ton
Total weight	594.32	ton

**The equipment weight is the weight that would lover the barge to minimum freeboard, and it is not a part of the computations.*

The loading condition for the hydrodynamic calculation is presented in Table 19.

Table 19 Model loading condition

Weight full tanks	454.49	ton
Structure weight	89.52	ton
Total weight	544.01	ton
Amidship draught	1.92	m
Freeboard	1.58	m
Trim	0.52	deg
Heel	0.00	deg

The loading condition in Table 19 has been chosen without equipment because the type of equipment and the location of the equipment on the barge are outside the scope of this report. Under these conditions the barge is within the freeboard regulation of NS9415.

4.2 Hydrodynamic computation

In this report there has been used wave statistics from two imaginary locations and the data is representative for NNS and NA. Therefore the results will be presented in to parts, one for NNS and one for NA.

4.2.1 Wave lengths

The wave lengths from WADAM are presented in Table 20 and Table 21.

Table 20 Wave lengths (NNS)

WAVE	WAVE PERIOD [s]	WAVE LENGTH [m]
1	2.45	9.37
2	3.27	16.69
3	4.09	26.11
4	4.91	37.63
5	5.73	51.24
6	6.55	66.96
7	7.37	84.78
8	8.19	104.69
9	9.01	126.70
10	9.83	150.82
11	10.65	177.03
12	11.47	205.34
13	12.29	235.74
14	13.11	268.21
15	13.93	302.71
16	14.75	339.16
17	15.57	377.40
18	16.39	417.25
19	17.21	458.45
20	18.03	500.72

Table 21 Wave lengths (NA)

WAVE	WAVE PERIOD [s]	WAVE LENGTH [m]
1	4.50	31.61
2	5.50	47.21
3	6.50	65.94
4	7.50	87.79
5	8.50	112.77
6	9.50	140.86
7	10.50	172.08
8	11.50	206.41
9	12.50	243.86
10	13.50	284.37
11	14.50	327.85
12	15.50	374.07
13	16.50	422.70
14	17.50	473.29

The wave lengths in Table 20 and Table 21 are the lengths calculated in WADAM from the inputs to HydroD.

4.2.3 Mooring

The mooring is assumed as the restoring matrix calculated from the trigonometric properties named in chapter 3 and appendix 1. The mooring line stiffness chosen for the two locations is presented in Table 22.

Table 22 Mooring line stiffness

Location	**Mooring line K [N/m]**	**Force direction**
NNS	1.51E+06	Surge
NA	6.91E+05	Sway

As shown in Table 22 the mooring lines are different for the two locations as the wave forces on the barge is different. The mooring line stiffness of each location is chosen from the largest force in horizontal direction over all the wave spectra and divided by the adjacent displacement in that direction. This result in two different restoring matrices added to the calculations in WADAM (Table 23 and Table 24).

Table 23 Restoring matrix NNS

Northern North Sea						
C	1	2	3	4	5	6
1	2,798E+06	0	-8,571E+05	1,264E+06	-2,125E+07	0
2	0	3,259E+06	-1,147E+06	-2,269E+06	-2,845E+07	5,165E+07
3	-8,571E+05	-1,147E+06	5,788E+05	2,392E+06	1,527E+07	-2,791E+07
4	1,264E+06	-2,269E+06	2,392E+06	1,186E+07	1,658E+08	-8,500E+07
5	-2,125E+07	-2,845E+07	1,527E+07	1,658E+08	4,198E+08	-7,926E+08
6	0	5,165E+07	-2,791E+07	-8,500E+07	-7,926E+08	1,542E+09

Table 23 is the restoring matrix used to correspond to the effect of mooring at location NNS.

Table 24 Restoring matrix NA

North Atlantic						
C	1	2	3	4	5	6
1	1,277E+06	0	-3,912E+05	5,768E+05	-9,703E+06	0
2	0	1,488E+06	-5,238E+05	-1,036E+06	-1,299E+07	2,358E+07
3	-3,912E+05	-5,238E+05	2,642E+05	1,092E+06	6,969E+06	-1,274E+07
4	5,768E+05	-1,036E+06	1,092E+06	5,416E+06	7,567E+07	-3,880E+07
5	-9,703E+06	-1,299E+07	6,969E+06	7,567E+07	1,916E+08	-3,618E+08
6	0	2,358E+07	-1,274E+07	-3,880E+07	-3,618E+08	7,037E+08

Table 24 is the restoring matrix used to correspond to the effect of mooring at location NA.

4.2.1 Natural periods

The uncoupled and undamped natural periods of the barge in heave, roll and pitch is presented in Table 25.

Table 25 Natural periods

Heave - T_{n3}	4.6	s
Roll - T_{n4}	7.2	s
Pitch - T_{n5}	4.3	s

When the barge is moored the natural periods will be affected as the natural period is dependent on the restoring coefficient. The moored natural periods for the two locations is presented in Table 26 and Table 27.

Table 26 Moored natural periods (NNS)

Heave - T_{n3}	13.0	s
Roll - T_{n4}	5.2	s
Pitch - T_{n5}	5.8	s

Table 26 shows that the assumed mooring leads to more restoring forces and therefore increases the natural periods of the barge.

Table 27 Moored natural periods (NA)

Heave - T_{n3}	19.7	s
Roll - T_{n4}	7.7	s
Pitch - T_{n5}	9.8	S

Table 27 is the natural periods after the effect of the mooring at NA. Also here the mooring assumed increases the restoring forces in each mode and thus leads to an increase of natural periods.

4.2.4 Critical damping

It has been added 5% in the three modes heave, roll and pitch in this case. This is to compensate for the lack of viscous damping in those modes because of the input model to HydroD. It is within the normal assumption between 3% - 7%.

4.2.5 Relative response

Since the relative response is dependent on both wave height and wave period, it will be presented in contour diagrams with zero up crossing period along the x- axis and significant wave height along the y-axis. The colors in the diagram show the response in combination between H_S and T_Z. The color bar to the right shows the size of the relative response connected to the colors in the diagram. The following contour diagrams shows in which areas of combination between significant wave height and wave period the largest relative response is occurring. For each wave direction it is shown relative response in three points. BOW, SIDE and AFT.

Relative vertical response at location NNS

The following diagrams are from the imaginary location NNS, with the appurtenant wave statistics (Figure 12 - Figure 14).

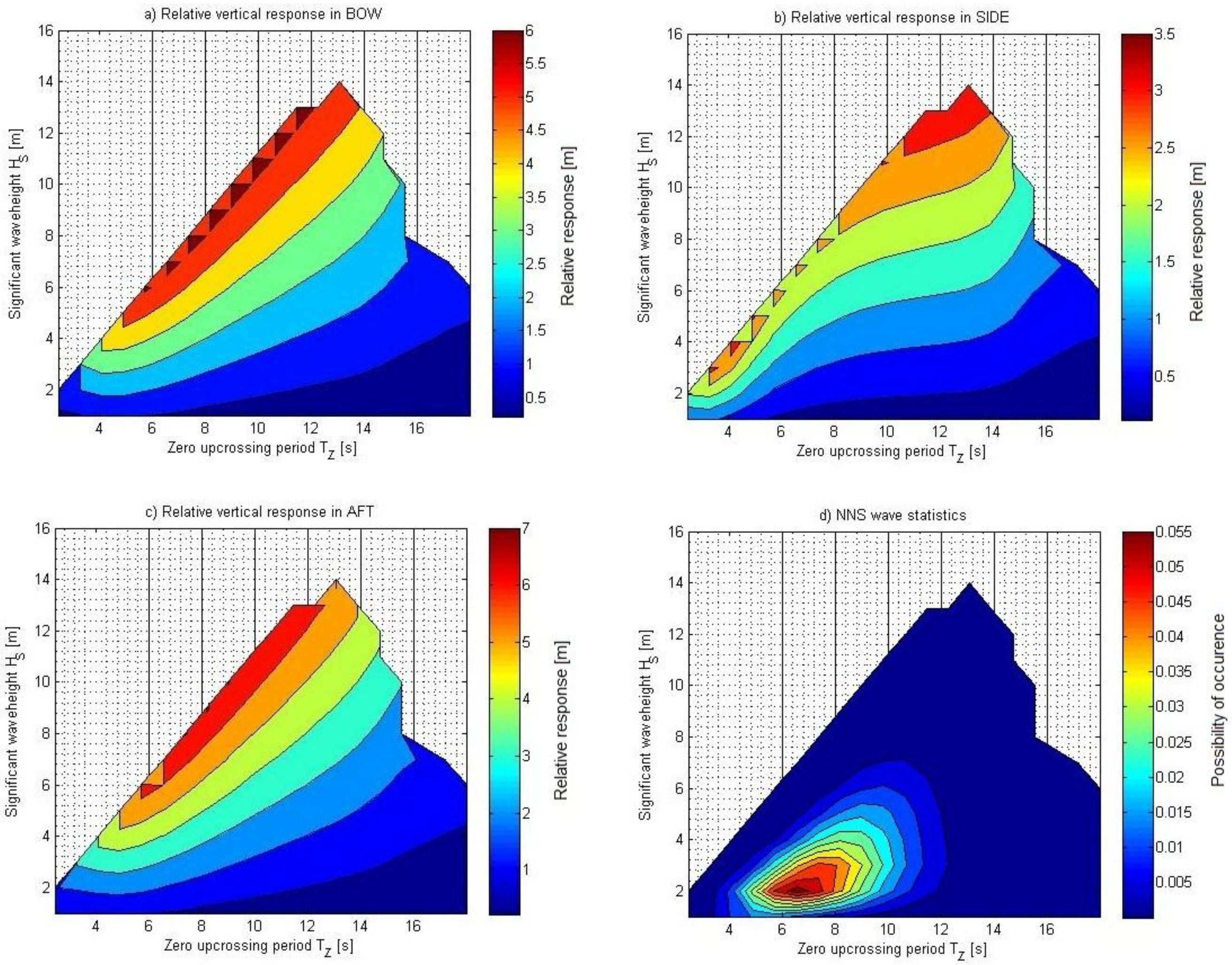


Figure 12 Relative vertical response at wave direction β = 0 degrees

In Figure 12 a) – c), the waves are heading in towards the bow of the barge. In diagram a) of Figure 12 the dark red area is where the largest relative response will occur. The 8 triangles of dark red is where the combination of significant wave height and zero up crossing period will lead to a relative response of 6.61 meters. One of these combinations is for 8 meter H_S combined with 8 seconds T_Z. The colours show the response and red means high response. The response and combination areas differ from figure to figure as will be shown in Figure 12 - Figure 14. In Figure 12 d) the wave statistics from location NNS is presented, here the colours show in what area the waves are most likely to occur. From statistics the amount of waves with one combination of H_S and T_Z is counted and in the end all is divided by the total amount of waves measured. In combination with the response diagrams this show what response level the barge is mostly having when exposed at location NNS.

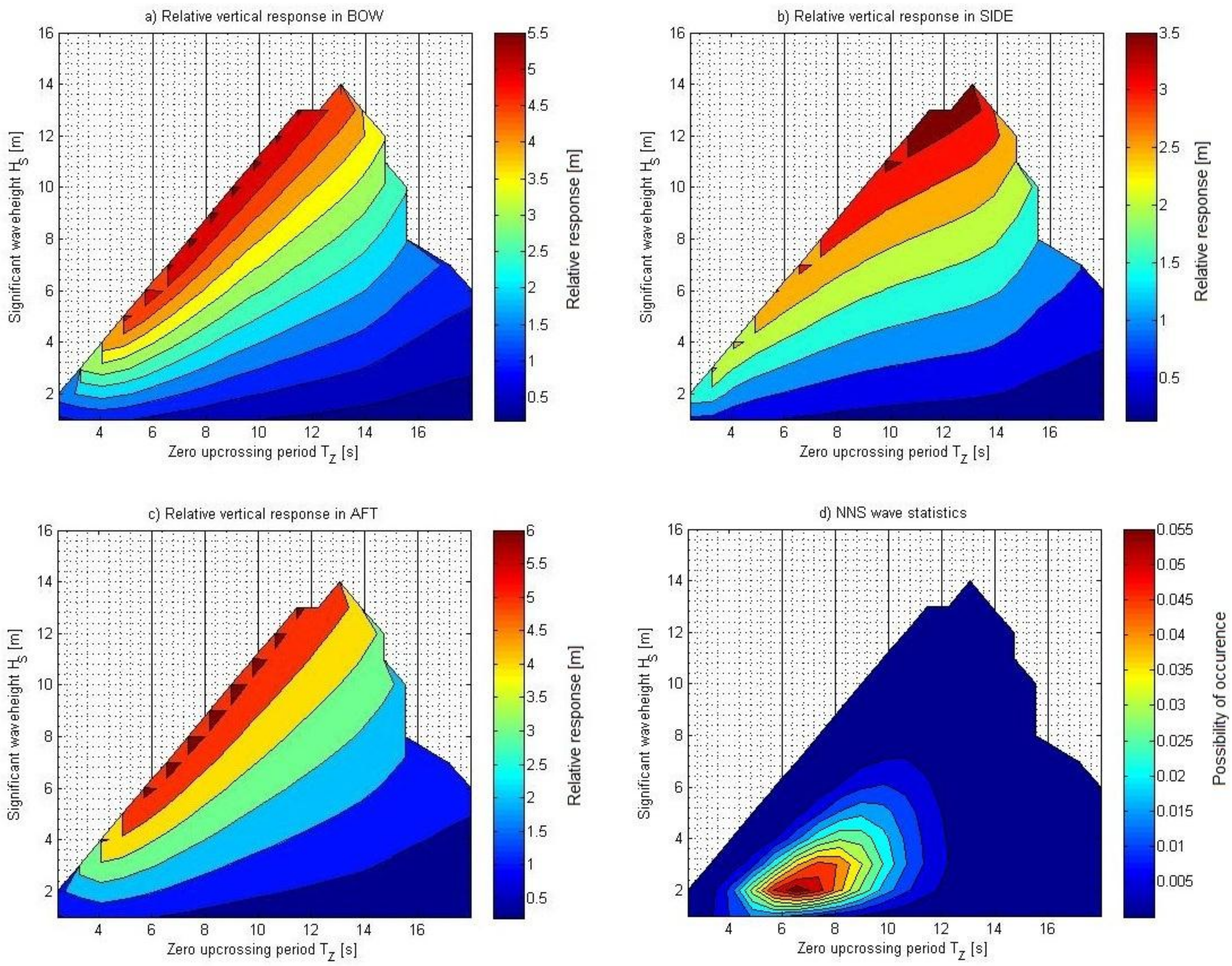


Figure 13 Relative vertical response at wave direction β = 45 degrees

In Figure 13 a) – c), the waves are heading with an angle of 45 degrees in towards the bow of the barge. Figure 13 d) represents the same as in Figure 12 d).

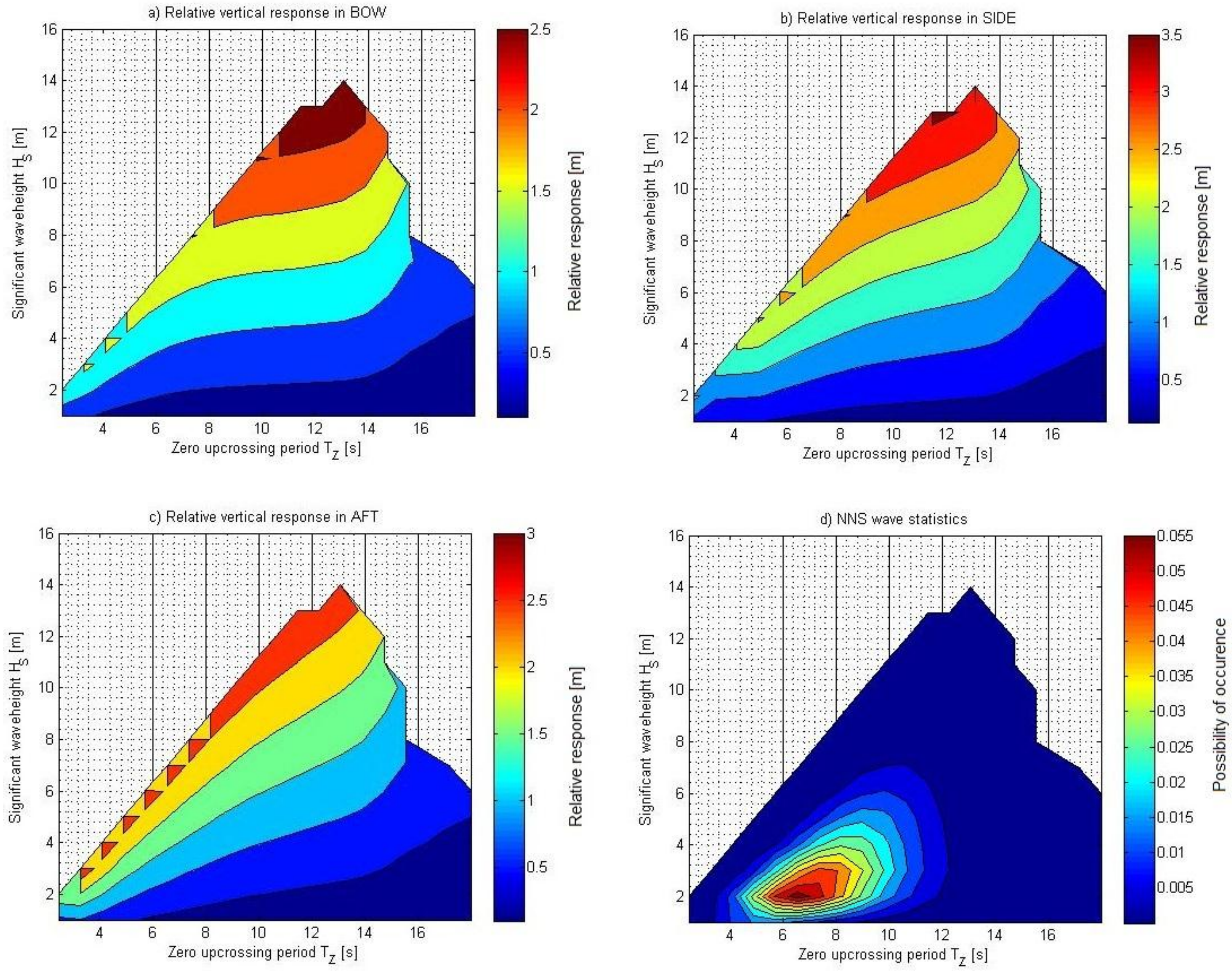


Figure 14 Relative vertical response at wave direction β = 90 degrees

In Figure 14 a) – c), the waves are heading in with an angle of 90 degrees relative to the bow, also called beam sea. Figure 14 d) represents the same as Figure 12 d).

Maximum relative vertical response at NNS

The maximum relative vertical response at the NNS location is presented in Figure 15, with significant wave height along the x-axis and relative response along the y-axis.

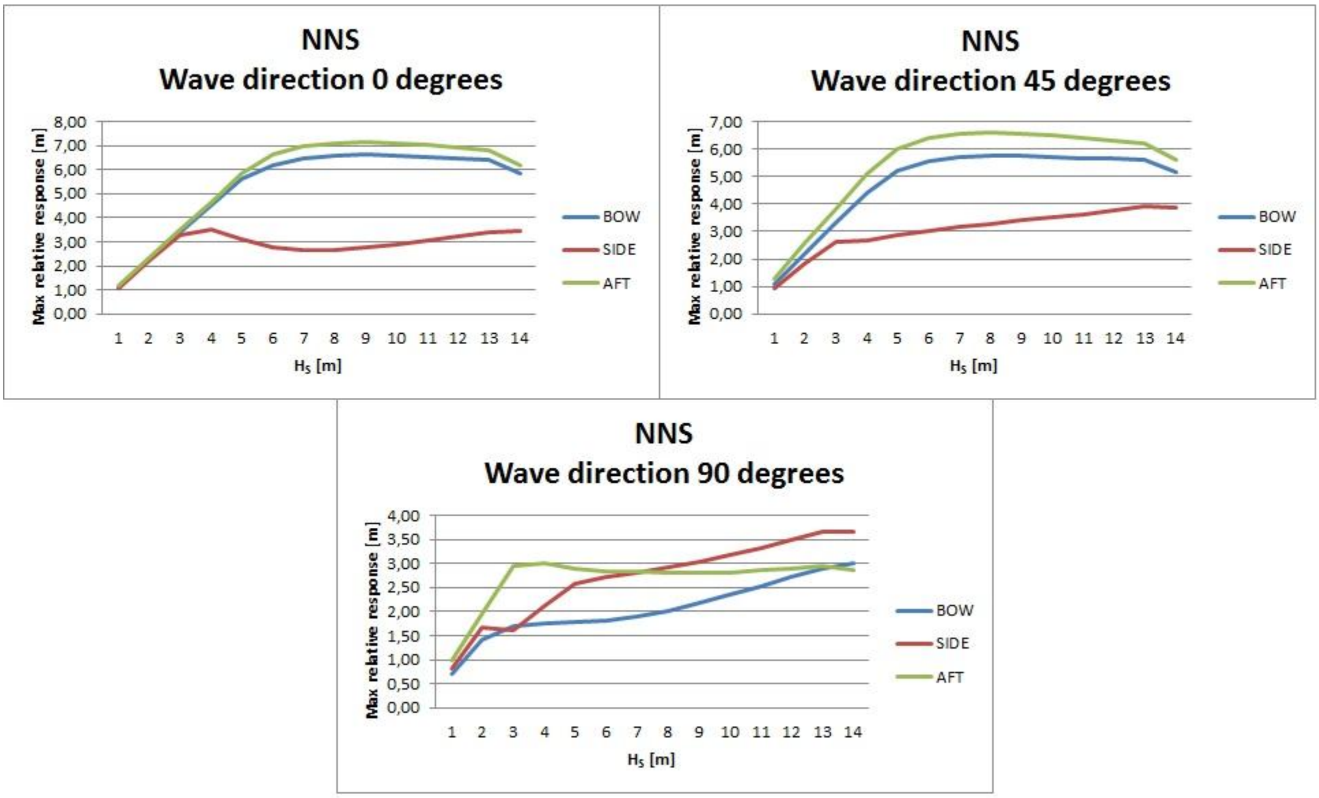


Figure 15 Maximum relative response in Northern North Sea (NNS)

In Figure 15 the maximum relative response from each wave direction at NNS is compared. The graphs in the diagrams are the maximum relative response for each wave height in each point on the barge. These graphs are following the response from the edges seen in red and dark shades of red in diagram a) – c) in Figure 12 - Figure 14. Figure 15 shows that for wave directions β = 0 degrees and β = 45 degrees the BOW- and AFT point has the same response pattern with a small difference in response, but the SIDE point has a different pattern and less response. For wave direction β = 90 degrees (beam sea), the three points have different response patterns, low response compared with the two other directions and less difference for higher H_S.

Relative vertical response at location NA

The following diagrams are from the imaginary location NA, with the appurtenant wave statistics (Figure 16 - Figure 18).

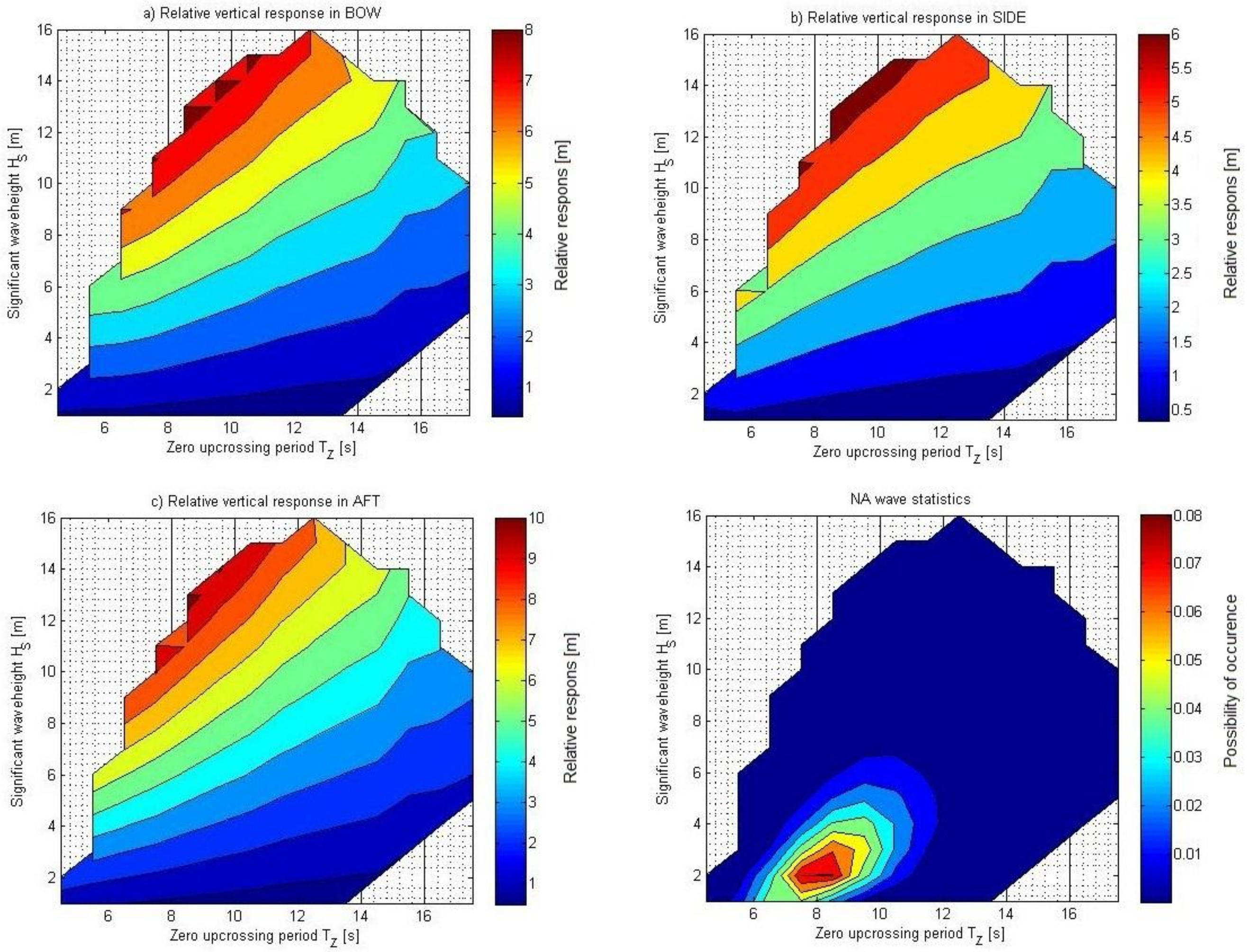


Figure 16 Relative vertical response at wave direction β = 0 degrees

In Figure 16 a) – c), the waves are heading in towards the bow of the barge. In diagram a) of Figure 16 the dark red area is where the largest relative response will occur. In this situation 3 triangles and two dots of dark red is where the combination of significant wave height and zero up crossing period will lead to a relative response of 8.7 meters. One of these combinations is for 13 meter H_S combined with 8.5 seconds T_Z. The colours show the response and red means high response. The response and combination areas differ from figure to figure as will be shown in Figure 16 - Figure 18. In Figure 16 d) the wave statistics from location NA is presented, here the colours show in what area the waves are most likely to occur. From statistics the amount of waves with one combination of H_S and T_Z is counted and in the end all is divided by the total amount of waves measured. In combination with the response diagrams this show what response level the barge is mostly having when exposed at location NA.

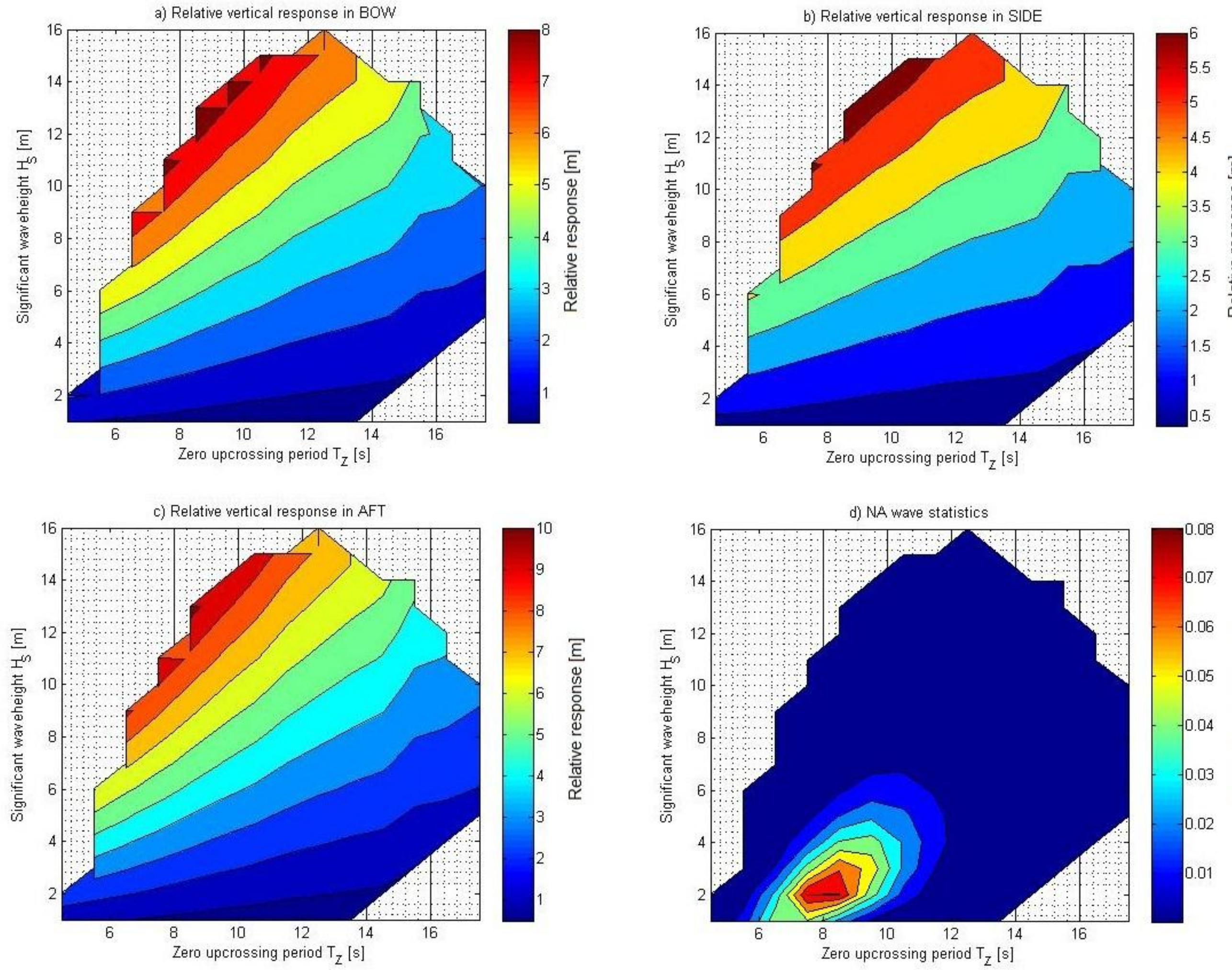


Figure 17 Relative vertical response at wave direction β = 45 degrees

In Figure 17 a) – c), the waves are heading with an angle of 45 degrees in towards the bow of the barge. Figure 17 d) represents the same as in Figure 16 d).

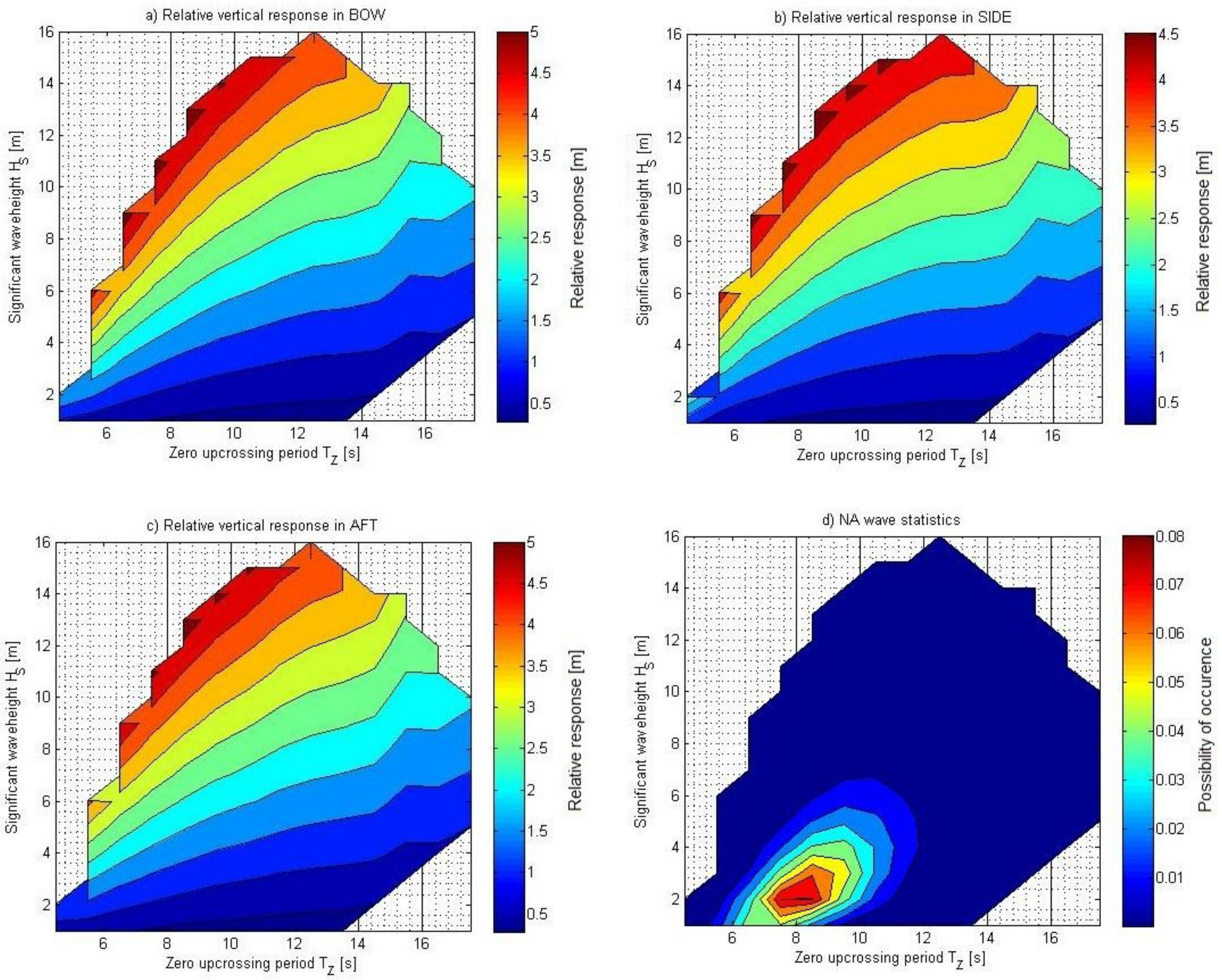


Figure 18 Relative vertical response at wave direction β = 90 degrees

In Figure 18 a) – c), the waves are heading in with an angle of 90 degrees relative to the bow, also called beam sea. Figure 18 d) represents the same as Figure 16 d).

Maximum relative response at NA

The maximum relative vertical response at the NNS location is presented in Figure 19, with significant wave height along the x-axis and relative response along the y-axis.

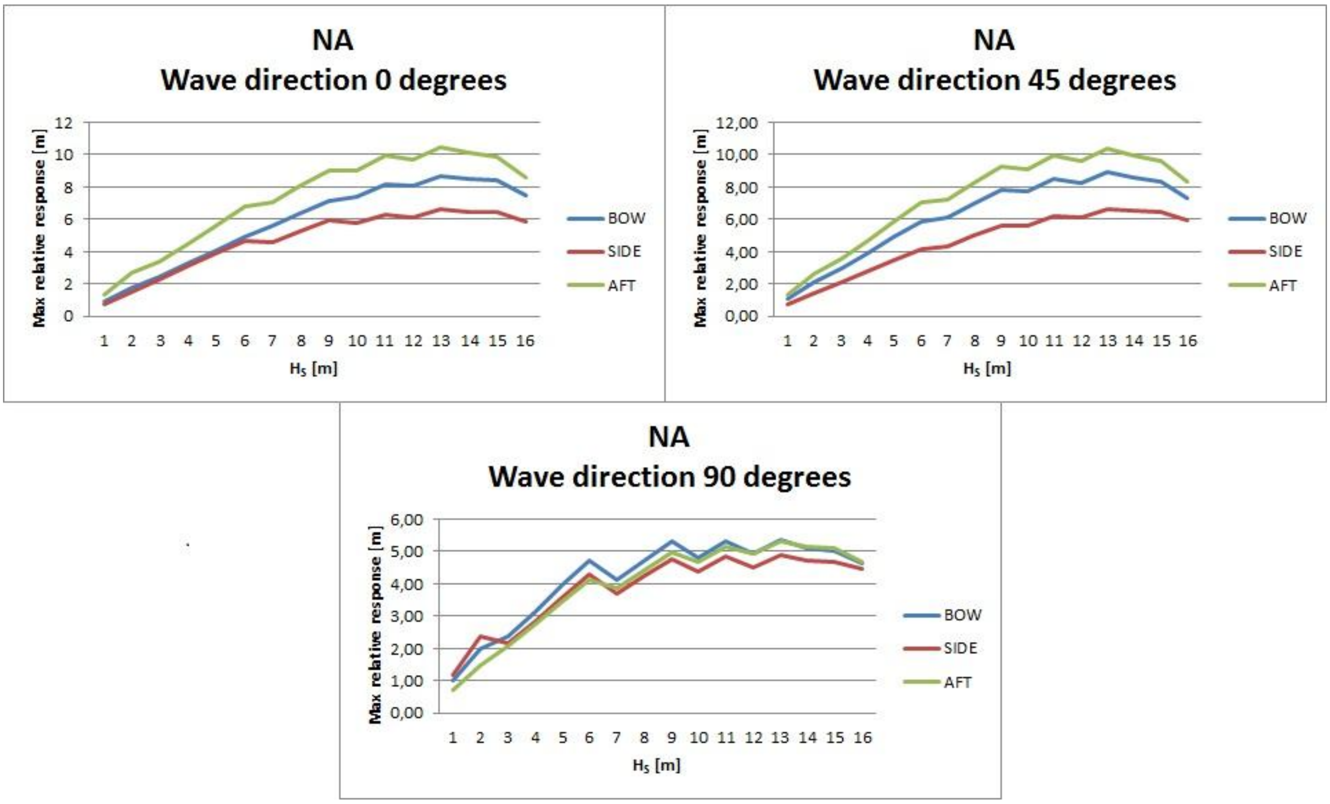


Figure 19 Maximum relative vertical response in North Atlantic (NA)

In Figure 19 the maximum relative response from each wave direction at NA is compared. The graphs in the diagrams are the maximum relative response for each wave height in each point on the barge. These graphs are following the response from the edges seen in red and dark shades of red in diagram a) – c) in Figure 16 - Figure 18. Figure 19 shows that for all wave directions the BOW-, SIDE- and AFT point have the same response pattern. For wave directions β = 0 degrees and β = 45 degrees the difference in response between the points increase for larger H_S. For wave direction β = 90 degrees (beam sea), the three points have low response compared with the two other directions and very little difference in response for increasing H_S.

4.2.6 Acceleration and rotation

The accelerations and rotations presented in this chapter are presented as root mean square values as a function of H_S. It is a significant value for the amplitude of the motions at hand, and a value the NORDFORSK cooperation uses in their recommendation. The figures have the RMS value along the Y-axis and H_S along the X-axis. The results are from the WHEELHOUSE point and the three different wave directions are compared.

Roll and pitch Root Mean Square (RMS)

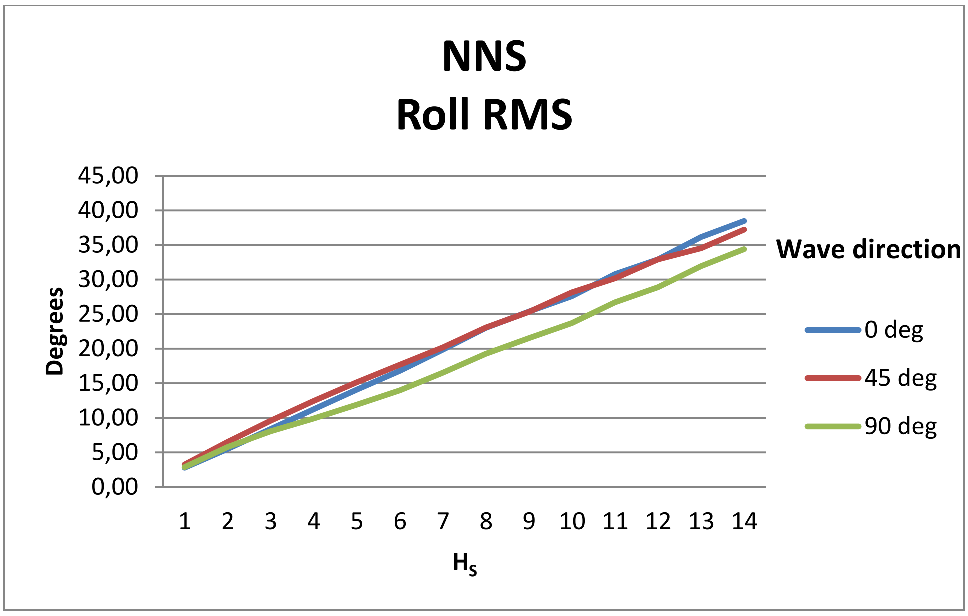


Figure 20 Roll RMS (NNS)

In Figure 20 the three wave directions lead to almost equal roll amplitude RMS and no more than 38.46 degrees. Roll is rotation about the X-axis.

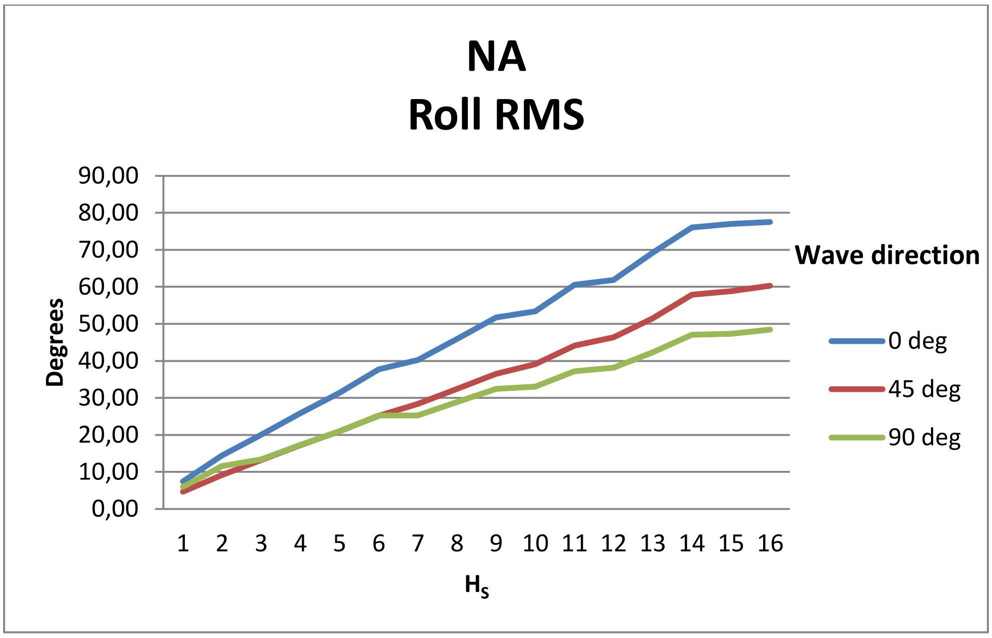


Figure 21 Roll RMS (NA)

In Figure 21 the three wave directions cause different roll RMS, which is rotation about the X- axis. Even though the values for β = 45 degrees and β = 90 degrees are almost similar up to about 6 meter H_S, the roll RMS for the larger H_S differs from 48.43 degrees to 77.52 degrees.

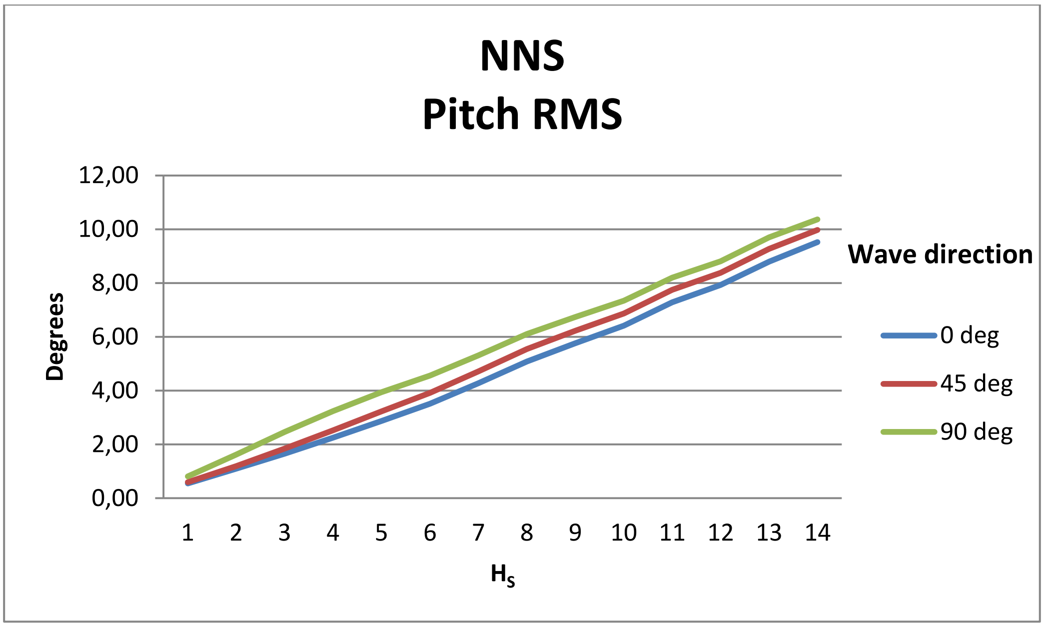


Figure 22 Pitch RMS (NNS)

Figure 22 shows that for the pitch, rotation about the Y-axis, the three wave directions is almost similar and follows the same pattern with increasing H_S.

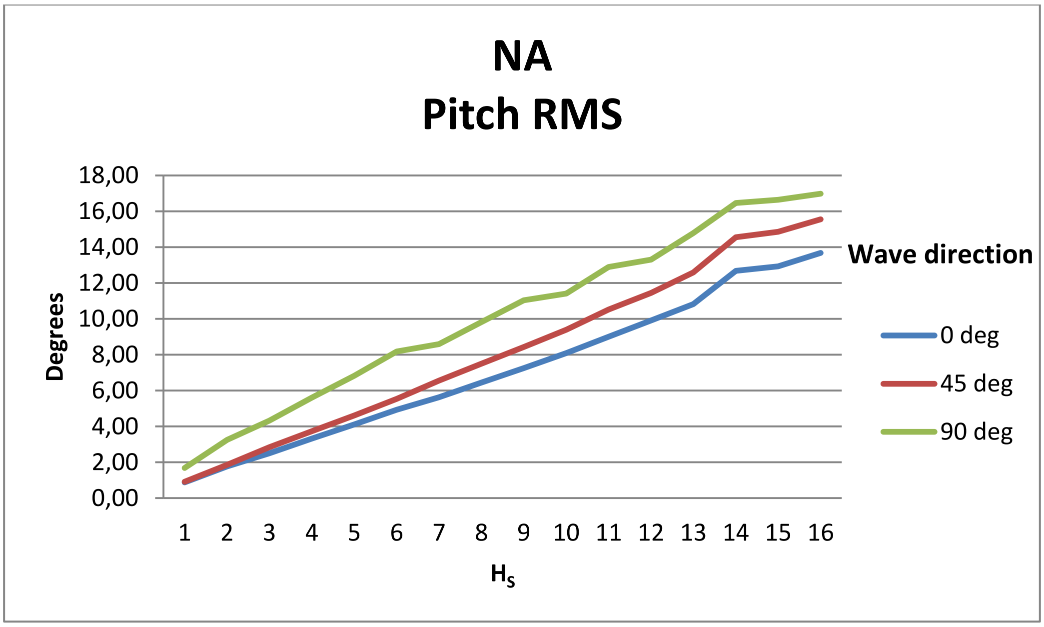


Figure 23 Pitch RMS (NA)

In Figure 23 the pitch amplitude RMS for the three wave directions has the same pattern, but the difference increase with increasing H_S.

Acceleration in WHEELHOUSE

In the following graphs the x-axis is the significant wave height (H_S) in meters and the y-axis is the acceleration Root Mean Square as a fraction of the gravitational acceleration. The WHEELHOUSE point is important to the work done on the barge as it is here the monitoring and feed is controlled.

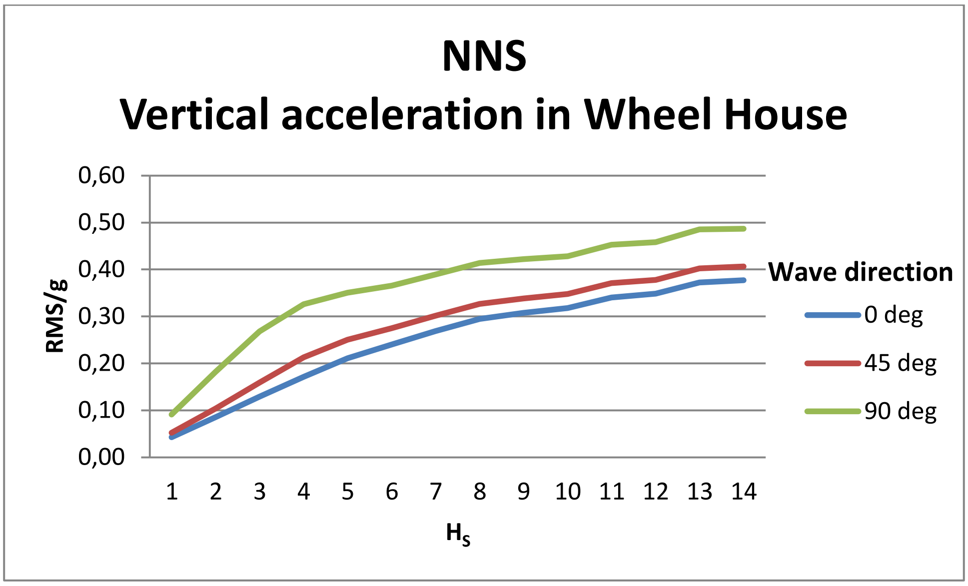


Figure 24 Vertical acceleration RMS (NNS)

Figure 24 shows that for the location NNS the highest vertical acceleration occurs when the waves comes in from the side, β = 90 degrees. The waves coming in towards the bow cause least vertical acceleration in the WHEELHOUSE point. The maximum computed vertical acceleration RMS is 0.49 g, which means it is ca. half of the gravitational acceleration.

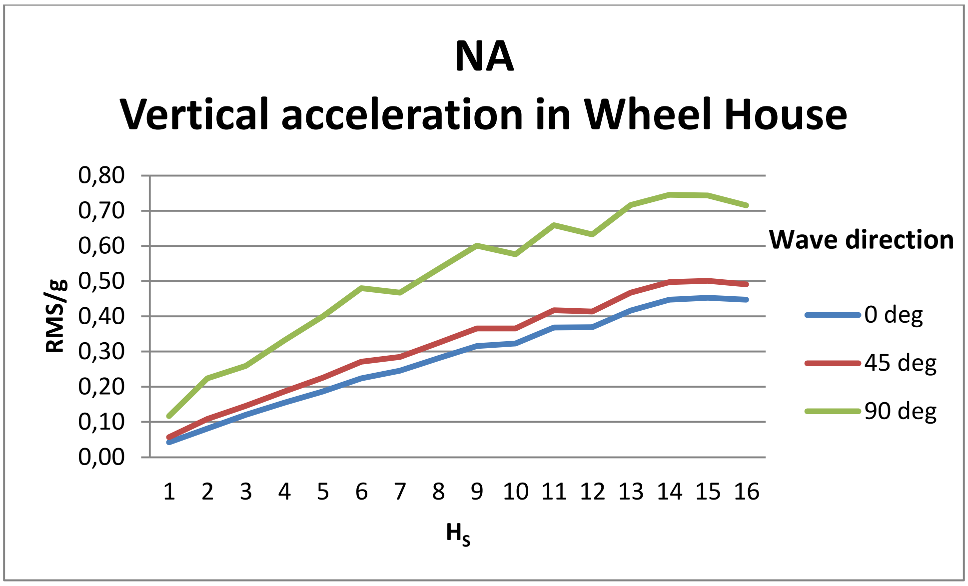


Figure 25 Vertical acceleration RMS (NA)

In Figure 25 the maximum computed vertical acceleration RMS is just above 75% of the gravitational acceleration, caused by beam sea. Beam sea is the heading causing the largest vertical acceleration for all H_S at location NA.

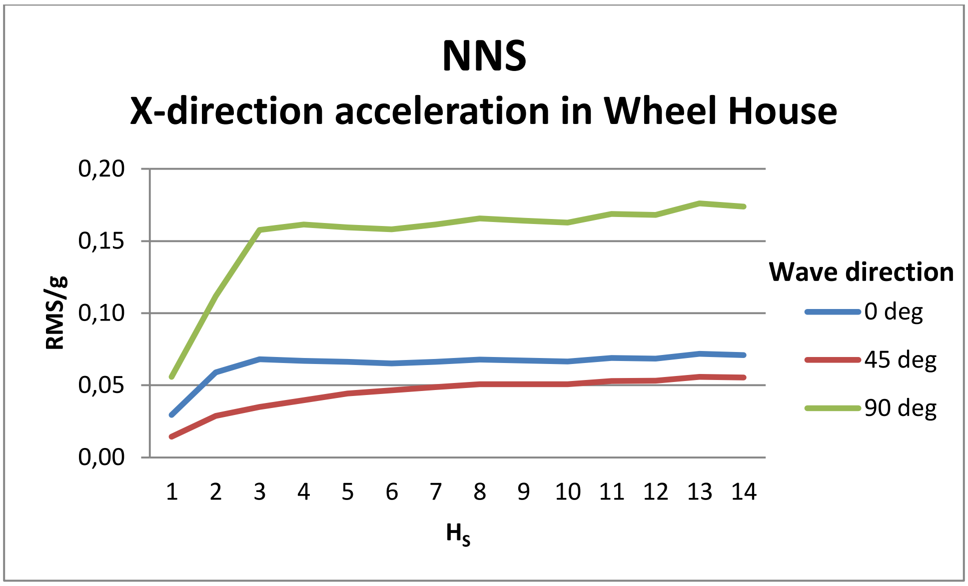


Figure 26 Lateral acceleration in x-direction (NNS)

The lateral acceleration RMS in Figure 26 is along the longitudinal direction of the barge. It shows that wave directions β = 0 degrees and β= 45 degrees have little difference in acceleration RMS value and that beam sea differs a lot and is over twice as large.

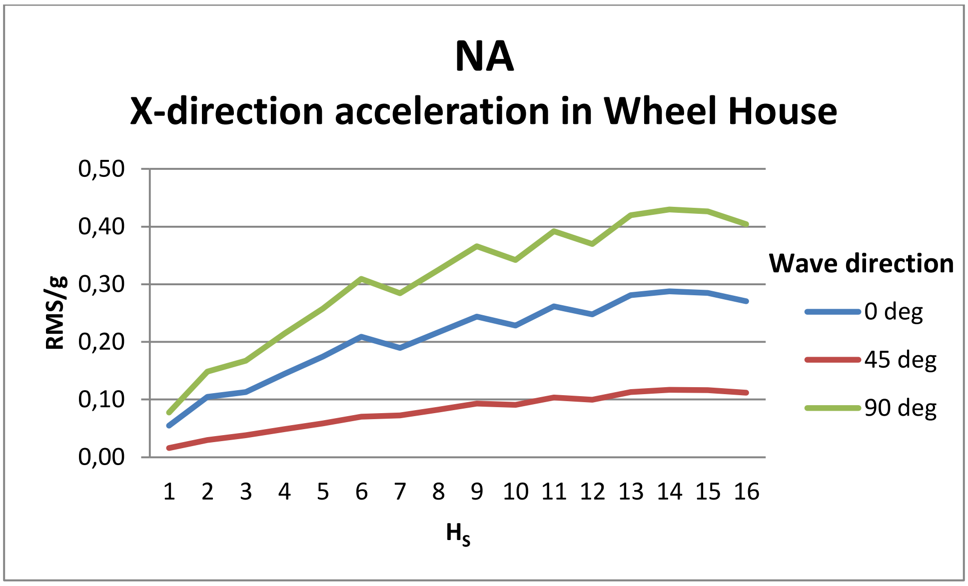


Figure 27 Lateral acceleration in x-direction (NA)

For the location NA Figure 27 shows that the acceleration RMS in longitudinal direction in the WHEELHOUSE point differs relatively much between the wave directions.

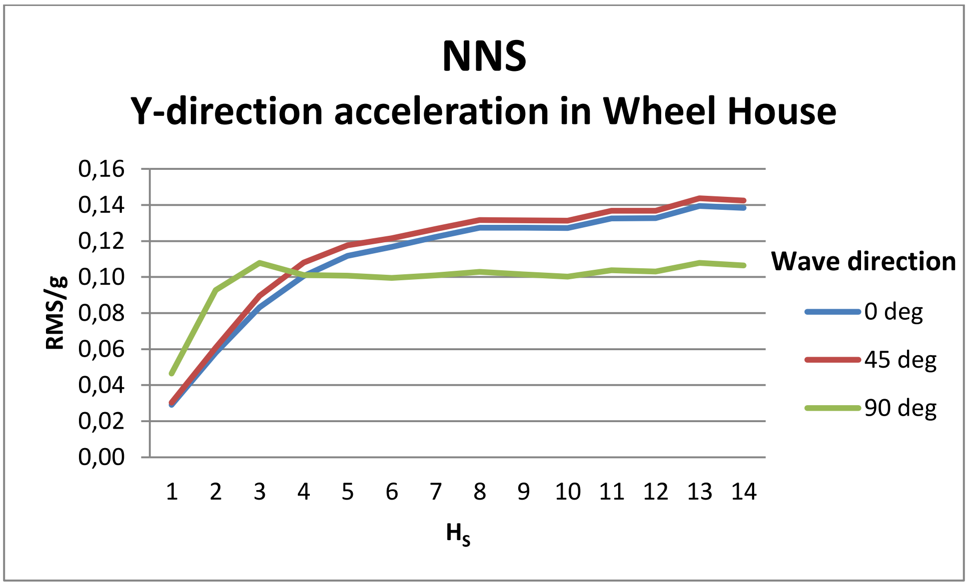


Figure 28 Lateral acceleration in y-direction (NNS)

The lateral acceleration RMS in Figure 28 is along the transversal direction of the barge. It shows that wave direction β = 0 degrees and β = 45 degrees the acceleration RMS is almost the same and has the same pattern. For wave direction β = 90 degrees the pattern is different and it starts out as a larger acceleration up to about 4 meters H_S before it flattens out and becomes almost constant at an RMS value of 10 % of the gravitational acceleration.

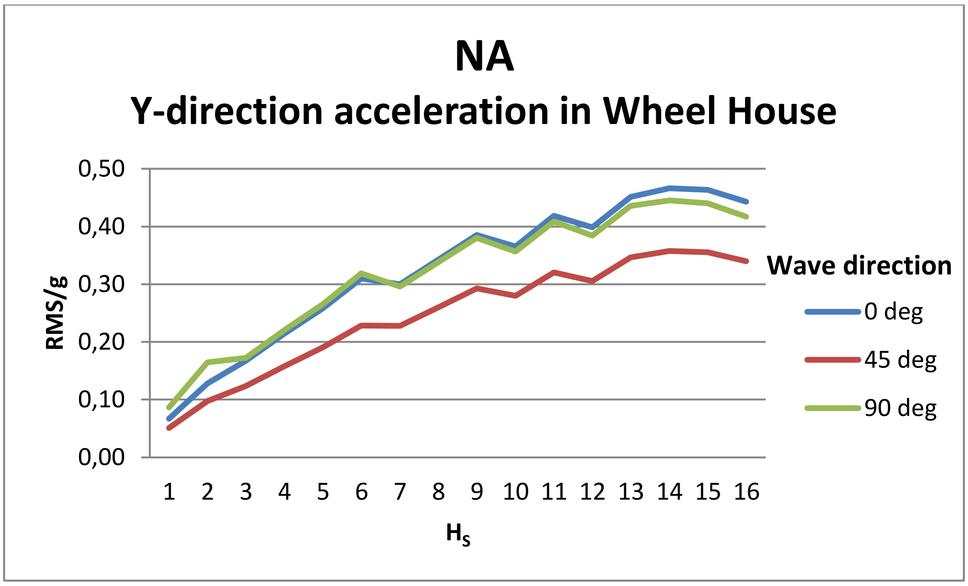


Figure 29 Lateral acceleration in y-direction (NA)

At location NA the lateral acceleration RMS in Y-direction shown in Figure 29 wave direction β =0 degrees and β = 90 degrees have the same pattern and ca. the same values from H_S = 3 meters. For wave direction β = 45 degrees the RMS value is a bit lower over all the H_S.

5 Discussion

This report is made to enlighten the need for new regulations and new design criteria for feed barges in the aquaculture industry as it is moving further offshore. In this process it is necessary to identify and enlighten the areas which affect the sea keeping of a barge. The model made is designed after pictures on the internet and from knowledge about feed barges, therefore this is not a 100% accurate model, but for the purpose of hydrodynamic computation it is sufficient. The most important factors in the hydrodynamic computation are the volume and the weight which in this case are consistent with reality.

5.1 Stability checks

To verify that the model is designed to the standards valid for floating structures the stability has been checked up against different rules and regulations. In this case the most important rules are the ones from NS9415. As shown in Table 15 the requirements from NS9415 are the least strict and the barge is designed with a good margin.

As the results show in Table 17 the barge is stable enough for the Norwegian Maritime Directorate (NMD), but for the IMO rule check in Table 16 it is not approved. The point where it is insufficient is the angle of max GZ. The barge falls in 3 degrees shy of the required 25 degrees heel. This is a small problem as it can be fixed by different measures as e.g. increasing the breadth of the barge or by lowering of the center of gravity.

A general requirement for stability is that the metacentric height (GM) is positive for a floating structure. That means that it is floating with the right side up. In this case the metacentric height is 1.42 meters and therefore the barge is floating right side up, and the GM has a good margin on the requirements set from both NMD and DNV.

5.2 Hydrodynamic computations

For the hydrodynamic computations there has been chosen a loading condition without equipment. It is not included in the computations because it was excluded in the model made in GeniE. HydroD has calculated the draught, trim and heel from the model. The weight of the equipment has been calculated from displaced weight if the draught had been 2.09 m, which is maximum draught according to NS9415 for H_S from 3 meters and above.

5.2.1 Computer program

The method used in WADAM is specified as good for large volume structures. The definition of a large volume structure is that has significant length over 1/5 of the wave length. In this case that would mean that WADAM is a good calculation program for waves up to 250 meters in length. The waves specified as inputs have length from 9 m – 500 m for the NNS location and from 31 m – 473 m for the NA location. For the model in waves above 250 meters WADAM will do a better computation if there also is a Morison model implemented in

HydroD. A Morison model is a model used in the situations where the mass forces are dominant and the Morison equation is applied. In the case where the structure is longer than 1/5 of the waves the model is dominated by reflection and diffraction. In this report the barge is 30.2 meters in length and as mentioned it is reflection and diffraction dominated up to wave lengths of 250 meters. For the two different locations the wave length are connected with wave period and if we take the period of the waves of about 250 meters in length we see that the limit in wave periods is about 13 second for both locations. From the relative response figures in Chapter 4.2.5 we see that the maximum relative response is achieved before or in the vicinity of the wave periods of 13 seconds, and that both of the locations have very few wave periods over 13 seconds. So the reflection and diffraction method used in this report is sufficient. Another aspect is that in reality such a small structure would never be exposed to such large waves. It is just done in this report to show a trend and that the design criteria should very much be linked with location data.

5.2.2 Mooring

The mooring is assumed to be strong enough to withstand the horizontal motion of the barge to keep it stationary in the horizontal plane. Therefor it can be a source for uncertainty, but as we look at the results from the restoring matrices and how the natural periods change it is reasonable to believe that the assumption is acceptable. Since the mooring is added as a restoring matrix and not as physical mooring lines in the computation it means that the model will move as long as it is exposed to a force and not have an absolute stop point due to the mooring.

Natural periods

The natural periods of the free floating barge is quite small and as the assumed mooring is applied the natural periods increase, which is as expected, but if the result is to be compared with e.g. a semi-submersible the natural periods are low and also compared to the wave periods this is not good. It is likely that some unwanted responses could occur if the wave periods merge with natural periods of the barge. In this report there were no such unwanted responses, but that could be because the input periods not are close enough to the natural periods for the barge.

5.2.3 Relative response

The relative response is the absolute value of the height between the free surface elevation and the barge motion. This means that in reality it is also a measure of how large the draught has to be, but in this report the focus has been towards the freeboard. The relative response is different for the two locations NNS and NA, but this difference is important for the enlightenment of the need for more specific design criteria.

Location NNS

In Chapter 4.2.5 and Figure 12 - Figure 15 the results of the relative response computation on location NNS is presented. From the figures with the response we see that the highest relative responses occur when the H_S is high and the wave period is low. Compared with the wave statistics the responses of the most occurring combination of H_S and T_Z are relatively low. The barge is ship shaped so it is designed to meet the waves head on, but we see from the results that with beam sea the response is at its lowest. This result could be because the earlier mentioned limitation of the length of the structure in the method used. Since significant length of the barge when it is exposed to beam sea is the breadth of the barge. So for beam sea the longest wave which gives trustworthy values is 50 meters and up to about 5 seconds. So for further discussion the results from head sea will be used as they are the most valid. One thing that occurs in the diagram is that the SIDE point has lower relative response than the BOW- and AFT point. This could be because the SIDE point also is affect by the roll motion of the barge and that together with the elevation of the barge could cause the response to be lower. The AFT point has the largest relative response, but that is expected since the barge when moored will give the AFT an effect of being pulled through the wave. The question regarding the relative response was if the requirement in NS9415 for minimum freeboard is sufficient and if there might some other regulations that are more sufficient. The interesting part is for H_S above 3 meters since the freeboard in NS9415 for this design is required to be constant at 1.41 m after that H_S. The other regulations from IMO, DNV and NMD have other requirements for the freeboard. NMD and DNV require that the freeboard is documented to be sufficient for the conditions the structure is exposed to. NMD refers to IMO as they say that the freeboard is to be sufficient though no less than IMO's requirement. The minimum required freeboard for this design in IMO is 0.34 m, which actually is lower than NS9415. But according to IMO it has to be added freeboard for hatchways, doors, ventilators and other opening if they are at a certain distance to the freeboard deck. If the model had been made more accurate the openings would have to be added and then the freeboard more accurately computed. In this case the barge has a larger freeboard than NS9415 requires and it has water on deck already at 2 meter H_S. To really compare the barge with the IMO regulations the model has to be designed more detailed and all of the openings mentioned in the regulations has to be accounted for. According to NMD and DNV the freeboard of the barge does not approve operation in the conditions it is to be exposed for.

Location NA

In Chapter 4.2.5 and Figure 16 - Figure 19 the results of the relative response computation on location NA is presented. For the NA location relative response is higher. The same freeboard regulations are valid for this location as for NNS. Also here the barge will have water on deck at 2 meter H_S. At this location the freeboard requirements according to NMD and DNV is not met and the requirements from IMO is not checked fully out as the openings is not in the model.

NNS vs. NA

When comparing the two locations it is clear that different wave statistics is of importance for the response of the barge. That is something that should be considered when designing a barge for more exposed locations. The mooring is also a reason the relative responses is different. The mooring assumed for NA is weaker than the mooring assumed for NNS. Therefore the relative response at NA is larger. This shows that there is need for more accurate mooring analysis for the two situations as the desired solution would be less difference between the locations.

5.3.4 Acceleration and rotation

The acceleration and rotation of the barge is important for the work environment on board as well as for the storage of feed pellets. If the pellets are exposed to high acceleration they could be crushed under storage and therefore the feed is destroyed. The feed is the highest expense of a fish farm so it is important to keep the acceleration to a minimum. For the work environment the acceleration and rotation should be kept to a minimum. In this report the data for what people can handle has been found, but not for what the feed can handle. The rotation is the global rotation in roll and pitch for the barge and the acceleration is calculated in a point representing the wheel house of the barge. The wheel house is where the control room is and where the fish cages are monitored and the fish is fed from. Also for acceleration and rotation it is a difference between the two locations.

Roll

From NORDFORSK the limit for heavy manual work is 4 degrees roll RMS. To compare the computed roll RMS with the limit set by NORDFORSK it is chosen to use the situation with head sea. At location NNS the roll RMS for the barge exceeds the limit already at 2 meter H_S, and at location NA the limit is exceeded already at 1 meter H_S. If we look at the maximum roll RMS at NNS it occurs at 14 meter H_S, the difference between port and starboard side is 6.22 meter. At NA the maximum roll RMS occurs at 16 m H_S and the difference here is 9.76 meters. These differences are good indicators that the results are unrealistic. From the stability analysis it is shown that the angle of vanishing stability is 39.26 degrees. The maximum roll angle at NNS is 38.46 degrees so it does not exceed that angle but is very close, for NA the barge reaches the angle of vanishing stability between 6 – 7 meters H_S. The roll RMS for the barge is thus not sufficient at the two locations for H_S above 3 meters, but since the mooring system is added as a restoring matrix the roll RMS could be better if the mooring is added as physical mooring lines.

Pitch

NORDFORSK does not specifically name pitch as one of the limitations, this could mainly be because the roll always exceeds the pitch. In this report the pitch RMS of the barge has been compared with the roll RMS in

NORDFORSK to see if the barge could exceed the limit also in pitch. The wave direction chosen here is the same as for the roll RMS, head sea. The limit in NORDFORSK is 4 degrees RMS, and the pitch RMS from NNS is exceeding the limit between 6 -7 meter H_S and for NA the limit is exceeded between 4 - 5 meter H_S. For maximum pitch RMS the difference in height between the bow and aft is 4.99 meters at NNS and 7.14 meters at NA with maximum pitch RMS respectively 9.52 degrees and 13.68 degrees. These differences are relatively high and again the reason for these large results could be the way the mooring is added to the model.

Vertical acceleration

The limit for vertical acceleration RMS given by NORDFORSK is 0.15 g for heavy manual work, where g is the gravitational acceleration. Head sea has been chosen as the situation for this discussion as it is assumed to give the most trustworthy results. When comparing the vertical acceleration RMS for each of the two locations it shows that they are relatively alike. They both exceed the limit at 4 meters H_S. For higher H_S than 4 meters the vertical acceleration could lead to uncomfortable and unsafe work situations for the crew.

Lateral acceleration

Lateral acceleration is acceleration in the horizontal plane i.e. along the x- and the y-axis. This limit is set by NORDFORSK at 0.07 g for heavy manual work. The results from the different locations show relatively large differences in results compared with the previous discussed results. The result from the NNS location shows that the acceleration in x-direction with head sea is within the limit set by NORDFORSK. The result from the NA location for x-direction acceleration RMS shows a different picture. Here the results is much higher, the same applies to y-direction acceleration RMS. The reason these values are so much higher than for the NNS location can be blamed on the assumption done for the mooring. This shows that there is need for a more thorough mooring analysis.

5.3.5 Validity

The results show a certain consistency which is expected. The scenario to put a relatively small barge in up to 16 meters H_S should be considered unreal, and in this case it is only done as an extreme way to show that the NS9415 is insufficient for extreme conditions. As mentioned about the computer program used for the computations it had its limits connected to the volume of the structure. The barge is only 30.2 meters long and therefore it sets some limitations to the validity of the results when the wave length is over 250 meters. That is the reason why the results from the condition with head sea is discussed before the conditions with wave heading 45- and 90 degrees, as the significant length of the barge for those headings are shorter.

The results show that the NS9415 is insufficient when it comes to minimum freeboard requirements, but it is only a requirement for minimum freeboard and no one would design a barge as the one in this report for such exposed conditions.

6 Conclusion

This report is made to enlighten the need for new thinking and development of feed barge design towards offshore fish farming. The hydrostatic computations show that the model made in GeniE is valid as a comparison model. The locations should be better documented, but since the data is hard to come by the wave statistics used is enough to prove the point of this report. The hydrodynamic analysis made in HydroD and WADAM clearly shows that the requirements set by NS9415 is insufficient and needs revising. When comparing the barge design with the other regulations it clear that the regulation agency for floating fish farms and its components has to look towards the oil industry for new regulations in the fish farming industry. The freeboard requirements investigated in this report show that DNV and NMD have more nuanced requirements, as they need documentation that the structure has enough freeboard for the conditions it is to be exposed to. For safer operations at more exposed locations the motion analysis shows that the acceleration and roll has to be accounted with regards to human work environment.

6.1 Further work

For the model in this report it could be an idea to do a more accurate mooring analysis in e.g. MIMOSA which is a computer program designed for mooring analysis. HydroD also has the ability to add more accurate model of the mooring. As mentioned the method used in this report only covered a panel model and a diffraction and reflection analysis. For a more accurate analysis it is possible to generate a Morison model in GeniE and thus use the full potential of WADAM for this purpose.

The model in this report was designed from what is normal in fish farming today. For future fish farming further offshore it might be necessary to change the design to something different. Maybe the size has to increase to store more feed because of availability and more biomass in the fish farm. These designs could be of totally different shape. The shape could be inspired by the round FPSO's of Sevan Marine (sevanmarine.com). The barge may not even need to be manned in the future and can be totally submerged to shelter it from wave interactions only to remerge to be loaded with fish feed. All these ideas are interesting to follow either for a future master thesis or PhD.

References

DNV (1994). SESAM User's manual - WADAM. SESAM User's manual. D. N. V. S. AS.

DNV (2010). DNV-OS-E301. DNV**:** 100.

DNV (2011). "GeniE." from http://www.dnv.no/tjenester/software/products/sesam/SesamFloatingStructures/GeniE.asp.

DNV (2011). "HydroD." from http://www.dnv.no/tjenester/software/products/sesam/SesamFloatingStructures/HydroD.asp.

DNV (2011). "POSTRESP." from http://www.dnv.com/services/software/products/sesam/SesamFloatingStructures/postresp.asp.

DNV (2011). "SESAM." from http://www.dnv.no/tjenester/software/products/sesam/index.asp.

DNV (2012). Rules for Classification of Floating Production, Storage and Loading Units. DNV-OSS-102. D. N. Veritas.

DNV (2012). Rules for classification of Ships. DNV**:** 130.

DNV (2012). Stability and Watertight Integrity. DNV-OS-C301. D. N. Veritas.

Faltinsen, O. M. (1998). Sea loads on ships and offshore structures. Cambridge, The press syndicate of the university of Cambridge.

IMO (2002). Load Lines. I. M. Organization.

Krokstad, J. and M. Lønseth (2003). Stabilitet og sikkerhet for havbruksflåten i sjøgang, SINTEF Fiskeri og Havbruk**:** 19.

NMD (2003). Regulations for Mobile Offshore Units. N. M. Directorate.

NORDFORSK (1987). Assessment of ship performance in a seaway, NORDFORSK.

NS9415 (2009). Flytende oppdrettsanlegg. Krav til lokalitetsundersøkelse, risikoanalyse, utforming, dimensjonering, utførelse, montering og drift. N. Standard, Norsk standard**:** 102.

NYTEK (2011). NYTEK-forskriften. FOR 2011-08-16 nr 849. http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20110816-0849.html, Fiskeri og kystdepartementet. **849:** 12.

Pettersen, B. (2004). Kompendium i faget TMR4210 - Marin hydrodynamikk og konstruksjonsteknikk grunnkurs 1.

sevanmarine.com (2012). "sevanmarine.com." from http://sevanmarine.com/.

Stansberg, D. C. T., D. G. Contento, et al. (2002). The Specialist Committee on Waves. 23rd International Towing Tank Conference**:** 61.

Appendix

Appendix 1 Restoring coefficients

$$C_{33} = k\sum_{i=1}^{4} sin^2\theta_i$$

$$C_{44} = k\sum_{i=1}^{4}(y_i \sin\ \varphi_i - z_i \cos\varphi_i)^2$$

$$C_{55} = k\sum_{i=1}^{4}(x_i \sin\ \theta_i - z_i \cos\theta_i)^2$$

$$C_{66} = k\sum_{i=1}^{4}(x_i \sin\ \Psi_i - y_i \cos\Psi_i)^2$$

$$C_{13} = C_{31} = k\sum_{i=1}^{4}(\cos\Psi_i \cdot \sin\theta_i)$$

$$C_{14} = C_{41} = k\sum_{i=1}^{4}(y_i \sin\varphi_i - z_i \cos\varphi_i)\cos\Psi_i$$

$$C_{15} = C_{51} = k\sum_{i=1}^{4}(x_i \sin\theta_i - z_i \cos\theta_i)\cos\Psi_i$$

$$C_{23} = C_{32} = k\sum_{i=1}^{4}(\sin\Psi_i \cdot \sin\theta_i)$$

$$C_{24} = C_{42} = k\sum_{i=1}^{4}(y_i \sin\varphi_i - z_i \cos\varphi_i)\sin\Psi_i$$

$$C_{25} = C_{52} = k\sum_{i=1}^{4}(x_i \sin\theta_i - z_i \cos\theta_i)\sin\Psi_i$$

$$C_{26} = C_{62} = k\sum_{i=1}^{4}(x_i \sin\Psi_i - y_i \cos\Psi_i)\sin\Psi_i$$

$$C_{34} = C_{43} = k\sum_{i=1}^{4}(y_i \sin\varphi_i - z_i \cos\varphi_i)\sin\varphi_i$$

$$C_{35} = C_{53} = k\sum_{i=1}^{4}(x_i \sin\theta_i - z_i \cos\theta_i)\sin\theta_i$$

$$C_{36} = C_{63} = k\sum_{i=1}^{4}(x_i \sin\Psi_i - y_i \cos\Psi_i)\sin\theta_i$$

$$C_{46} = C_{64} = k\sum_{i=1}^{4}(y_i \sin\varphi_i - z_i \cos\varphi_i)(x_i \sin\Psi_i - y_i \cos\Psi_i)$$

$$C_{56} = C_{65} = k\sum_{i=1}^{4}(x_i \sin\theta_i - z_i \cos\theta_i)(x_i \sin\Psi_i - y_i \cos\Psi_i)$$

Appendix 2 Electronic appendix (appendix2.rar)

Contents of appendix2.zip

Barge_440C.xlsx	Barge main dimensions, wave statistics and natural periods
Barge_Stability_1.htm	HydroD report of stability analysis
Restoring_matrix.xlsx	The calculation of the restoring due to mooring in excel
wavest.m	Matlab script to generate the contour diagram of the wave statistics
WADAM_NA.txt	Hydrodynamics report generated by WADAM for location NA
WADAM_NNS.txt	Hydrodynamics report generated by WADAM for location NNS
Freeboard.xlsx	Calculation of relative vertical response in excel
Dir0.m	Matlab script to generate the contour diagram of vertical relative response for wave direction β=0
Dir45.m	Matlab script to generate the contour diagram of vertical relative response for wave direction β=45
Dir90.m	Matlab script to generate the contour diagram of vertical relative response for wave direction β=90
Rotation and acceleration.xlsx	Calculation of rotation and acceleration in excel