Hydrodynamic analysis and structural design of the Concrete Star Wind Floater

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TITLE:

Structural design and hydrodynamic analysis on a floating concrete hull for offshore wind

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SUMMARY:

This thesis addresses an existing concept for a floating offshore wind turbine fundament, with the goal of changing the geometry so that the natural periods reach the design criteria. These criteria have been set to at least 20 seconds in heave and at least 25 seconds in pitch and roll. To accomplish this, hand calculations, Wadam from DNV and 3DFloat from IFE have been used.

When this thesis was written, 3DFloat was still under development at IFE, giving it some limitations in the use. Even so, the purpose of using the software was also to gain experience and report back to the programmers how it works.

The thesis starts with a literature study in hydrodynamic stability and calculations of floating vessels properties. It then continues with how to model and analyse in Patran.Pre, Wadam and 3DFloat. After that, calculations and results on the given concept are produced. With those results at hand, changes are applied to the basic concept to see how the different geometrical changes affect the natural periods of the hull. This is used to choose a final design of the outer geometry that can fulfill the design criteria. The last chapter calculates the final concept and gives the results, followed by a comparison of the two concepts, conclusions and appendices.

RESPONSIBLE TEACHER: Professor Kjell Holthe
SUPERVISOR(S) Associate Professor Michael Muskulus (NTNU) and Trond Landbø (Dr.techn. Olav Olsen AS)
CARRIED OUT AT: Institute of Structural Engineering, NTNU

Master thesis

Structural design and hydrodynamic analysis on a floating concrete hull for offshore wind

Student: Knut-Ola Lunde at the Departement of Structural Engineering

Supervisors at NTNU: Kjell Holthe and Michael Muskulus

External supervisor at Dr.Techn.Olav Olsen AS: Trond Landbø

This master thesis takes aim to further develop the "Concrete Star Wind Floater"-concept , developed by Dr.Techn. Olav Olsen AS, that shall support a designated wind turbine. By use of Wadam and 3DFloat, different design parameters shall be compared with the effects from waveloads on the hull to look at the effects of different design parameters of the hull with respect to its hydrodynamic properties.

This task is divided into five main parts:

1. Literature study into hydrodynamics and hydrostatics
2. Calculate the given concept for a floating hull with a given wind turbine. Shall fulfill set requirements to stability and natural periods.
3. Apply the program 3Dfloat to the basic model and calculate motions using the new software.
4. Make structural changes and compare the impact on natural periods to optimize the design.
5. Take out forces in specified hull sections to see if the hull can resist the applied forces.

Computeranalysis:

For Wadam/Sestra, Dr.Techn. Olav Olsen has enough experience to give assistance in the use. For 3DFLoat, Tor Anders Nygaard at IFE is willing to assist.

The thesis is due at the Department of Structural Engineering at the 10th of June 2013.

Kjell Holthe

Trond Landbø

Knut-Ola Lunde

Preface

This master thesis was written in the spring of 2013 and submitted as a part of the degree of Master of Science in Civil and Environmental Engineering, specializing in structural engineering. The thesis was formulated by Trond Landbø from Dr.techn. Olav Olsen AS .

Knut-Ola Lunde

Acknowledgements

Abstract

This thesis was initiated by Trond Landbø from Dr.techn. Olav Olsen after an internship there during the summer of 2012. Amongst other projects, Dr.techn. Olav Olsen works with different concepts for floating concrete hulls to support wind turbines in deep seas. They have a patented structural concept under development which inspired this master thesis.

The main goal of this thesis was to modify the design of the basic concept to fulfill requirements with respect to higher natural periods in heave, pitch and roll. To reach this goal, calculations made by hand and analysis in Wadam were to be used. Another aim was to utilize a new IFE-program, called 3DFloat, to gain experience of the new software that's under development. The design criteria for the natural periods were set to at least 20 seconds in heave and 25 seconds in pitch/roll, with a distance of 4-6 seconds between the periods.

The first part of the work was a literature study into hydrodynamics and hydrostatics, and also how to use the two computational tools needed for the analysis.

Once the setup-phase was completed, calculations of the basic concept were made. The basic concept was given as input to this thesis and calculations were therefore made to allow for a comparison with that of Dr.techn. Olav Olsen and thus explore whether the methods for calculation and analysis were correct. The results matched, with natural periods on 15.9 seconds in heave and 22.5 in pitch/roll for the basic concept.

The second phase of the design was to alter the outer geometries and examine the effects of different parameters on the natural periods. This thesis chose to study five parameters of the outer geometry. Through the use of hand calculations and Wadam, the necessary outer geometry was found with natural periods over the criteria. Graphs depicting the increase/decrease in concrete volumes as a result of changing the parameters were also added as a way to monitor the effects such changes have on cost.

Lastly, the final concept was adjusted with regards to the wall thickness and concrete volumes, before it was modeled and analyzed. Natural periods were found to be 21.5 seconds in heave and 26 seconds in pitch/roll, fulfilling the criteria. Static tilt was calculated at 6.593 degrees, which is was little high, as ideally it should not exceed 6 degrees.

With the help of 3DFloat, a check was made of the forces that would result the wave regime at the intended location of the hull. During this process, it was discovered that 3DFloat calculates all waves with period Tp=10 seconds. Comparing the forces from the waves against the capacity of the hull gave a utilization of below 50% of the hulls capacity.

The use of 3DFloat was very interesting. Modeling of the basic concept was succesful and it behaved as intended, but the final concept did not. This was due to the fact that at present, 3DFloat, is only able to calculate with cylindrical elements. The adaptations required between rectangular elements and conical elements for the final concept therefore seem to have created some problems for 3DFloat that were not solved by the time this thesis was completed.

Sammendrag

Denne masteroppgaven ble igangsatt av Trond Landbø hos Dr.techn. Olav Olsen etter at jeg hadde hatt sommerjobb hos dem i 2012. Dr.techn Olav Olsen jobber blant annet med flytende betongfundamenter til vindturbiner tiltenkt brukt på dypt vann. De har patentert et eget konsept som denne masteroppgaven dreier seg om.

Hovedmålet for masteroppgaven er å forandre konseptets ytre geometri for å øke egenperiodene i heave, pitch og roll slik at konseptet ikke blir påført resonans på grunn av bølgene i havområdet fundamentet er planlagt utsatt. Kravene er fastsatt til minst 20 sekunder egenperiode i heave og minst 25 sekunder egenperiode i pitch/roll. Det andre målet for oppgaven er å beregne konseptet i 3DFloat, et program som er under utvikling hos IFE, for å få erfaring med bruken av programmet og gi tilbakemelding til programmets utviklere.

Arbeidets første fase besto av et litteraturstudium i hydrostatikk og hydrodynamikk, samt å sette seg inn i bruken av dataprogrammene som ble brukt til analysene. Etter dette startet arbeidet med å kontrollregne konseptet som ble gitt av Dr.techn. Olav Olsen. Beregningene viste seg å stemme overens med de resultatene Olav Olsen hadde kommet frem til, med egenperioder på 15.9 sekunder i heave og 22.5 sekunder i pitch/roll.

Den andre fasen av arbeidet bestod i å forandre konseptets ytre geometri, og undersøke hvordan disse endingene påvirket egenperiodene. Et overslag over forandringen i betongvolum ble også inkludert for å få en grov oversikt over kostnadene som de forskjellige endringene i geometri medførte. Beregning av medhørende egenperioder ble deretter utført for å bestemme anbefalt ytre geometri.

I den tredje fasen av arbeidet var konseptets anbefalte ytre geometri fastsatt, og tykkelsen på betongelementene ble tilpasset slik at konstruksjonen flyter med riktig dypgang. De endelige analysene i Wadam viser at den anbefalte konstruksjonen er beregnet til å ha egenperioder på 21.5 sekunder i heave og 26 sekunder i pitch/roll, noe som tilfredsstiller designkravene.

Til slutt ble det kjørt bølgeanalyser for å sammenligne kreftene i elementene fra 3DFloat med betongtverrsnittene. Der ble det oppdaget at 3DFloat utelukkende kan beregne med bølger som har bølgeperiode på 10 sekunder. Dette ble rapportert til IFE slik at de kan gjøre rettelser i programvaren. Resultatene fra beregninger med en bølgeperiode på 10 sekunder og medhørende bølgehøyde viser at kapasitetsutnyttelsen er under 50 % på skrogets tverrsnitt.

Bruken av 3DFloat har gitt god og nyttig erfaring med programvaren og ble benyttet på det originale og det endelige konseptet. Det originale konseptet ble modellert med få problemer og oppførte seg som forventet. Konsept nummer 2 oppfører ikke seg slik som forventet. Det skyldes sannsynligvis at 3DFloat foreløpig bare kan operere med sylindriske eller koniske elementer. Det viser seg at dersom en modellerer med koniske elementer under vannlinjen, resulterer det i uventede bevegelser som verken IFE eller jeg fant årsaken til innenfor tidsrammen på denne masteroppgaven.

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Nomenclature

Added mass	Mass of the accelerated water moved by the structure.
CSWF	Concrete Star Wind Floater
Draft	Height of the submerged part of the hull
GM	Metacentric height. Factor for stability of a floating body.
GUI	Graphical User Interface, a graphical window for modeling.
Heave	Translation of the hull along the vertical axis.
JONSWAP	Joint North Sea Wave Atmosphere Program, a wave spectrum that defines the distribution of energy within the ocean.
Nacelle	Cover housing for all power-generating components
Natural period	see "Rigid body motion".
Pitch	Rotation of the hull along its longitudal axis.
RAO	Response Amplitude Operator, statistics used to determine a floating vessels behavior at sea.
Rigid body motion	Translations and rotations without structural deformations
Roll	Rotation of the hull along its transversal axis.
VCOB	A structures vertical center of buoyancy.
VCOG	A structures vertical center of gravity.
Zero upcrossing period	The average time between successive crossings of the mean water level in an upward direction for a wave.

List of symbols

A_{mass}	Added mass
A_w	Total area of the water plane
F_c	Normalized concrete strength
F_{cn}	Concrete compression capacity
g	Acceleration of gravity
Hs	Significant wave height
I	Moment of inertia
$I_{Waterplane}$	Moment of inertia of the water plane
M	Total structural mass
Rx/Ry	Radii of gyration around the respective axis
Tp	Peak wave periode
Tz	Mean zero upcrossing period
$V_{displaced}$	Total displaced volume of the hull
D	Total displaced volume for the floating body
γ	Peak enhancement factor determining the concentration of the spectrum on the peak frequency. $1 \leq γ \leq 7$
$γ_c$	Partial factor for concrete
η	Reduction factor for concrete capacity
ρ	Density of the fluid that surrounds the floating body
ρ'	Density of the fluid inside the tank
$ρ_1$	Density of non-reinforced concrete
$ρ_2$	Density of reinforced concrete
$σ_A$	Scaling factor for peak enhancement factor based on wave frequency
$σ_B$	Scaling factor for peak enhancement factor based on wave frequency
∝	Angle of rotation

1 Introduction

1.1 Offshore wind today

Offshore wind is a huge developing market with many companies investing in and developing offshore wind farms, as renewable energy attracts more and more focus from governments worldwide. Offshore wind can be divided into two different types; bottom-fixed structures and floating hulls. Development and installation have today come much farther with bottom-fixed structures than floating hulls, with many different concepts being used. Figure 1 illustrates a few of the different options available today.

Figure 1 Illustration of different bottom fixed structures (Offshore Center Danmark, u.d.)

Among others, The European Wind Energy Association (EWEA) works gives an overview of the progress made in offshore wind installations and technology. In their report of the market as of 2011 (the report for 2012 is not published at the time this thesis is written), a good overview of the situation is given (European Wind Energy Association, 2012):

Statistics for the offshore wind industry	
Worldwide total offshore wind turbines installed	1 371 (up 235 from 2010)
Types of substructures	75 % monopiles, 21 % gravity based, 2 % jackets and 2 % tripiles
Floating structures	2 full scale floating turbines
Floating concepts	2 floating concepts where erected

Table 1 Key figures for the offshore wind industry

As the numbers from EWEA show, floating wind is still in the beginning phase, while different types of bottom fixed structures are the dominant type being used to this date. Statoil is for example installing 88 wind turbines on Sheringham Shoal off the coast of England (Statoil, u.d.). These are bottom-fixed monopiles in water depth from 15 to 22 meters at lowest sea water level (Scira, 2006). With increasing water depths, the bottom fixed structures are subject to enlarged construction and installation costs. As the oceans worldwide also contain vast areas that are too deep for bottom fixed structures to be used, research and development has shifted to floating hulls.
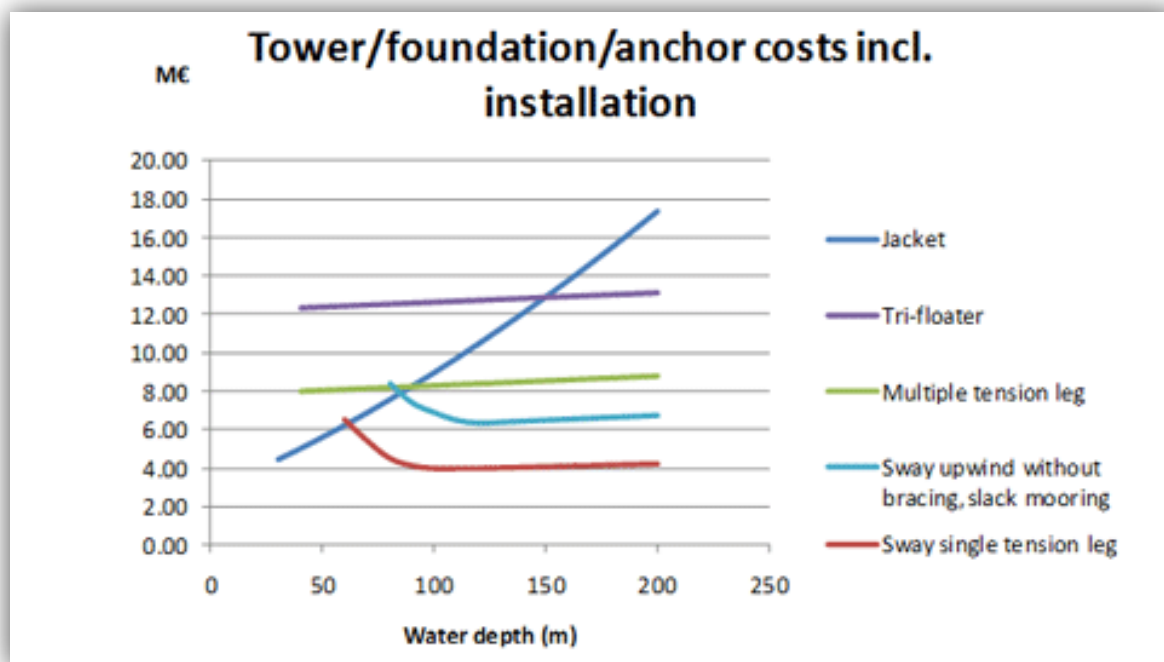
Figure 2 Cost of offshore wind installations (Sway, u.d.)

Sway produced a Norwegian concept for floating wind and has installed a scale model for testing. Figure 2 shows Sway's estimation of costs for a few different concepts. Looking at the graph for jackets, which is the only bottom-fixed structure in the overview, cost rises dramatically over the increasing depths. For a floating concept however, the cost does not increase much from the initial cost, despite this increase in depth. For the five concepts shown in the graph, from a waterdepth of 50 meters, floating concepts can compete with existing bottom fixed concepts in terms of cost.

For floating wind there are currently three main methods in use today, as illustrated in Figure 3 (Renewables International, u.d.). The three different types are defined as follows:

1. **Ballast:** These hulls achieve their stability by using ballast placed below the buoyancy tanks. The spar-buoy to the left in Figure 3 is a ballast-stabilized structure.
2. **Mooring line stabilized:** These hulls are stabilized by the use of mooring lines in tension. The tensioned lines hold the hull in place and stable, like the structure in the centre in Figure 3.

2

3. **Buoyancy:** These hulls are moored with lines without any tension that keeps them in place. Instead, they achieve their stability using distributed buoyancy and the water plane area to create the righting moment needed to keep the hull stable.
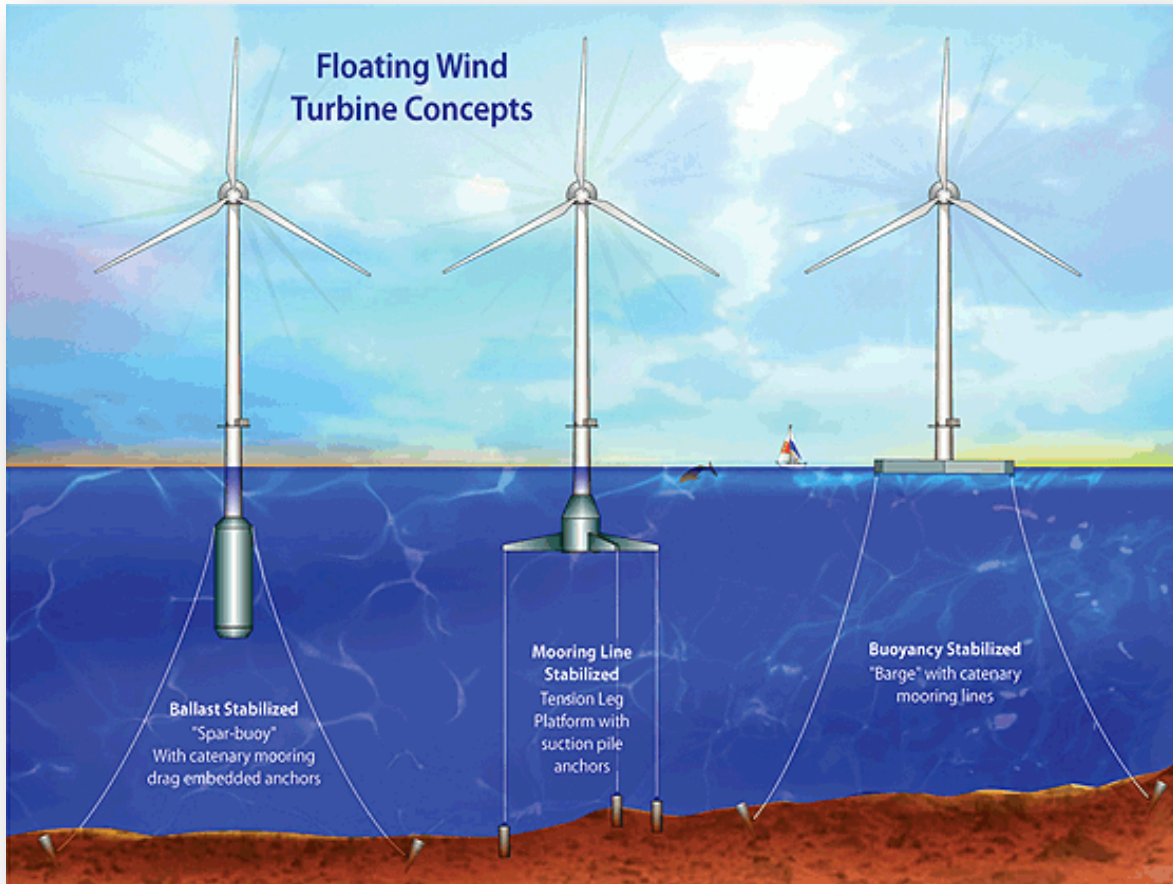
Figure 3 Types of floating substructures(Renewables International, u.d.)

A few different prototypes have so far been placed in the oceans for testing, but no concepts have so far been put in mass production. As previously mentioned, Sway has put a few of its prototypes in the water for field testing, but none of the concepts have to date been put in commercial production. Statoil has also tested a prototype of the HyWind-concept. Both are a version of the ballast-stabilized spar-buoy like the one seen to the left in Figure 3.

The report entitled "Engineering Challenges for Floating Offshore Wind Turbines" (S. Butterfield, 2005) used Figure 4 to illustrate the three different ways of stabilizing a floating body and plotted the different types of floating hulls and vessels that exist today for comparison.

Written by Knut-Ola Lunde
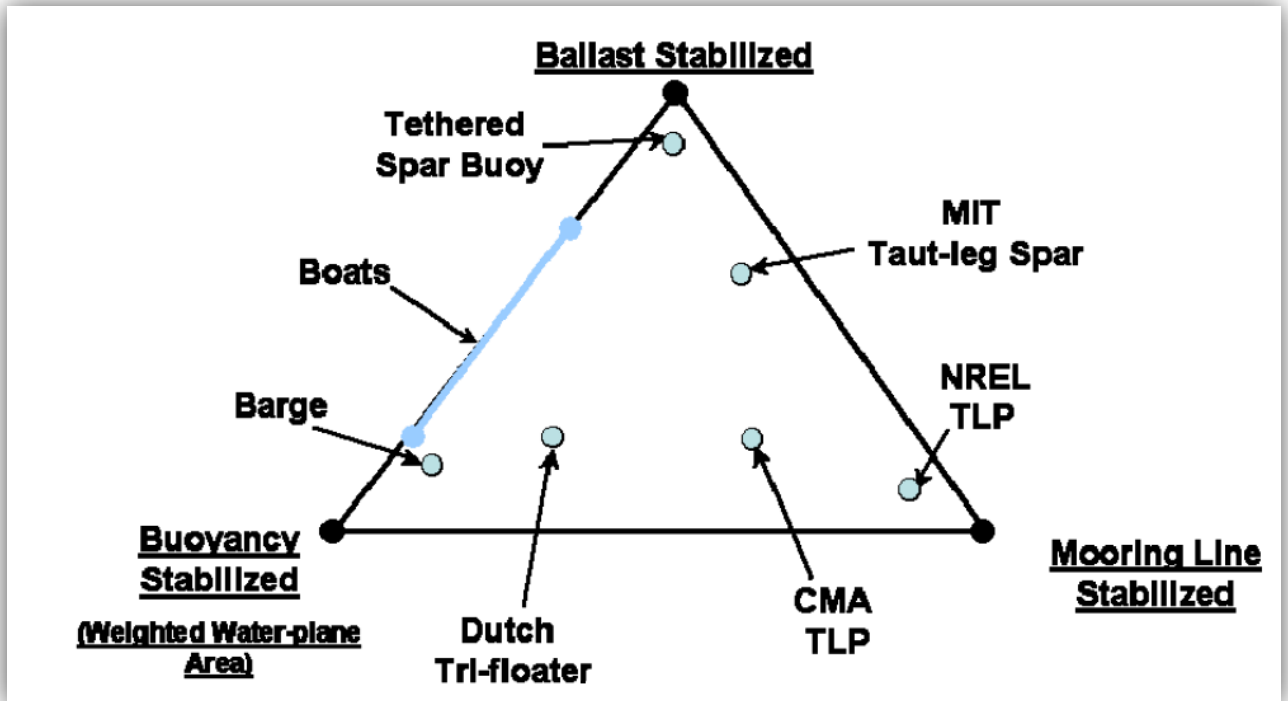
Figure 4 Stability triangle (S. Butterfield, 2005)

The European Union (EU) is currently involved in several projects involving renewable energy. One among them is a project called HiPRWind, a multi-national research and development (R&D) project that aims to "develop and test new solutions for enabling offshore wind technologies at an industrial scale"(HiPRWind, 2011). The projects final goal is to develop a 1:10 scale model installed in the ocean in order to generate field data.

Figure 5 depicts the current design for the HiPRWind hull. As the picture shows, it is a steel truss hull with corner cylinders for ballast and stability.

4

Figure 5 HiPrWind floating windturbine structure, picture from (HiPRWind, 2011)

Dr.techn. Olav Olsen AS is one of the 19 companies working on this project. The company has been working with offshore concrete structures since the early 1970's (Olav Olsen AS, u.d.). With the company's experience in offshore concrete structures, it has worked on its own concept for floating wind called the "Concrete Star Wind Floater" in parallel with the HiPRWind-project.

In addition, the Institute for Energy Technology (IFE) is currently working on a design tool called 3DFloat. In the report "Engineering challenges for floating offshore wind turbines" (S. Butterfield, 2005) the ability to predict loads and dynamic response of both the wind turbine and the platform system as one, is named the great challenge for floating offshore wind turbines. Having a tool that can analyze the coupled system will benefit the whole industry and hopefully contribute to more reliable analyses. 3DFloat is being programmed with that purpose in mind, specifically to analyze the whole floating hull and take all load conditions into account, for the steel tower, nacelle and the sub-structure.

1.2 Concrete Star Wind Floater

The "Concrete Star Wind Floater", from here on referred to as CSWF, is a concept hull for offshore floating wind. Dr.techn.Olav Olsen is engaged in a joint two-year R&D project together with IFE to further develop their own concept, sponsored by the Norwegian Research Council.

The R&D project aims to achieve the following (Landbø, 2012);

- Document feasibility and competitiveness of this new concept compared to existing solutions
- Develop a foundation technology which will be perfect for Norwegian waters and which can also be exported to other deepwater areas worldwide.
- Optimize the concept based on use of the Norwegian developed analysis and simulation tool 3DFloat, specifically made for floating offshore wind.
- Design the concrete floater based on the most advanced design software for offshore concrete structures, Shelldesign.
- To engage master students in a number of master thesis over the next two years, related to structural and marine issues.

Achieving these goals will mean that the CSWF is more cost effective than bottom-fixed structures and other floating concepts for water depths of 50 meters and more.

1.3 Description of the CSWF – concept
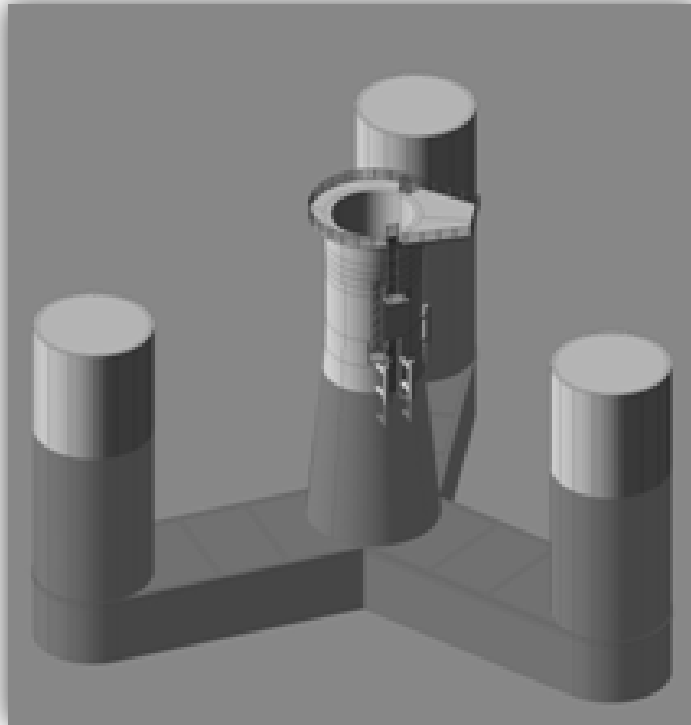
Figure 6 Concept model of the CSWF

As seen in Figure 6, the hull is symmetrical and made up of only a few elements in order to better facilitate production. This also makes it easier to scale up or down for larger wind turbines.

In each of the three corners there is a hollow cylinder measuring 30 meters tall from the base of the hull. These are fitted with pumping systems so that the floating hull can be trimmed by taking in ballast water. This provides stability and allows the structure to float at the desired draft, which in this case is 20 meters for operational conditions. Connecting the corner cylinders to the center column, the shaft, in the center are three rectangular shaped pontoons with perforated walls between the inner cells. The pontoons are filled with water when the structure is in operation, sinking the structure to the approximate draft.

The shaft is a composite lofted structure with different wall thickness at each element. It is sealed and not intended to contain any ballast water. It stretches 35 meters above main sea level. For connecting the base of the tower, the top is a bucket with a bottom 5 meters below the top of the outer walls, making for easy assembly of the steel tower with the substructure.

Key figures	
Draft	20 meters
Displacement	11 369 tonnes
Concrete volume	2505 m^3
Internal water in pontoons	2887 tonnes
Ballast water	1110 tonnes
Metacentric height	5,59 meters
Natural period, heave	15 seconds
Natural period, pitch/roll	22 seconds

Table 2 Key figures for the basic CSWF-concept in operation

Concrete has been chosen as the preferred construction material for a number of reasons including its potential for mass production, lifespan (100 years compared to around 30 years for steel concepts), resistance to fatigue, small draft (easy towing from production site to operation site) and due to its resistance to impact loads (Landbø, 2012).

1.4   Criteria for the final design

The final design is required to meet certain given parameters under operational conditions. First of all, this means the natural periods in heave have to be at least 20 seconds and pitch/roll to be at 25 seconds, so that they are outside the range of the waves in the area it is to be placed in. The maximum static tilt of the tower when subject to the maximum wind loads should not exceed 6 degrees.

Demands for the final design	
Natural period, heave	At least 20 seconds
Natural period, pitch/roll	At least 25 seconds
Static tilt	<6 degrees

Table 3 Demands for the final design

The design can be adjusted +- 1 meter with regards to the draft, but the top of the concrete hull must remain 15 meters above MSL.

The natural period in pitch/roll should be 4-6 seconds higher than the period in heave. Pitch/roll must also not be in the range of 1.5*heave or the whole multiple, as in 2*heave or 3*heave.

1.5   Input values for analysis in Wadam

For the Wadam analysis, environmental conditions are needed. The following data is given as the design basis for this thesis and are to be used for the hydrodynamic analysis:

- Water depth: 300 meters
- Structure type: Floating
- Wave period: 4 to 20 seconds with steps of 0.5 seconds
- Wave direction: 0 to 360 degrees with 15 degrees per step
- 7 % of critical damping is applied as additional damping

When the final concept has been chosen, analysis for the maximum response shall also be performed. The analysis is done using wave data from the Floatgen-project which researches floating wind concepts in Mediterranean deep seas (European Commission, 2012) . These wave conditions are calmer than that of the North Sea, where this concept was originally intended to be used.

id	Hs	Tp	Gamma	Dir_waves	V_wind 1h 70m	V_wind 10min 10m	Dir_wind	V_curr	Dir_curr
	m	s		º	m/s	m/s	º	m/s	º
1	5,50	11,40	1,17	0,0	23,00	19,16	0,0	0,60	180,0
2	5,50	11,40	1,17	30,0	23,00	19,16	270,0	0,60	180,0
3	3,60	8,00	2,46	0,0	28,80	23,30	250,0	0,60	180,0
4	3,60	8,00	2,46	0,0	28,80	23,30	0,0	0,60	180,0
5	3,00	19,00	1,00	0,0	17,0	14,62	0,0	0,60	180,0
6	4,00	17,00	1,00	0,0	19,0	16,16	0,0	0,60	180,0
7	5,00	16,00	1,00	0,0	23,0	19,16	0,0	0,60	180,0
8	5,00	8,00	5,00	0,0	25,0	20,61	0,0	0,60	180,0
9	3,60	8,00	2,46	0,0	28,80	23,30	270,0	0,20	90,0
10	---	---	---	---	---		---	0,60	180,0
11	5,50	11,40	1,17	0,0	---		---	---	---
12	---	---	---	---	28,80	23,30	250,0	---	---
13	---	---	---	---	28,80	23,30	0,0	---	---
14	---	---	---	---	28,80	23,30	0,0	0,60	180,0

Figure 7 Load conditions in Mediterranean seas

1.6   Input values for analysis in 3DFloat

3DFloat also operates with a given environment for calculation of beam forces and moments. These parameters therefore have to be set for the analysis of the structures. 3DFloat analysis is conducted with a single wave of a higher order, based on streamline function theory, with a given

height and period (Det Norske Veritas, 2010). The program calculates the appropriate order based on the given wave properties and geometry.

2 Theory and method

2.1 Stability of floating structures

For any floating body that has a desired purpose in its liquid, the stability has to be carefully calculated to ensure that the body behaves as intended. The hydrodynamic and hydrostatic properties are crucial for the final design.

A body floating in a liquid has six degrees of freedom. The first three are heave, sway and surge. Heave is a linear movement along the Z-axis (up and down) while sway and surge are linear movements along the X- and Y-axis. The other three are roll, pitch and yaw which are rotations about the respective axis. Yaw is rotation along the vertical axis, while roll and pitch are along the X- and Y-axis.
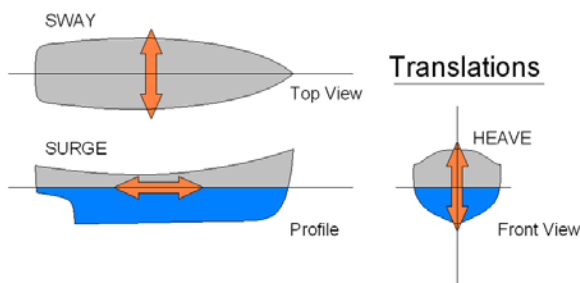
Figure 8 Translations on floating vessels(Brighthubengineering, u.d.)
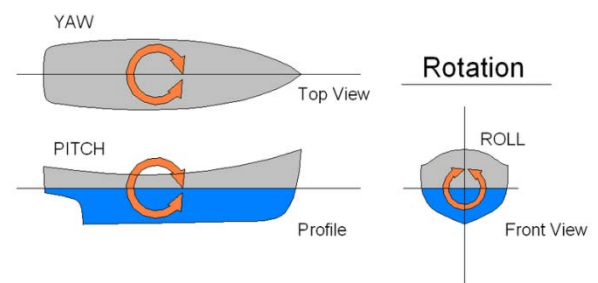
Figure 9 Rotations of floating vessels (Brighthubengineering, u.d.)

For a structure floating in the water, like the one this thesis is calculating, the period of heave (how long it takes the structure to move one full motion up and down vertically) and pitch/roll are the most relevant. The period in pitch and roll is the same for any structure that is symmetrical in the XY-plane.

Before the natural periods can be calculated, a model of the structure with its properties must be established.

Any floating body has a vertical center of mass (VCOG) and a vertical center of buoyancy (VCOB). These are the points in the body where the resultant mass- and buoyancy-force work. These are straight forward to calculate once the geometry and material density of the structure is known. The center of buoyancy depends on the structures draft. Draft is calculated from Archimedes rule, which states that "any body completely or partially submerged in a fluid at rest is acted upon by an upward (buoyant) force that is equal to the weight of the displaced fluid" (Office of Naval Research, u.d.). The practical meaning of this is that if you have a design draft and the

buoyant force is larger than the structural mass, you can add more mass to the structure to equalize the two opposite forces, making the structure float at the designated draft.
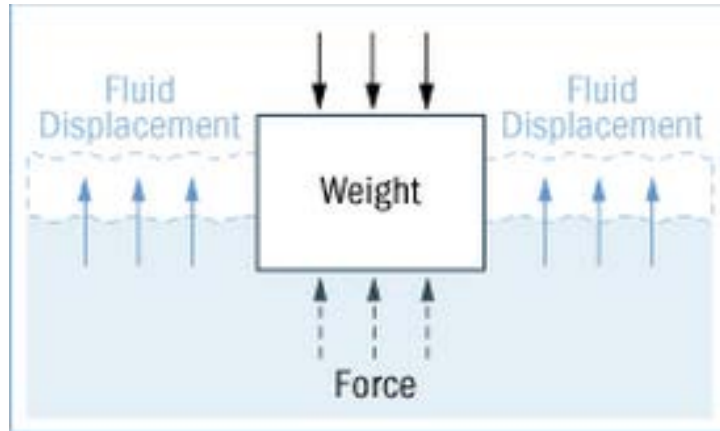
Figure 10 Illustration of Archimedes law (Howstuffworks.com, u.d.)

So, as an example, a design draft at 20 meters can be set. The total submerged volume is then calculated and the VCOB can be found. The submerged volume is multiplied by the density of the liquid, for saltwater this is 1.025 t/m^3, and the total displaced mass is found. The total mass of the structure and ballast has to equal this weight. If these forces are the same, the body is floating with the designed draft.

The main factor for assessing a floating body's stability is the metacentric height (GM). From (Fuglerud, 2005) the equation for GM can be obtained:

$$GM = VCOB + BM - VCOG$$

Where BM is calculated by the following fraction:

$$BM = \frac{I_{Waterplane}}{V_{displaced}}$$

- $I_{Waterplane}$ is the second moment of area of the water plane, meaning the area of the structure breaching MSL
- $V_{displaced}$ is the structures displaced volume

GM is a factor to describe the body's stability and is calculated when the inclination is small (<10°), which is the initial stability. For small angles it is safe to assume that GM will remain in the same position. GM describes the point around which the floating body rotates.

ANGLE OF HEEL IS
GREATLY EXAGGERATED
FOR CLARITY
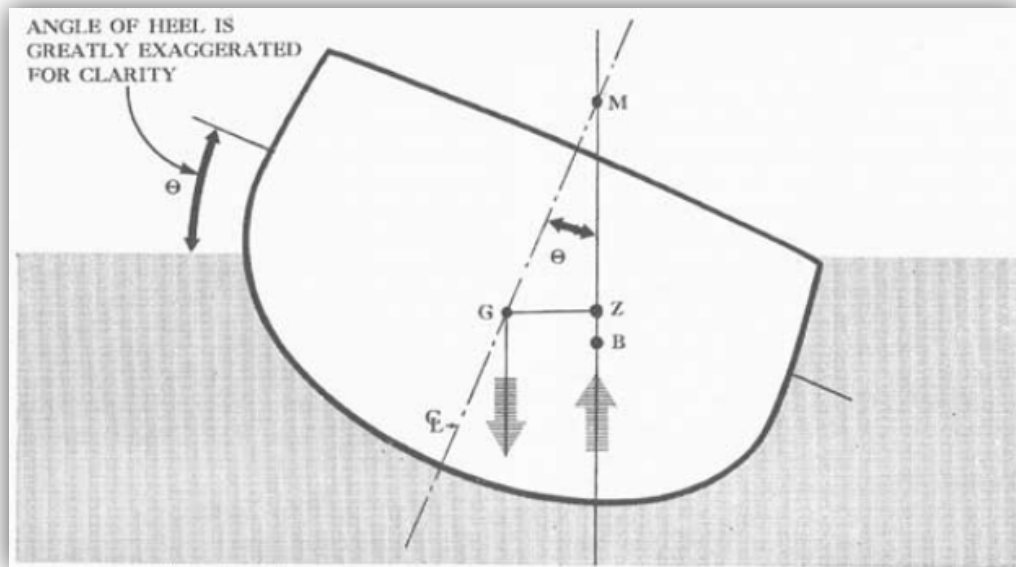
Figure 11 Visualization of stability parameters

GM is defined by three threshold values;

- GM>0: This means the body has a positive initial stability and is defined as stable. When an inclination occurs, it will restore itself to the natural position. However, this is not valid for angles above 10°.
- GM=0: The body has indifferent stability, meaning that it, in principle, will float steadily for all small inclinations.
- GM<0: The body has a negative initial stability, and is therefore unstable. This means that it will start to incline by itself and eventually capsize. For any floating vessel with a desired purpose this is unacceptable, as it will be unable to float at a horizontal angle.

2.1.1 Free water surface

For a structure with ballast-tanks that are not completely full, like the corner cylinders on the CSWF-concept, the effects of the free water surface have to be taken into account.

When calculating a structure's VCOG, every element must be taken into account, including the ballast in the tanks. But when the structure rotates, the ballast water in tanks that are not full will shift and then shift the VCOG in the tanks, depending on how much ballast there is. This may increase the whole structures VCOG which will in turn reduce the GM and thereby the total stability of the floating body.

The effect of free water surface is calculated according to (Fuglerud, 2005):
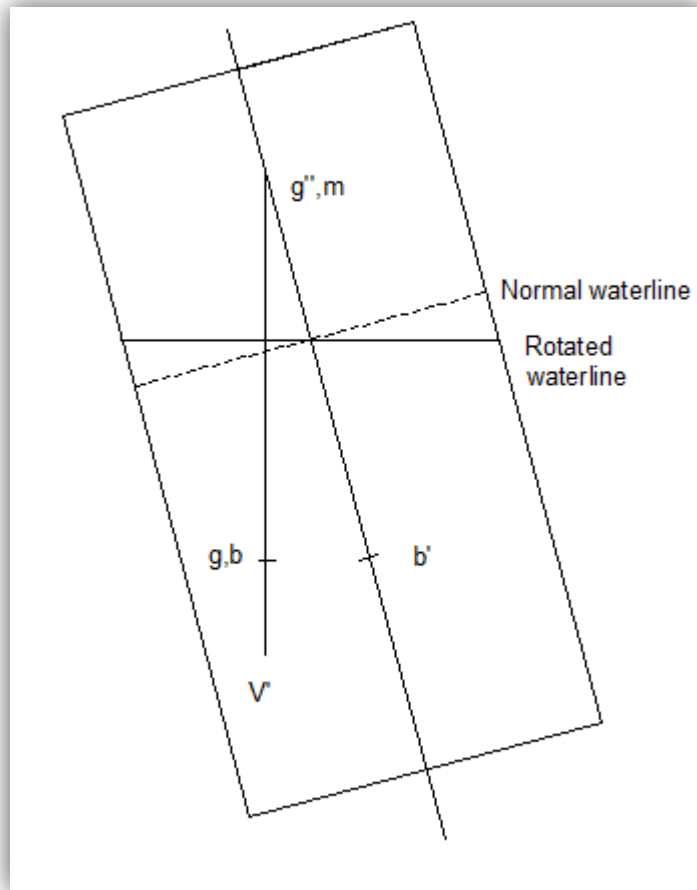
Figure 12 Illustration of free water surface

Where:

- g is the real center of mass for the tank before rotation
- g'' is the virtual center of mass after rotation
- b is the center of volume before rotation
- b' is the center of volume after rotation
- V' is the fluid volume
- m is the fluids metacenter

Using the same calculations as for the BM in the last chapter, the tanks initial metacenter, BM, is therefore;

$$BM = \frac{I}{V'} = gg'$$

Where:

- I is the moment of inertia for the fluid surface with 0^0 rotation
- gg' is the virtual increase of the tanks center of mass

It is now possible to calculate the gg'':

$$\Delta * \rho * gg'' = V' * \rho' * gg'' = V' * \rho' * bm = V' * \rho' * \frac{i}{V'} = \rho' * i$$

Where:

- D is the total displaced volume for the floating body
- ρ is the density of the fluid that surrounds the body
- ρ' is the density of the fluid inside the tank

This then leads to the expression for the virtual center of mass:

$$gg'' = \frac{\rho' * i}{\rho * \Delta}$$

For n number of tanks with the same fluid density inside and outside of the tanks, the following expression is valid:

$$gg'' = \sum_n \frac{i}{\Delta}$$

2.1.2 Tilt of the structure

The stability of the sub-structure is also important when considering the purpose of the complete structure, power production.

Power production is directly related to the area of the turbine's blades that is in the wind zone. Tilting the hull will move the blades so that less area is exposed to the wind, reducing the amount of power produced. This affects the total cost of production, as the installation costs are the same, but the output of the wind turbine will diminish for a structure that is allowed to tilt much. The demand for the static tilt is therefore set at around 5-6 degrees for full wind thrust on the blades. The thrust will vary around a design value; the effects of dynamic tilt will vary the static tilt up and down with the thrust.

To calculate the static tilt, the acting moment is needed. This is the design thrust value times the moment arm. Depending on how the wind turbine is fastened to the sub-structure, this arm varies. The moment will try to tilt the whole structure, meaning the structural weight is the inertia that tries to withstand the tilting moment, working around the point of rotation; GM. Calculations are therefore done as shown in Figure 13 from Mathcad.

Calculated forces:

$$M_{acting} := Thrust \cdot M_{arm} \quad = \quad 0 \cdot kN \cdot m$$

$$F_{gravity} := M_{structure} \cdot g = 0 \cdot kN$$

Static tilt:

$$\alpha_{static} := asin\left(\frac{M_{acting}}{F_{gravity} \cdot GM}\right) \quad = \quad 0 \cdot deg$$

Figure 13 Calculation of static tilt

2.2 Calculation of natural periods

Once a satisfying level off stability has been found, an estimation of the natural periods can be made to see if a structure is in the vicinity of the desired rigid body motions. As previously mentioned, for a floating offshore wind structure, the periods for heave, pitch and roll are the main interesting ones. A symmetrical structure in the XY-plane has the same period for pitch and roll.

The natural period of heave of a ship or semi-submersible structure can be calculated using the following formula from (Faltinsen, 1990):

$$T_{Heave} = 2\pi \sqrt{\frac{M + A_{mass}}{\rho g A_w}}$$

Where:

- M is the total structural mass including the ballast
- A_{mass} is the added mass of the water from exciting the structure
- A_w is the area of the water plane.

For pitch and roll, the formula is similar (Faltinsen, 1990):

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$$T_{pitch/roll} = 2\pi \sqrt{\frac{M * (R_i)^2 + A_{moment}}{\rho g V_{displaced} * GM}}$$

Where:

- R_i is Rx or Ry, radii of gyration around the respective axis, depending if pitch or roll is being calculated
- A_{moment} is the added moment for pitch or roll, calculated from the added mass from heave and the distance to the VCOG
- ρ is the saltwater density
- g is the acceleration of gravity
- $V_{displaced}$ is the structures displacementvolume

The added moment is the most problematic issue here. It is hard to estimate the shape and weight of the added mass working with the structure with different moment arms. Some work with the different geometries and added mass is therefore needed to get good results.

2.2.1 Added mass

For any body that is partly or wholly submerged in a fluid, that body must move some volume of the surrounding fluid as it moves through it. This adds inertia to the system and needs to be taken into account when calculating the body's movements.

For the different geometrical shapes, much work has been done to find good approximations of the added mass. The hull in question for this thesis has vertical, cylindrical columns and rectangular shapes. There are several ways of estimating the added mass and many experts have released their own estimations. However, there exists a "best practice" for the geometrical shapes to be used in this thesis. The formulas for the natural periods require the added mass in heave in the calculations.

Looking in (Baltrop, 1998) for rectangular and cylindrical shapes, the formule for added mass are given:
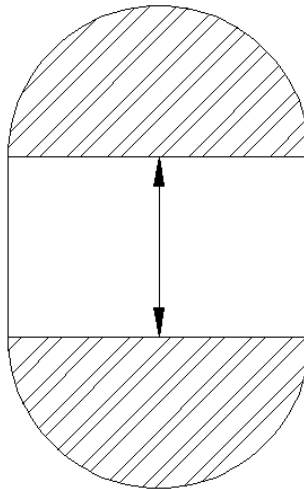
Figure 14 Added mass for a submerged rectangle

With the hatched areas being the added mass, the following estimation for added mass can be used:

$$M_Z = \pi \rho \left(\frac{B}{2}\right)^2 L$$

Where:

- B is the width of the rectangle.
- L is the length of the rectangle.

So for a submerged rectangle, the added mass is one half cylinder above the rectangle and one half cylinder below over the whole structure's length. Similarly, for a cylindrical body the added mass is a sphere below the cylinder as shown in Figure 15.
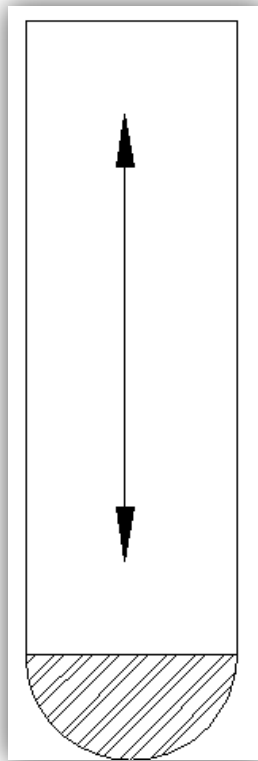
Figure 15 Added mass in heave for a semi-submerged cylinder

With the added mass shown here again by the hatched area, the formula for added mass is:

$$M_Z = \frac{4\pi}{3} R^3 \rho$$

Where:

- R is the radius of the cylinder

Calculating with these values is, as stated above, an approximation of the real added mass. As a comparison, the added mass from this approximation will be examined alongside the answer from Wadam in order to explore how close the approximations are.

2.3   Application of computer software

For a problem similar to that which this thesis is focused on, the software from Det Norske Veritas [DNV] is very good. This master thesis is using Wadam [Version 4.5-08, DNV], which is a program that carries out analysis on floating structures based on potential flow theory working with the HydroD-package. Wadam operates on user-specified input for the model, which has to be calculated by hand before any analysis can be run. It also needs a FE-model which must be modeled in another program; in this case, Patran.Pre [Version 2010.2.3, DNV] is the preferred FE-program.

2.3.1   FE-modeling in Patran.Pre

Patran.Pre is used to create the FE-models. It is not very complicated, but being quite old, it has almost no internal memory making modeling a time-consuming task if unaware of the few pitfalls. This chapter will therefore try to give as short introduction to how modeling in Patran.Pre works.

The best way to model is to finish the outlines of the geometry first, using only curves and straight lines, preferably unconnected. Once the outer geometry is finished, saving of copies is important so it is easy to go back if something happens. The program only allows one "undo" as it has, as earlier mentioned, almost no internal modeling memory. It is therefore important to save an external copy before making any changes to the model.
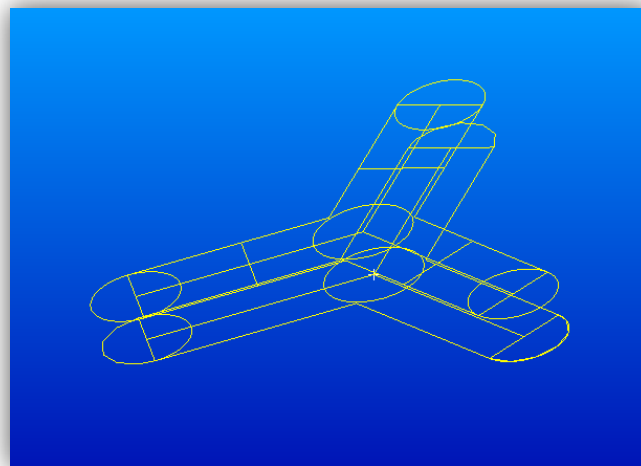
Figure 16 Outline of structure from Patran.Pre

The figure above shows the outline of the geometry of the base plate of a structure. With the outline of the structure drawn, surfaces can be added between the curves. Patran is particular about the way this is done, so the right order of commands must be followed. Some of the commands for

making surfaces do not work on some of the curves, so if the model fails due to holes in the geometry when analyzing, a different set of commands for making the surfaces should be applied the second time.

First the curves, straight lines and arcs, must be linked together using the "chain"-command. This reduces the half circles to a number of straight lines, making it a little bit more inaccurate than it was, but that is how the program operates. Then surfaces can be added between the curves that are chained together and translated in the Z-direction according to each other.
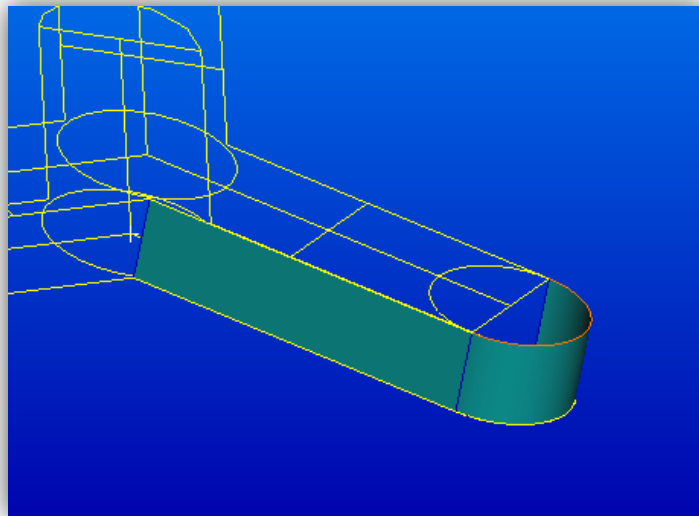
Figure 17 Surface between two curves

For surfaces in the X-Y- plane it is more difficult. There is a command than can subtract a hole from a surface, but then the surface has to be untrimmed to begin with. Therefore, in order to get the center hole open, a square surface bigger than the structure has to be made, and then the hole in the middle subtracted, before the surface can be trimmed around the edges.

Following this procedure, and attaching the outer cylinders, the end result will be something like the model in Figure 18.
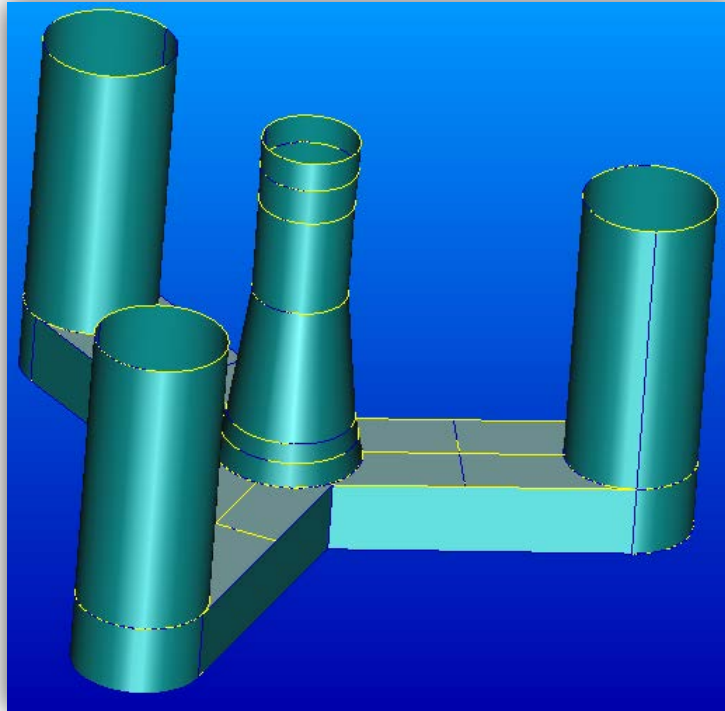
Figure 18 Whole structure with surfaces

The structure Figure 18 is modeled with all the outer surfaces, no inner surfaces. Once this has been completed, some properties need to be applied before the final FE-model can be exported and used in the hydrodynamic analysis.

The hydrostatic load that is being applied works on the surfaces in the opposite direction of the surfaces normal vector. Therefore, all vectors need to be checked to ensure that they are pointing outwards from the surfaces, and those surfaces facing the wrong way must be flipped. An inspection the vectors is made using the command Show – Surface – Normal.

Once the model is complete after the previous descriptions, mesh can be added to the model. The graphic engine sometimes makes some strange panels when applying this order, so it is important to look over the structure once the mesh has been created. It is also important to delete the current mesh before applying a new one, as that can often lead to errors later on, when the program doesn't always fully delete the previous mesh on the surface.
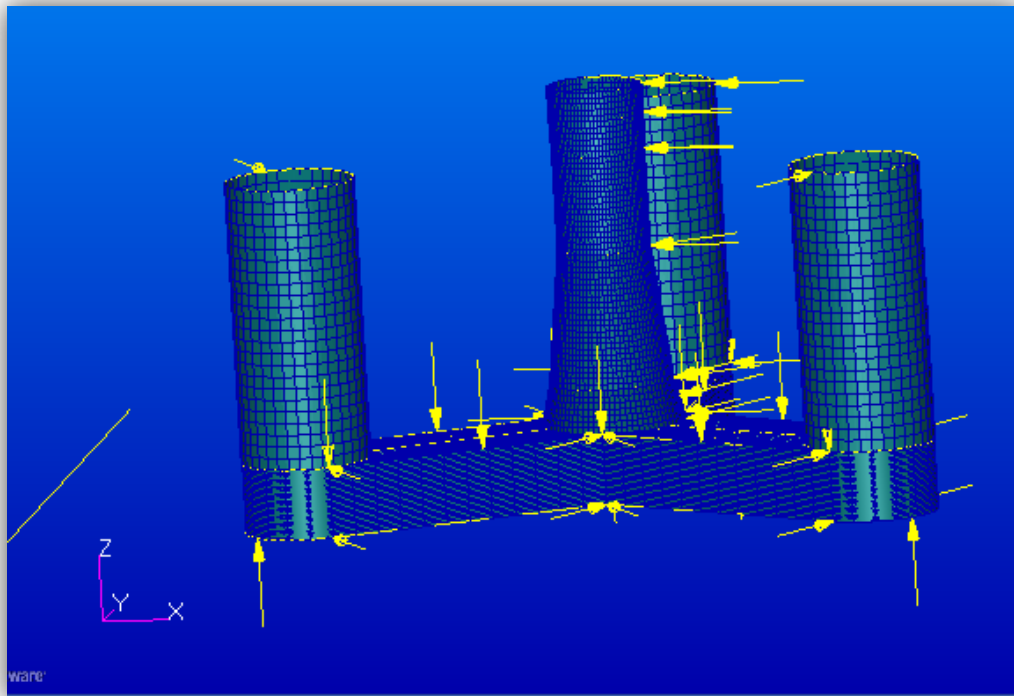
Figure 19 Meshed structure with yellow hydro force arrows

After the mesh is applied and the vectors are approved, the complete FE-model will look something like Figure 19. We then define the material properties and the hydrodynamic force. The material is not valid for these calculations, but a name needs to be inserted for it so that the program does not return an error message. Once all of the above is completed, the model can be exported.

2.3.2 Check of FE-model

DNV also supplies a program called Xtract for, amongst other things, checking results and mesh. Before the model is used in Wadam it can be a good idea to load it into Xtract and check the mesh for any irregularities or errors.
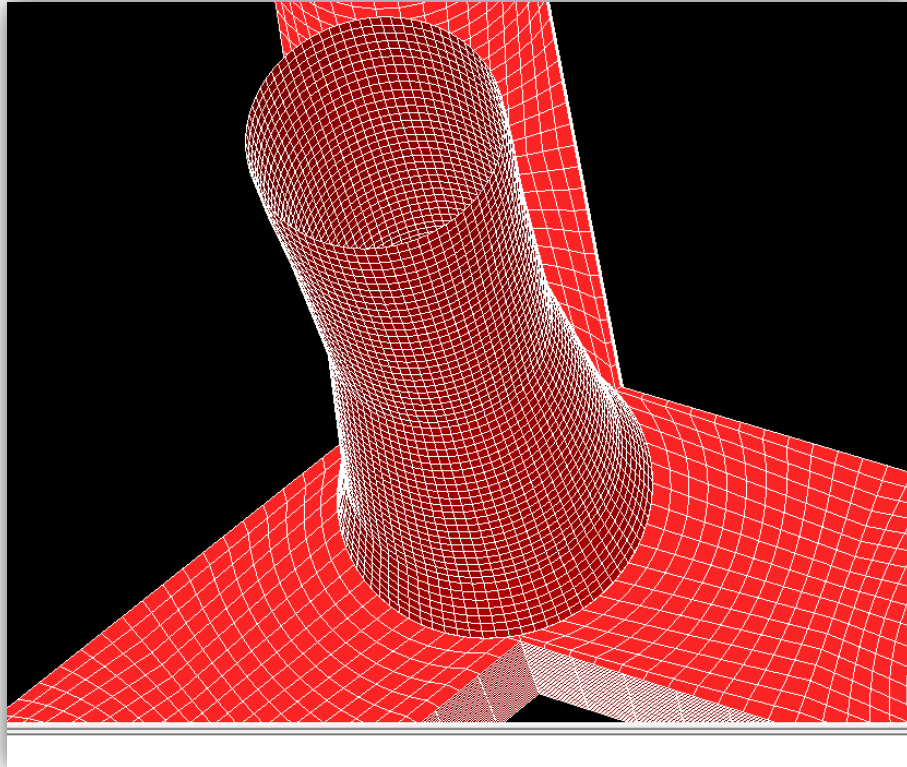
Figure 20 Elementmodel from Xtract

Another important thing to remember is that the analysis can take a longer time depending on the number of panels and nodes, i.e. how fine the mesh is. Xtract tells the user how many panels and nodes the model has, in this case it has 11 508 panels and 12 822 nodes. After the analysis in Wadam is done and the time spent on analyzing is given, it is quite easy to see the impact on the time spent on analysis compared to the amount of panels and nodes.

2.3.3 Hydrodynamic analysis using Wadam

Wadam is run through the GUI in HydroD. For a panel model like the one created here, Wadam is based on linear methods for marine hydrodynamics. It uses Morison's equation and first and second order 3D potential theory for the wave load calculations (DNV, 2011).

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2.3.3.1 How to set up the hydrodynamic analysis in Wadam

After opening the program, start the Wadam-wizard, which is a tool that takes the user through all of the steps for inputting the information required by the program;

1. The first step is choosing a model from four options; Panel, Morrison, Composite or Dual. As the FE-models created in Patran are panel-models, that is the chosen option in this case.

2. Create direction set:
    The directions that the waves hit the structure has to be defined.. For a symmetrical structure, it is sufficient to calculate for the directions in which the structure is symmetrical. This can help reduce the analysis time.

3. Create frequency set:
    Here, the waves on the structure are defined. It is possible to define the waves based on period, wavelength or frequency. For calculation of rigid body motions, unit waves with periods from 4-20 seconds are used.

4. Create location:
    The environment and location needs to be given, with respect to densities and viscosity for the fluid in addition to the water depth.

5. Create frequency domain conditions:
    This window combines the frequency-set of the waves with the direction of the waves.

6. Create hydro model:
    Here, the hydro model is created. There are options for a floating or a bottom-fixed construction, as well as options for deciding the baseline z-position. The easiest method is choosing a baseline Z-position at 0 meters and check the box for "floating structure"

7. Create Panel Model:
    This is where the FE-model is imported. If it is modeled around its axis of symmetry the program can mirror it around XZ- or YZ-plane. It's also possible to translate the model to have the correct draft, which is the preferred method in this thesis.

    Once these steps are complete, a jump to step 12 in the wizard is possible, as the steps in between are of no concern for an analysis of this type.

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8. Create loading Condition:
   The Z-position of the waterline, with trim if needed, needs to be defined. If the baseline Z-position has been set at 0 and the structure translated down to the draft we have, the Z-waterline can be set at 0 meters.

9. Create mass model:
   At this point, the properties of the structure need to be input. Choose a user-specified structure with an input coordinate system. This means all the necessary values calculated by hand for the structure in question are input manually.
   The program automatically calculates the buoyancy volume and center of buoyancy, parameters that should be checked straight away against the hand calculations already made to ensure accuracy. The panel-model is not perfect, as it on the size of the mesh. Therefore the volume may differentiate a bit from what is calculated, but it should be close to the correct answer.
   The total mass, VCOG and radii of gyration are the properties that need to be input for the analysis.

10. Create run:
    This compiles the analysis and prepares everything that's needed. Choose the specified hydro model, loading condition and environmental condition that are to be analyzed.

11. Create analysis;
    The created analysis is ready and can be run by Wadam. Depending on the number of elements and conditions, this may take some time.

2.3.4 Postprocessing in Wadam

Wadam gives the output in a .LIS – file that opens in any text-editor. It contains large amounts of data and calculations, so it is important to know what you are looking for and how to best read the results.

2.3.4.1 Check of model

Wadam calculates the displaced volume of the model using three different methods and lists all three in the output file under point 2.7. These three values should be equivalent. It is also important to compare the calculated values for "mass of the structure" with "mass of displaced volume". If these exceed 5%, the analysis will automatically stop, but they should be identical.

If the mass properties and structural data are correct the analysis will calculate the rigid body motions for the given model.

2.3.4.2 Natural periods

The natural periods are calculated for each wave period. Results are given with an added mass matrix, damping matrix and eigen solutions. The natural period results are shown in Figure 27

```
EIGEN SOLUTIONS TO THE RIGID BODY MOTION
----------------------------------------

EIGEN VALUES:
NO    PERIOD [T]    ANG. FREQ.

  1      INFINITE
  2      INFINITE
  3      INFINITE
  4     2.2544E+01   2.7871E-01
  5     2.2541E+01   2.7875E-01
  6     1.5856E+01   3.9627E-01
```

Figure 21 Eigen solutions from Wadam

Numbers 4 and 5 are the natural period in seconds for pitch and roll, while 6 is for heave. The angular frequency is a measurement of how many radians the structure moves per second, with one cycle being equal to 2π.

2.4   Maximum responses in Postresp

When the rigid body motions are calculated and found to be within the correct area for the structure it is interesting to look at the maximum motion responses in physical units. This means the number of meters the structure moves vertically in heave and how many degrees it pitches/rolls. To do these kind of calculations, Postresp [DNV,version 6.3-01] is used. Postresp calculates and plots the responses based on the response amplitude operators (RAO) from Wadam .

Response amplitude operators are transfer functions which are used to predict the floating body's behavior at the different sea conditions (Wikipedia, u.d.). With a given wave period and wave height, the RAO's are used to determine the movement of the calculated design. The peaks in response indicate where the resonant behavior happens, revealing the structures natural periods.

The RAO's are calculated from unit waves. This is carried out according to the previous chapter. These are then used as input for Postresp together with the wave spectrums for the desired

location. With the RAO's and the wave spectrums it is possible to predict the structures movements in the ocean.

2.4.1 Postresp setup and input

Wadam creates a .SIF-file that contains all the necessary data for plotting the structure's movements when the structure is subjected to different waves.

Postresp must be run through Sesam Brix Explorer to be able to function properly. When this is set up, it is possible to either read a .jnl-file with setup of wave spectrums and other necessary input, or it is possible to start a new database and do this manually, which will be explained later in this chapter.

After opening a new database, the user must read the .SIF-file to get the data from the Wadam analysis. Once this has been done, Create → Wave Spectrum can be applied. For this thesis, JONSWAP wave specters are used. JONSWAP is input with significant wave height (Hs) and the zero upcrossing periods (Tz) together with a gamma value.

Figure 22 Create Wave Spectrum Postresp

Looking at the wave input for this thesis in chapter 1.5, it is given in peak period (Tp), Hs and gamma. This therefore has to be recalculated by the following formula to Tz (Lund University, u.d.) to fit into Figure 22;

$$T_z = \frac{T_p}{(1.30301 - 0.01698\gamma + \frac{0.12102}{\gamma})}$$

Where;

- γ is the peak enhancement factor determining the concentration of the spectrum on the peak frequency. $1 \leq \gamma \leq 7$

Tz is the zero up-crossing period of the waves. This is the average time between two wave crossings of the mean sea water level in an upward direction by waves in a wave train (Carbon Trust, 2011).

Once all the different wave spectrums that are to be evaluated have been programmed correctly it is possible to check the response variables (RAO). This can be done by clicking Display → Response Variable and then choosing the desired variables and wave directions. Figure 23depicts the RAO's for a non-symmetrical structure in heave, pitch and roll motion with the waves hitting the structure at an angle of 0 degrees.
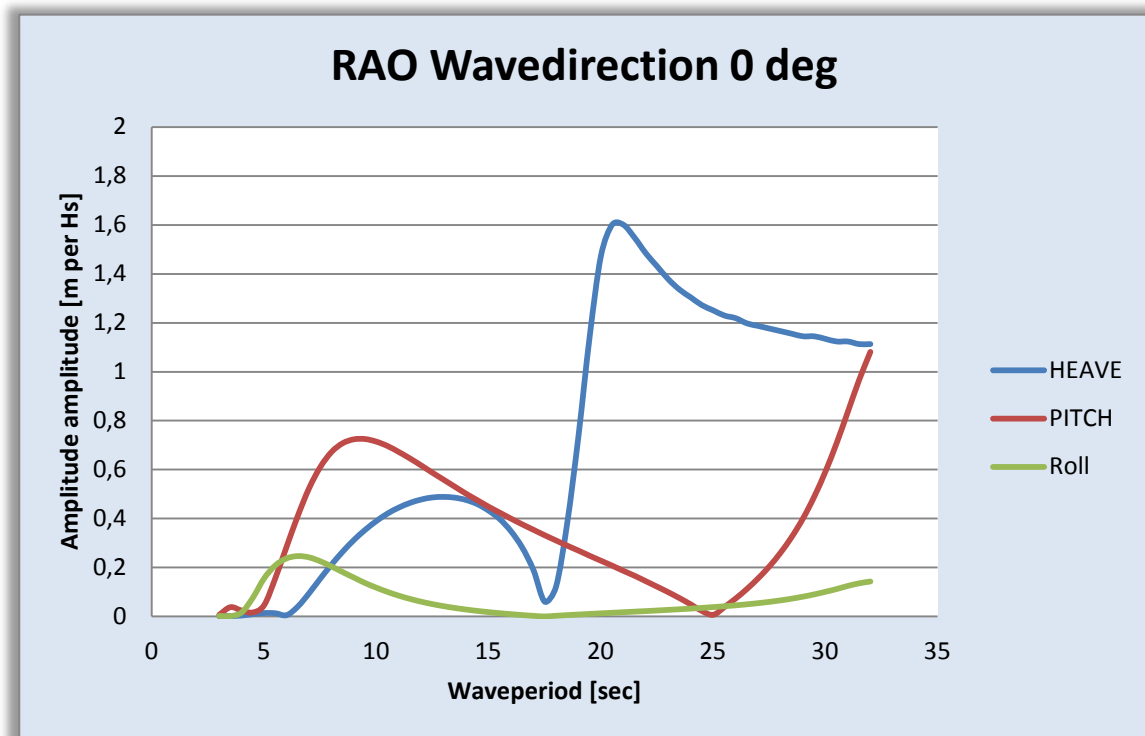
Figure 23 Example of response variables

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The RAO's are given with the X-axis showing the wave period and the Y-axis showing the amplitude. The large peaks indicate natural periods of the structure, as a structures maximum response is when the induced load, in this case the waves, is exerted on the hull with the same period as the natural periods. For the wave regime at the hulls location, between 4 and 20 seconds for example, the total movement of the hull is possible to predict from reading the graph and multiply the value with the significant wave height.

The response variables come from the .SIF-file from Wadam. It can be smart to check for the different directions to see that, for example, the heave period is almost identical for all wave directions as a way of making sure the input is correct.

2.4.2 Postresp post processing and results

With the input correct, the short term response of the hull can be displayed. This is achieved by clicking Display → Short Term Response. Depending on the chosen variable and wave direction, the result should be similar to Figure 24.
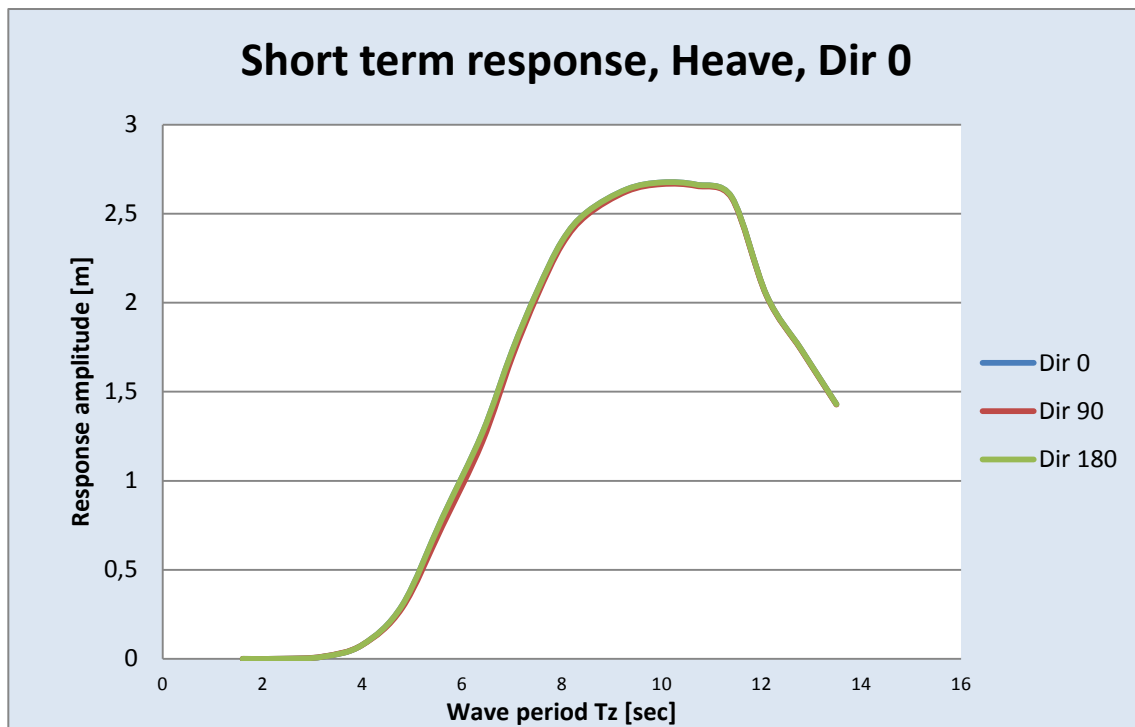
Figure 24 Example of short term response

In the figure, the X-axis shows Tz, while the Y-axis shows the significant response. For heave it is meters, for pitch/roll it is deg per wave height(Hs). To transform these results into the desired maximum response, the values from Postresp have to be divided by 2.0 and multiplied by 2.12 (Det Norske Veritas, 2010). The results can then be plotted in Excel to present the final values for the hull's extreme motions when subjected to the design waves. This hull has been analyzed in Postresp with the waves from chapter 1.5. The results can therefore be read straight from the graph, in this case resulting in a maximum heave-motion of 2.7 meters.

2.5   3DFloat

2.5.1   Program description and use

3DFloat is a program currently under development by IFE (Institute of Energy Technology at Kjeller). Programming started in 2006 with participants from IFE and the Norwegian University of Life Sciences (UMB) in Oslo. The program is a so-called "aero-hydro-servo-elastic" simulation tool(Myhr & Nygård, 2012). It is being developed for the specific purpose of complete offshore floating wind calculations. While Wadam gives the natural periods, the goal with 3DFloat is to incorporate both the wind turbine and substructure in one model. Once finished, it might therefore become a good tool to use in the design process for floating wind.
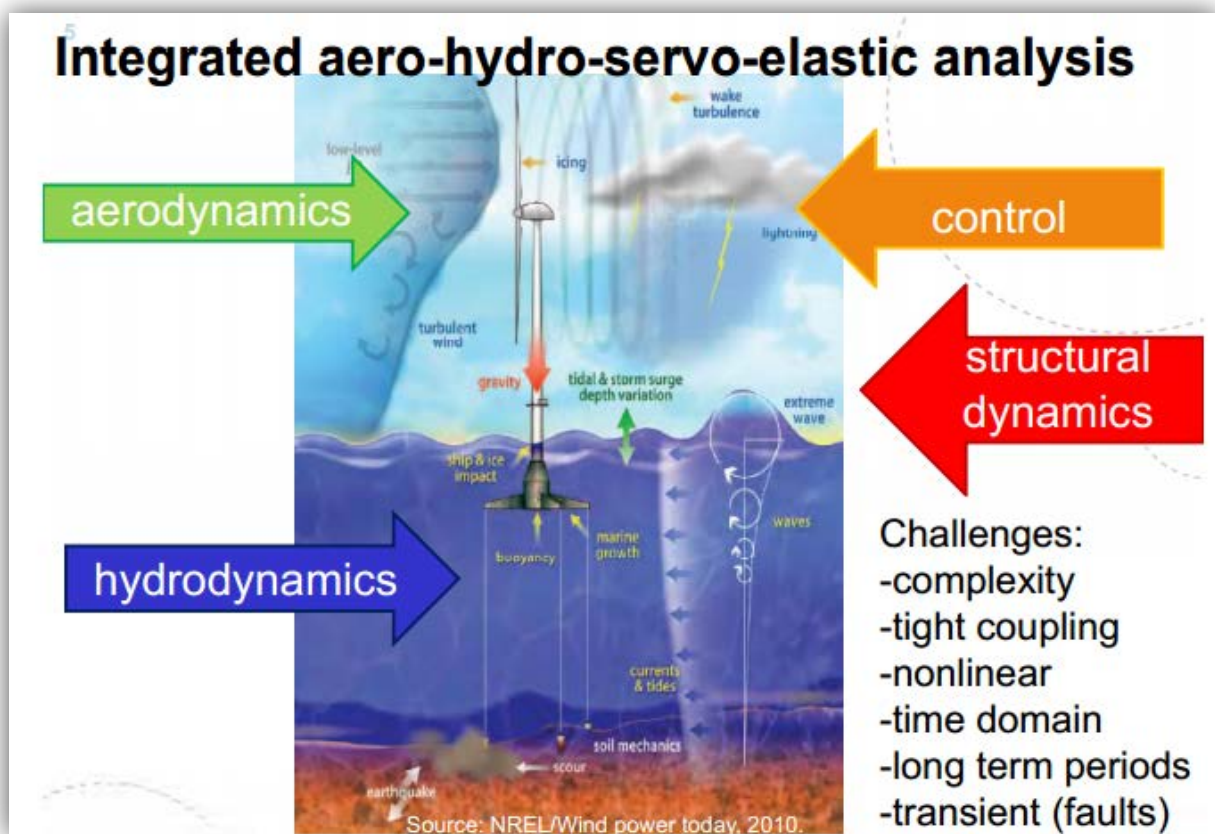
Figure 25 Visualisation of Aero-Hydro-Servo-Elastic(Bachynski, 2013)

Since 3DFloat is under development and has no manual yet, 3DFloat must be used with help from the program developers. Therefore, I spent one day with Karl Jacob Maus at IFE's office to learn the basics. One month after that, we had two intensive weeks going over modeling, calculations and post processing of the results by email before he moved on to another firm. During the work on this thesis, Tor Anders Nygaard at IFE has also been available via email for questions related to the modeling and post processing.

The following chapters will attempt, briefly, to explain how to use the program, its limitations and what to look out for. Results shown in the following chapter are not from any relevant model, but rather a training example to study how the program works and what it results it can output.

2.5.2 How to use 3DFloat

3DFloat has no graphical user interface unlike other modeling and analysis programs. Instead, it is based on strings of input commands written in a text editor. For the program to be able to make the calculations, the user has to input all the commands in the intended order of execution before reading the inputfile in 3DFloat. The program contains a limited help-function that can explain some of the necessary input parameter values. This can be of some support on how to build the command strings together when the user knows which one to use. It cannot be used to build a model from scratch, as so far it does not contain all the information needed. Therefore, a stripped down, basic version of an input file, with all the starting basic commands for environment and a few commands for the output must be obtained from IFE before the modeling and calculating can begin.

The structural models are based on general nonlinear FEM-framework, and work as stick-model calculation tools. Each element is given the desired material and cross-sectional properties as input and is then calculated from node 1 to node 2 as specified in the modeling file.

2.5.3 Limitations

There is a limited amount of modeling possibilities currently implemented in the program, which placed restrictions on its use. However, as long as the user is aware of these limitations, it is possible to adjust the input parameters to get valid results for the designed hull.

The main limitation is the number of cross-sections that can currently be used in the calculations. So far, 3DFloat can only operate with cylindrical and conical elements, making a specified design with more complex members difficult. If the actual model contains other geometrical elements, their properties have to be transferred into cylindrical or conical elements before being programmed into the model. This will of course inflict the calculations of, amongst other things, added mass, but that can be taken into account by increasing or reducing the added mass for each element via coefficients.

The second main limitation is that the program has no internal postprocessor interpreting the results. All output is given in .txt-files as numbers/matrices with limited information regarding

what is what. Some work is therefore needed on the results in order to render them readable to the user before the programming moves further along.

The third limitation is that, at the current stage, there is no graphical interface for either input or output in 3DFloat. This makes checking the model for errors difficult and time consuming, as the only place to look is in the input file, which contains a large amount of commands and numbers.

2.5.4 Environmental setup

Prior to any modeling, it is important to program the environment in which the model is operating. Commands for the environment may look like those in Figure 26.

```
set_environment  gravity on  buoyancy on  hydro_force morison
wind_force ndrg  waves extrapolated_airy  norder -1  wind no_mean_profile
pre_computed_waves_file off  random_mode write_file  randomfile   rho_water 1025.
rho_air 0.001  nu_water 1.e-5  nu_air 1.e-6  wave_amplitude 0.
wavelength 156.07768226721353  wave_direction 0.  current_speed 0.  current_direction 0.
tsweeps 0.  tsweepe -1  stretch 0.  wind_speed  0.
wind_ref_height 90.  wind_exponent 0.  wind_direction 0.  spectral_peak 10.
seed .3  nfreq 64.  wave_ramps  0.  wave_rampe  20.  depth 200.0
tshift_waves 800  tshift_wind 0.

wave_forces cm_morison 1.63
```

Figure 26 Example of environmental setup in 3DFloat

The property for water- and air density is known. For the semi-submersible analyzed in this thesis, values for wind speeds are ignored, as it only focuses on the sub-structure. So for an analysis of a similar semi-submersible hull, this setup of the environment can be used. Waterdepth can be adjusted to the desired level of the site in which the hull is going to operate. Other than that, the main focus for the environmental commands should be put on the wave input. 3DFloat calculates the waves acting on the hull from wave amplitude and spectral peak (Tp). So for the design wave, these values have to be input in the environmental data. "Wave_ramps" and" wave_rampe" are the start and end of the wave buildup time so that the hull is not hit with a full wave from the beginning; rather there is a buildup. So in the case above, the waves will only become the designed wave after 20 seconds and the wave train will hit the hull as long as the timestepping is allowed to continue.

In order to get the forces and moments on the hull, the analysis must run for as long as needed for the hull to reach a transient state. Once this has been obtained, the forces for one full cycle can be

plotted and the maximum values can be taken out and compared with the cross-sectional capacities.

Through the work with this thesis, it was ultimately discovered that regardless of the input in spectral_peak, the wave period in 3DFloat would be 10 seconds. This has been reported to the program developers at IFE and will be fixed at a later stage.

2.5.5 Modeling in 3DFloat

Modeling in 3DFloat is carried out through strings of commands and beam elements connected by nodes. It is very important to have nodes in the model at all places where an element is starting or ending. Point masses and monitors, codes that monitor and return the desired calculated values as forces, moments etc, are automatically put at node 1 of the element. The program does not add nodes automatically where elements cross, so if there are no nodes where two elements cross, they will not connect and the model will fall apart in the calculation process.

Modeling in 3DFloat is a repetitive process of programming elements and elemental properties in the text editor that can be studied further in input-file in appendix 2. Instead, focus here will be aimed at the calculation commands that need to be programmed into the input file for natural periods and forces on the hull.

2.5.6 Calculation of natural periods

When calculating the natural periods, 3DFloat linearizes all the externally applied loads and adds them to the stiffness matrix at the relevant degree of freedom (DOF). This includes the effects of buoyancy, mooring lines and restoring moments due to the metacentric height (Myhr & Nygård, 2012). For these periods, gravity and buoyancy need to be turned from ON to OFF in the set_environment part of the input. With this done, the buoyancy force, water plane stiffness and restoring moments have to be calculated as follows;

```
!Restoring moment due to buoyancy

add_node_stiffness  find  0.  0. 0.
f_lin  0. 0. 1.26e8    0.  0.  0.
x_lin  0. 0. 0. 0. 0. 0.
1    1      0 !Stiffness from mooring
2    2      0 !Stiffness from mooring
3    3      2890422.558
4    4      4.182e8
5    5      4.182e8
6    6      0 !Stiffness from mooring
```

Figure 27 Stiffness input for 3DFloat

The first line in Figure 27 is the XYZ coordinates for the waterline, which in 3DFloat always has to be at 0 0 0. After that follows "force linear", f_lin, for the buoyancy. That is the force in newton [N] for the hull. X_lin can be ignored. 1-1, 2-2 and 6-6 are places for stiffness from mooring to surge, sway and yaw, which can be ignored in these calculations.

For the buoyancystiffness, 3-3 is stiffness of the waterplane area in N/m, while 4-4 and 5-5 are the restoring moment due to buoyancy in Nm/rad. Stiffness of the water plane area is calculated using the following equation:

$$I_{waterplane} = g * \rho_{water} * A_W$$

Where:

- $I_{waterplane}$ is the second moment of area of the hull's waterplane.
- A_W is the area of the water plane, meaning the cross-sectional area of the structural elements breaching the water surface at the point of calculation.

Restoring moment due to buoyancy is calculated using the following formula (Norwegian Offshore Consultants, 1975):

$$RM_{buoyancy} = Displacement[t] * g * \sin(\propto) * (GM + 0.5 * tan(\propto)^2)$$

For these calculations the angles are assumed sufficiently small so that

$$\sin(\propto) = \propto$$

Implementing this assumption in the equation gives us the result equation for restoring moment in Nm/rad;

$$RM_{buoyancy} = Displacement[tonnes] * g * GM$$

2.5.7 Added mass

When modeling rectangular elements as cylinders, like in this thesis, it is important to adjust the added mass to reflect the true structural element. An adjustment of added mass can be made to each element in two different ways;

1. Cma – axial added mass to any element with a lid. This calculates a half sphere with the diameter of the lid times(Cma-1)
2. Cmn – transverse added mass. Added mass becomes the elements displaced volume times (Cmn-1)

This is added to each element at the end of the command string:

$$cmn \# \ or \ cma \#$$

This means, inputting #=2 in the command for cma gives one half sphere at the end of the cylinder as added mass. 3DFloat calculates this value and adds it to the mass matrix before doing the calculation of the models natural periods.

3DFloat outputs the added mass in kg, in the same table as the results from the natural periods are presented. So far, the program only outputs one value for 3DFloat and it is not known from IFE which mode this result belongs to, even if heave is the natural assumption. Changing the factors for the added mass can therefore result in some unpredictable behavior of the structural model. Therefore, the values are kept the same as they were in the provided modelingfile from IFE in this thesis.

2.5.8 Postprocessing in 3DFloat

For this thesis, two types of results from 3DFloat are on the main focus; natural periods and forces exerted on the different beam elements. This chapter will try to explain how to interpret the vast amount of data output into the results we are looking for.

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2.5.8.1 Check of model

With the version of 3DFloat used in this thesis, there is no direct way of checking the model. The log file reports the total structural mass, which is good to check with the user's hand calculations of the structural weight. So far, 3DFloat does not report displaced mass, VCOB or other parameters that can be used to check the model. Also, with no graphic window, it becomes difficult to check if the modeling has been done correctly. Therefore, this must be done when looking at the results for natural periods. As explained later, a method for plotting the model is made in a third-party program to see if all elements are connected correctly and that the structure is modeled as intended when writing the input-file.

2.5.8.2 Natural periods

3DFloats calculates the natural periods for an oscillating structure, so it is important to have enough time steps to make sure that the structure has fallen to rest at its natural period. This will result in a high number of results that need to be interpreted to find the correct ones.

Natural periods directly from 3DFloat are hard to interpret. Firstly, the natural periods should be calculated in advance, to provide a clear view of which results should be expected. Secondly, 3DFloat doesn't only calculate the rigid body motions, so it is difficult to be certain from the outputfile which results are for the rigid body motions. To have the program calculate the natural period, the following command string needs to be added to the program input:

$$eigen\_analysis\ old\ nfreq\ 20\ amplitude\ 10\ filename\ frekvenser.txt$$

This string yields 20 modes with eigen frequencies and periods plotted in Figure 28.

```
%Displacement vector, eigen frequencies [Hz] and period [s]
        1        334     1.45999667E-05     6.84933070E+04     9.17342962E-05     0.00000000E+00
        2        332     1.44776480E-04     6.90719931E+03     9.09657450E-04     0.00000000E+00
        3        331     7.93390264E-02     1.26041375E+01     4.98501805E-01     0.00000000E+00
        4        330     1.34901109E+00     7.41283750E-01     8.47608666E+00     0.00000000E+00
        5        329     1.34944860E+00     7.41043413E-01     8.47883564E+00     0.00000000E+00
        6        328     1.41013332E+00     7.09152806E-01     8.86012895E+00     0.00000000E+00
        7        327     1.41381005E+00     7.07308597E-01     8.88323051E+00     0.00000000E+00
        8        326     1.76603131E+00     5.66241377E-01     1.10963020E+01     0.00000000E+00
        9        325     2.33200266E+00     4.28815977E-01     1.46524049E+01     0.00000000E+00
       10        323     2.67538865E+00     3.73777470E-01     1.68099627E+01     0.00000000E+00
       11        324     2.70709196E+00     3.69400085E-01     1.70091604E+01     0.00000000E+00
       12        321     3.78584354E+00     2.64141925E-01     2.37871565E+01     0.00000000E+00
       13        322     3.78637891E+00     2.64104577E-01     2.37905203E+01     0.00000000E+00
       14        320     5.66106614E+00     1.76645172E-01     3.55695276E+01     0.00000000E+00
       15        319     6.86881446E+00     1.45585531E-01     4.31580341E+01     0.00000000E+00
       16        318     6.87667860E+00     1.45419040E-01     4.32074459E+01     0.00000000E+00
       17        317     8.24081088E+00     1.21347282E-01     5.17785418E+01     0.00000000E+00
       18        314     1.02453295E+01     9.76054505E-02     6.43733037E+01     0.00000000E+00
       19        316     1.05957383E+01     9.43775668E-02     6.65749873E+01     0.00000000E+00
       20        315     1.06115070E+01     9.42373217E-02     6.66740649E+01     0.00000000E+00
```

Figure 28 Output from natural period analysis

The results are read:

- Column 1: Mode number.
- Column 2: Program internal degree of freedom.
- Column 4: Eigen frequencies [Hz].
- Column 5: Natural period [s].
- Column 6 and 7: Program debug, ignored by the user.

From 3DFloat there is no direct way of knowing which of the 20 modes are connected to the 6 degrees of freedom the floating body has, as the results are sorted each time from lowest to highest frequencies, not by DOF. To solve this problem Karl Jacob Maus with IFE made a script in Python, plotting an image for all the 20 modes making it easier to determine which is which. I got his original script file and adjusted it so that it works on my computer as well.

The script plots all 20 modes in XY-, XZ- and YZ-plots. These can then be used as an attempt to interpret which period belongs to which degree of freedom.

From the simulation run above in 3DFloat, the following three plots from mode 15 can be produced.
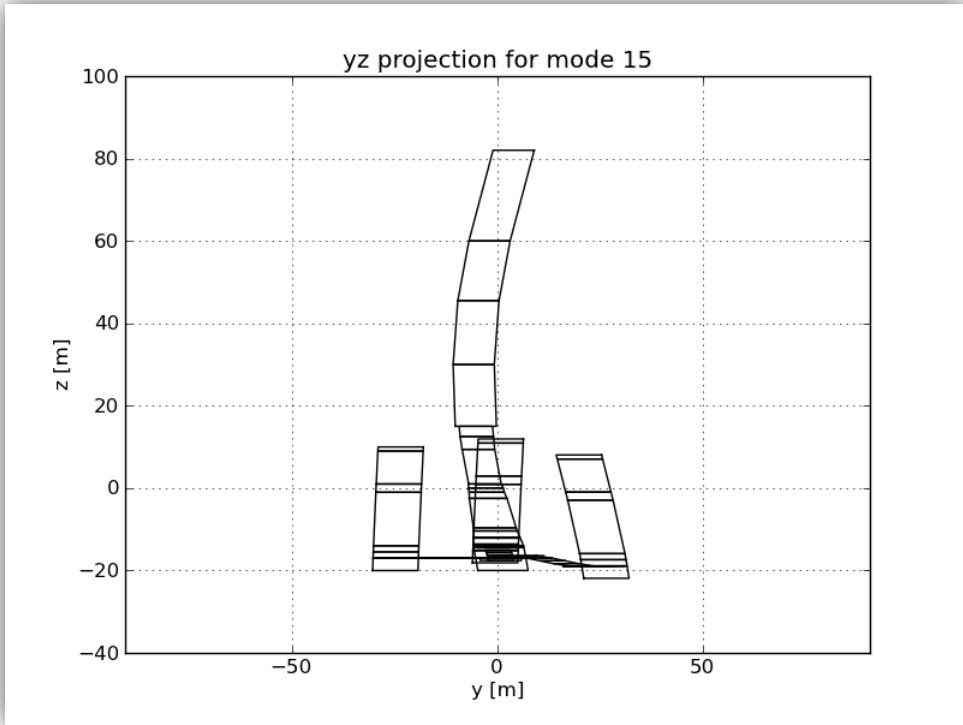
Figure 29 YZ-projection of mode 15
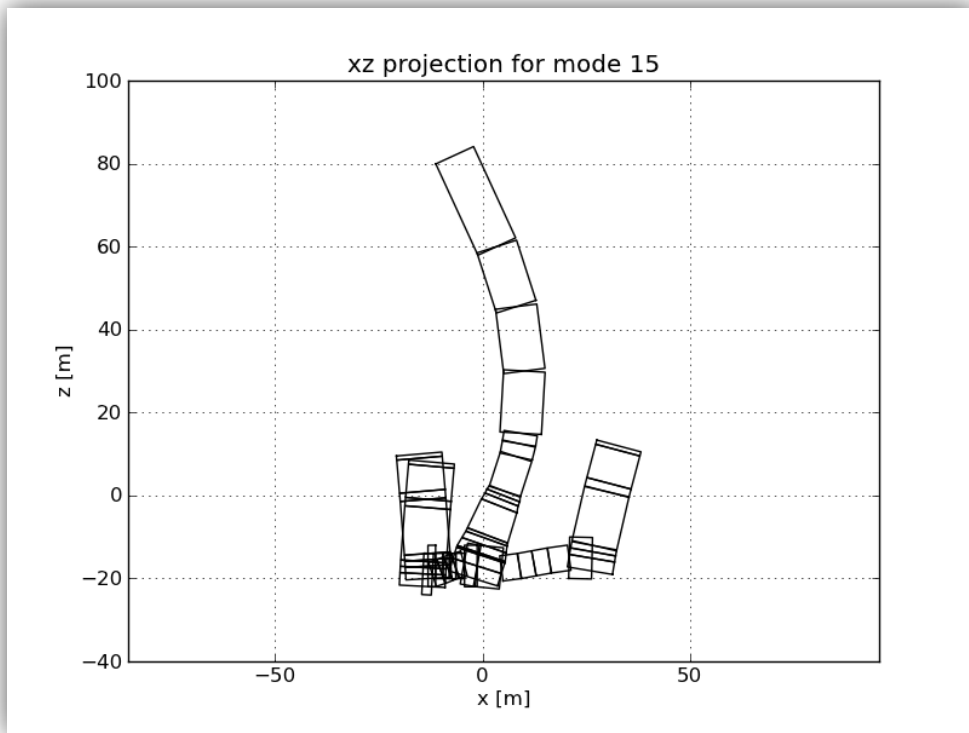
Figure 30 XZ projection of mode 15
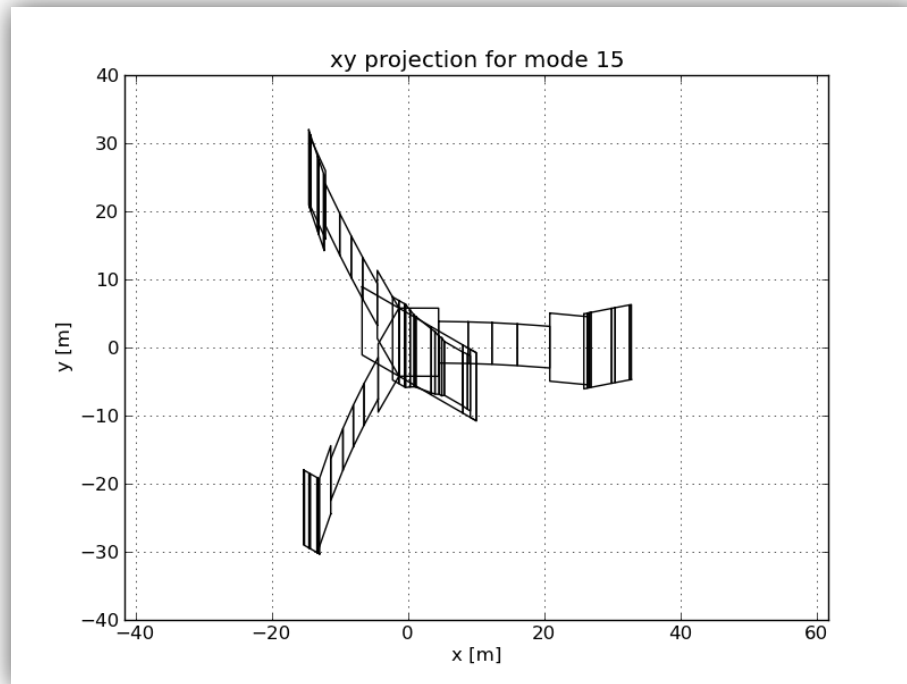
Figure 31 XY projection of mode 15

As can be seen from Figure 29, Figure 30, and Figure 31, it is not easy to state exactly from the plots which DOF these belong to.

When unsure of which mode belongs to which DOF, it becomes troublesome to spot the desired results. Therefore, a better way to check the modes is needed. Another supporting script for interpreting the results in a program called ImageMagick has therefore been made. This is freeware and can be easily downloaded and installed. The script is not meant for external use and therefore still has its bugs. Nevertheless, it is usable to give a better understanding of the output from 3DFloat.

To make this work, after ImageMagick is installed on the computer;

- Create a new folder containing plotmodes_anim.py, turb1.plot, logfile.txt, frekvenser.txt and frekvenser.txt_modes (commands for these files are in the stripped down basic version of an inputfile for 3DFloat provided in appendix 7.
- Rename frekvenser.txt_modes to frekvenser_modes
- Type in command: c:\Folder\plotmodes_anim.py makeAnims=True myfile='frekvenser.txt.txt'
- If desired; Add NPLOT=# to only animate # number of modes.
- Execute the command
- When the error message at the bottom appears write:logfile.txt

Based on the calculated results the ImageMagic script then plots all 20 modes from all three directions side by side as animations. Unfortunately it isn't possible to show the result in this thesis, but it provides an opportunity to make more qualified assumptions on which mode is representing the desired degree of freedom.

From the 60 .gif-movies produced, 20 per XY-, XZ- and YZ-projection, it is possible to determine the calculated values for the natural periods from the results in 3DFloat. So, for the model above it becomes evident that mode shape 2 is for heave while mode 3 and 4 seem to be representing pitch and roll. This only applies to one specific analysis of that model and cannot be assumed for another analysis when changes have been made to the mode.

Although this process is the best way of interpreting the results so far, it is time-consuming because the mode shapes have to be plotted each time. 3DFloat sorts the answers by values, not DOF, so each time a change is made to the model and a new analysis is run, the 20 different mode shapes may have shifted to a different DOF. It is therefore very important to do exact modeling beforehand, so the need to animate all the mode shapes can be reduced to a minimum.

2.5.8.3 Element forces

As for a regular stick-model program, 3DFloat calculates forces and moments on each element. The forces/moments are externally calculated values from the environment. Values are calculated in the center of an element and give as Newton (N) or Newtonmeter (Nm). These forces then have to be hand-calculated onto their respective cross-section to control the capacities. This will give a good estimation of how high stresses the hull may be subject to and if the cross-section can carry the applied load.

There are two monitors that can be applied in the program to get results, one for forces and one for moments.

Commandlines for the monitors are:

$$monitor\_element\_b1\ type\ moments\ file\ moment.txt\ nmonitor\ 10\ find\ 0\ 0\ 0\ node\ 1$$

or

$$monitor\_element\_b1\ type\ forces\ file\ krefter.txt\ nmonitor\ 10\ find\ 0\ 0\ 0\ node\ 1$$

The first string of text depicts what type of element to be monitored followed by what type of monitor is desired; forces or moments. Then the name for the result file is added. Nmonitor denotes for which time steps the program shall write results for, 10 means at every 10th time step starting at the 1st. Find X Y Z node 1 show where the coordinates for the to be monitored are input.

This does not need to be accurate, as the program locates the closest node 1. The monitored element can be checked at the top of the result file where it states which element it is monitoring. This can then be crossreferenced with the result files that numbers all modeled elements to see if they are correct. To ensure the correct element is being monitored, the best solution is to give the coordinates of the elements midpoint, not its end point. The program will then go to the closest node 1 which is on the same element. Inputting the coordinates for the node 1 that is to be monitored may result in the node for the adjacent element being monitored instead.

The output is written in the specified external textfile. Figure 32 shows the force monitor output for one time step.

```
ISTEP TIME  F2 ( 3 comp) in element and body system
    10   2.500000E-01   1.590203E+06  -3.635173E+04   9.836164E+06  -7.655614E+05   1.398717E+06   9.835532E+06
```

Figure 32 Outputformat of force monitor

The output is read as follows, with units in N;

- Column 1: Monitored time step
- Column 2: Time, in seconds, since calculation begun.
- Column 3: Fx in element local orientation
- Column 4: Fy in element local orientation
- Column 5: Fz in element local orientation
- Column 6: Fx in global orientation
- Column 7: Fy in global orientation
- Column 8: Fz in global orientation

Figure 33 shows the corresponding output for the moment monitor.

```
ISTEP TIME  M2 ( 3 comp) in element and body system
    10   2.500000E-01  -4.206210E-01  -4.854428E+04  -8.239723E+04   8.239723E+04  -4.854428E+04  -4.194187E-01
```

Figure 33 Outputformat of moment monitor

The unit for the results is here Nm, but the column set up is the same as for the force monitor.

For the directions, it is important to check that the calculated forces and moments are transformed correctly to the cross-section for a check of the capacities. For the local element, Fx will be the axial force, with positive values indicating compression in the element. The same applies for the transversal forces. Directions for Fx, Fy and Fz follow the "right hand rule" as depicted in Figure 34.
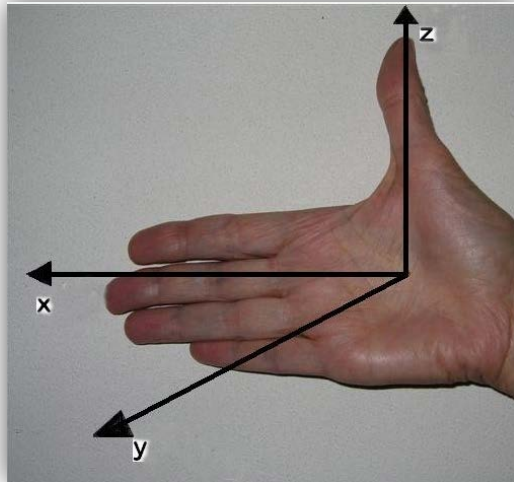
Figure 34 Right hand rule of force directions

3 Calculating and modeling the main concept

3.1 Input values for modeling

The main concept is given with a full description of its main parameters and weights. This is the basis for calculating all the properties that are needed for analysis in Wadam and 3DFloat.

Overview of dimensions	
Corner cylinder outer diameter	11 m
Wall thickness corner cylinder	0,35 m
C/C shaft/corner cylinder	28 m
Pontoon height	6 m
Pontoon width	11 m
Steel weights	
Turbine tower	350 tonnes
Nacelle+Rotor	310 tonnes
Hull mechanical weights	200 tonnes
Additional weight	570 tonnes
Mooring tension, vertical	240 tonnes

Table 4 Overview of input dimensions
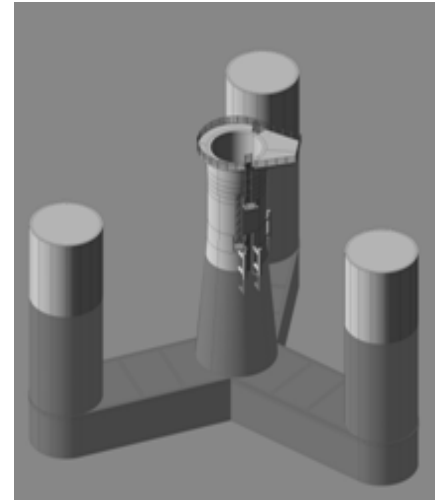
Figure 35 Illustration of the main concept

Material properties	
Concrete density, height 0-6 meters	2,272 t/m^3
Concrete density, height 6-35 meters	2,281 t/m^3
Saltwater density	1,025 t/m^3
Concrete strength	50 N/mm^2

Table 5 Material properties

3.1.1 Design of shaft

The given shaft design has many components and is modeled as shown in Figure 36.

The shaft is a composite of cones and cylinders. Dimensions are for cylinder/cone outer radius, Ro, and wall thickness, t. On the right is the height above the base of the hull of each element given.

Written by Knut-Ola Lunde
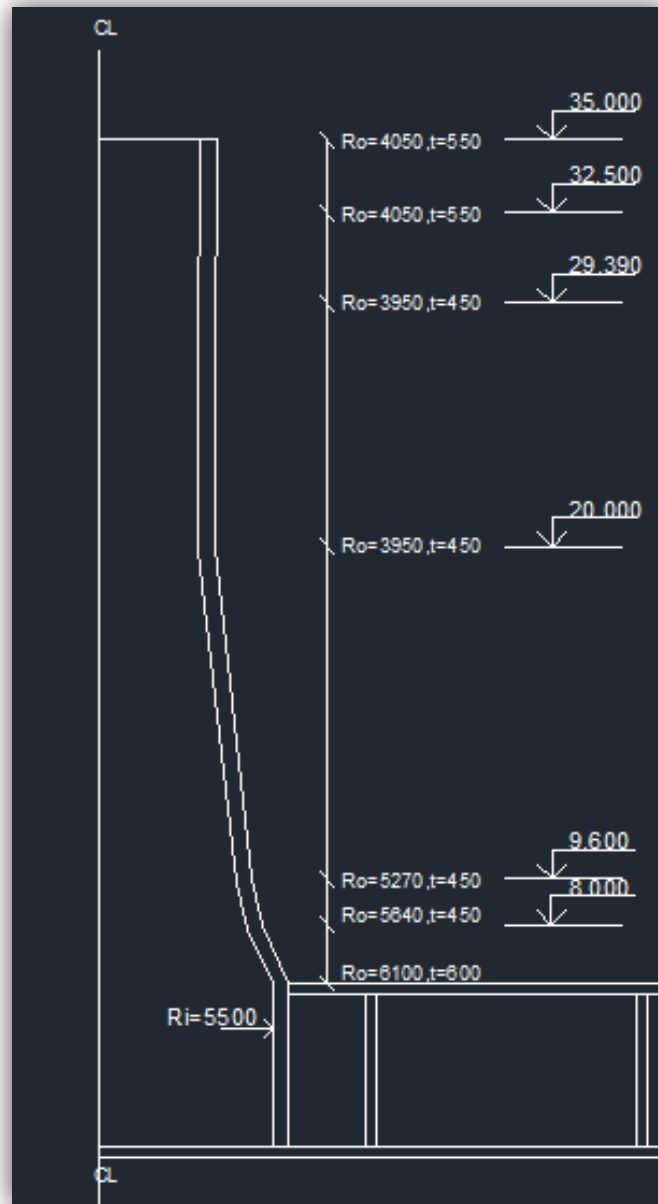
Figure 36 Shaft design

3.1.2 Comments on the design

The center column, hereby called shaft, does not contain any water. The pontoons are completely filled with water in operational conditions, which is the condition calculated in this thesis. In order to get the desired draft; the corner cylinders must be able to pump water in and out. The amount of water is the ballast needed to make the hull float at the aimed draft.

3.1.3 Calculation of natural periods

Following the formulae from (Faltinsen, 1990) shown in chapter 2.2, the natural periods are calculated using MathCad. The calculations are shown in full in appendix 1, while the results are shown in Figure 37.

Results:

$$T_{heave} := 2 \cdot \pi \cdot \sqrt{\frac{M_{structure} + Addedmass}{\rho \cdot g \cdot A_{waterplane}}} = 15.685 \text{ s}$$

$$T_{pitch.roll} := 2 \cdot \pi \cdot \sqrt{\frac{M_{structure} \cdot R_x^2 + A_{moment}}{\rho \cdot g \cdot V_{structure} \cdot GM}} = 22.777 \text{ s}$$

Figure 37 Natural periods calculated with MathCad

3.1.4 Free water surface

This hull has limited free water surface, but the calculations are made to distinguish how much they impact on the hull.

From chapter 2.1.1, the formula for the virtual increase in VCOG for a floating body that has the same fluid density both inside and outside its tanks is:

$$gg'' = \sum_n \frac{i}{\Delta}$$

For the current hull, the calculations in MathCad yield the following results:

Input:

Inner diameter of corner cells: $R_{cell} := 5.2 \cdot m$

Number of tanks: $n := 3$

Displaced volume of the structure: $V_{displaced} := 11158 \cdot m^3$

Calulations:

Second moment of inertia for the water plane inside the tanks: $I_{tank} := \frac{\pi}{4} \cdot R_{cell}^4$

Solution:

$$gg := n \cdot \left(\frac{I_{tank}}{V_{displaced}} \right) = 0.154\,m$$

Figure 38 Calculation of free water surface effect

This means that the tanks VCOG will rise by 15.4 cm when the hull is tilting. The ballast tanks contains a small amount of mass compared to the whole hull, so adding 15.4 cm to the VCOG of the tanks to account for the free water surface effect, only adds around 2 cm to the total VCOG of the hull, making the effect of the free water surface negligible for the subsequent calculations.

The given input is placed into an Excel sheet that is built to calculate all the necessary input values. The output per element is verified to a model in Autocad 3D to be certain that the formulae for mass, center of mass, volumes etc are correct.

The following table summarizes some key results of the basic hull from hand calculations. For the heights, the point of reference is at the hulls MSL.

Table of result	
Volume concrete [m^3]	2521
VCOG [m]	-7.918
VCOB [m]	-12.54
Metacentric height [m]	5,6
Displaced volume [m^3]	11 158
Displaced mass [t]	11 437
Internal water in pontoons [t]	2816
Ballast water corner cylinders [t]	1181
Natural period, heave [sec]	15.488
Natural period, pitch/roll [sec]	22.777

Table 6 Table of results from main concept

3.3 Calculation with Wadam

3.3.1 Input for Wadam – analysis

Inputparameter	Value
VCOG [m]	-7.918
VCOB [m]	-12.54
Structural Mass [kg]	11 494 000
Radii of gyration, X and Y [m]	23.81
Radii of gyration Z [m]	19.1

Table 7 Input for Wadam-analysis of the basic concept

The structural mass is the displaced mass multiplied by the density of water to make sure the analysis runs smoothly and must not be given as the real structural mass in this analysis.

3.3.2 Results

When the analysis is complete, the .LIS-file should be checked for the hydrostatic output. In this case, the three volumes are found to give good agreement.

```
DISPLACED VOLUMES OF THE PANEL MODEL      VOL 1     = 1.11185E+04   [L**3]
                                          VOL 2     = 1.11186E+04
                                          VOL 3     = 1.10869E+04
```

Figure 39 Results from volume calculations of .FEM-file in Wadam

The second item to verify is the water plane area, in this case calculated to 333.2 m^2, which corresponds well with the hand calculations of 337 m^2. The difference is explained by the roughness of the meshing, but is well within the acceptable limits of accuracy.
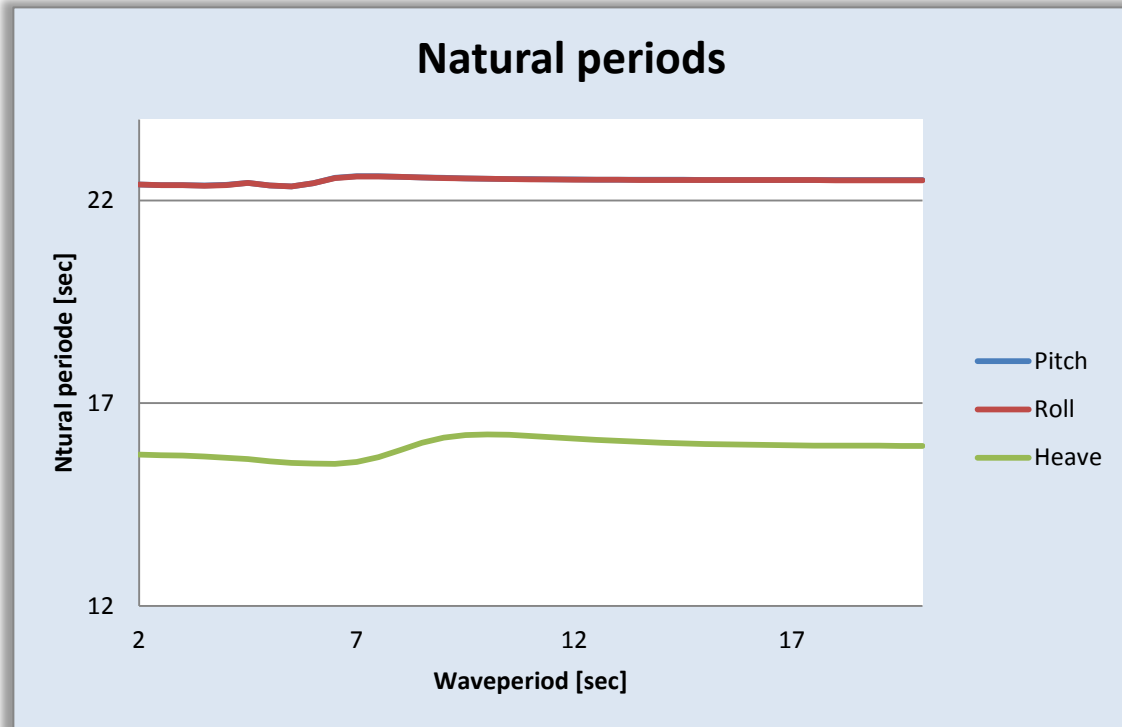
Figure 40 Natural periods over all wave frequencies

As showed by the graph in Figure 40, the natural periods for roll and pitch mirror each other perfectly, showing that the small imperfections from the meshing of the model did not influence the results significantly. It lies steady around 22.5 seconds. Heave fluctuates more, with the extreme values varying from 15.507 to 16.231 depending on the wave period.

Average values are 22.49 seconds for pitch/roll and 15.9 seconds for heave.

3.3.3 Added mass

3.3.3.1 Explanation and definitions

An estimation of added mass is difficult to establish correctly, but it is a good idea to compare the results from Wadam with the values used for hand calculations, so that later calculations can be tuned with the errors in order to reach the correct results.

From the resultfile, Wadam gives an added mass matrix looking like this:

```
ADDED MASS MATRIX
-----------------
                  1          2          3          4          5          6

1        5.5589E-01 -1.3109E-04 -1.5045E-04 -1.7584E-05 -5.9433E-02  2.1893E-05
2       -1.5635E-04  5.5613E-01 -8.3960E-05  5.9458E-02  1.9452E-05 -3.0343E-05
3       -2.7587E-04 -1.2370E-04  8.8069E-01 -3.0571E-04  5.0528E-04 -2.4525E-05
4       -1.1928E-05  5.9865E-02 -2.2698E-04  1.8312E-02 -2.8403E-05 -5.2054E-06
5       -5.9829E-02  3.0397E-05  3.7194E-04 -2.5593E-05  1.8345E-02 -4.2081E-06
6        2.2520E-05 -3.5027E-05 -2.3612E-06 -4.3507E-06 -4.9195E-06  3.3817E-02
```

Figure 41 Example of an added mass matrix from Wadam

Item 3-3 gives the added mass coefficient for heave, 0.88069, while 4-4 and 5-5 give pitch and roll at 0.018312 and 0.018345. These values are dimensionless, and therefore need to be multiplied to provide the mass in tonnes.

At the beginning of the result file, it is stated that the values in the added mass matrix are made dimensionless by rho*volume, rho*volume*L and rho*volume*L*L. Rho is here the density of water, while L is calculated by Wadam and given at the end of the result file.

The explanation of the matrix is as shown in Figure 42.

```
NON-DIMENSIONAL DEFINITIONS:
----------------------------            I=1-3           I=1-3  I=4-6       I=4-6
                                        J=1-3           J=4-6  J=1-3       J=4-6

MASS INERTIA MATRIX NON-DIMENSIONALIZED BY:   RO*VOL,        RO*VOL*L           RO*VOL*L*L
ADDED MASS MATRIX   NON-DIMENSIONALIZED BY:   RO*VOL,        RO*VOL*L           RO*VOL*L*L
DAMPING MATRIX      NON-DIMENSIONALIZED BY:   RO*VOL*SQRT(G/L)  RO*VOL*SQRT(G*L)  RO*VOL*L*SQRT(G*L)
RESTORING MATRICES  NON-DIMENSIONALIZED BY:   RO*VOL*G/L,     RO*VOL*G           RO*VOL*G*L
```

Figure 42 Non-dimensional definitions

In this definition of the matrices I is for the rows, while J is for the columns. To make the interpretation clear, a supplementary matrix in Excel is used to do the calculations, shown in Figure 43.

	I1	I2	I3	I4	I5	I6
J1	A1-1	A2-1	A3-1	A4-1	A5-1	A6-1
J2	A1-2	A2-2	A3-2	A4-2	A5-2	A6-2
J3	A1-3	A2-3	A3-3	A4-3	A5-3	A6-3
J4	A1-4	A2-4	A3-4	A4-4	A5-4	A6-4
J5	A1-5	A2-5	A3-5	A4-5	A5-5	A6-5
J6	A1-6	A2-6	A3-6	A4-6	A5-6	A6-6

is multiplied by rho*volume*L

is multiplied by rho*volume*L^2

is multiplied by rho*volume

Figure 43 Explenation to added mass matrix

The definitions of movement here are as follows; surge,sway,heave,roll,pitch,yaw. This means, A3-3 is added mass in heave (3-3 means heave-heave), A4-4 is roll and A5-5 is pitch.

3.3.3.2 Comparing Wadam-results with estimations in hand calculations

The results from Wadam are as stable for the added mass as for the natural periods. Using the average values, added mass in heave is 9950 tonnes.

The estimation made in the hand calculations uses a half sphere under the shaft and the corner cylinders. For the pontoons, the added mass is estimated by one half cylinder above the pontoon and the other half below, resulting in one full cylinder over the length with the same diameter as the pontoon width.

Using the center/center length and subtracting the radius from both the shaft and the corner cylinder gives the pontoons a length of 16.4 meters and a total added mass of 9214 tonnes (which the calculations above are based on). This estimate is approx. 700 tonnes lower than the results from Wadam, which makes a difference of 7.4%. This difference is a little high, but can be accepted if the end results from the hand calculations are not too different to the Wadam results.

With the estimation of added mass being lower than the answer from Wadam it is natural that the results from the hand calculation of natural periods are lower than the ones calculated by Wadam.

3.3.4 Response variables
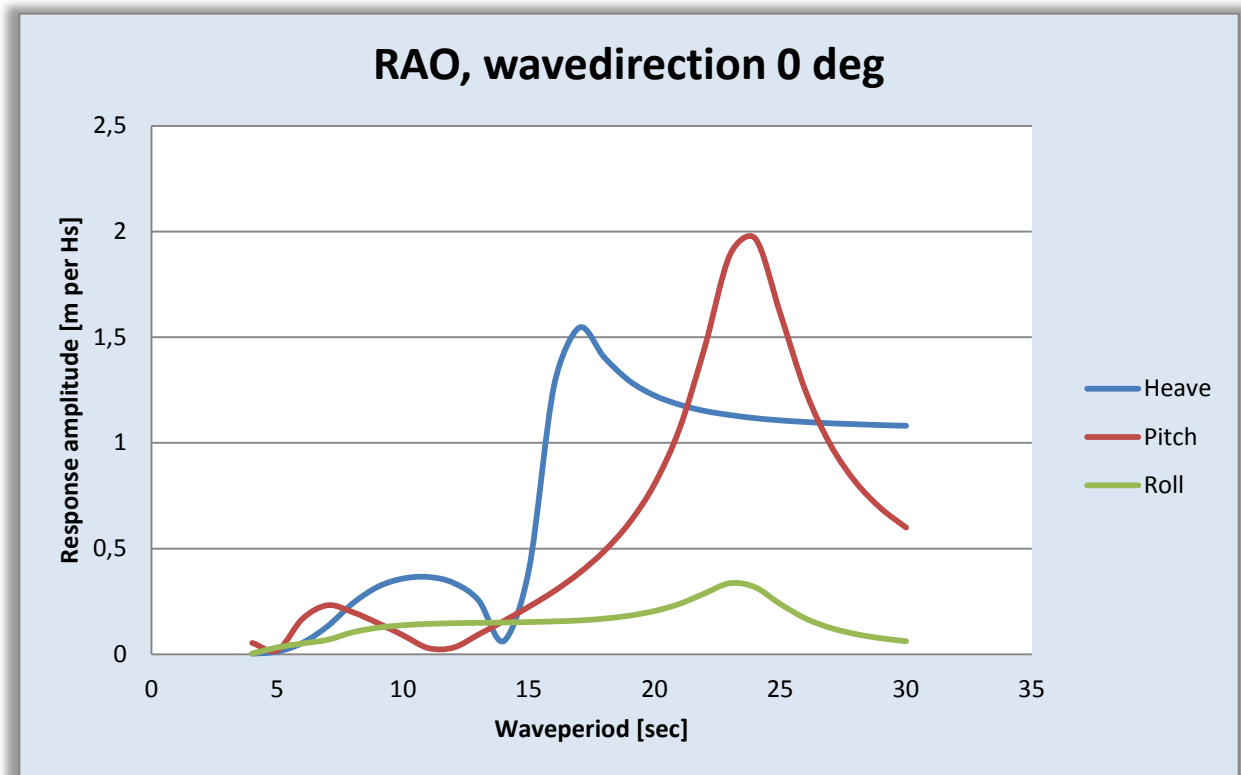
Figure 44 Response variables for the basic concept

Figure 44 shows the RAOs for the basic concept for waves hitting the hull directly from the front. The roll response is very low, as it should be, while the peaks for heave and pitch show at which period resonance is obtained, meaning the hull's natural frequencies. In this case, a little over 15 seconds in heave and around 22 seconds in pitch. The graph also shows that the hull is symmetrical, as the pitch and roll graph peaks out for the same period, but with less response in the roll motion as the wave direction is such that pitch is the most influenced motion.

3.4 Calculating with 3DFloat

3.4.1 Adaptations from the real structural model to 3DFloat

The model in 3DFloat are adjusted and modified so that the properties of the rectangular pontoons, which need to be modeled as cylinders are taken into account. The adjustments can be viewed in the input-file for 3DFloat in appendix 2, but the main differences are the pontoons which are modeled as cylinders with Dy=6.11 m and a thickness of 0.631 meters. This yields the same outer volume and same mass as the rectangular pontoons.

3DFloat operates, as stated earlier, with cylindrical elements only. The shaft is modeled according to the way it is designed - with conical shapes. The main difference is that it is divided into more elements then the original shaft because elemental nodes are needed at every point where point masses (mechanical weights, lids etc) or monitors are added to the hull.

The corner cylinders are also modeled as they should be with the applied ballast water in the bottom of the cylinders. These are also divided into a greater number of elements, but the dimensions and properties are kept the same as in the original model.

3.4.2 Other calculated input

The stiffness values from buoyancy need to be calculated and input by hand. For this model the calculated values are shown in Table 8 and programmed as shown in Figure 27

Buoyancy input for 3DFloat	
F_lin	$1.12158165*10^8$ N
3-3	$3.388942*10^6$ N/m
4-4	$6.28085728*10^8$ Nm
5-5	$6.28085728*10^8$ Nm

Table 8 Buoyancy input for 3DFloat

Written by Knut-Ola Lunde

3.4.3 Checking the model

Applying the Pythonscript plotting the full hull, which monitors every node, XZ-, XY- or YZ-plots of the hull are produced to check if all elements are present and attached to the hull in the way they were intended. One of those plots is shown below.
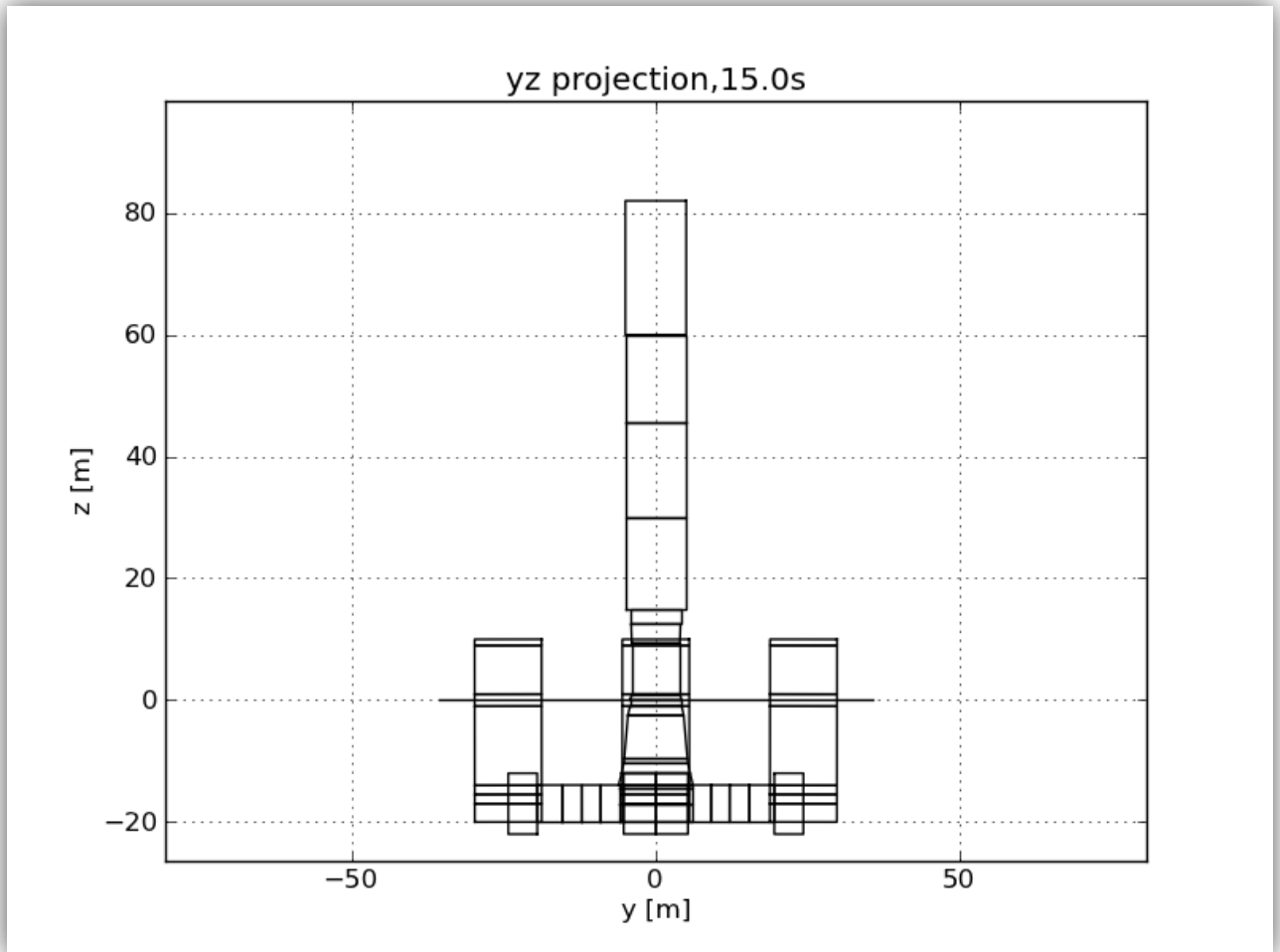
Figure 45 YZ-projection from 3DFloat

From Z=15 upwards, thick elements are visible. These are stiff elements with zero mass, carrying the point mass of the steel tower and nacelle. The same type of elements can also be seen inside the corner cells as infinite stiff elements with zero mass and buoyancy that connect the corner cylinders with the pontoons.

With both plots confirming that the hull is modeled as intended and floating with the correct draft, it is safe to move on to check the results from the analysis.

3.4.4 Results

3DFloat outputs the following results for the natural undamped periods:

```
Added mass     :     9.792559E+06

Eigen analysis, undamped modes

Symmetric eigensolver: working on structural mass and stiffness matrices.
%Displacement vector, eigen frequencies [Hz] and period [s]
       1        338      4.65390974E-02     2.14873097E+01     2.92413773E-01     0.00000000E+00
       2        340      4.65391499E-02     2.14872855E+01     2.92414103E-01     0.00000000E+00
       3        339      7.13655328E-02     1.40123665E+01     4.48402867E-01     0.00000000E+00
       4        336      1.33852501E+00     7.47091006E-01     8.41020070E+00     0.00000000E+00
       5        335      1.33876200E+00     7.46958759E-01     8.41168971E+00     0.00000000E+00
       6        334      1.47238979E+00     6.79167979E-01     9.25129791E+00     0.00000000E+00
       7        333      1.47676656E+00     6.77155097E-01     9.27879793E+00     0.00000000E+00
       8        332      1.82108170E+00     5.49124184E-01     1.14421938E+01     0.00000000E+00
       9        331      2.39803859E+00     4.17007467E-01     1.50673208E+01     0.00000000E+00
      10        330      2.66124418E+00     3.75764091E-01     1.67210903E+01     0.00000000E+00
      11        329      2.69058823E+00     3.71665938E-01     1.69054645E+01     0.00000000E+00
      12        327      3.80078471E+00     2.63103563E-01     2.38810346E+01     0.00000000E+00
      13        328      3.80220566E+00     2.63005237E-01     2.38899628E+01     0.00000000E+00
      14        326      5.57281474E+00     1.79442534E-01     3.50150277E+01     0.00000000E+00
      15        325      6.86007475E+00     1.45771006E-01     4.31031209E+01     0.00000000E+00
      16        324      6.86650343E+00     1.45634530E-01     4.31435134E+01     0.00000000E+00
      17        323      7.52110377E+00     1.32959208E-01     4.72564887E+01     0.00000000E+00
      18        322      9.81351320E+00     1.01900306E-01     6.16601220E+01     0.00000000E+00
      19        321      9.83161520E+00     1.01712687E-01     6.17738602E+01     0.00000000E+00
      20        320      1.01513558E+01     9.85090094E-02     6.37828493E+01     0.00000000E+00
```

Figure 46 Natural period results from 3DFloat

Using the animation script in Python, it can be seen which modes are the most interesting for the current analysis, namely the rigid body motions for heave, pitch and roll. For this analysis the desired modes where also the highest frequencies, so it corresponded with mode 1, 2 and 3.

Rigid body motions from 3DFloat	
Natural period heave [sec]	14.0
Natural period pitch [sec]	21.5
Natural period roll [sec]	21.5

Table 9Rigid body motions calculated by 3DFloat

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3.5 Results from the basic model

3.5.1 Results

	Hand calculation	Wadam	3DFloat
Natural period heave [sec]	15.685	15.9	14.01
Natural period pitch [sec]	22.397	22.49	22.98
Natural period roll [sec]	22.397	22.49	22.98

Table 10 Comparison of natural periods from all three calculation methods

3.5.2 Experiences

The calculations in Excel can be very time-consuming if many properties of the hull shall be input variables. It can therefore be better to have a few set values and a limited number of variables and rather make more than one calculation.

The Wadam analysis took longer time to execute than expected; about 3.5 hours. To reduce the consumed time, it is smart to make a few adjustments. First of all, only create the models of the hull below MSL, excluding everything that is above. The other main change is to model using symmetry. Only model half the hull and then when importing the .fem-file into Wadam, let the program mirror the model so it turns into a full hull. The third change is to reduce the wave directions from 360 degrees around the hull to 180 as it is symmetrical.

3DFloat also consumed a lot more time than expected, mostly due to time spent trying to find errors in the input file because the hull did not behave as expected in the plots. It is also time-consuming to work with the modeling and inputs when it is not clear what needs to be input before the analysis can begin, since there is no previous work with 3DFloat to look at. During the process these problems were mostly solved with Tor Anders Nygaard and Karl Jacob Maus at IFE. For the 3DFloat-analysis of the final concept, the time spent in 3DFloat is hopefully reduced, since these problems have been overcome. The external programs for plotting were also installed and ready to be used, so that should also considerably reduce the time needed to get a full model working.

3.5.3 Conclusions from the basic model

As can be seen from the results, the natural periods of this hull are too low compared to the criteria of this thesis, which is at least 20 seconds natural period in heave and at least 25 seconds in pitch/roll. As the mass, both structural and added, is a key factor for the natural periods this point toward a geometrical hull design that gives more of both.

When searching for another hull design, focus should therefore be laid on a design that increases the added mass and structural mass.

It is also worth noting that the natural periods for the hull as calculated by 3DFloat are too low compared to the results from the hand calculations and Wadam-analysis. Despite rigorous search, the source for this error is not quite clear. The qualified guess is that is has to do with the method of added mass calculation. The problem is that 3DFloat so far only outputs one number for the added mass as seen at the top of Figure 46. Which mode this refers to has not been discovered so far, making adaptations to the model using added mass coefficients very difficult. But, as the program is under development, the results are accepted as they stand for the basic concept.

4   Changing the geometry

4.1   Outer geometry

The first part of the testing aimed at reaching the optimal design on the hull with respect to the design criteria is to test the outer geometry when it comes to natural periods and subsequently to look at a few different alternatives with regards to buoyancy.

In order to make the design process more efficient than modeling and analyzing many different alternatives in Wadam, most of the work will be done in Excel. The conclusions from the calculations done on the basic model in the previous chapter, points towards the design changes that are needed to obtain the desired results.

4.1.1   Parameterization

To make a sheet in Excel with parameterization to test the different geometry that is needed, some parameters needs to be set. Since earlier results show that more mass and added mass are needed to bring the natural period in heave up, the shaft design will be kept as it is for the basic concept. Testing of different geometry will therefore focus on the pontoons and corner cylinders.

As a start, changes will be made one by one to see the effect on the natural periods, before a few changes can be simultaneously introduced in the final design.

The parameters that are going to be tested to compare the effects on the hull are:

1. Change of the angle in the pontoon wall from the corner cylinder to the center
2. Change the C/C distance between the shaft and the corner cylinder
3. Change the width of the pontoon
4. Cantilever on the bottom slab around the whole hull
5. Increasing the outer diameter of the corner cylinders

For the results, the change in natural period per unit change in the parameter is the most interesting. But cost is always an important factor in projects like this. The total cost of the hull is difficult to estimate in this thesis, but the increase in the necessary material – concrete - can be calculated. Therefore, the increase in concrete mass will be taken into account as that directly affects the total cost.

4.1.2 Results of changing the outer geometry

4.1.2.1 Change of the angle in the pontoon wall

The first geometrical change to be checked is an increase in the angle of the pontoon walls. The change is shown in the figure below, which describes where the outer lines of the geometry lie.
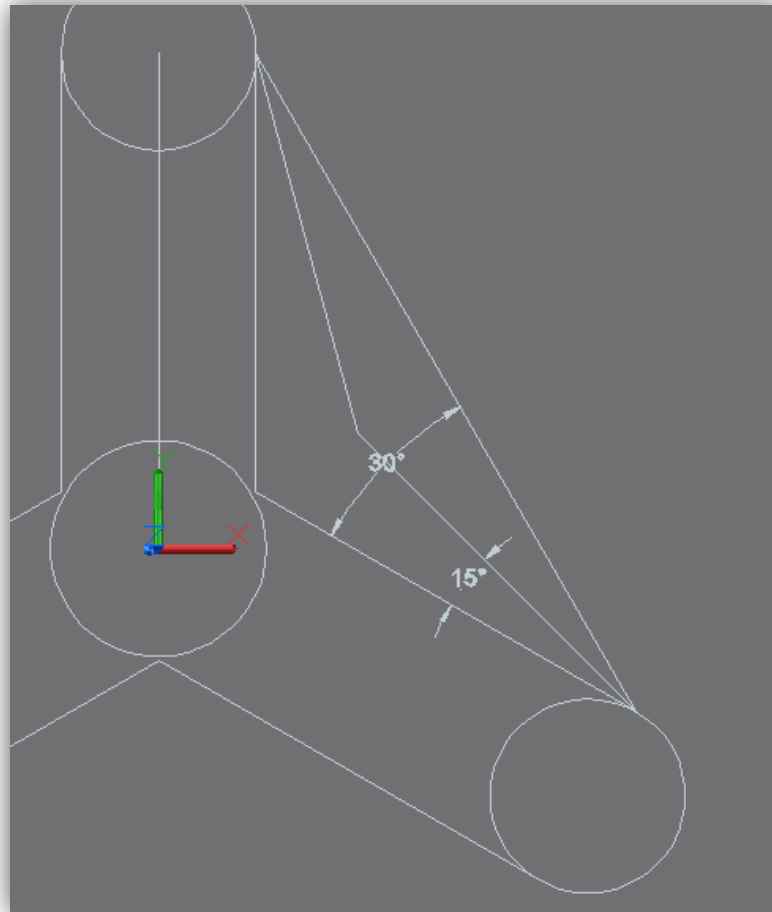
Figure 47 Change of angle on pontoon wall

Figure 47 shows the top view of the basic concept, with increasing angles on the pontoon walls. The maximum angle is 30 degrees from the original setting, which results in a triangular bottom slab on the hull. The outer boundary of the wall with an angle of 15 degrees is also shown to give a better understanding of the changes.

For the natural periods, Figure 48 shows the change in estimated natural periods per degree increase in the angle.
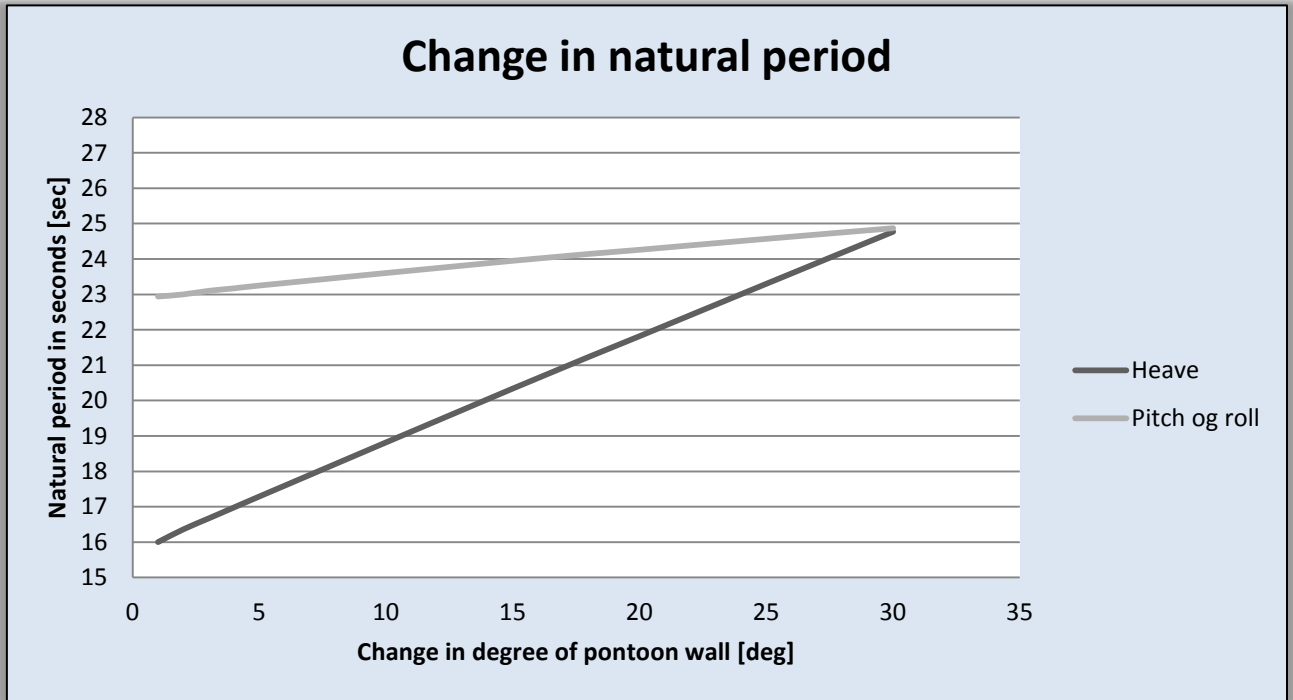
Figure 48 Natural periods with varying angle on pontoon walls

As can be seen in the results, the natural periods converge around 25 seconds when the walls are at their maximum angle. The natural period for heave increases about 0.3 seconds per degree, while pitch/roll changes about 0.07 seconds per degree.
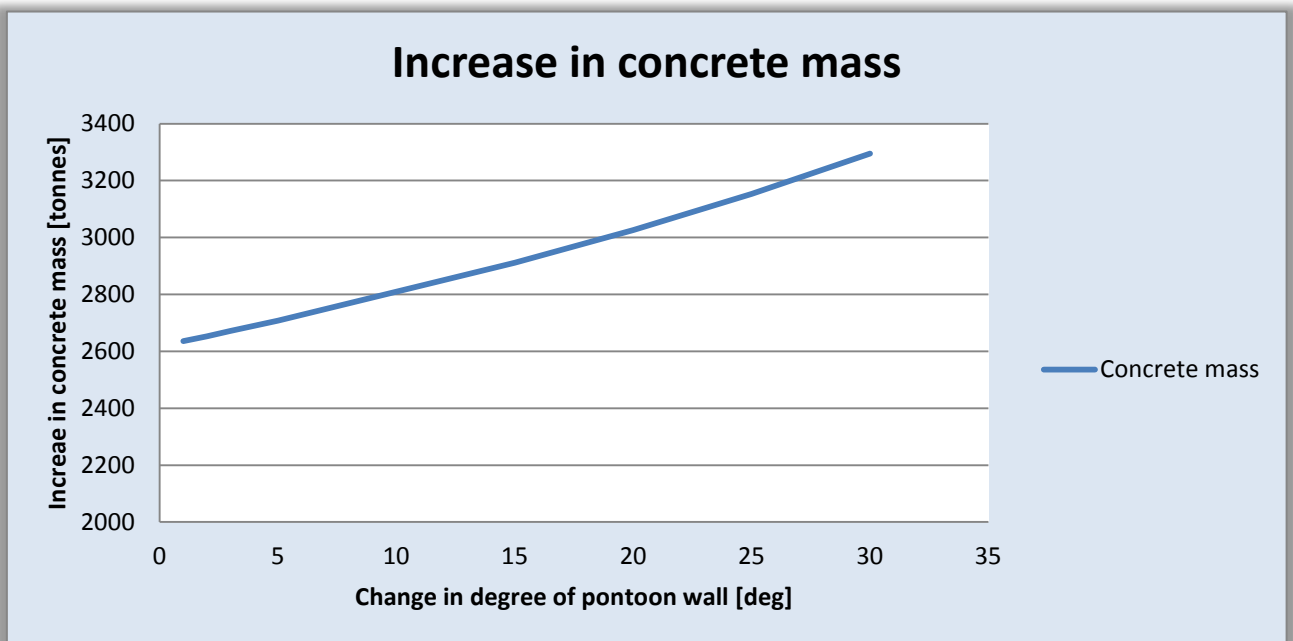
Figure 49 Increase in concrete mass from changing degree on pontoon wall

It is clear to see that changing the angle is most effective for the natural period in heave, as expected, and makes little difference on the periods in pitch/roll. The increase in concrete mass is almost linear, corresponding well with the increase in heave. Per degree, the increase in concrete varies from 20 to 28 tonnes, since the graph is not linear.

As the two graphs show, increasing the natural periods by increasing the angle on the pontoon wall seems to be very effective for heave and at a low cost with regards to increased concrete mass.

4.1.2.2 Changing the C/C distance between shaft and corner cylinder

Changing the C/C distance will lengthen the pontoons, contributing primarily to the total stability of the hull, which affects the natural periods in pitch/roll. For this parameter, varying the C/C +-5 meters from the original setting of 28 meters is sufficient.
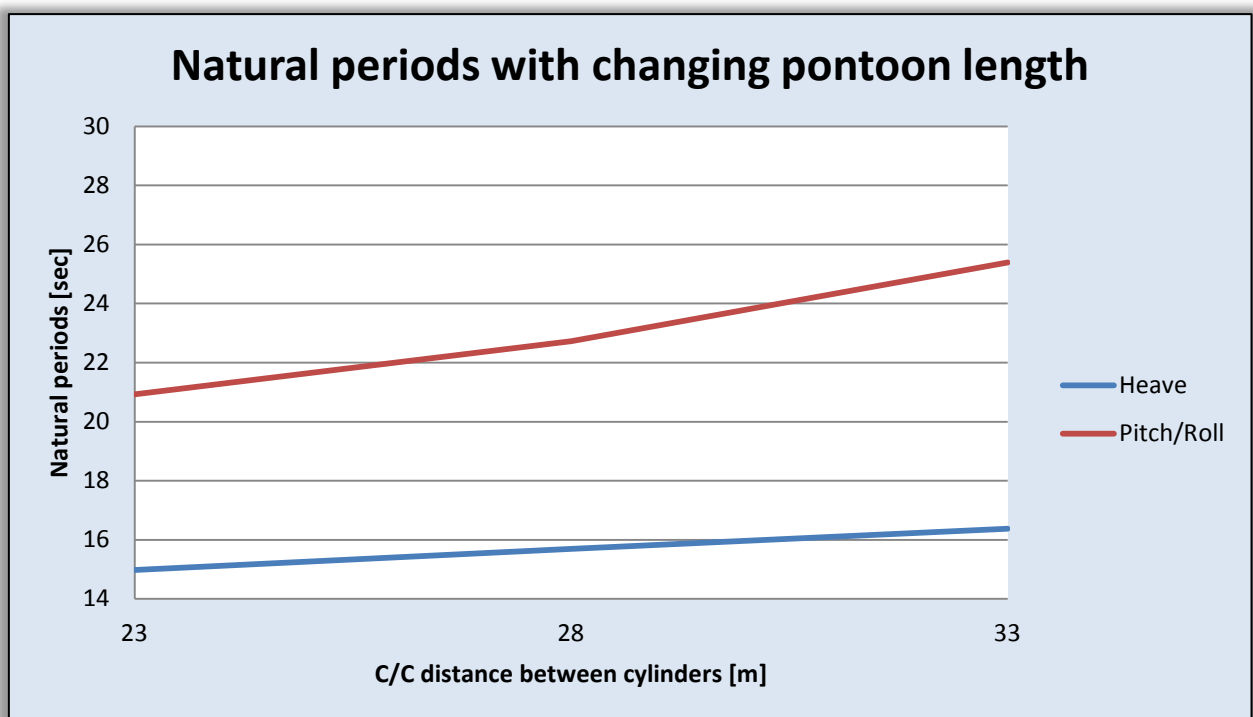
Figure 50 Natural periods with changing pontoon length

For this particular change, the natural period in heave increases by about 0.14 seconds per meter length of the pontoon, while pitch/roll increases by about 0.54 seconds per meter.
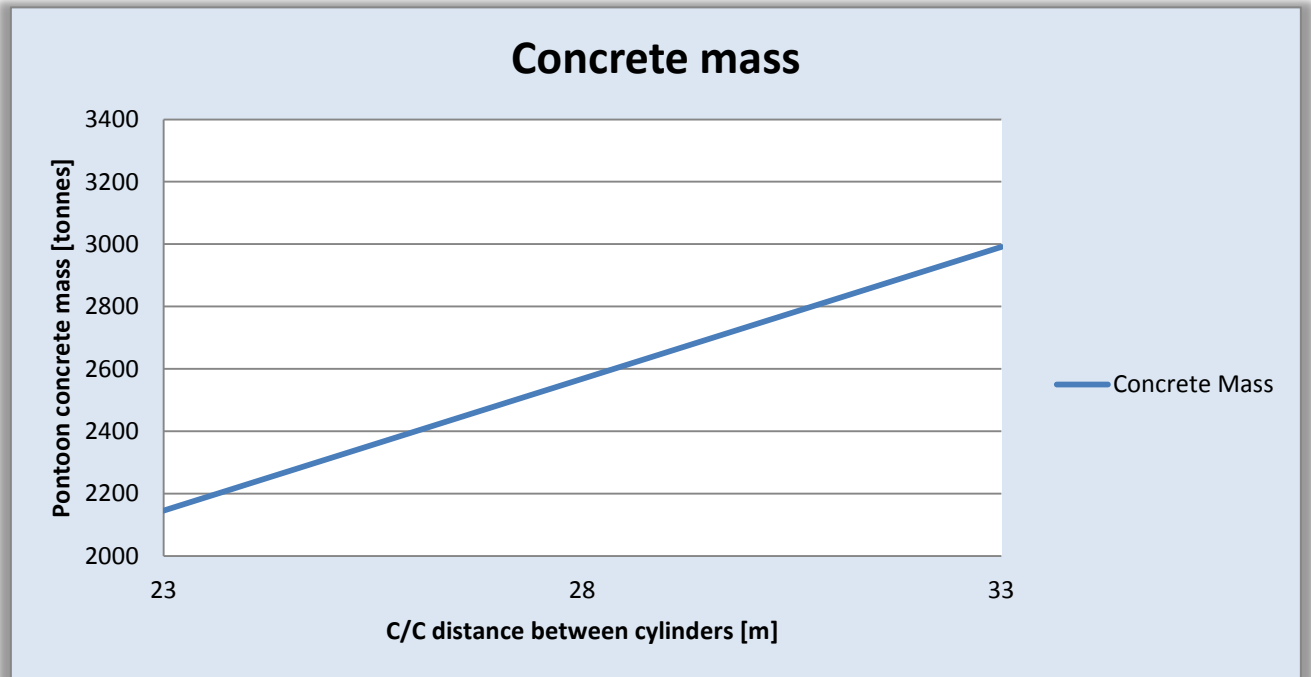
Concrete mass

Figure 51 Concrete mass in pontoons

As expected, this change affects the stability the most, and with an increase of 0.5 second in pitch/roll per meter of increased length, this change can be a very effective tool to increase the natural periods in pitch/roll.

Looking at the graph for concrete mass, this increases a significantly without noticeably affecting the natural period in heave. But for increases above a C/C-distance of 30 meters, the length affects the periods in pitch/roll much more than for the first two meters. If this is to be considered, it looks to be most effective for changes above 2 meters. Per meter, an increase in the length of the pontoon adds around 85 tonnes of concrete mass. Increasing the length may therefore be an expensive way to increase the natural periods if we only increase it by one or two meters.

4.1.2.3 Changing the width of the pontoon

By changing the width, the pontoons will introduce more added mass to the hull, which will contribute to the natural period in heave. It will also gain both structural and added, away from the center of the floater, adding to the stability.

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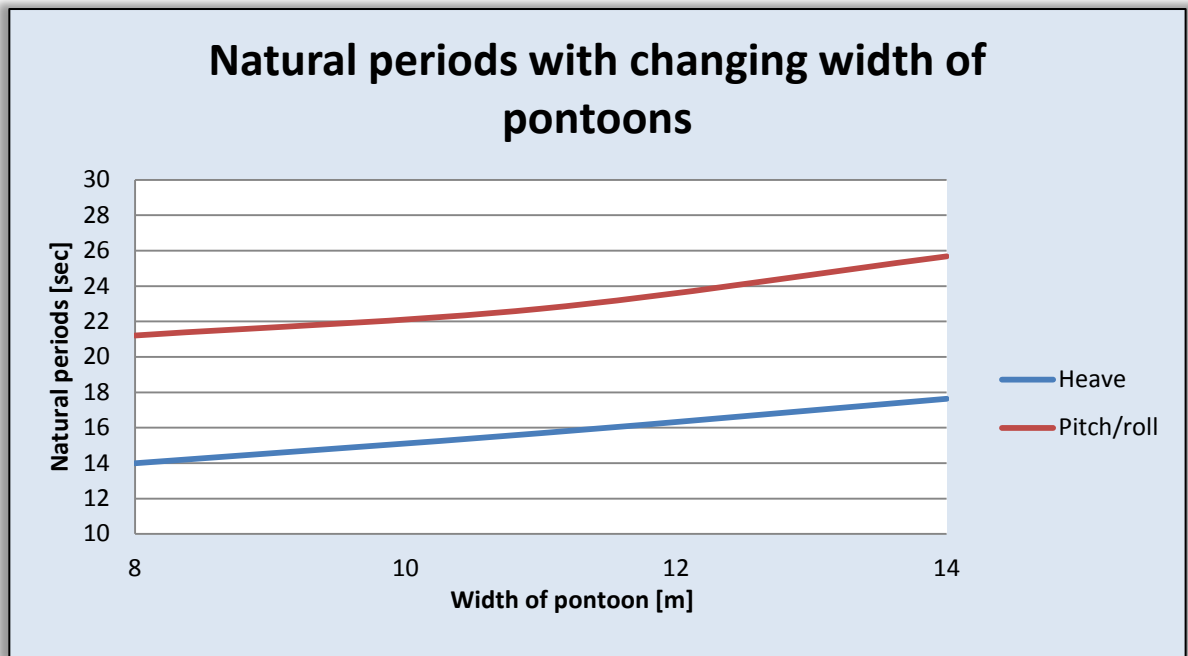
Figure 52 Natural periods with changing width of pontoon

The effect on the natural periods in this case is about 0.6 seconds per meter for heave and 0.75 seconds per meter in pitch/roll.
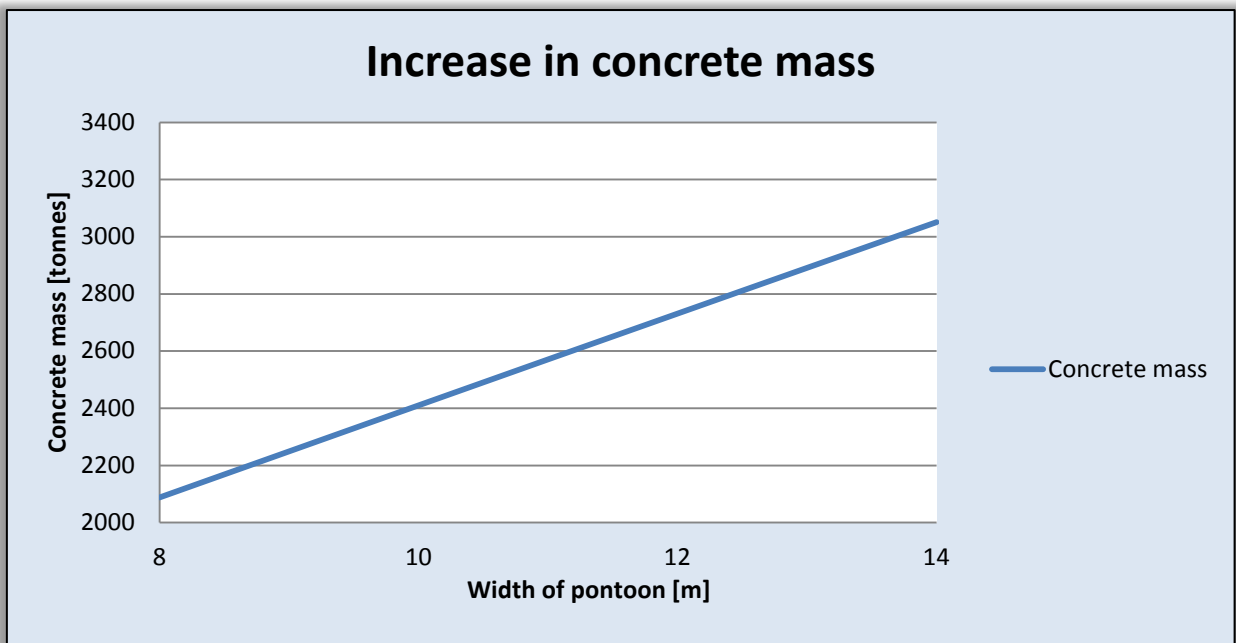
Figure 53 Increase in concrete mass

Looking at the graph for increased concrete mass, it increases by 160 tonnes per meter of increased width. Compared to the two previous parameters, this increase adds much more concrete to the hull concept than the others.

4.1.2.4 Cantilever on the bottom slab around the hull

By extending the bottom slab to the outside of the pontoons, a heave plate is added, which is designed to increase the added mass and therefore slow down the heave-motion. For this calculation the bottom slab will be increased to act like a cantilever on the outside of the pontoons with straight edges.
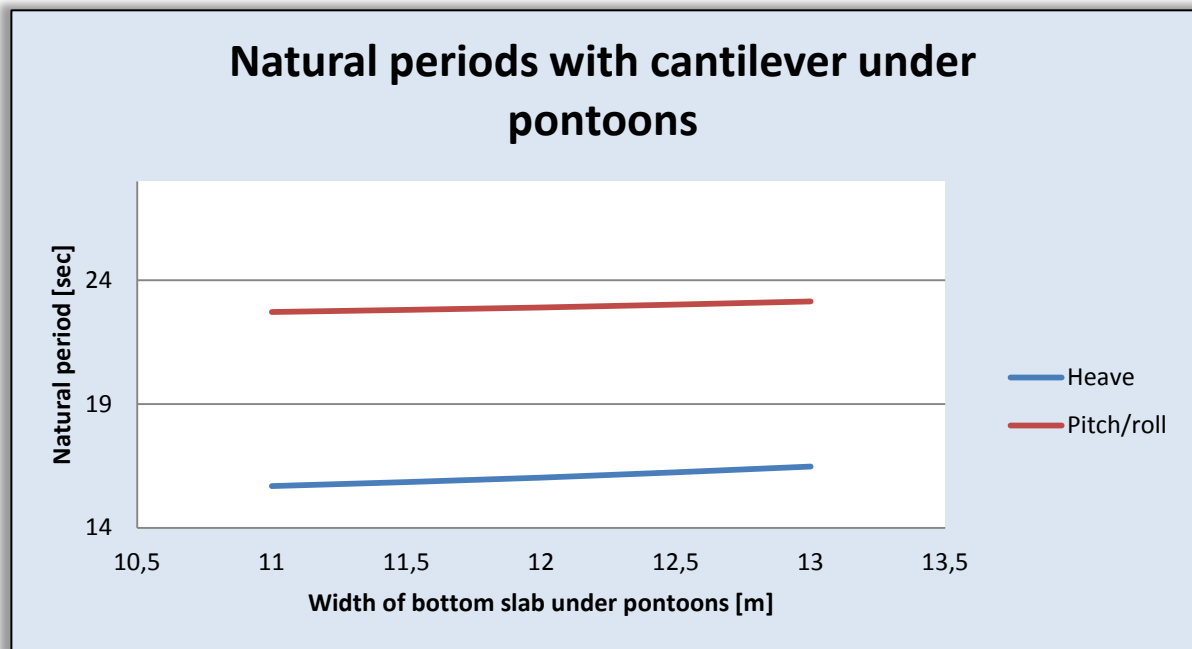
Figure 54 Change in natural periods with cantilever

The gradient for heave natural period is twice as large as for pitch/roll here natural period, increasing by around 0.37 seconds per meter cantilever, meaning 0.5 meters on each side of the pontoon. For pitch/roll natural period, this geometrical change means an increase in the natural periods of about 0.2 seconds per meter.
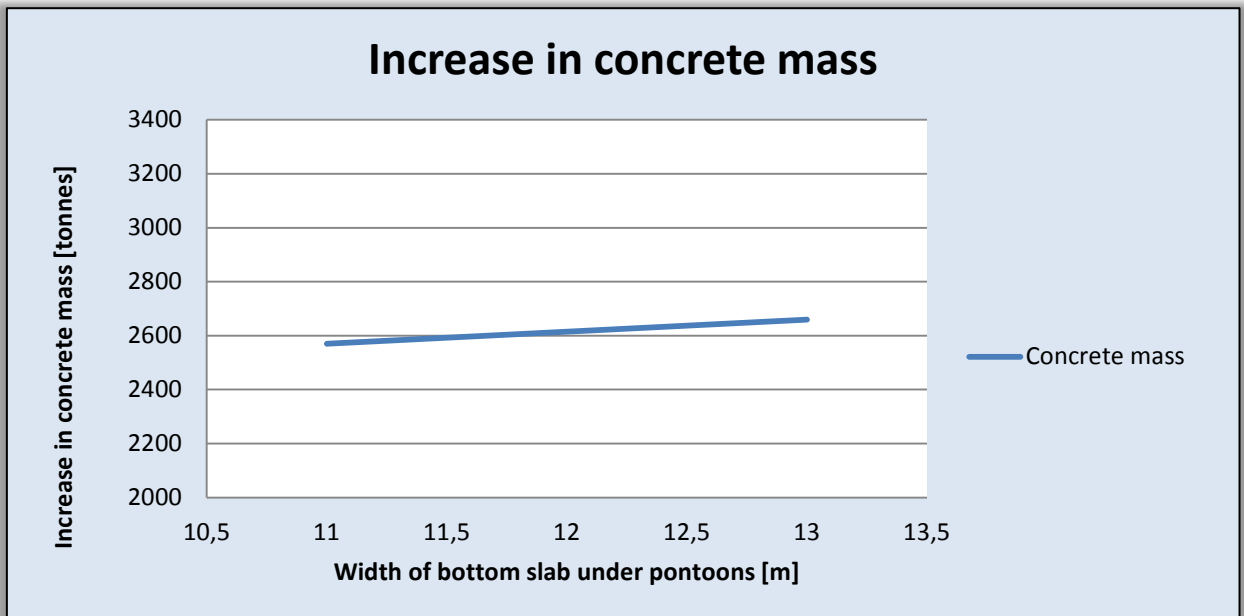
Figure 55 Concrete mass with heaveplate

Extending the bottom slab to the outside of the pontoons and the corner cylinders is a cheap and effective way to increase the heave period without adding much concrete mass.

4.1.2.5 Increasing outer diameter of the corner cylinders

This change involves increasing and decreasing the outer diameter of the corner cylinders to see the effect on the natural periods. A stand-alone change in the diameter of the cylinders will not be a good design as it will be outside the pontoons, but it is interesting to see what change is to be expected from this modification with regards to the final solution for the hull.

Natural periods when changing the diameter of the corner cylinder
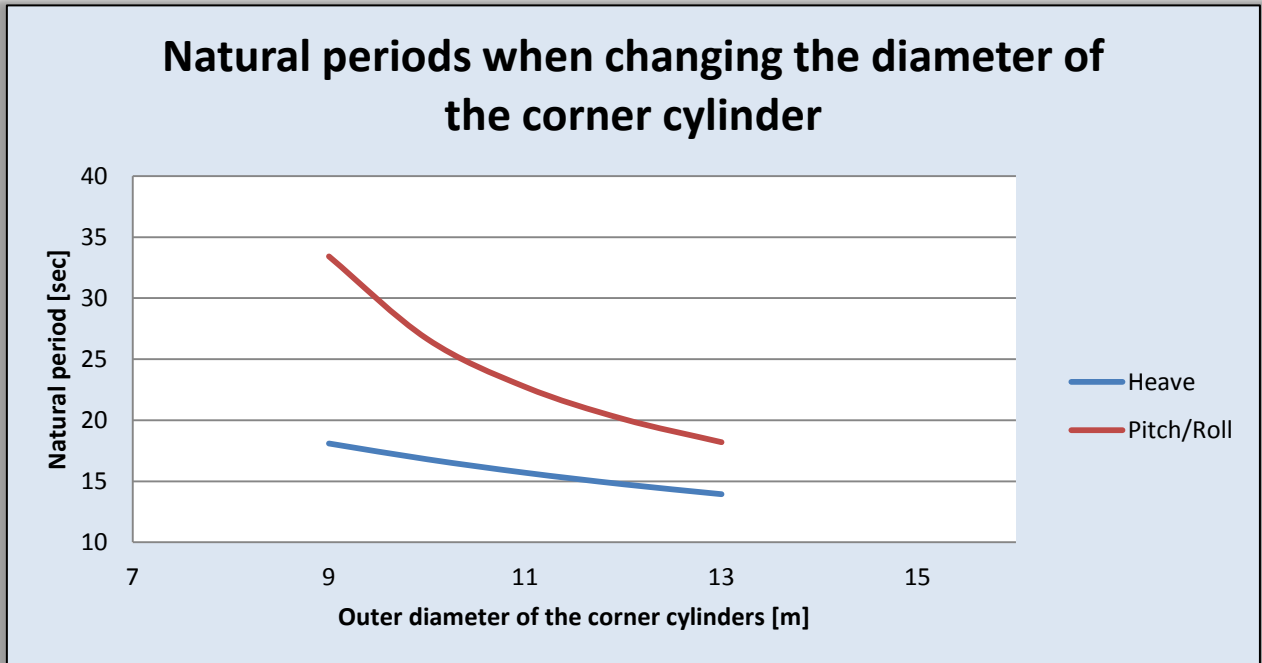
Figure 56 Natural periods with changing the diameter of the corner cylinders

As the graph shows, the change in natural period for heave is almost linear at 1 second per meter diameter. The change in pitch/roll follows a more exponential rather than linear curve. This is mainly due to the calculations of BM, the initial metacenterradius, which causes a decrease in GM, on which the calculations of pitch/roll are based.
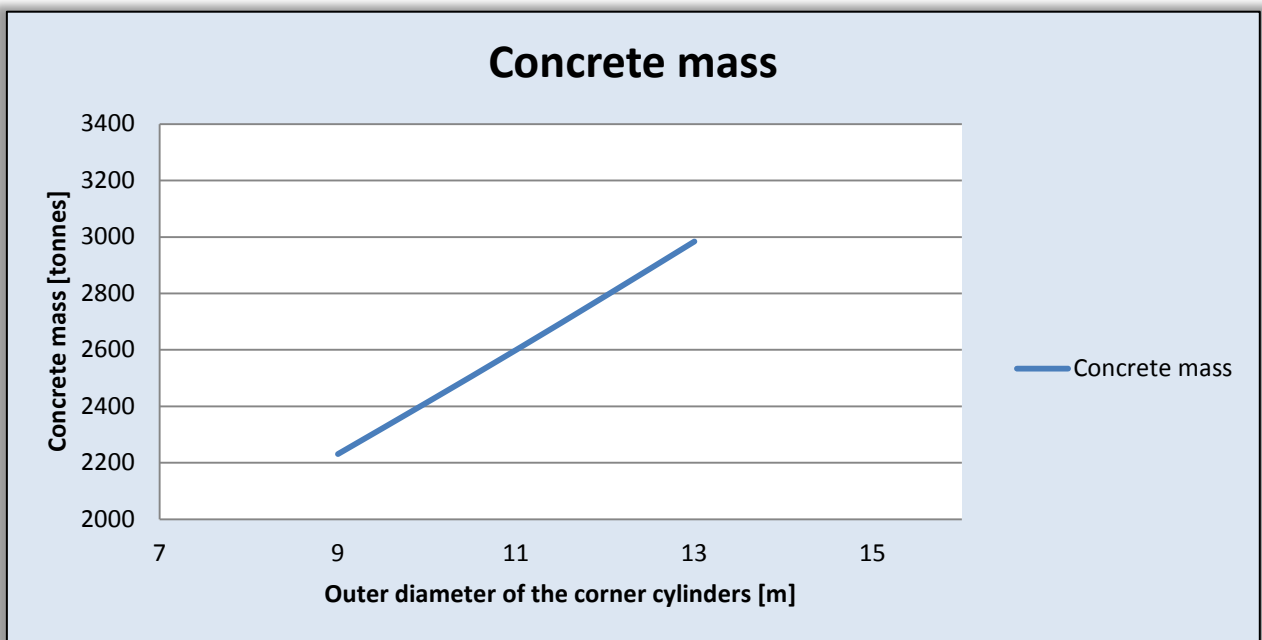
Concrete mass

Figure 57 Concrete mass with changing corner cylinder diameter

BM is calculated using the water plane area, which comes from the area of the components breaching the surface divided by the displaced volume. For this hull, contribution to the water plane area comes from the corner cylinders and the shaft, where the corner cylinders play the main part. Increasing the outer diameter of the corner cylinder increases the area exponentially and therefore also the stiffness. The area and volume increase the same, as the height of the cylinders are unaltered. Since the shaft is not changed, the resulting graph will not be identical to an exponential curve, but almost, as we can see.

The concrete mass increase quite substantially per meter diameter of the corner cylinders. But since decreasing the diameter is what will affect the natural periods in the desired way, it is only positive that the total mass decreases as well.

4.1.3 Evaluation of geometrical changes to the hull

As for an initial assumption, the effects given by the different changes are added together to give a rough estimate on what geometrical changes are needed in order to meet the design criteria for the natural periods, namely natural periods of at least 20 seconds in heave and 25 seconds in pitch/roll.

The best solution for the hull is to keep the diameter of the cylinder the same size as the pontoon width. The shaft will, as stated earlier, be kept as it is in the main concept. A change in the angle on the pontoon walls also seems to be a necessary change in order to find the most optimal design.

With the known alterations for increasing the different parameters by one meter it is possible to set up a table illustrating the changes to the natural periods:

Change in parameter from original setting [D m]	Width of pontoon, change in heave/pitch [sec]	Outer diameter corner cylinders, change in heave/pitch [sec]	Length of pontoons, change in heave/pitch [sec]	Cantilever on the bottom plate, change in heave/pitch [sec]
-2	-1.166/-1.094	2.39/10.7	-0.28/-0.808	-
-1	-0.598/-0.599	1.1/3.938	-0.14/-0,419	-
0	-	-	-	-
1	0.624/0.75	-0.944/-2.62	0.139/0.453	0.37/0.2
2	1.27/1.699	-1.756/-4.526	0.27/0.94	0.74/0.4

Table 11 Overview of changes in natural periods from parameter changes

By modifying just the parameters in Table 11 we cannot expect the natural periods to change much for the better, as changes to the outer cylinders will counterweigh much of the change. Therefore,

it seems important to avoid increasing the diameter of the corner cylinders too much, but instead to try to keep it more or less at the same range as it is now. Angled walls from the corner cylinders towards the shaft are a better hull design than increasing the walls linearly, as the corner cylinder diameter and pontoon width are best kept the same. Looking at the angles again, the following breakdown of the increase in natural periods per degree change is given;

Angle	Heave natural period [sec]	Pitch/Roll natural period [sec]
1	0.19	0.01
2	0.36	0.06
3	0.67	0.16
4	0.98	0.23
5	1.29	0.31
15	4.32	1.01
20	5.82	1.32
25	7.3	1.63
30	8.77	1.93

Table 12 Overview of changes per angle

So, with an angle of 15 degrees we can add 4.32 seconds to heave natural period and 1 second in pitch/roll natural period. Decreasing the width of the pontoons to 10 meters and the outer diameter of the corner cylinders to 10 meters will yield about 0.5 seconds in heave and 3.5 seconds in pitch/roll. Adding this to the original values of 15.5 and 22.77 seconds, the expected values lie around 20.32 seconds for heave and 27 in pitch/roll.

However, changing the geometry based on these criteria only will also change the general buoyant properties of the hull. The CSWF is still expected to float with a draft of 20 meters and still keep all the extra weights described in the basic concept. Therefore iterations and tests are necessary in order to balance the displaced mass with the structural mass and to keep the draft at the correct level.

4.2 Buoyancy check of concepts

To make sure that the mass and displaced mass of the hull at 20 meters draft remain the same, some configurations are calculated with a focus on the structural mass and displaced volume. With a negative difference, the structural mass is larger than the displaced mass and the hull will float deeper in the water with the current parameters than with the basic concept. A positive difference

means that ballast water is needed in the corner cells to make the hull float at the desired level with 20 meters draft.

Angle of pontoon wall [deg]	Width pontoon and corner cylinder [m]	C/C distance [m]	Height of pontoon [m]	Fixed steel weights [tonnes]	Internal water pontoons [tonnes]	Concrete mass [tonnes]	Total mass [tonnes]	Displaced mass [tonnes]	Diff [tonnes]
15	10	28	6	1670	4868	6241	12 780	12 815	102
15	10	30	6	1670	5554	6529	13 753	13 630	-123
13	10	30	6	1670	5259	6333	13 262	13 247	-15

Table 13 Summary of buoyancy calculations

The values in this table are for the three different configurations where the thickness of the top slab is set to 0.3 meters and the bottom slab at 0.5 meters. All inner values will be subject to adjustment in the final calculations, but the results here serve as a guideline for the final result.

The hull is allowed +- 1meter adjustment in the draft, which will add around 200 extra tonnes of displaced mass after elongation of the shaft and corner cylinders. Considering the values from the table above, the first and last configuration look like the most suitable and can be modeled in Wadam to show the natural periods.

Modeling the two concepts from the previous chapters using the same thicknesses and extra weights as for the basic concept, Wadam gives the following rough estimates on the FE-models from Patran.Pre;

Angle of pontoon wall	C/C length	Diameter of cylinder	Heave	Pitch/Roll
15	28	10	21,1	27,7
13	30	10	21,8	24,75

Table 14 Results from Wadam analysis

The estimated value for these two configurations where 20.4/27 seconds for the first configuration and 20.3/27 for the second. The first assumption of adding the effects from the different geometrical changes proves to be, as the results show, a little rough. It overestimates the pitch/roll by around two seconds for the second concept and underestimates heave by around one second for both. The results also show that both concepts have reached high enough natural periods in heave, but the natural period in pitch/roll for the second concept is a little low.

A series of Wadam-runs with different input values to search for errors show that the models are sensitive to VCOG and radii of gyration. This was not well enough accounted for in the hand calculations, resulting in the errors given above between the Wadam analysis and the hand calculations. The FE-models used also have quite rough element meshing which can influence the results. This was done to reduce the time needed for the analysis.

Both configurations are nonetheless a good rough match for the design criteria. One must therefore be chosen before further work can take place. Looking back at Table 13, the total concrete volume for the first concept in Table 14 is 92 tonnes less than the other alternative and it has a surplus of buoyant forces. This concept therefore gives the best basis to start a more thorough calculation.

4.3   Chosen design

The chosen concept for further optimization will therefore have an outer geometry on the hull defined by the following parameters:

- A 15 degree angle on the pontoon walls from the corner cells towards the shaft
- Corner cell diameter is 10 meters
- C/C between shaft and corner cylinder is 28 meters
- Pontoon height is 6 meters

Inner geometry, such as wall thickness and small changes to the shaft design can be implemented to make sure the draft is correct. This will most probably affect the radii of gyration and the VCOG which in turn will reduce the natural periods in pitch/roll.

5   Final design for the CSWF

5.1   Calculations on the final hull concept

From the results in the previous chapter, the outer geometry with 10 meters in diameter on the cylinders, C/C at 28 meters and an angle of 15 degrees on the pontoon legs is the best fit for the design criteria's in this thesis. That hull concept will therefore be calculated and fine-tuned in this chapter.

The outline of the hull with area for the bottom slab, between heights 0 and 6 meters above the base, is drawn in Autocad 2013 to feed values into the Excel spreadsheet. This will then serve as the basis for calculating volumes, buoyancy and all other parameters required for further analysis.

While working on the design, the radii of gyration is reduced from the estimated values in the earlier calculation, as more of the hull's mass is located closer to the center. This will reduce the natural periods in pitch/roll from the estimations in the previous chapter.

5.1.1   Hand calculations

Fine-tuning the design depends substantially on Archimedes law of buoyancy so that the hull floats with the designed draft. Other factors, like the static tilt, must also be taken into account when making calculations. This therefore becomes an iterative process culminating in the end result given below.

Calculated natural periods	
Heave [sec]	20.87
Pitch/Roll [sec]	26.439

Table 15 Natural periods on final concept

The natural periods are calculated using 19 100 tonnes as added mass.

Calculated input for Wadam analysis	
VCOG [m] from MSL	-9.44
VCOB [m] from MSL	-13.59
Structural mass [kg]	12 790 000
Radii of gyration pitch/roll [m]	22.3
Radii of gyration heave [m]	17.13
Wave frequencies [rad/sec]	2 – 20, stepvalue 0.5
Wave directions [degrees]	0 – 180, stepvalue 15 degrees

Table 16 Input for Wadam analysis, last concept

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For the final concept, the ballast cells contain almost no water, so the effect of free water surface is also negligible here.
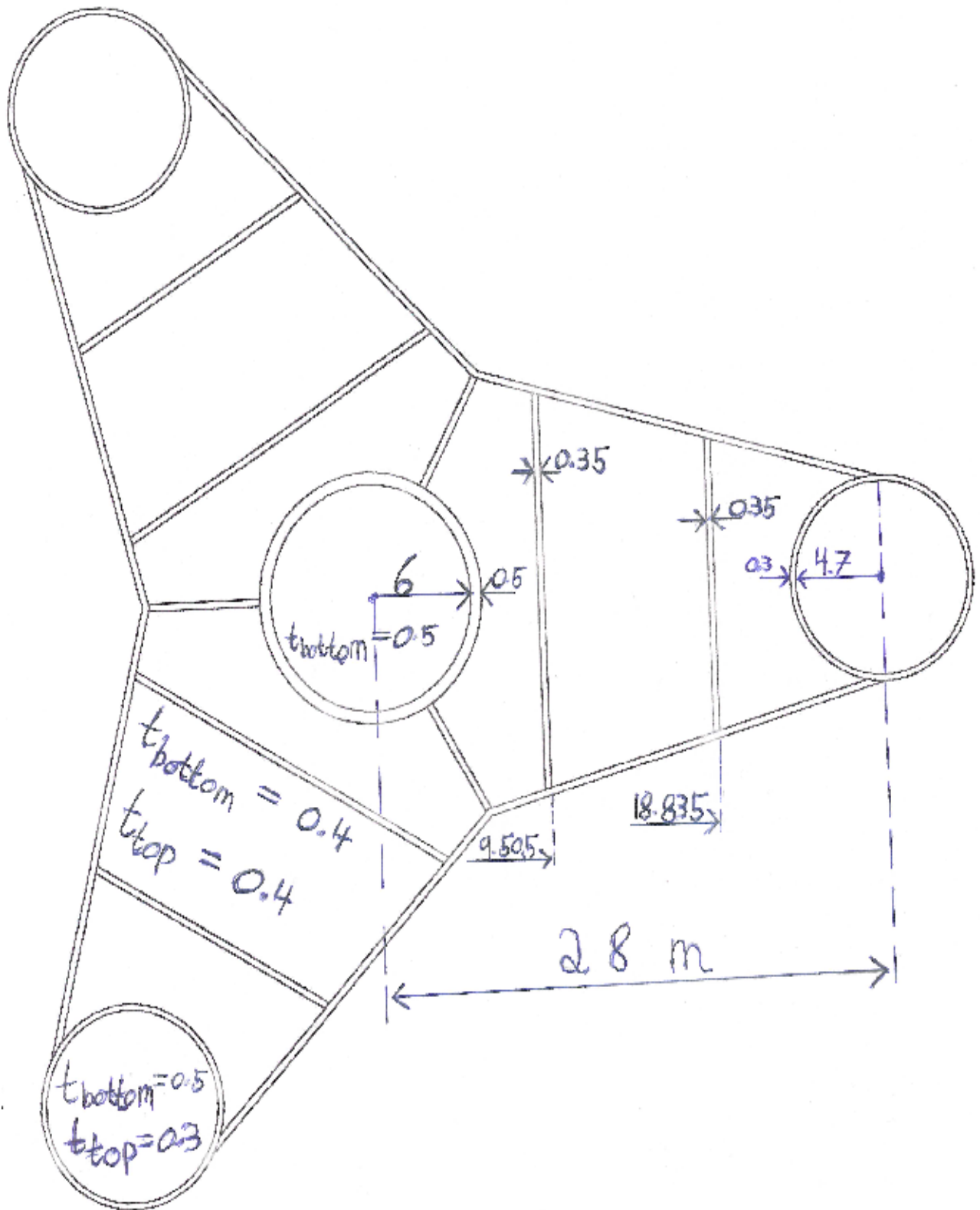
Figure 58 Overview of the bottom plate
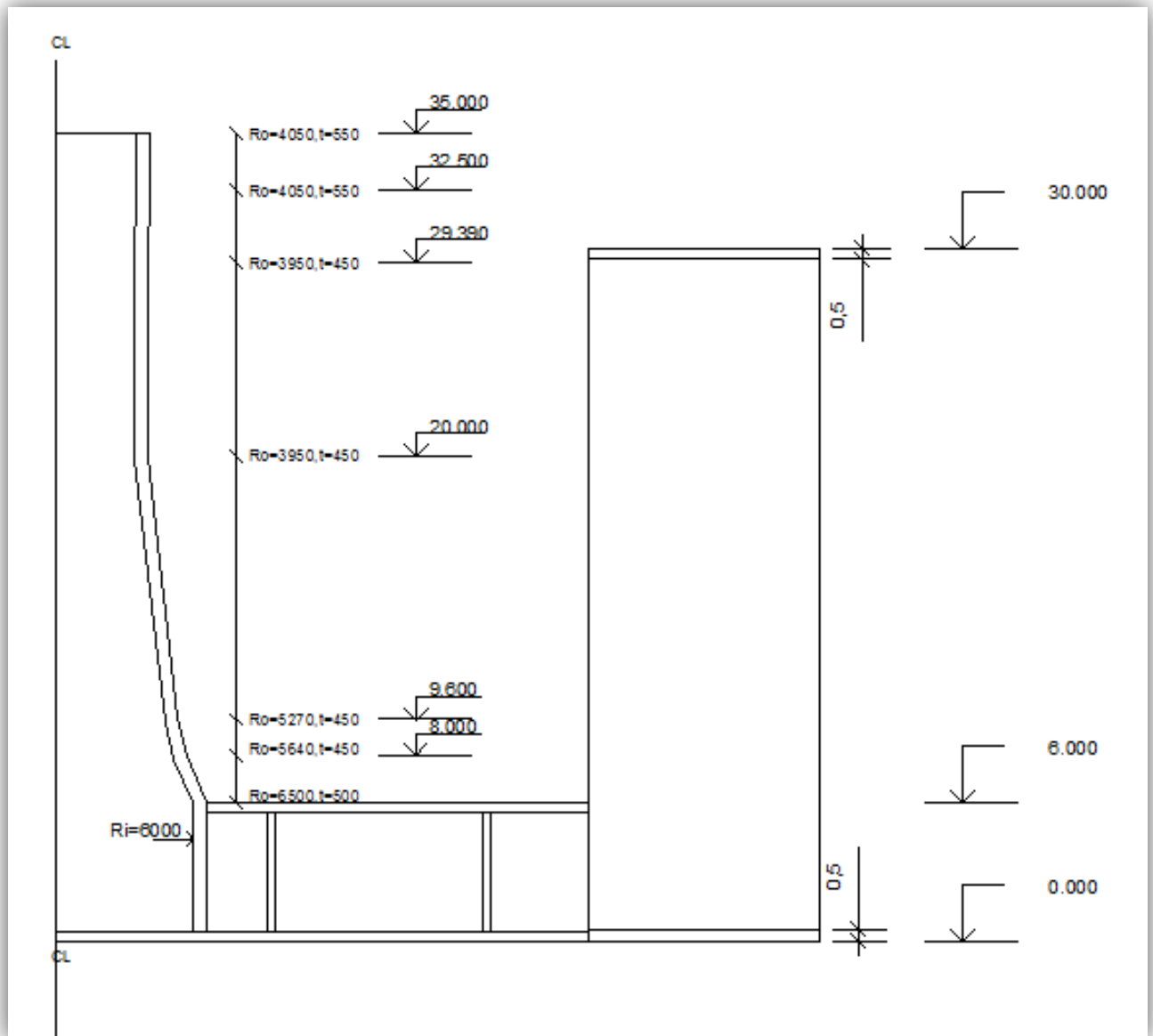
Figure 59 Sideview of the hull with heights and lengths in meters

5.1.1.1 Static tilt

Calculations of static tilt are done by hand calculations. For the wind turbine in this thesis, 660 kN is the maximum thrust. The tower will be connected to the top of the concrete corner cells, making the moment arm from the top of the corner cylinders to the nacelle as shown in the calculations in Figure 60.

<u>Input:</u>

$$\text{Thrust} := 660 \cdot kN \qquad\qquad M_{struktur} := 12790000 \cdot kg$$

$$H_{top.corner.cell} := 30m \qquad\qquad H_{nacelle} := 102 \cdot m$$

$$M_{arm} := H_{nacelle} - H_{top.corner.cell} = 72\,m$$

$$GM := 3.3 \cdot m$$

<u>Calculated forces:</u>

$$M_{acting} := \text{Thrust} \cdot M_{arm} = 4.752 \times 10^4 \cdot kN \cdot m$$

$$F_{gravity} := M_{struktur} \cdot g = 1.254 \times 10^5 \cdot kN$$

<u>Static tilt:</u>

$$\alpha_{static} := \operatorname{asin}\left(\frac{M_{acting}}{F_{gravity} \cdot GM}\right) = 6.593 \cdot deg$$

Figure 60 Calculation of static tilt

As the results show, this concept has a calculated static tilt of 6.593 degrees.

5.2   FE-model

For the Wadam-analysis, a symmetrical model around its YZ-axis has been used. The Wadam-software has then mirrored the model to create one in full as shown in Figure 61 and Figure 62.
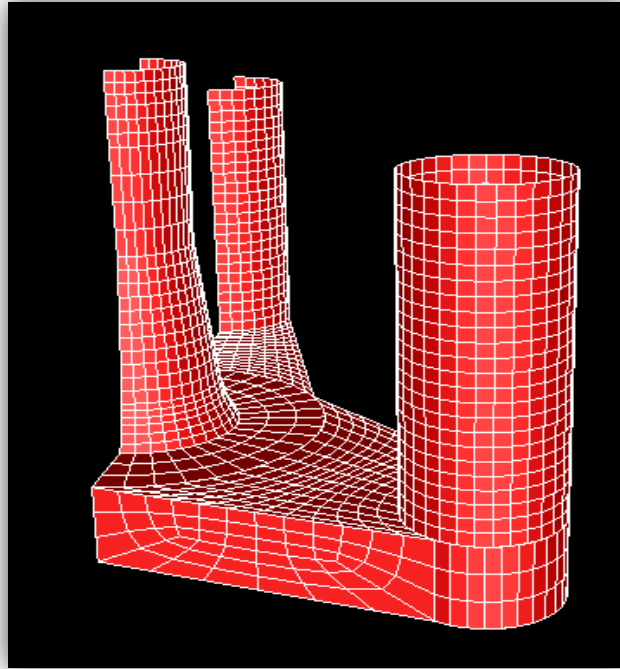
Figure 61 FE-model of the final concept,Patran.Pre
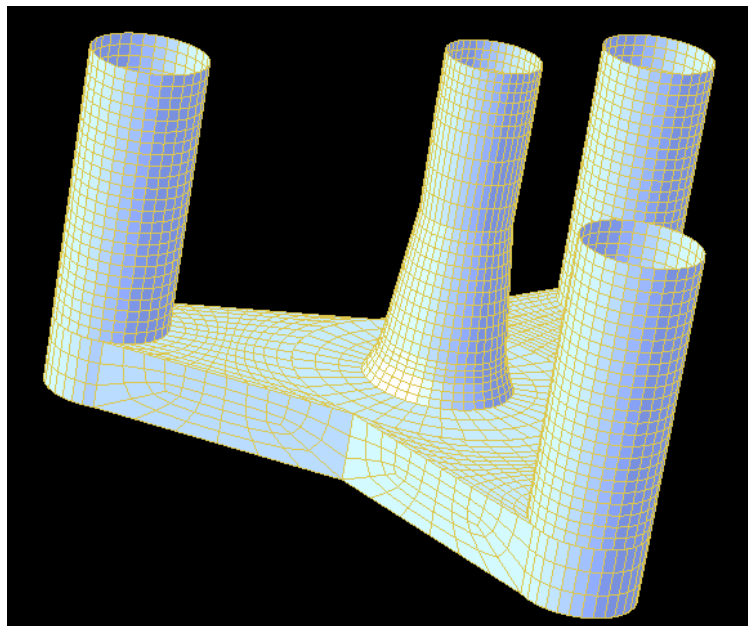
Figure 62 Mirrored model in Wadam

5.3 Results from Wadam analysis

5.3.1 Check of the model data

The Wadam-analysis has been done with the FE-model in Figure 62 and the calculated input values from Table 16.

Check of model data	
Displaced volume of the model	12 487 m^3
Volume 1	12 486,6 m^3
Volume 2	12 486,6 m^3
Volume 3	12 494,1 m^3
Water plane area	286.228 m
VCOB	-13.59 m (from MSL)

Table 17 Check of Wadam model data, final concept

The results show first of all that with the current mesh, the hull displaces 12 487 m^3 seawater, compared to 12 516 m^3 in the hand calculations. The mesh size is therefore acceptable, differing only 0.23% from the correct displaced volume.

The three ways Wadam calculates the displaced volume are also shown, being almost identical. The water plane area and the vertical center of buoyancy also correspond with the calculated values. Check of the model is therefore correct and it is safe to proceed to the results.

5.3.2 Results

Figure 63 shows the rigid body calculations from Wadam.
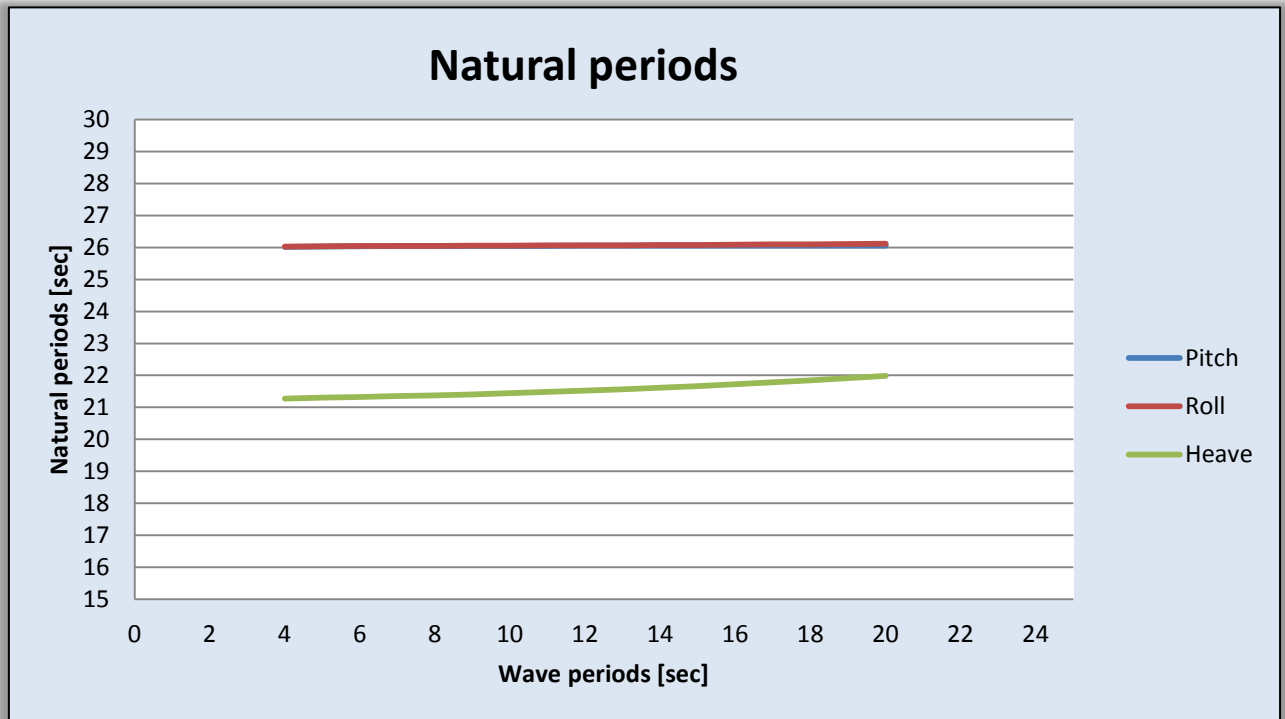
Figure 63 Natural periods from Wadam

For this concept, as for the basic concept, the graphs for roll and pitch natural periods follow each other almost perfectly, making the blue graph invisible as it is directly behind the red graph. The natural period in heave varies a little more over the analyzed wave periods with extreme values 21.274 to 21.981

The mean periods from the previous graphs give the following values for the natural periods:

Solution for natural periods in Wadam	
Heave [sec]	21.5
Pitch [sec]	26
Roll [sec]	26

Table 18 Results from Wadam, final concept

5.3.2.1 Added mass

Wadam gives around 20 000 tonnes as added mass, differentiating 6% from what was estimated in the hand calculations. This is roughly the same discrepancy as for the basic concept and even though it is a little high, the result from the hand calculations is not too different from Wadam's results.

5.3.3 Maximum response using Postresp

In order to check the hulls maximum response, the load cases given in chapter 1.5 are used after the periods have been recalculated into Tz.

id	Hs	Tp	Gamma	Tz	
	m	s		s	
1	5,50	11,40	1,17	8,22	
2	5,50	11,40	1,17	8,22	
3	3,60	8,00	2,46	6,11	
4	3,60	8,00	2,46	6,11	
5	3,00	19,00	1,00	13,50	
6	4,00	17,00	1,00	12,08	
7	5,00	16,00	1,00	11,37	
8	5,00	8,00	5,00	6,44	
9	3,60	8,00	2,46	6,11	
10	---	---	---		
11	5,50	11,40	1,17	8,22	
12	---	---	---		
13	---	---	---		
14	---	---	---		

Figure 64 Wave spectrum input for the final concept

Taking the results for the directions 0, 90 and 180 degrees of the hull due to symmetry and plotting for heave and pitch (roll is identical to pitch with a phaseshift), the following graphs for heave and pitch are produced;
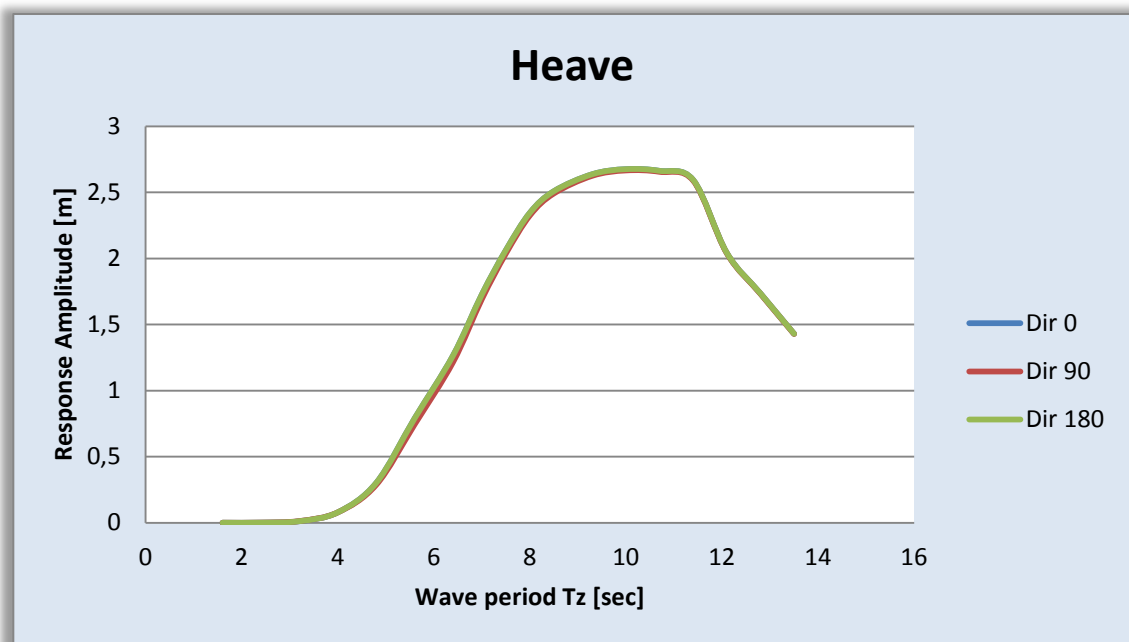
Figure 65 Short term response heave
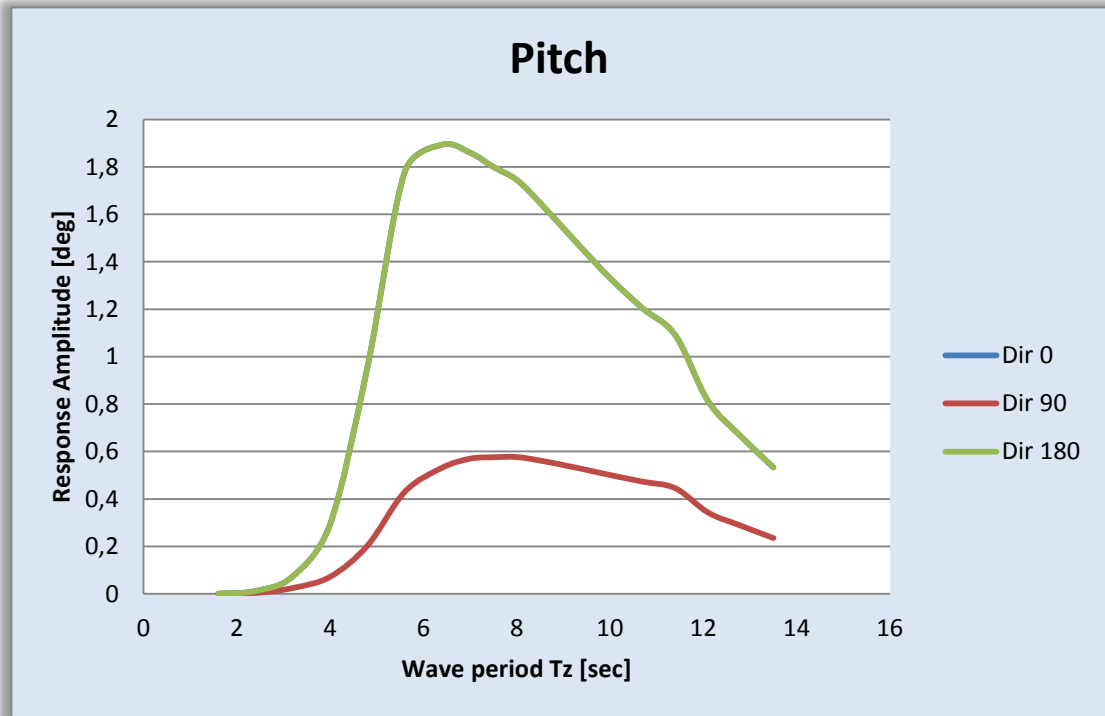
Figure 66 Short term response pitch

Heave is identical for all wave directions, while pitch will naturally vary depending on the direction of the waves. For the three different directions reported in Figure 66, waves hitting the hull at the front, at direction 0^0, and at 180^0 all impact the pitching motion identically, making the blue graph invisible under the green graph. For waves coming in at 90^0 degrees the response in pitch is naturally low, but equally high for the roll motion.

By reading the graphs made from the wave regime at the desired location, the hulls maximum movement in meters and degrees is possible to find. For the final concept, the maximum results are 2.7 meters for the heave motion and 1.9 degrees in pitch/roll.

5.3.4 Plot of response variables
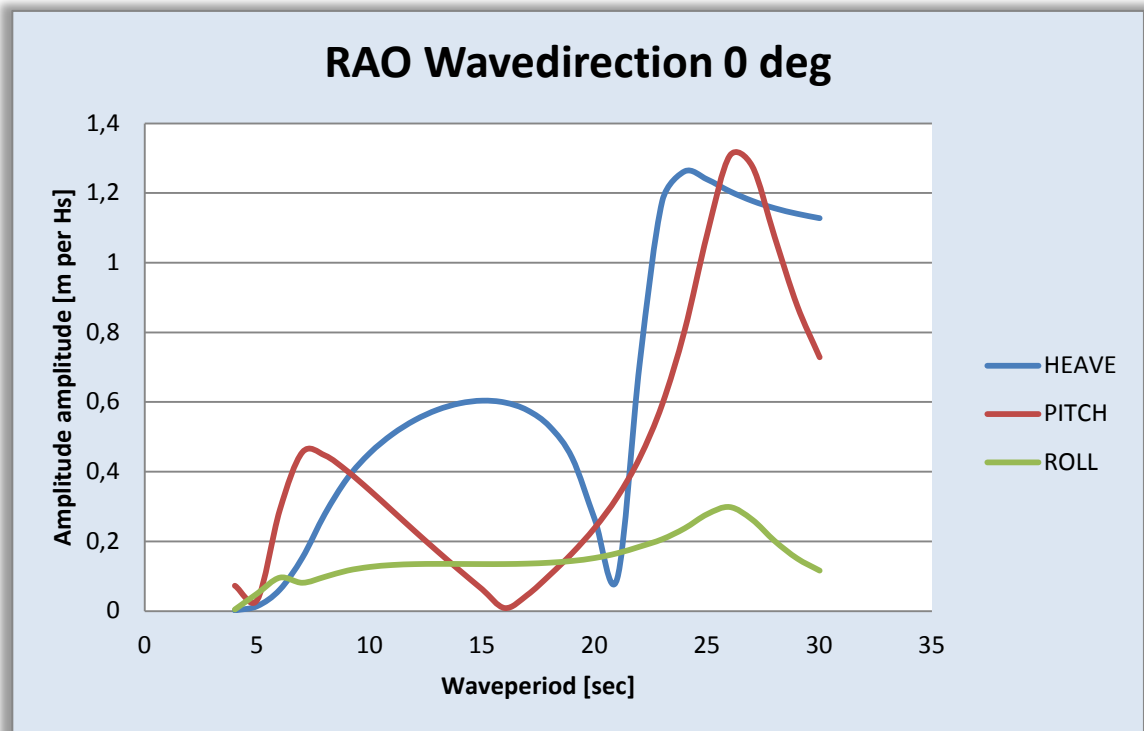
Figure 67 Response variables for wave direction 0 degrees

As can be read from Figure 67, the resonant behavior starts around 21 seconds for the heave motion and around 26 seconds for the pitch/roll motion, confirming the earlier results on the final concept.

5.4 3DFloat-analysis

5.4.1 Input

For the final concept, the pontoons increase in width towards the center of the hull as rectangular sections. As 3DFloat so far only operates with cylindrical or conical elements, this has to be taken into account and relevant adjustments made. The shaft is kept the same as for the basic concept, except that the bottom part is increased to 6.5 meters in radius.

The conical elements have been calculated so that they have the same total outer volume as the regular pontoons. This ensures the displaced mass is correct. The wall thickness is calculated to keep the masses the same as for the real model.

The stiffness-inputs for the natural periods are calculated in Mathcad and are shown in Figure 68.

Input:

$Displacement := 12531.3566 \cdot m^3$ $M_{structure} := 12790000 \cdot kg$

$A_{waterplane} := 287.5522678 \cdot m^2$ $VCOG := 10.5574 \cdot m$

$GM := 3.32 \cdot m$ $MSL := 20m$

Physical values:

$g = 9.807\, m \cdot s^{-2}$ $rho := 1025 \cdot \dfrac{kg}{m^3}$

Buoyancy:

$f\_lin := Displacement \cdot g \cdot rho = 125962893.906 \cdot N$

$3 - 3 := g \cdot rho \cdot A_{waterplane} = 2890422.558 \cdot \dfrac{N}{m}$

$4 - 4 := -Displacement \cdot rho \cdot g \cdot GM = -418196807.769 \cdot N \cdot m$

$5 - 5 := -Displacement \cdot rho \cdot g \cdot GM = -418196807.769 \cdot N \cdot m$

Figure 68 Stiffness input for 3DFloat

5.4.2 Natural periods

The natural periods, in this calculation, correspond with mode 3,4 and 5 for pitch, roll and heave, as read from the animated modes to see which are rigid body motions. The input file can be read in appendix 2, but the three natural periods interesting for this thesis are given in Table 19.

Rigid body motions from 3DFloat	
Heave	20.04
Pitch	28.5
Roll	28.5

Table 19 Rigid body motions from 3DFloat

5.4.3 Local forces on the hull

The rigid body calculations are done through the buoyancy-input, the structural mass and the added mass from the model, without any time passing and with gravity and buoyancy in the environment turned off. Turning these back on to get the forces on the hull, some unexpected movements on the hull appeared. The source of this error has not been definitively located, but it is suspected to be with the conically shaped elements below the waterline in the final concept. Since this could not be found in the remaining time, the forces and cross-sections are from the basic concept to show how to obtain the forces and moments from 3DFloat and how to transfer them to the real cross-sections.

5.4.3.1 Input

Buoyancy and gravity must be switched to ON and the stiffness-input from calculating the natural periods must be removed. When the analysis is run, it does not compute natural periods, only forces on the hull. For this hull concept, three points have been chosen as the most critical;

1. Bottom of the shaft (at elevation 6 meters above the hulls base)
2. Transition from pontoon to corner cylinder
3. Transition from pontoon to shaft

The output yields the forces as local forces on the element at the specific node.

Waveinput	
Hs	5.5 meters
Tp	10 seconds

Table 20 Waveinput 3DFloat

For this particular analysis, 20 000 timesteps of 0.025 seconds are done, meaning 500 seconds. In that time the hull should be able to stabilize itself so that the moments and forces reach a transient state in which the maximum forces can be extracted and compared to the capacities.

5.4.3.2 Forces on the hull

1. **Bottom of the shaft**

From the Logfile.txt the orientation can be obtained so that the local Fx-, My- and Mz – forces can be checked with the cross-sectional capacity. This element is oriented vertically, making the local forces into the global forces as shown in Figure 69. Fx is the axial force, positive values are compression.
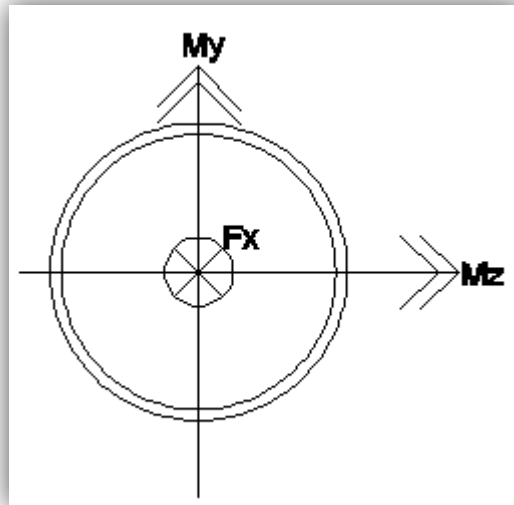
Figure 69 Force directions on the bottom of the shaft

Graphs with the force and moments are produced for the cross-section at the desired node:
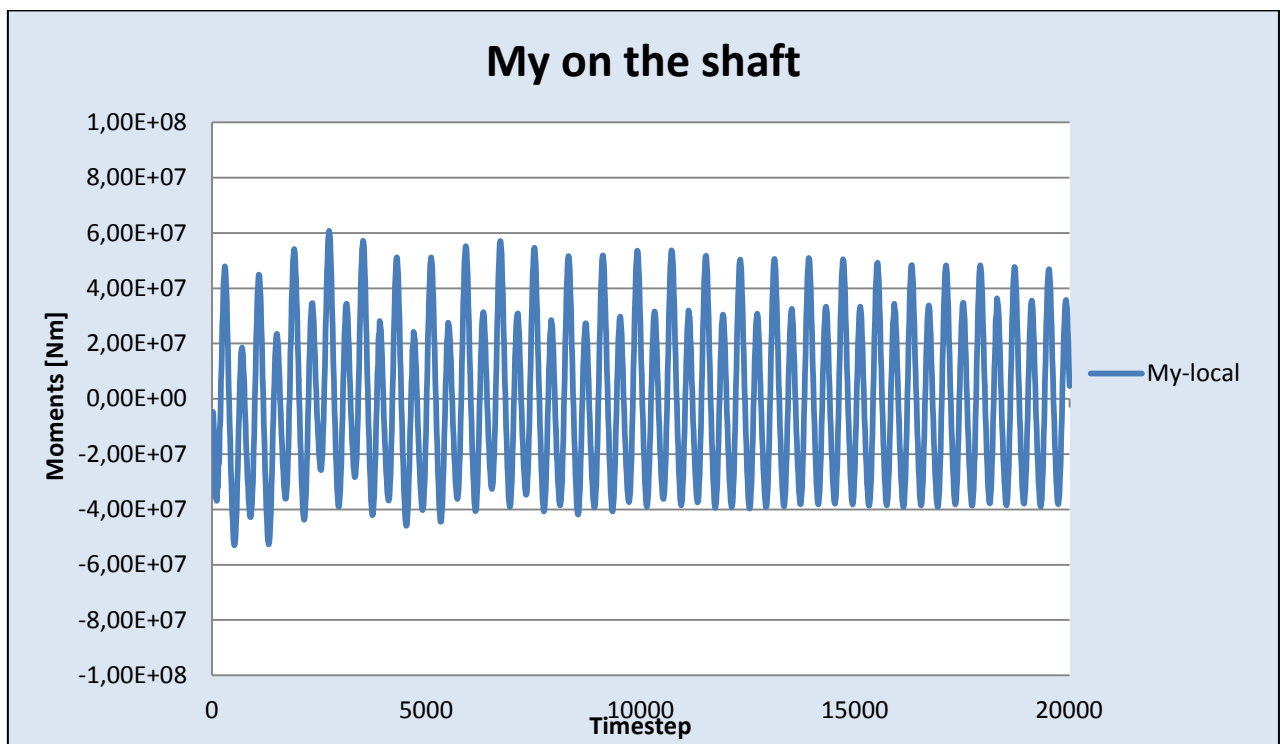
Figure 70 My-diagram for the shaft
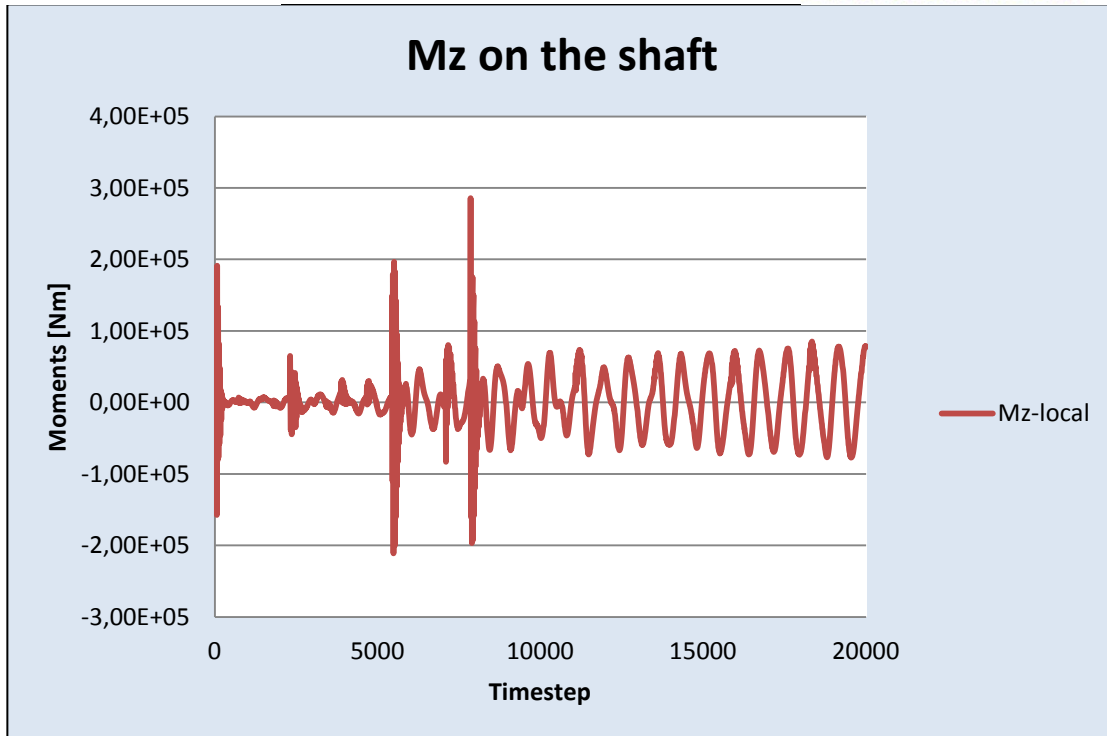
Figure 71 Mz-diagram for the shaft

Some discrepancies are evident at the start, for My and a little later for Mz. After that the hull reaches a transient motion and the moments vary around the same values. From these values the maximum is extracted for the cross-section.
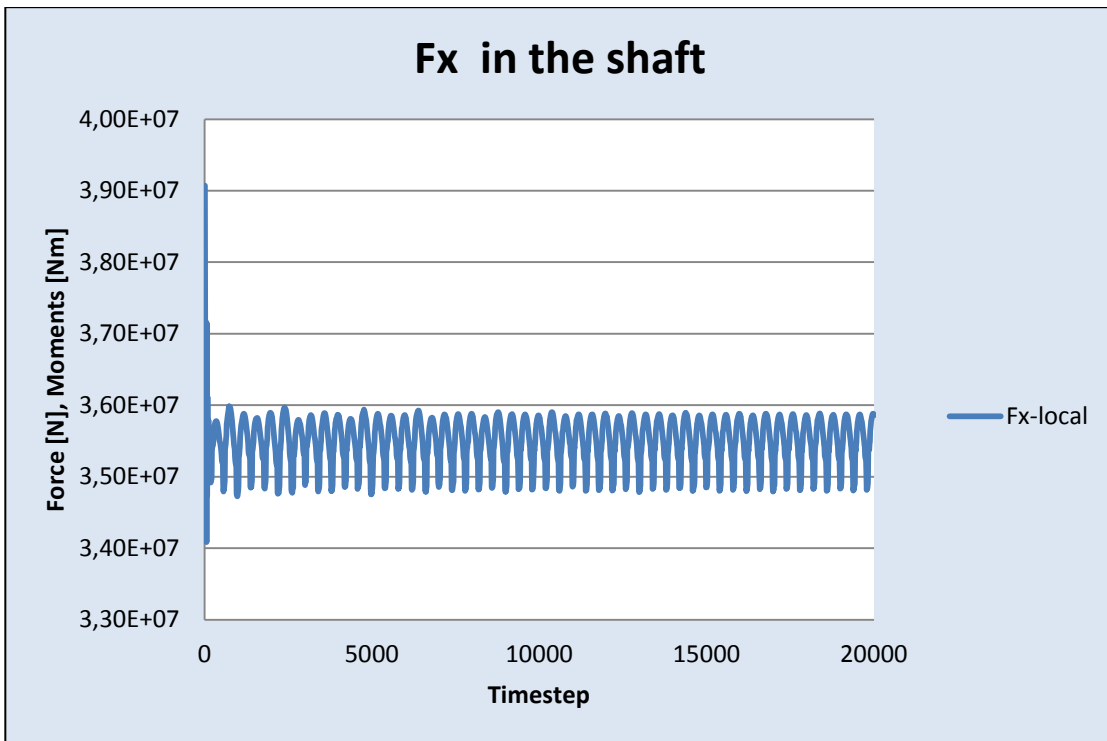
Figure 72 Axial force in the shaft

Similar graphs are made for the other two monitored nodes, at the transition to the shaft from the pontoon (2) and to the corner cylinder from the pontoons (3), marked in the schematic below.
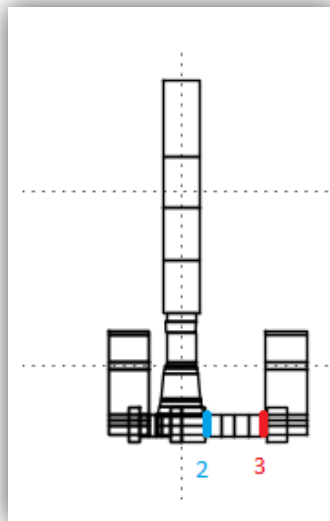
Figure 73 Placement of monitors

5.4.3.3 Maximum forces

	Maximum exerted force		
	Shaft	From pontoon to corner cylinder	From pontoon to shaft cylinder
Fx [kN]	36 000	2000	2000
My [kNm]	50 400	175 000	166 000
Mz [kNm]	100	300	9.1

Table 21 Maximum forces on the hull

Table 21 shows the maximum forces exerted on the hull at the different nodes.

Capacity of the cross-sections are calculated according to the offshore rules from DNV(DNV, 2012).

A complete overview of forces, calculations on the capacities and combinations is found in appendix 6.

For the load combinations the axial force is set as a constant value, while the moments are calculated into compressive and tensile stress on each side of the cross-sections. The compression components are then added and checked towards the capacities.

Load combinations in the cross-sections	
Combinations	Utilization [%]
Bottom of shadt	
Fx+My	0.199
Fx+Mz	0.095
Pontoon to corner cylinder	
Fx+My	0.483
Fx+Mz	0.006
Pontoon to shaft cylinder	
Fx+My	0.459
Fx+Mz	0.006

Table 22 Load combinations

As the results shows, the stresses are below half the capacity, indicating that the sea-conditions at the current placement will not be problematic for this hull.

5.5   End results on the final design

5.5.1   Summarization of key results

Summarization of rigid body motions			
	Hand calculations	Wadam	3DFloat
Heave [sec]	20.87	21.5	20.04
Pitch [sec]	26.439	26	28.5
Roll [sec]	26.439	26	28.5

Table 23 Summarization of final results

Key Properties	
Structural mass [tonnes]	12 790 000
Displaced mass [tonnes]	12 845 000
Concrete volume [m^3]	2887
GM	3.39
Internal water in pontoons [tonnes]	4785
Extra weight [tonnes]	1670
Ballastwater [tonnes]	55
Static tilt at full thrust [deg]	6.593
Maximum response, heave [m]	2.67544
Maximum responste, pitch/roll [deg]	1.9

Table 24 Key properties on the final design

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5.5.2 Comments on the 3DFloat-results

3DFloat returns rigid body motions that differ somewhat from Wadam's results. This is not unexpected from a program under development and for a structural model that does not match the reality. Some problems with the structural modeling from rectangular pontoons in the real hull, to the conical sections in 3DFloat are the most likely source of the problem. Other areas that can cause discrepancies in the results are the added mass coefficients and the drag coefficients, which are kept constant from the basic model to the final concept in this thesis. The natural periods in pitch and roll are the same, implying that the hull is modeled symmetrical around its centroid. However, in the time-stepping the model behaves in a way that does not correspond with a symmetrical model when looking at the plots. With more time, further work would have been done on the input file for the final concept in 3DFloat with the aim of discovering the causes of the problems with the current model.

5.5.3 Design-process improvement

This thesis and its final concept have not taken contingencies into account, meaning design errors, additional steel weights etc, usually set at 10% of the total structural weight. The ballast water is only 55 tonnes, which can be too little to, if needed, trim the hull if that should prove necessary. Had this been known at an earlier stage in the process, it would have been included in the process.

6 End results

6.1 Comparison of key properties on the two concepts

Comparison of the two concepts		
Basic concept	Parameter	Final concept
15.9	Heave [sec]	21.5
22.5	Pitch/Roll [sec]	26
2521	Concrete volume [m3]	2887
11 369 000	Displaced mass [tonnes]	12 845 000
5.6	GM [m]	3.39

Table 25 Key figures of the two concepts
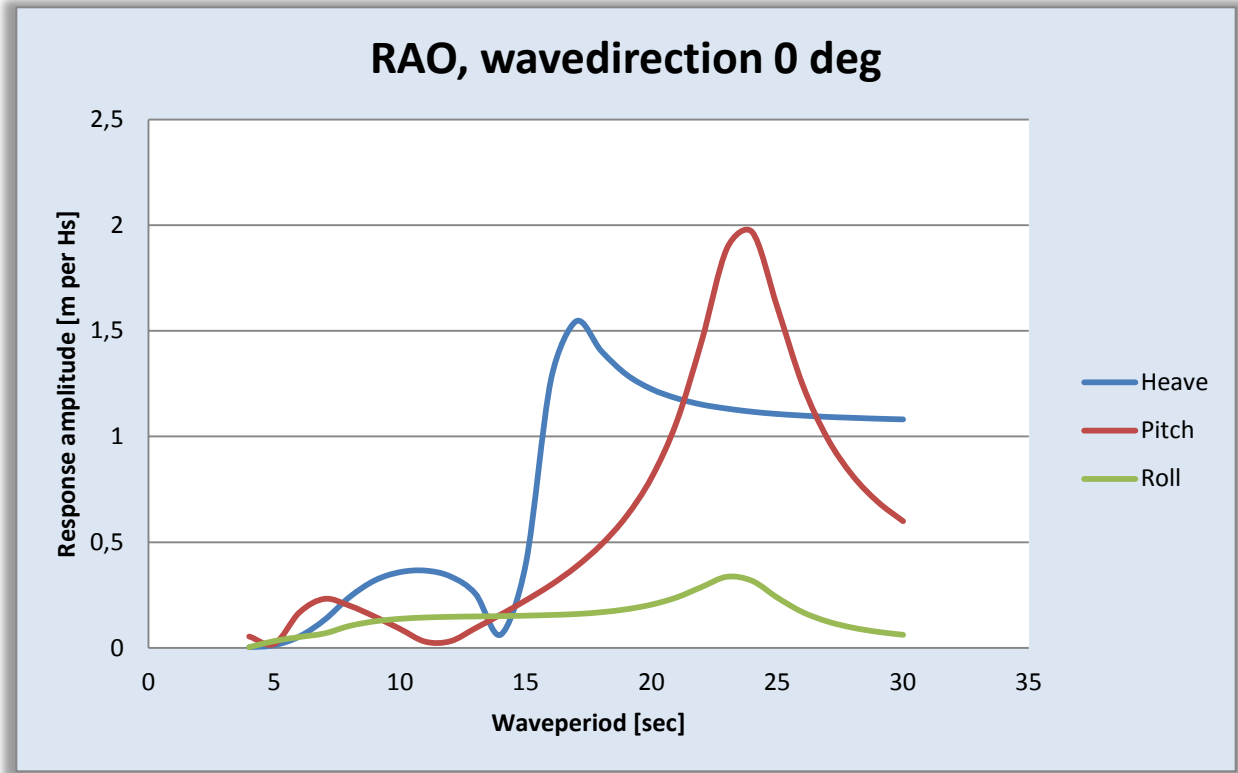
Figure 74 RAO basic concept
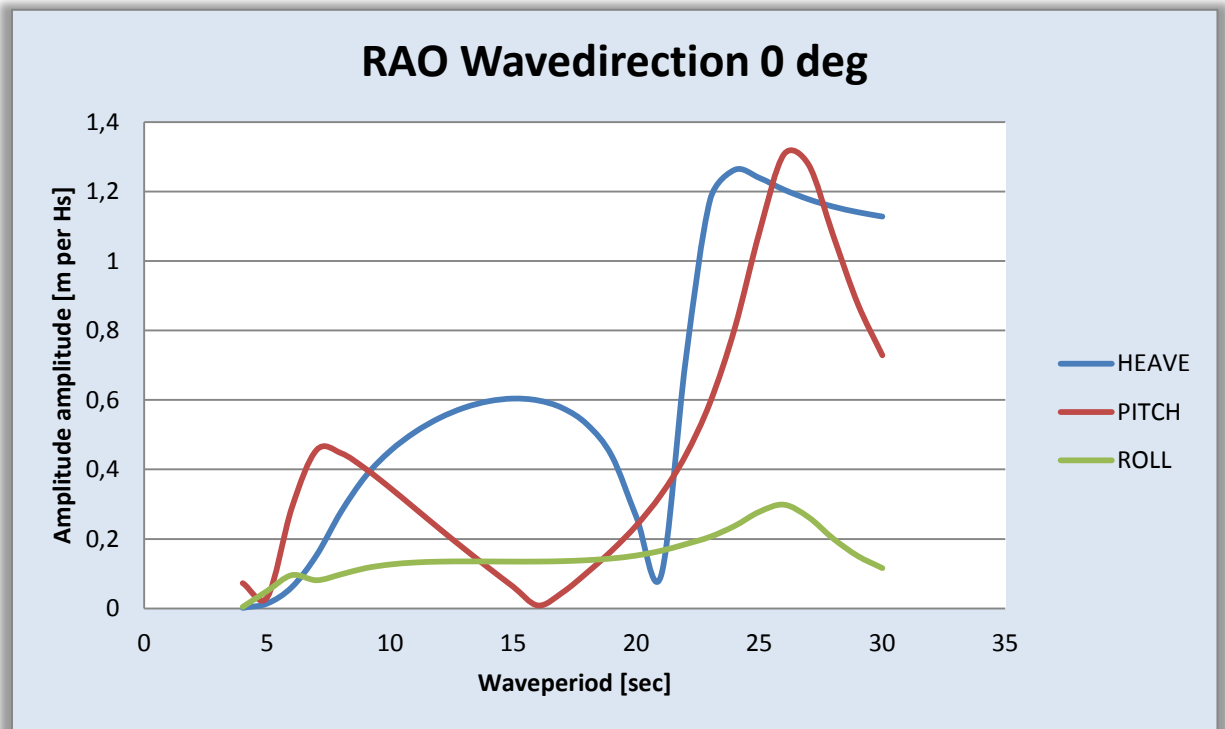
Figure 75 RAO final concept

Figure 74 and Figure 75 shows the RAOs for the two concepts - where the response is plotted for waves coming at direction 0^0. The roll response is therefore close to zero and does not give a peak where the hull's natural period lies, as both pitch and heave do in these plots. As can be seen in the graphs, the natural periods have been moved to the required level for the final concept. The scaling on the two graphs is a little different for the Y-axis, the response, due to the fact that the final concept has less response per wave height than the basic concept.

6.2   Conclusion

Based on the calculated natural periods, taking Wadam's results as definitive, the final hull concept fulfills the design criteria's very well, with 21.5 seconds in heave and 26 seconds in pitch/roll. The static tilt with regards to full wind thrust is little above the requirement, but for other geographical areas where the design wind speed is lower than the 660 kN used in this thesis, the final concept will work very well.

Working with 3DFloat has revealed several areas of interest in the modeling and post processing parts of the program for the developers, and produced, to some degree, a starting point for modeling and calculating semi-submersible hulls. The work done in this thesis with 3DFloat will benefit others who are modeling in 3DFloat and experiencing the same kind of challenges. A stripped input file is provided in the appendix for others to start modeling without worrying about the environmental settings that are needed.

The final calculation of the forces on the hull are done using a wave with wave period 10 seconds, which is a little low compared to where the maximum response is when looking at the RAO's for the final concept. This was due to the discovered limitations in 3DFloat. Even so, the forces on the hull were below 50% of the total capacity on the basic concept. It can therefore be concluded that the design is robust for the wave conditions in the areas where it is intended to operate.

With calculations done on the added mass coefficients and drag coefficients of the cylindrical elements so that they match that of the real rectangular sections, it should be possible to model the semi-submersible hull in 3DFloat so that it behaves as expected. It is then possible to find the correct forces and compare them to the cross-sectional capacities on the final concept the same way as this thesis demonstrated on the basic hull concept. When the programmers also make it possible to create waves with wave periods other than 10 seconds, a better use of 3DFloat will be possible.

The 7% added damping used in this thesis is provided by Dr.techn. Olav Olsen AS and is a number used by them in their calculations on other semi-submersible hulls. A sensitivity-study on this effect on the natural periods would have been natural to include if the time had permitted it, to see how much the added damping affects the final results.

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8 Overview of appendix

Nr	Name	Type	Pages
1	Natural periods, basic concept	Mathcad calculation sheets	2
2	3DFloat inputfile, basic concept	Textfile	12
3	Natural periods, final concept	Mathcad calculation sheets	2
4	3DFloat inputfile, final concept	Textfile	12
5	Fx/Mz/My on cross-sections	Excel graphs	5
6	Calculation of capacity	Mathcad calculation sheets	6
7	Stripped 3DFloat inputfile	Textfile	5

Appendix

1

Beregning av egenperioder:

<u>Input:</u>

Mass of structure:	$M_{structure} := 11369 \cdot tonne$	Widt of pontoon:	$W_{pontoon} := 11 \cdot m$
Waterplanearea:	$A_{waterplane} := 337 \cdot m^2$	Length of pontoon:	$L_{pontoon} := 16.4 \cdot m$
		Height of pontoon:	$H_{pontoon} := 6 \cdot m$
Metacentric height:	$GM := 5.6 \cdot m$	Radius corner cylinder	$R_{cylinder} := 5.5 \cdot m$
Displaced voume:	$V_{structure} := 11158 \cdot m^3$	Radius shaft:	$R_{shaft} := 6.1 \cdot m$
Radii of gyration:	$R_X := 23.81 \cdot m$		

<u>Physical values:</u>

$$g = 9.807 \frac{m}{s^2} \qquad tonnes := 1000 \cdot kg \qquad \rho := 1.025 \cdot \frac{tonnes}{m^3}$$

<u>Calculating added mass in heave:</u>

$$A_{mass.Pontoon} := 28 \cdot m \cdot \pi \cdot (5.5 \cdot m)^2 = 2.661 \times 10^3 \cdot m^3$$

$$A_{mass.Cylinder} := R_{cylinder}^3 \cdot 0.5 \left(\frac{4}{3}\right) \cdot \pi = 348.455 \cdot m^3$$

$$A_{mass.Shaft} := 0.5 \left(\frac{4}{3}\right) \cdot \pi \cdot R_{shaft}^3 = 475.388 \cdot m^3$$

$$Addedmass := \left(A_{mass.Shaft} + 3 \cdot A_{mass.Cylinder} + 3 \cdot A_{mass.Pontoon}\right) \cdot \rho = 9741.128 \cdot tonnes$$

Calculating added moment for pitch/roll:

C/C cylinders:

$cc_{cylinder} := 28 \cdot m$ $Cg := 20 \cdot m - 12.81 \cdot m = 7.19\,m$

$Cg2 := Cg - 3 \cdot m = 4.19\,m$

Center of pontoon in Y-direction: $Pontoon_{center} := R_{shaft} + \dfrac{L_{pontoon}}{2} = 14.3\,m$

Moment arm cylinder: $Arm_{cylinder} := \sqrt{cc_{cylinder}^2 + Cg^2} = 28.908\,m$

Moment arm pontoon: $Arm_{pontoon} := \sqrt{Pontoon_{center}^2 + Cg2^2} = 14.901\,m$

$A_{mom.cylinder} := \rho \cdot A_{mass.Cylinder} \cdot Arm_{cylinder}^2 = 2.985 \times 10^8\,m^2 \cdot kg$

$A_{mom.pontoon} := \rho \cdot A_{mass.Pontoon} \cdot Arm_{pontoon}^2 = 6.056 \times 10^8\,m^2 \cdot kg$

$A_{moment} := A_{mom.cylinder} \cdot 2 + A_{mom.pontoon} \cdot 2 = 1.808 \times 10^9\,m^2 \cdot kg$

Results:

$T_{heave} := 2 \cdot \pi \cdot \sqrt{\dfrac{M_{structure} + Addedmass}{\rho \cdot g \cdot A_{waterplane}}} = 15.685\,s$

$T_{pitch.roll} := 2 \cdot \pi \cdot \sqrt{\dfrac{M_{structure} \cdot R_x^2 + A_{moment}}{\rho \cdot g \cdot V_{structure} \cdot GM}} = 22.777\,s$

Appendix

2

```
!Environment;

set_environment  gravity on  buoyancy on  hydro_force morison
wind_force ndrg  waves streamfunction  norder -1  wind no_mean_profile
pre_computed_waves_file off  random_mode write_file  randomfile  rho_water 1025.
rho_air 0.001  nu_water 1.e-5  nu_air 1.e-6  wave_amplitude 2.75
wavelength 156.07768226721353  wave_direction 0.  current_speed 0.  current_direction
0.
tsweeps 0.  tsweepe -1  stretch 0.  wind_speed  0.
wind_ref_height 90.  wind_exponent 0.  wind_direction 0.  spectral_peak 11.4
seed .3  nfreq 64.  wave_ramps  0.  wave_rampe  20.  depth 200.0
tshift_waves 0.  tshift_wind 0.

wave_forces cm_morison 1.63

!for egenfrekvenser; gravity off buoyancy off; må lage en linearisert stivhetsmatrise
på bunn

!Defining materials needed to construct model:

define_material  name betong0-6  rho 2272  e 0.55e+11  g 21.15e+9
define_material  name betong6-35  rho 2281  e 0.55e+11  g 21.15e+9
define_material  name betong0  rho 0.001  e 0.55e+11  g 21.15e+9
define_material  name betong_hjørne  rho 1295  e 0.55e+11  g 21.15e+9


!==========================================================================================
==============================
!------------------------------------------------------------------------------------------
---------------------------------
!
!!! SEMI-SUBMERSIBLE
!==========================================================================================
==============================
!
!!    Sentersoyle    Koordinat (0,0,0) er i vannlinjen!
!!    Sette inn lokket i bucketen?
! Punktmasser til skaftet:
! Hull machanical weights 200 000 kg vcg -2.5
! Extra weights 570 VCG -9.644
! Mooring tension 240 000 VCG -14.4

new_body  name   Sentersoyle   parent   inertial   reftype   inertial
axes normal

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 0.0 0.0 -20.0  dcyl1 12.2  tcyl1 0.6  pre_strain_long  0.0
x2 0.0 0.0 -17  dcyl2 12.2  tcyl2 0.6  btype beam_lid1 pointmass 107957.69
frac_stiff 1.0   cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 0.0 0.0 -17  dcyl1 12.2  tcyl1 0.6  pre_strain_long  0.0
x2 0.0 0.0 -14.4  dcyl2 12.2  tcyl2 0.6  btype beam pointmass 107957.69 !tan removed
_lid1
frac_stiff 1.0   cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 0.0 0.0 -14.4  dcyl1 12.2  tcyl1 0.6  pre_strain_long  0.0
x2 0.0 0.0 -14  dcyl2 12.2  tcyl2 0.6  btype beam pointmass 240000
frac_stiff 1.0   cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong6-35 connect_mode auto
x1 0.0 0.0 -14  dcyl1 12.2  tcyl1 0.5  pre_strain_long  0.0
x2 0.0 0.0 -12  dcyl2 11.28  tcyl2 0.5  btype beam pointmass 0
frac_stiff 1.0   cdn 0.56 cma 1.0
```

```
new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 -12 dcyl1 11.28  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 -10.4  dcyl2 10.54  tcyl2 0.45  btype beam pointmass 0
frac_stiff 1.0   cdn 0.56 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 -10.4 dcyl1 10.54  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 -9.644  dcyl2 10.365  tcyl2 0.45  btype beam pointmass 444700
frac_stiff 1.0   cdn 0.56 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 -9.644 dcyl1 10.365  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 -2.5  dcyl2 9.154  tcyl2 0.45  btype beam pointmass 570000
frac_stiff 1.0   cdn 0.56 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 -2.5 dcyl1 9.154  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 -1  dcyl2 8.509  tcyl2 0.45  btype beam pointmass 200000
frac_stiff 1.0   cdn 0.56 cma 1.0


!Der hvor et element krysser vannlinjen, lag et finere element i det området.

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 -1 dcyl1 8.509  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 0  dcyl2 7.9  tcyl2 0.45  btype beam pointmass 0
frac_stiff 1.0   cdn 0.56 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 0 dcyl1 7.9  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 1  dcyl2 7.9  tcyl2 0.45  btype beam pointmass 0
frac_stiff 1.0   cdn 0.56 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 1 dcyl1 7.9  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 9.39  dcyl2 7.9  tcyl2 0.45  btype beam pointmass 0
frac_stiff 1.0   cdn 0.56 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 9.39 dcyl1 7.9  tcyl1 0.55  pre_strain_long  0.0
x2 0.0 0.0 12.5  dcyl2 8.1  tcyl2 0.55  btype beam pointmass 43900
frac_stiff 1.0   cdn 0.56 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 12.5 dcyl1 8.1  tcyl1 0.55  pre_strain_long  0.0
x2 0.0 0.0 15  dcyl2 8.1  tcyl2 0.55  btype beam pointmass 0 ! removed _lid2
frac_stiff 1.0   cdn 0.56 cma 1.0


! ----------------------------------------------

!Turbine tower   - VCG 45.5 over vannflaten

new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 15 dcyl1 10  tcyl1 0.55  pre_strain_long  0.0
x2 0.0 0.0 30  dcyl2 10  tcyl2 0.55  btype beam pointmass 0
frac_stiff 1.0   cdn 0.56 cma 1.0


new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 45.5 dcyl1 10  tcyl1 0.55  pre_strain_long  0.0
x2 0.0 0.0 30  dcyl2 10  tcyl2 0.55  btype beam pointmass 350000
frac_stiff 1.0   cdn 0.56 cma 1.0


!Nacelle+rotor   - VCG i 82 over vannflaten
```

```
new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 45.5 dcyl1 10  tcyl1 0.55  pre_strain_long  0.0
x2 0.0 0.0 60  dcyl2 10  tcyl2 0.55  btype beam pointmass 0
frac_stiff 1.0   cdn 0.56 cma 1.0


new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 82 dcyl1 10  tcyl1 0.55  pre_strain_long  0.0
x2 0.0 0.0 60  dcyl2 10  tcyl2 0.55  btype beam pointmass 310000
frac_stiff 1.0   cdn 0.56 cmn 1.0 cma 1.0



!================================================================================
===============================
!
!!     Leg 1 - pontongen og sylinderen som er rett frem
!
new_body  name  Leg1  parent  Sentersoyle  reftype  refnode  xfind  0.0 0.0 -20.0

rotorder 123  rotation  0. 0. 0.0   axes normal

! Leg Column Denne går fra senter shaft ut til radiusen, bare et tynt bjelkeelement
uten masse,oppdrift osv. bare for å ha noe å feste pontongelementet på

new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 3  dcyl1 10  tcyl1 0.06  pre_strain_long  0.0
x2 6.1 0.0 3  dcyl2 10  tcyl2 0.06  btype beamwb pointmass 0
frac_stiff 1.0   cdn 0 cda 0 cma 1
!beamwb fordi jeg ikke skal ha dobbel oppdrift,fjerner denne delens oppdrift

!! Pontongen er delt opp i 3 elementer pluss to endestykker som får fra senter søylene

! Første del av pontongelementet - trenger lokk i x1

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 6.1 0.0 3  dcyl1 6.11  tcyl1 0.631  pre_strain_long  0.0
x2 10.475 0.0 3  dcyl2 6.11  tcyl2 0.631  btype beam pointmass 0 !tan _lid1
frac_stiff 1.0   cdn 0.68 cmn 3.5

! Andre del av pontongelementet - har en pointmass for alt vannet i pontongene - her
satt i enden av elementet,ikke helt i midten men kan justeres siden.
! Plusser på vekten av tverrskottene til punktmassen her.

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 10.475 0.0 3  dcyl1 6.11  tcyl1 0.631  pre_strain_long  0.0
x2 14 0.0 3  dcyl2 6.11  tcyl2 0.631  btype beam pointmass 0
frac_stiff 1.0   cdn 0.68 cmn 3.5

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 14 0.0 3  dcyl1 6.11  tcyl1 0.631  pre_strain_long  0.0
x2 17.725 0.0 3  dcyl2 6.11  tcyl2 0.631  btype beam pointmass 1023876.12
frac_stiff 1.0   cdn 0.68 cmn 3.5

! Tredje del av pontongelementet - trenger lokk i x2

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 17.725 0.0 3  dcyl1 6.11  tcyl1 0.631  pre_strain_long  0.0
x2 22.5 0.0 3  dcyl2 6.11  tcyl2 0.631  btype beam  pointmass 0 !tan _lid2
frac_stiff 1.0   cdn 0.68 cmn 3.5


!Forbindelseselement fra andre del av pontongen inn til senter hjørnesøyle.

new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 22.5 0.0 3  dcyl1 10  tcyl1 0.06  pre_strain_long  0.0
```

```
x2  28.0 0.0 3  dcyl2 10  tcyl2 0.06  btype beambw pointmass 0.0
frac_stiff 1.0    cdn 0.68 cma 1.677

!beamwb fordi jeg ikke skal ha dobbel oppdrift,fjerner denne delens oppdrift

! Hjørnesylinderen
! Kan legge til litt masser ved å legge til lokk i bunn og på toppen som vekt, må da
ha flere elementer.

new_elements_beam1  nelem 1  material betong_hjørne connect_mode auto
x1 28.0 0.0 0  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 3  dcyl2 11.0  tcyl2 0.3  btype beam_lid1 pointmass 96883.9528
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong_hjørne connect_mode auto
x1 28.0 0.0 3  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 4.52  dcyl2 11.0  tcyl2 0.3  btype beam pointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong0-6 connect_mode auto
x1 28.0 0.0 4.52  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 6  dcyl2 11.0  tcyl2 0.3  btype beam pointmass 393693
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 6  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 19  dcyl2 11.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 19  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 21  dcyl2 11.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 21  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 29  dcyl2 11.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 30  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 29  dcyl2 11.0  tcyl2 0.3  btype_lid1 beam pointmass 57901.0103
frac_stiff 1.0    cdn 0.61 cma 1.0




!======================================================================================
==================================
!
!     Leg 2 pontongen og sylinderen som er rotert 120 grader på den i midten

new_body name  Leg2  parent  Sentersoyle  reftype  refnode  xfind  0.0 0.0 -20.0

rotorder 123  rotation  0.0 0.0 120.0    axes normal

! Leg Column Denne går fra senter shaft ut til radiusen, bare et tynt bjelkeelement
uten masse,oppdrift osv. bare for å ha noe å feste pontongelementet på

new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 3  dcyl1 10  tcyl1 0.06  pre_strain_long  0.0
x2 6.1 0.0 3  dcyl2 10 tcyl2 0.06  btype beamwb pointmass 0
frac_stiff 1.0    cdn 0 cda 0 cma 1
!beamwb fordi jeg ikke skal ha dobbel oppdrift,fjerner denne delens oppdrift
```

```
!! Pontongen er delt opp i 3 elementer pluss to endestykker som får fra senter søylene

! Første del av pontongelementet - trenger lokk i x1

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 6.1 0.0 3  dcyl1 6.11  tcyl1 0.631  pre_strain_long  0.0
x2 10.475 0.0 3  dcyl2 6.11  tcyl2 0.631  btype beam  pointmass 0 ! tan _lid1
frac_stiff 1.0    cdn 0.68 cmn 3.5

! Andre del av pontongelementet - har en pointmass for alt vannet i pontongene - her
satt i enden av elementet,ikke helt i midten men kan justeres siden.
! Plusser på vekten av tverrskottene til punktmassen her.

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 10.475 0.0 3  dcyl1 6.11  tcyl1 0.631  pre_strain_long  0.0
x2 14 0.0 3  dcyl2 6.11  tcyl2 0.631  btype beam pointmass 0
frac_stiff 1.0    cdn 0.68 cmn 3.5

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 14 0.0 3  dcyl1 6.11  tcyl1 0.631  pre_strain_long  0.0
x2 17.725 0.0 3  dcyl2 6.11  tcyl2 0.631  btype beam pointmass 1023876.12
frac_stiff 1.0    cdn 0.68 cmn 3.5

! Tredje del av pontongelementet - trenger lokk i x2

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 17.725 0.0 3  dcyl1 6.11  tcyl1 0.631  pre_strain_long  0.0
x2 22.5 0.0 3  dcyl2 6.11  tcyl2 0.631  btype beam  pointmass 0   !tan _lid2
frac_stiff 1.0    cdn 0.68 cmn 3.5


!Forbindelseselement fra andre del av pontongen inn til senter hjørnesøyle.

new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 22.5 0.0 3  dcyl1 10  tcyl1 0.06  pre_strain_long  0.0
x2  28.0 0.0 3  dcyl2 10  tcyl2 0.06  btype beambw pointmass 0.0
frac_stiff 1.0    cdn 0.68 cma 1.677

!beamwb fordi jeg ikke skal ha dobbel oppdrift,fjerner denne delens oppdrift

! Hjørnesylinderen
! Kan legge til litt masser ved å legge til lokk i bunn og på toppen som vekt, må da
ha flere elementer.

new_elements_beam1  nelem 1  material betong_hjørne connect_mode auto
x1 28.0 0.0 0  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 3  dcyl2 11.0  tcyl2 0.3  btype beam_lid1 pointmass 96883.9528
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong_hjørne connect_mode auto
x1 28.0 0.0 3  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 4.52  dcyl2 11.0  tcyl2 0.3  btype beam pointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong0-6 connect_mode auto
x1 28.0 0.0 4.52  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 6  dcyl2 11.0  tcyl2 0.3  btype beam pointmass 393693
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 6  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 19  dcyl2 11.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0
```

```
new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 19  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 21  dcyl2 11.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 21  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 29  dcyl2 11.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 30  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 29  dcyl2 11.0  tcyl2 0.3  btype_lid1 beam pointmass 57901.0103
frac_stiff 1.0    cdn 0.61 cma 1.0



!===========================================================================
================================
!
!!     Leg 3   Pontongen og sylinderen som er rotert 240 grader på den normale
!
new_body  name  Leg3  parent  Sentersoyle  reftype  refnode  xfind   0.0 0.0 -20.0

rotorder 123  rotation   0.0 0.0 240.0   axes normal

! Leg Column Denne går fra senter shaft ut til radiusen, bare et tynt bjelkeelement
uten masse,oppdrift osv. bare for å ha noe å feste pontongelementet på

new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 3  dcyl1 10  tcyl1 0.06  pre_strain_long  0.0
x2 6.1 0.0 3  dcyl2 10  tcyl2 0.06  btype beamwb pointmass 0
frac_stiff 1.0    cdn 0 cda 0 cma 1

!beamwb fordi jeg ikke skal ha dobbel oppdrift,fjerner denne delens oppdrift

!! Pontongen er delt opp i 3 elementer pluss to endestykker som får fra senter søylene

! Første del av pontongelementet - trenger lokk i x1

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 6.1 0.0 3  dcyl1 6.11  tcyl1 0.631  pre_strain_long  0.0
x2 10.475 0.0 3  dcyl2 6.11  tcyl2 0.631  btype beam pointmass 0   ! tan _lid1
frac_stiff 1.0    cdn 0.68 cmn 3.5

! Andre del av pontongelementet - har en pointmass for alt vannet i pontongene - her
satt i enden av elementet,ikke helt i midten men kan justeres siden.
! Plusser på vekten av tverrskottene til punktmassen her.

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 10.475 0.0 3  dcyl1 6.11  tcyl1 0.631  pre_strain_long  0.0
x2 14 0.0 3  dcyl2 6.11  tcyl2 0.631  btype beam pointmass 0
frac_stiff 1.0    cdn 0.68 cmn 3.5


new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 14 0.0 3  dcyl1 6.11  tcyl1 0.631  pre_strain_long  0.0
x2 17.725 0.0 3  dcyl2 6.11  tcyl2 0.631  btype beam pointmass 1023876.12
frac_stiff 1.0    cdn 0.68 cmn 3.5


! Tredje del av pontongelementet - trenger lokk i x2

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 17.725 0.0 3  dcyl1 6.11  tcyl1 0.631  pre_strain_long  0.0
x2 22.5 0.0 3  dcyl2 6.11  tcyl2 0.631  btype beam  pointmass 0  ! tan _lid2
frac_stiff 1.0    cdn 0.68 cmn 3.5
```

!Forbindelseselement fra andre del av pontongen inn til senter hjørnesøyle.

```
new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 22.5 0.0 3  dcyl1 10  tcyl1 0.06  pre_strain_long  0.0
x2  28.0 0.0 3  dcyl2 10  tcyl2 0.06  btype beambw pointmass 0.0
frac_stiff 1.0   cdn 0.68 cma 1.677
```

!beamwb fordi jeg ikke skal ha dobbel oppdrift,fjerner denne delens oppdrift

! Hjørnesylinderen
! Kan legge til litt masser ved å legge til lokk i bunn og på toppen som vekt, må da
ha flere elementer.

```
new_elements_beam1  nelem 1  material betong_hjørne connect_mode auto
x1 28.0 0.0 0  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 3  dcyl2 11.0  tcyl2 0.3  btype beam_lid1 pointmass 96883.9528
frac_stiff 1.0   cdn 0.61 cma 1.0
```

```
new_elements_beam1  nelem 1  material betong_hjørne connect_mode auto
x1 28.0 0.0 3  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 4.52  dcyl2 11.0  tcyl2 0.3  btype beam pointmass 393693
frac_stiff 1.0   cdn 0.61 cma 1.0
```

```
new_elements_beam1  nelem 1  material betong0-6 connect_mode auto
x1 28.0 0.0 4.52  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 6  dcyl2 11.0  tcyl2 0.3  btype beam pointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0
```

```
new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 6  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 19  dcyl2 11.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0
```

```
new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 19  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 21  dcyl2 11.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0
```

```
new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 21  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 29  dcyl2 11.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0
```

```
new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 30  dcyl1 11  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 29  dcyl2 11.0  tcyl2 0.3  btype_lid1 beam pointmass 57901.0103
frac_stiff 1.0   cdn 0.61 cma 1.0
```

!===
===============================

!Define sea bed

```
apply_nodal_bc find 0.  0.  0.  wall  idofs 3 idofe 3  displ -200.0 1.    dstat 0.01
```

!===
===============================

!! Apply gravitational force to pointmasses:
!! her må alle pointmasser som er satt inn settes inn igjen i globale koordinater! DVS
vannlijen er 0 0 0
!!dette er i M*g !!! g er her 9,80665. de tre siste koordinatene er rotasjon.

```
!Nacelle+rotor

apply_nodal_bc find 0 0.0 82 apply_force 0.0 0.0 -3040061.5 0. 0. 0.

!Tower

apply_nodal_bc find 0 0.0 45.5 apply_force 0.0 0.0 -3432327.5 0. 0. 0.

!Hull mechanical weights

apply_nodal_bc find 0 0.0 -2.5 apply_force 0.0 0.0 -1961330 0. 0. 0.

!Mooring tension

apply_nodal_bc find 0 0.0 -14.4 apply_force 0.0 0.0 -2353596 0. 0. 0.

!Extra weights

apply_nodal_bc find 0 0.0 -9.644 apply_force 0.0 0.0 -5589790.5 0. 0. 0.

!Manglende masse
apply_nodal_bc find 0 0.0 -10.4 apply_force 0.0 0.0 -4361017.255 0. 0. 0.

!Må også ha med vann+skrog i pontongene

apply_nodal_bc find 0 14 -17 apply_force 0.0 0.0 -10272613 0. 0. 0.
apply_nodal_bc find -12.12435 -7 -17 apply_force 0.0 0.0 -10272613 0. 0. 0.
apply_nodal_bc find 12.12435 -7 -17 apply_force 0.0 0.0 -10272613 0. 0. 0.

!De diverse lokkene på sylindrene som jeg har satt på

!Bunn shaft:
apply_nodal_bc find 0 0 -20 apply_force 0.0 0.0 -1058703.281 0. 0. 0.
!Lokk i bucket
apply_nodal_bc find 0 0 9.39 apply_force 0.0 0.0 -430511.935 0. 0. 0.
!Bunnlokk hjørnesylindre:
apply_nodal_bc find 0 28 -20 apply_force 0.0 0.0 -946358.3963 0. 0. 0.
apply_nodal_bc find -24.24871131 -14 -20 apply_force 0.0 0.0 -946358.3963 0. 0. 0.
apply_nodal_bc find 24.24871131 -14 -20 apply_force 0.0 0.0 -946358.3963 0. 0. 0.

!Topplokk hjørnesylindre:
apply_nodal_bc find 0 28 10 apply_force 0.0 0.0 -570064.4872 0. 0. 0.
apply_nodal_bc find -24.24871131 -14 10 apply_force 0.0 0.0 -570064.4872 0. 0. 0.
apply_nodal_bc find 24.24871131 -14 10 apply_force 0.0 0.0 -570064.4872 0. 0. 0.

!=============================================================================
===============================


!Sensorer inn her

!Dette er en monitor i vannplansnoden. Lager en egen outputfil så vi kan se om
konstruksjonen flyer/synker,dvs fungerer.

monitor_element_b1 type orientation file vannplan_node.txt nmonitor 10 find 0. 0. 1
node 1

!For krefter, setter inn en nodei overgangen til pontongen f.eks

monitor_element_b1 type forces  file bottom_shaft_force.txt  nmonitor 10 find 0 0 -
14.2   node 1

monitor_element_b1 type moments file bottom_shaft_moment.txt nmonitor 10 find 0 0 -
14.2   node 1
```

```
monitor_element_b1 type forces  file pontooncorner_force.txt  nmonitor 10 find 20.1125
0 -17 node 1

monitor_element_b1 type moments file pontooncorner_moment.txt nmonitor 10 find 20.1125
0 -17 node 1

monitor_element_b1 type forces file pontoonshaft_force.txt  nmonitor 10 find 8.2875 0 -
17 node 1

monitor_element_b1 type forces file pontoonshaft_moment.txt nmonitor 10 find 8.2875 0 -
17 node 1




!================================================================================
================================

file IFE_3Dfloat_WP2_LC2.1.txt  label oc4p2_gather  toffset 250
sensors:
nfact: 1 source: WindVxi        scale: 1.             unit: [m/s]  ! header as source
label
nfact: 1 source: WindVyi        scale: 1.             unit: [m/s]  !
nfact: 1 source: WindVzi        scale: 1.             unit: [m/s]  !
nfact: 1 source: WaveElev       scale: 1.             unit: [m]    !
nfact: 1 source: GenPwr         scale: 0.  .001        unit: [kW]   !
nfact: 1 source: GenTq          scale: 0.  1.030927835e-5       unit: [kNm]  !
1./97.e3
nfact: 1 source: Azimuth        scale: 0.  57.295779513082323    unit: [deg]  !
180./rpi
nfact: 1 source: RotSpeed       scale: 0.  60.           unit: [rpm]  !
nfact: 1 source: RotSpeed       scale: 0.  5820.         unit: [rpm]  header:
GenSpeed   ! 60*97
nfact: 1 source: OoPDefl1       scale: 0.  1.            unit: [m]    !
nfact: 1 source: IPDefl1        scale: 0.  1.            unit: [m]    !
nfact: 1 source: Twst_yx        scale: 0.  57.295779513082323  unit: [deg]  header:
TwstDefl1
nfact: 1 source: BldPitch1      scale: 0.            unit: [deg]  !  ???
nfact: 1 source: TTDspFA        scale: 1.            unit: [m]    !
nfact: 1 source: TTDspSS        scale: 1.            unit: [m]    !
nfact: 1 source: TTDsp_yx       scale: 57.295779513082323  unit: [deg]  header:
TTDspTwst
nfact: 1 source: PtfmSurge      scale: 1.            unit: [m]    ! rel. inertia
nfact: 1 source: PtfmSway       scale: 1.            unit: [m]    !
nfact: 1 source: PtfmHeave      scale: 1.            unit: [m]    !
nfact: 1 source: Ptfm_yz        scale: 57.295779513082323  unit: [deg]  header:
PtfmRoll
nfact: 1 source: Ptfm_xx        scale: 57.295779513082323  unit: [deg]  header:
PtfmPitch
nfact: 1 source: Ptfm_yx        scale: -57.295779513082323  unit: [deg]  header:
PtfmYaw
nfact: 2 source: blrootfx blrootfxi scale: 0.  0.  .001  .001 unit: [kN] header:
RootFxc1  !
nfact: 2 source: blrootfy blrootfyi scale: 0.  0.  .001  .001 unit: [kN] header:
RootFyc1  !
nfact: 2 source: blrootfz blrootfzi scale: 0.  0.  .001  .001 unit: [kN] header:
RootFzc1  !
nfact: 2 source: blrootmx blrootmxi scale: 0.  0.  .001  .001 unit: [kN] header:
RootMxc1  !
nfact: 2 source: blrootmy blrootmyi scale: 0.  0.  .001  .001 unit: [kN] header:
RootMyc1  !
```

```
nfact: 1 source: RootMzc1      scale:  0.          unit: [kNm] !
nfact: 1 source: RotTorq       scale: 0.  -.001     unit: [kNm] !
nfact: 1 source: LSSGagMya     scale: 0.  -.001     unit: [kNm] !
nfact: 1 source: LSSGagMza     scale: 0.  -.001     unit: [kNm] !
nfact: 1 source: YawBrFxp      scale: -.001        unit: [kN]  ! Nacelle coord.syst.
nfact: 1 source: YawBrFyp      scale:  .001        unit: [kN]  !
nfact: 1 source: YawBrFzp      scale: -.001        unit: [kN]  !
nfact: 1 source: YawBrMxp      scale:  .001        unit: [kNm] !
nfact: 1 source: YawBrMyp      scale:  .001        unit: [kNm] !
nfact: 1 source: YawBrMzp      scale:  .001        unit: [kNm] !
nfact: 1 source: TwrBsFxt      scale:  .001        unit: [kN]  ! Tower base
coord.sys.
nfact: 1 source: TwrBsFyt      scale:  .001        unit: [kN]  !
nfact: 1 source: TwrBsFzt      scale: -.001        unit: [kN]  !
nfact: 1 source: TwrBsMxt      scale: -.001        unit: [kNm] !
nfact: 1 source: TwrBsMyt      scale: -.001        unit: [kNm] !
nfact: 1 source: TwrBsMzt      scale:  .001        unit: [kNm] !
nfact: 1 source: UC1YU1Fx      scale:  .001        unit: [kN]  ! Local element
coord.sys.
nfact: 1 source: UC1YU1Fy      scale:  .001        unit: [kN]  ! x-axis beam axis
nfact: 1 source: UC1YU1Fz      scale:  .001        unit: [kN]  ! z-axis UC axis
upwards
nfact: 1 source: UC1DU1Fx      scale:  .001        unit: [kN]  !
nfact: 1 source: UC1DU1Fy      scale:  .001        unit: [kN]  !
nfact: 1 source: UC1DU1Fz      scale:  .001        unit: [kN]  !
nfact: 1 source: Fair1Ten      scale: -.001        unit: [kN]  ! Positive when in
tension
nfact: 1 source: Fair2Ten      scale: -.001        unit: [kN]  !
nfact: 1 source: Fair3Ten      scale: -.001        unit: [kN]  !
nfact: 1 source: Fair1Ang      scale: 0.           unit: [deg] ! Angle from
horizontal
nfact: 1 source: Fair2Ang      scale: 0.           unit: [deg] !   POSITIVE value
nfact: 1 source: Fair3Ang      scale: 0.           unit: [deg] !
nfact: 1 source: Anch1Ten      scale:  .001        unit: [kN]  ! Positive when in
tension
nfact: 1 source: Anch2Ten      scale:  .001        unit: [kN]  !
nfact: 1 source: Anch3Ten      scale:  .001        unit: [kN]  !
nfact: 1 source: Anch1Ang      scale: 0.           unit: [deg] ! Angle from
horizontal
nfact: 1 source: Anch2Ang      scale: 0.           unit: [deg] !   POSITIVE value
nfact: 1 source: Anch3Ang      scale: 0.           unit: [deg] !
nfact: 1 source: Fair1_xz      scale: -1.          unit: [sin] !
nfact: 1 source: Fair2_xz      scale: -1.          unit: [sin] !
nfact: 1 source: Fair3_xz      scale: -1.          unit: [sin] !
nfact: 1 source: Anch1_xz      scale: -1.          unit: [sin] !
nfact: 1 source: Anch2_xz      scale: -1.          unit: [sin] !
nfact: 1 source: Anch3_xz      scale: -1.          unit: [sin] !


!================================================================================
====================================

!Stivhetsmatriser for egenfrekvens og draft (hvor i vannet vi flyter)

!Restoring moment due to buoyancy

!add_node_stiffness  find  0.  0.  0.
f_lin  0. 0. 107140102.912   0.  0.  0.
x_lin  0. 0. 0. 0. 0. 0.
3    3     3388941.85
4    4     623452085.1
5    5     623452085.1


!Restoring moment due to gravity
```

```
!add_node_stiffness  find   0.  0.  0.
f_lin  0.  0.  -53906675.05   0.  0.  0.
x_lin  0.  0.  0.  0.  0.  0.
4  4      -70747963.67
5  5      -70747963.67


!f_lin  0.  0.  -1839.e3  0.  0.  0.  ! OC4


add_node_stiffness  find   0.  0.  0.    ! mooring, from the OC4 semisub, adjusted for
ballast
f_lin  0.  0.  -3361.e3  0.  0.  0.
x_lin  0.  0.  0.  0.  0.  0.
 1   1     70.8e3
 2   2     70.8e3
 3   3     19.1e3
 4   4     87.3e6
 5   5     87.3e6
 6   6     117.e6
 1   5     -108.e3
 5   1     -107.e3
 2   4      108.e3
 4   2      107.e3



!_____

!For egenfrekvensene

!damping type ratio2rayl  ratio_1 0.05  ratio_2 0.05  omega_1  0.05  omega_2   1.



!
! plotting with Python script plot_geo.py

monitor_element_b1  type plot nmonitor 100 file turb1.plot

!
newmark dt 0.025  nassemble 1 nnewton 5 nsubmin 2  rwilson 0.9
relax 0.0  resid_newton  1e-06  nmonitor 100


!damping type rayleigh    alpha .1  beta .1


damping type ratio2rayl  ratio_1 .01  ratio_2 .01  omega_1  0.1  omega_2   1.


step nstep 20000 method gen_alpha

end

eigen_analysis old nfreq 20 amplitude 10 filename frekvenser.txt

!_____

!printing og plotting til outputfiler

!print_nodes
nodes.txt
-1  -1

!print_b1_elements
elements.txt
```

```
-1 -1
 3 2 3 2


! Tecplot
!
!monitor_element_b1  type tecplot nmonitor 10
file turb1.dat


print_solution
solution.txt

END
!_____
```

Appendix

3

Beregning av egenperioder:

Input:

Mass of structure: $M_{structure} := 12790 \cdot tonne$

Waterplanearea: $A_{waterplane} := 287.552268 \cdot m^2$

Metacentric height: $GM := 3.32 \cdot m$

Displaced voume: $V_{structure} := 12531.3566 \cdot m^3$

Radii of gyration: $R_x := 22.3 \cdot m$

Widt of pontoon: $W_{pontoon1} := 10 \cdot m$

Length of pontoon: $L_{pontoon} := 16.4 \cdot m$

Height of pontoon: $H_{pontoon} := 6 \cdot m$

Radius shaft: $R_{shaft} := 6.5 \cdot m$

Radius corner cylinder: $R_{cylinder} := 5 \cdot m$

Width of pontoon2: $W_{pontoon.2} := 21.6551 \cdot m$

Physical values:

$$g = 9.807 \frac{m}{s^2} \qquad tonnes := 1000 \cdot kg \quad \rho := 1.025 \cdot \frac{tonnes}{m^3}$$

Calculating added mass in heave:

$$A_{mass.Pontoon} := \frac{28 \cdot m}{12} \cdot \pi \cdot \left(W_{pontoon1}^2 + W_{pontoon1} \cdot W_{pontoon.2} + W_{pontoon.2}^2 \right)$$

$$A_{mass.Pontoon} = 5.758 \times 10^3 \cdot m^3$$

$$A_{mass.Cylinder} := R_{cylinder}^3 \cdot 0.5 \left(\frac{4}{3} \right) \cdot \pi = 261.799 \cdot m^3$$

$$A_{mass.Shaft} := 0.5 \left(\frac{4}{3} \right) \cdot \pi \cdot R_{shaft}^3 = 575.173 \cdot m^3$$

$$Addedmass := \left(A_{mass.Shaft} + 3 \cdot A_{mass.Cylinder} + 3 \cdot A_{mass.Pontoon} \right) \cdot \rho = 19100.357 \cdot tonnes$$

<u>Calculating added moment for pitch/roll</u>:

C/C cylinders: $cc_{cylinder} := 28 \cdot m$ $Cg := 20 \cdot m - 10.55 \cdot m = 9.45\,m$

$Cg2 := Cg - 3 \cdot m = 6.45\,m$

Center added mass cylinder in X-direction: $Pontoon_{center} := 7.27 \cdot m$

Moment arm cylinder: $Arm_{cylinder} := cc_{cylinder} = 28\,m$

Moment arm pontoon: $Arm_{pontoon} := Pontoon_{center} = 7.27\,m$

$A_{mom.cylinder} := \rho \cdot A_{mass.Cylinder} \cdot Arm_{cylinder}^2 = 2.104 \times 10^8\,m^2 \cdot kg$

$A_{mom.pontoon} := \rho \cdot A_{mass.Pontoon} \cdot Arm_{pontoon}^2 = 3.119 \times 10^8\,m^2 \cdot kg$

$A_{moment} := A_{mom.cylinder} \cdot 2 + A_{mom.pontoon} \cdot 2 = 1.045 \times 10^9\,m^2 \cdot kg$

Results:

$$T_{heave} := 2 \cdot \pi \cdot \sqrt{\frac{M_{structure} + Addedmass}{\rho \cdot g \cdot A_{waterplane}}} = 20.87\,s$$

$$T_{pitch.roll} := 2 \cdot \pi \cdot \sqrt{\frac{M_{structure} \cdot R_x^2 + A_{moment}}{\rho \cdot g \cdot V_{structure} \cdot GM}} = 26.439\,s$$

Appendix

4

```
!Set environment

set_environment  gravity off  buoyancy off  hydro_force morison
wind_force ndrg  waves extrapolated_airy  norder -1  wind no_mean_profile
pre_computed_waves_file off  random_mode write_file  randomfile  rho_water 1025.
rho_air 0.001  nu_water 1.e-5  nu_air 1.e-6  wave_amplitude 0.
wavelength 156.07768226721353  wave_direction 0.  current_speed 0.  current_direction
0.
tsweeps 0.  tsweepe -1  stretch 0.  wind_speed  0.
wind_ref_height 90.  wind_exponent 0.  wind_direction 0.  spectral_peak 10.
seed .3  nfreq 64.  wave_ramps  0.  wave_rampe  20.  depth 200.0
tshift_waves 800  tshift_wind 0.

wave_forces cm_morison 1.63

!for egenfrekvenser; gravity off buoyancy off; må lage en linearisert stivhetsmatrise
på bunn

!Defining materials needed to construct model:

define_material  name betong0-6  rho 2272  e 0.55e+11  g 21.15e+9
define_material  name betong6-35  rho 2281  e 0.55e+11  g 21.15e+9
define_material  name betong0  rho 0.001  e 0.55e+11  g 21.15e+9
define_material  name betong_hjørne  rho 1295  e 0.55e+11  g 21.15e+9


!=============================================================================
===============================
!-----------------------------------------------------------------------------
-------------------------------
!
!!! SEMI-SUBMERSIBLE
!=============================================================================
===============================
!
!!    Sentersoyle     Koordinat (0,0,0) er i vannlinjen!
!!     Sette inn lokket i bucketen?
! Punktmasser til skaftet:
! Hull machanical weights 200 000 kg vcg -2.5
! Extra weights 570 VCG -9.644
! Mooring tension 240 000 VCG -14.4

new_body  name  Sentersoyle  parent  inertial  reftype  inertial
axes normal

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 0.0 0.0 -20.0  dcyl1 13  tcyl1 0.5  pre_strain_long  0.0
x2 0.0 0.0 -17  dcyl2 13  tcyl2 0.5  btype beam_lid1 pointmass 537345.358
frac_stiff 1.0   cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 0.0 0.0 -17  dcyl1 13  tcyl1 0.5  pre_strain_long  0.0
x2 0.0 0.0 -14.4  dcyl2 13  tcyl2 0.5  btype beam_lid1 pointmass 0
frac_stiff 1.0   cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 0.0 0.0 -14.4  dcyl1 13  tcyl1 0.5  pre_strain_long  0.0
x2 0.0 0.0 -14  dcyl2 13  tcyl2 0.5  btype beam pointmass 240000
frac_stiff 1.0   cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong6-35 connect_mode auto
x1 0.0 0.0 -14  dcyl1 12.2  tcyl1 0.5  pre_strain_long  0.0
x2 0.0 0.0 -12  dcyl2 11.28  tcyl2 0.5  btype beam pointmass 0
frac_stiff 1.0   cdn 0.56 cma 1.0
```

```
new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 -12 dcyl1 11.28  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 -10.4  dcyl2 10.54  tcyl2 0.45  btype beam pointmass 0
frac_stiff 1.0    cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 -10.4 dcyl1 10.54  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 -9.644  dcyl2 10.365  tcyl2 0.45  btype beam pointmass 0
frac_stiff 1.0    cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 -9.644 dcyl1 10.365  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 -2.5  dcyl2 9.154  tcyl2 0.45  btype beam pointmass 570000
frac_stiff 1.0    cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 -2.5 dcyl1 9.154  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 -1  dcyl2 8.509  tcyl2 0.45  btype beam pointmass 200000
frac_stiff 1.0    cdn 0.56 cma 1.0

!Der hvor et element krysser vannlinjen, lag et finere element i det området.

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 -1 dcyl1 8.509  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 0  dcyl2 7.9  tcyl2 0.45  btype beam pointmass 0
frac_stiff 1.0    cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 0 dcyl1 7.9  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 1  dcyl2 7.9  tcyl2 0.45  btype beam pointmass 0
frac_stiff 1.0    cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 1 dcyl1 7.9  tcyl1 0.45  pre_strain_long  0.0
x2 0.0 0.0 9.39  dcyl2 7.9  tcyl2 0.45  btype beam pointmass 0
frac_stiff 1.0    cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 9.39 dcyl1 7.9  tcyl1 0.55  pre_strain_long  0.0
x2 0.0 0.0 12.5  dcyl2 8.1  tcyl2 0.55  btype beam pointmass 43900
frac_stiff 1.0    cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 0.0 0.0 12.5 dcyl1 8.1  tcyl1 0.55  pre_strain_long  0.0
x2 0.0 0.0 15  dcyl2 8.1  tcyl2 0.55  btype beam_lid2 pointmass 0
frac_stiff 1.0    cdn 0.56 cma 1.0

! ------------------------------------------------

!Turbine tower   - VCG 45.5 over vannflaten

new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 15 dcyl1 10  tcyl1 0.55  pre_strain_long  0.0
x2 0.0 0.0 30  dcyl2 10  tcyl2 0.55  btype beam pointmass 0
frac_stiff 1.0    cdn 0.56 cma 1.0

new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 45.5 dcyl1 10  tcyl1 0.55  pre_strain_long  0.0
x2 0.0 0.0 30  dcyl2 10  tcyl2 0.55  btype beam pointmass 350000
frac_stiff 1.0    cdn 0.56 cma 1.0

!Nacelle+rotor   - VCG i 82 over vannflaten
```

```
new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 45.5  dcyl1 10  tcyl1 0.55  pre_strain_long  0.0
x2 0.0 0.0 60  dcyl2 10  tcyl2 0.55  btype beam pointmass 0
frac_stiff 1.0    cdn 0.56 cma 1.0


new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 82  dcyl1 10  tcyl1 0.55  pre_strain_long  0.0
x2 0.0 0.0 60  dcyl2 10  tcyl2 0.55  btype beam pointmass 310000
frac_stiff 1.0    cdn 0.56 cmn 1.0 cma 1.0



!===============================================================================
==============================
!
!!     Leg 1 - pontongen og sylinderen som er rett frem
!
new_body  name   Leg1   parent   Sentersoyle   reftype  refnode  xfind   0.0 0.0 -20.0

rotorder 123   rotation   0. 0. 0.0    axes normal

! Leg Column Denne går fra senter shaft ut til radiusen, bare et tynt bjelkeelement
uten masse,oppdrift osv. bare for å ha noe å feste pontongelementet på

new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 3  dcyl1 10  tcyl1 0.06  pre_strain_long  0.0
x2 6.5 0.0 3  dcyl2 10  tcyl2 0.06  btype beamwb pointmass 0
frac_stiff 1.0    cdn 0 cda 0 cma 1
!beamwb fordi jeg ikke skal ha dobbel oppdrift,fjerner denne delens oppdrift

!! Pontongen er delt opp i 3 elementer pluss to endestykker som får fra senter søylene

! Kammer 1 Første del av pontongelementet - trenger lokk i x1

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 6.5 0.0 3  dcyl1 16  tcyl1 0.6765  pre_strain_long  0.0
x2 7.0115 0.0 3  dcyl2 15.52  tcyl2 0.6765  btype beam_lid1 pointmass 0
frac_stiff 1.0    cdn 0.68 cmn 3.5

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 7.0115 0.0 3  dcyl1 15.52 tcyl1 0.6765  pre_strain_long  0.0
x2 9.505 0.0 3  dcyl2 13.2  tcyl2 0.6765  btype beam_lid2 pointmass 425922.965
frac_stiff 1.0    cdn 0.68 cmn 3.5

! Kammer 2
! Plusser på vekten av tverrskottene til punktmassen her.

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 9.505 0.0 3  dcyl1 16  tcyl1 0.738 pre_strain_long  0.0
x2 13.756 0.0 3  dcyl2 11.888  tcyl2 0.738  btype beam_lid1 pointmass 0
frac_stiff 1.0    cdn 0.68 cmn 3.5

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 13.756 0.0 3  dcyl1 11.888  tcyl1 0.738  pre_strain_long  0.0
x2 18.835 0.0 3  dcyl2 6.974  tcyl2 0.738  btype beam_lid2 pointmass 803761.335
frac_stiff 1.0    cdn 0.68 cmn 3.5

! Kammer 3
! Tredje del av pontongelementet - trenger lokk

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 18.835 0.0 3  dcyl1 16  tcyl1 0.6565 pre_strain_long  0.0
x2 21.6682 0.0 3  dcyl2 9.7655  tcyl2 0.6565  btype beam_lid1 pointmass 0
frac_stiff 1.0    cdn 0.68 cmn 3.5
```

```
new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 21.6682 0.0 3  dcyl1 9.7655  tcyl1 0.6565 pre_strain_long  0.0
x2 23 0.0 3  dcyl2 6.835  tcyl2 0.6565  btype beam_lid2 pointmass 365825.083
frac_stiff 1.0   cdn 0.68 cmn 3.5


!Forbindelseselement fra andre del av pontongen inn til senter hjørnesøyle.

new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 23 0.0 3  dcyl1 10  tcyl1 0.06  pre_strain_long  0.0
x2  28.0 0.0 3  dcyl2 10  tcyl2 0.06  btype beambw pointmass 0.0
frac_stiff 1.0   cdn 0.68 cma 1.677

!beamwb fordi jeg ikke skal ha dobbel oppdrift,fjerner denne delens oppdrift

! Hjørnesylinderen
! Kan legge til litt masser ved å legge til lokk i bunn og på toppen som vekt, må da
ha flere elementer.

new_elements_beam1  nelem 1  material betong_hjørne connect_mode auto
x1 28.0 0.0 0  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 3  dcyl2 10.0  tcyl2 0.3  btype beam_lid1 pointmass 96883.9528
frac_stiff 1.0   cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong_hjørne connect_mode auto
x1 28.0 0.0 3  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 4.52  dcyl2 10.0  tcyl2 0.3  btype beam pointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong0-6 connect_mode auto
x1 28.0 0.0 4.52  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 6  dcyl2 10.0  tcyl2 0.3  btype beam pointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 6  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 19  dcyl2 10.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 19  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 21  dcyl2 10.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 21  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 29  dcyl2 10.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 30  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 29  dcyl2 10.0  tcyl2 0.3  btype_lid1 beam pointmass 57901.0103
frac_stiff 1.0   cdn 0.61 cma 1.0




!================================================================================
==================================
!
!    Leg 2 pontongen og sylinderen som er rotert 120 grader på den i midten

new_body  name  Leg2   parent  Sentersoyle  reftype  refnode  xfind   0.0 0.0 -20.0

rotorder 123  rotation   0.0 0.0 120.0   axes normal
```

! Leg Column Denne går fra senter shaft ut til radiusen, bare et tynt bjelkeelement
uten masse,oppdrift osv. bare for å ha noe å feste pontongelementet på

new_elements_beam1 nelem 1 material betong0 connect_mode auto
x1 0.0 0.0 3 dcyl1 10 tcyl1 0.06 pre_strain_long 0.0
x2 6.5 0.0 3 dcyl2 10 tcyl2 0.06 btype beamwb pointmass 0
frac_stiff 1.0   cdn 0 cda 0 cma 1
!beamwb fordi jeg ikke skal ha dobbel oppdrift,fjerner denne delens oppdrift

!! Pontongen er delt opp i 3 elementer pluss to endestykker som får fra senter søylene

! Kammer 1 Første del av pontongelementet - trenger lokk i x1

new_elements_beam1 nelem 1 material betong0-6 connect_mode auto
x1 6.5 0.0 3 dcyl1 16 tcyl1 0.6765 pre_strain_long 0.0
x2 7.0115 0.0 3 dcyl2 15.52 tcyl2 0.6765 btype beam_lid1 pointmass 0
frac_stiff 1.0   cdn 0.68 cmn 3.5

new_elements_beam1 nelem 1 material betong0-6 connect_mode auto
x1 7.0115 0.0 3 dcyl1 15.52 tcyl1 0.6765 pre_strain_long 0.0
x2 9.505 0.0 3 dcyl2 13.2 tcyl2 0.6765 btype beam_lid2 pointmass 425922.965
frac_stiff 1.0   cdn 0.68 cmn 3.5

! Kammer 2
! Plusser på vekten av tverrskottene til punktmassen her.

new_elements_beam1 nelem 1 material betong0-6 connect_mode auto
x1 9.505 0.0 3 dcyl1 16 tcyl1 0.738 pre_strain_long 0.0
x2 13.756 0.0 3 dcyl2 11.888 tcyl2 0.738 btype beam_lid1 pointmass 0
frac_stiff 1.0   cdn 0.68 cmn 3.5

new_elements_beam1 nelem 1 material betong0-6 connect_mode auto
x1 13.756 0.0 3 dcyl1 11.888 tcyl1 0.738 pre_strain_long 0.0
x2 18.835 0.0 3 dcyl2 6.974 tcyl2 0.738 btype beam_lid2 pointmass 803761.335
frac_stiff 1.0   cdn 0.68 cmn 3.5

! Kammer 3
! Tredje del av pontongelementet - trenger lokk

new_elements_beam1 nelem 1 material betong0-6 connect_mode auto
x1 18.835 0.0 3 dcyl1 16 tcyl1 0.6565 pre_strain_long 0.0
x2 21.6682 0.0 3 dcyl2 9.7655 tcyl2 0.6565 btype beam_lid1 pointmass 0
frac_stiff 1.0   cdn 0.68 cmn 3.5

new_elements_beam1 nelem 1 material betong0-6 connect_mode auto
x1 21.6682 0.0 3 dcyl1 9.7655 tcyl1 0.6565 pre_strain_long 0.0
x2 23 0.0 3 dcyl2 6.835 tcyl2 0.6565 btype beam_lid2 pointmass 365825.083
frac_stiff 1.0   cdn 0.68 cmn 3.5

!Forbindelseselement fra andre del av pontongen inn til senter hjørnesøyle.

new_elements_beam1 nelem 1 material betong0 connect_mode auto
x1 23 0.0 3 dcyl1 10 tcyl1 0.06 pre_strain_long 0.0
x2 28.0 0.0 3 dcyl2 10 tcyl2 0.06 btype beambw pointmass 0.0
frac_stiff 1.0   cdn 0.68 cma 1.677

!beamwb fordi jeg ikke skal ha dobbel oppdrift,fjerner denne delens oppdrift

! Hjørnesylinderen
! Kan legge til litt masser ved å legge til lokk i bunn og på toppen som vekt, må da
ha flere elementer.

```
new_elements_beam1  nelem 1  material betong_hjørne connect_mode auto
x1 28.0 0.0 0  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 3  dcyl2 10.0  tcyl2 0.3  btype beam_lid1 pointmass 96883.9528
frac_stiff 1.0   cdn 0.61 cma 1.0


new_elements_beam1  nelem 1  material betong_hjørne connect_mode auto
x1 28.0 0.0 3  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 4.52  dcyl2 10.0  tcyl2 0.3  btype beam pointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0


new_elements_beam1  nelem 1  material betong0-6 connect_mode auto
x1 28.0 0.0 4.52  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 6  dcyl2 10.0  tcyl2 0.3  btype beam pointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 6  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 19  dcyl2 10.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 19  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 21  dcyl2 10.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 21  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 29  dcyl2 10.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0   cdn 0.61 cma 1.0


new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 30  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 29  dcyl2 10.0  tcyl2 0.3  btype_lid1 beam pointmass 57901.0103
frac_stiff 1.0   cdn 0.61 cma 1.0




!================================================================================
=================================
!
!!    Leg 3   Pontongen og sylinderen som er rotert 240 grader på den normale
!
new_body  name  Leg3   parent  Sentersoyle  reftype refnode xfind  0.0 0.0 -20.0

rotorder 123  rotation   0.0 0.0 240.0   axes normal

 ! Leg Column Denne går fra senter shaft ut til radiusen, bare et tynt bjelkeelement
uten masse,oppdrift osv. bare for å ha noe å feste pontongelementet på

new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 3  dcyl1 10  tcyl1 0.06  pre_strain_long  0.0
x2 6.5 0.0 3  dcyl2 10  tcyl2 0.06  btype beamwb pointmass 0
frac_stiff 1.0   cdn 0 cda 0 cma 1
!beamwb fordi jeg ikke skal ha dobbel oppdrift,fjerner denne delens oppdrift

!! Pontongen er delt opp i 3 elementer pluss to endestykker som får fra senter søylene

! Kammer 1 Første del av pontongelementet - trenger lokk i x1

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 6.5 0.0 3  dcyl1 16  tcyl1 0.6765  pre_strain_long  0.0
x2 7.0115 0.0 3  dcyl2 15.52  tcyl2 0.6765  btype beam_lid1 pointmass 0
frac_stiff 1.0   cdn 0.68 cmn 3.5
```

```
new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 7.0115 0.0 3  dcyl1 15.52 tcyl1 0.6765  pre_strain_long  0.0
x2 9.505 0.0 3  dcyl2 13.2  tcyl2 0.6765  btype beam_lid2 pointmass 425922.965
frac_stiff 1.0    cdn 0.68 cmn 3.5


! Kammer 2
! Plusser på vekten av tverrskottene til punktmassen her.

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 9.505 0.0 3  dcyl1 16  tcyl1 0.738 pre_strain_long  0.0
x2 13.756 0.0 3  dcyl2 11.888  tcyl2 0.738  btype beam_lid1 pointmass 0
frac_stiff 1.0    cdn 0.68 cmn 3.5

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 13.756 0.0 3  dcyl1 11.888  tcyl1 0.738  pre_strain_long  0.0
x2 18.835 0.0 3  dcyl2 6.974  tcyl2 0.738  btype beam_lid2 pointmass 803761.335
frac_stiff 1.0    cdn 0.68 cmn 3.5


! Kammer 3
! Tredje del av pontongelementet - trenger lokk

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 18.835 0.0 3  dcyl1 16  tcyl1 0.6565 pre_strain_long  0.0
x2 21.6682 0.0 3  dcyl2 9.7655  tcyl2 0.6565  btype beam_lid1 pointmass 0
frac_stiff 1.0    cdn 0.68 cmn 3.5

new_elements_beam1  nelem 1  material betong0-6  connect_mode auto
x1 21.6682 0.0 3  dcyl1 9.7655  tcyl1 0.6565 pre_strain_long  0.0
x2 23 0.0 3  dcyl2 6.835  tcyl2 0.6565  btype beam_lid2 pointmass 365825.083
frac_stiff 1.0    cdn 0.68 cmn 3.5



!Forbindelseselement fra andre del av pontongen inn til senter hjørnesøyle.

new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 23 0.0 3  dcyl1 10  tcyl1 0.06  pre_strain_long  0.0
x2  28.0 0.0 3  dcyl2 10  tcyl2 0.06  btype beambw pointmass 0.0
frac_stiff 1.0    cdn 0.68 cma 1.677


!beamwb fordi jeg ikke skal ha dobbel oppdrift,fjerner denne delens oppdrift


! Hjørnesylinderen
! Kan legge til litt masser ved å legge til lokk i bunn og på toppen som vekt, må da
ha flere elementer.

new_elements_beam1  nelem 1  material betong_hjørne connect_mode auto
x1 28.0 0.0 0  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 3  dcyl2 10.0  tcyl2 0.3  btype beam_lid1 pointmass 96883.9528
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong_hjørne connect_mode auto
x1 28.0 0.0 3  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 4.52  dcyl2 10.0  tcyl2 0.3  btype beam pointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong0-6 connect_mode auto
x1 28.0 0.0 4.52  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 6  dcyl2 10.0  tcyl2 0.3  btype beam pointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 6  dcyl1 10 tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 19  dcyl2 10.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0
```

```
new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 19  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 21  dcyl2 10.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 21  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 29  dcyl2 10.0  tcyl2 0.3  btype beampointmass 0
frac_stiff 1.0    cdn 0.61 cma 1.0

new_elements_beam1  nelem 1  material betong6-35  connect_mode auto
x1 28.0 0.0 30  dcyl1 10  tcyl1 0.3  pre_strain_long  0.0
x2 28.0 0.0 29  dcyl2 10.0  tcyl2 0.3  btype_lid1 beam pointmass 57901.0103
frac_stiff 1.0    cdn 0.61 cma 1.0

!===============================================================================
================================

!Define sea bed

apply_nodal_bc find 0.  0.  0.  wall  idofs 3 idofe 3  displ -200.0  1.    dstat 0.01

!===============================================================================
================================

!! Apply gravitational force to pointmasses:
!! her må alle pointmasser som er satt inn settes inn igjen i globale koordinater! DVS
vannlijen er 0 0 0
!!dette er i M*g !!! g er her 9,80665. de tre siste koordinatene er rotasjon.

!Nacelle+rotor

apply_nodal_bc find 0 0.0 82 apply_force 0.0 0.0 -3040061.5 0. 0. 0.

!Tower

apply_nodal_bc find 0 0.0 45.5 apply_force 0.0 0.0 -3432327.5 0. 0. 0.

!Hull mechanical weights

apply_nodal_bc find 0 0.0 -2.5 apply_force 0.0 0.0 -1961330 0. 0. 0.

!Mooring tension

apply_nodal_bc find 0 0.0 -14.4 apply_force 0.0 0.0 -2353596 0. 0. 0.

!Extra weights

apply_nodal_bc find 0 0.0 -9.644 apply_force 0.0 0.0 -5589790.5 0. 0. 0.

!Manglende masse
apply_nodal_bc find 0 0.0 -10.4 apply_force 0.0 0.0 0 0. 0. 0.

!Må også ha med vann i pontongene:
Pontong 1:
apply_nodal_bc find 7.0115 0 -17 apply_force 0.0 0.0 -4178304.287 0. 0. 0.
apply_nodal_bc find 13.756 0 -17 apply_force 0.0 0.0 -7884898.696 0. 0. 0.
apply_nodal_bc find 21.6682 0 -17 apply_force 0.0 0.0 -3588744.064 0. 0. 0.

Pontong 2
apply_nodal_bc find -6.07213 -3.50575 -17 apply_force 0.0 0.0 -4178304.287 0. 0. 0.
apply_nodal_bc find -11.91304545 -6.878 -17 apply_force 0.0 0.0 -7884898.696 0. 0. 0.
apply_nodal_bc find -18.76521165 -10.8341 -17 apply_force 0.0 0.0 -3588744.064 0. 0. 0.
```

```
Pontong 3:
apply_nodal_bc find 6.07213 -3.50575 -17 apply_force 0.0 0.0 -4178304.287 0. 0. 0.
apply_nodal_bc find 11.91304545 -6.878 -17 apply_force 0.0 0.0 -7884898.696 0. 0. 0.
apply_nodal_bc find 18.76521165 -10.8341 -17 apply_force 0.0 0.0 -3588744.064 0. 0. 0.


!De diverse lokkene på sylindrene som jeg har satt på

!Bunn shaft:
apply_nodal_bc find 0 0 -20 apply_force 0.0 0.0 -1260374.8 0. 0. 0.
!Lokk i bucket
apply_nodal_bc find 0 0 9.39 apply_force 0.0 0.0 -430511.935 0. 0. 0.
!Bunnlokk hjørnesylindre:
apply_nodal_bc find 0 28 -20 apply_force 0.0 0.0 -946358.3963 0. 0. 0.
apply_nodal_bc find -24.24871131 -14 -20 apply_force 0.0 0.0 -946358.3963 0. 0. 0.
apply_nodal_bc find 24.24871131 -14 -20 apply_force 0.0 0.0 -946358.3963 0. 0. 0.

!Topplokk hjørnesylindre:
apply_nodal_bc find 0 28 10 apply_force 0.0 0.0 -570064.4872 0. 0. 0.
apply_nodal_bc find -24.24871131 -14 10 apply_force 0.0 0.0 -570064.4872 0. 0. 0.
apply_nodal_bc find 24.24871131 -14 10 apply_force 0.0 0.0 -570064.4872 0. 0. 0.


!===============================================================================
==============================

!Sensorer inn her

!Dette er en monitor i vannplansnoden. Lager en egen outputfil så vi kan se om
konstruksjonen flyer/synker,dvs fungerer.

monitor_element_b1 type orientation file vannplan_node.txt nmonitor 10 find 0. 0. 1
node 1

!For krefter, setter inn en nodei overgangen til pontongen f.eks

monitor_element_b1 type forces file krefter.txt nmonitor 10 find 0 0 0 node 1

monitor_element_b1 type moments file moment.txt nmonitor 10 find 0 0 0 node 1

!===============================================================================
==============================

file IFE_3Dfloat_WP2_LC2.1.txt  label oc4p2_gather  toffset 250
sensors:
nfact: 1 source: WindVxi        scale: 1.            unit: [m/s]  ! header as source
label
nfact: 1 source: WindVyi        scale: 1.            unit: [m/s]  !
nfact: 1 source: WindVzi        scale: 1.            unit: [m/s]  !
nfact: 1 source: WaveElev       scale: 1.            unit: [m]    !
nfact: 1 source: GenPwr         scale: 0. .001          unit: [kW]   !
nfact: 1 source: GenTq          scale: 0. 1.030927835e-5        unit: [kNm] !
1./97.e3
nfact: 1 source: Azimuth        scale: 0. 57.295779513082323    unit: [deg]  !
180./rpi
nfact: 1 source: RotSpeed       scale: 0. 60.           unit: [rpm]  !
nfact: 1 source: RotSpeed       scale: 0. 5820.         unit: [rpm]   header:
GenSpeed    ! 60*97
nfact: 1 source: OoPDefl1       scale: 0. 1.            unit: [m]    !
nfact: 1 source: IPDefl1        scale: 0. 1.            unit: [m]    !
nfact: 1 source: Twst_yx        scale: 0. 57.295779513082323  unit: [deg]  header:
TwstDefl1
nfact: 1 source: BldPitch1      scale: 0.              unit: [deg]  ! ???
nfact: 1 source: TTDspFA        scale: 1.              unit: [m]    !
nfact: 1 source: TTDspSS        scale: 1.              unit: [m]    !
```

```
nfact: 1 source: TTDsp_yx        scale: 57.295779513082323  unit: [deg]   header:
TTDspTwst
nfact: 1 source: PtfmSurge        scale: 1.            unit: [m]     ! rel. inertia
nfact: 1 source: PtfmSway         scale: 1.            unit: [m]     !
nfact: 1 source: PtfmHeave        scale: 1.            unit: [m]     !
nfact: 1 source: Ptfm_yz          scale: 57.295779513082323  unit: [deg]   header:
PtfmRoll
nfact: 1 source: Ptfm_xx          scale: 57.295779513082323  unit: [deg]   header:
PtfmPitch
nfact: 1 source: Ptfm_yx          scale: -57.295779513082323  unit: [deg]  header:
PtfmYaw
nfact: 2 source: blrootfx blrootfxi scale:  0.  0.  .001  .001 unit: [kN] header:
RootFxc1  !
nfact: 2 source: blrootfy blrootfyi scale:  0.  0.  .001  .001 unit: [kN] header:
RootFyc1  !
nfact: 2 source: blrootfz blrootfzi scale:  0.  0.  .001  .001 unit: [kN] header:
RootFzc1  !
nfact: 2 source: blrootmx blrootmxi scale:  0.  0.  .001  .001 unit: [kN] header:
RootMxc1  !
nfact: 2 source: blrootmy blrootmyi scale:  0.  0.  .001  .001 unit: [kN] header:
RootMyc1  !
nfact: 1 source: RootMzc1         scale:  0.           unit: [kNm] !
nfact: 1 source: RotTorq          scale: 0.  -.001      unit: [kNm] !
nfact: 1 source: LSSGagMya        scale: 0.  -.001      unit: [kNm] !
nfact: 1 source: LSSGagMza        scale: 0.  -.001      unit: [kNm] !
nfact: 1 source: YawBrFxp         scale: -.001          unit: [kN]  ! Nacelle coord.syst.
nfact: 1 source: YawBrFyp         scale:  .001          unit: [kN]  !
nfact: 1 source: YawBrFzp         scale: -.001          unit: [kN]  !
nfact: 1 source: YawBrMxp         scale:  .001          unit: [kNm] !
nfact: 1 source: YawBrMyp         scale:  .001          unit: [kNm] !
nfact: 1 source: YawBrMzp         scale:  .001          unit: [kNm] !
nfact: 1 source: TwrBsFxt         scale:  .001          unit: [kN]  ! Tower base
coord.sys.
nfact: 1 source: TwrBsFyt         scale:  .001          unit: [kN]  !
nfact: 1 source: TwrBsFzt         scale: -.001          unit: [kN]  !
nfact: 1 source: TwrBsMxt         scale: -.001          unit: [kNm] !
nfact: 1 source: TwrBsMyt         scale: -.001          unit: [kNm] !
nfact: 1 source: TwrBsMzt         scale:  .001          unit: [kNm] !
nfact: 1 source: UC1YU1Fx         scale:  .001          unit: [kN]  ! Local element
coord.sys.
nfact: 1 source: UC1YU1Fy         scale:  .001          unit: [kN]  ! x-axis beam axis
nfact: 1 source: UC1YU1Fz         scale:  .001          unit: [kN]  ! z-axis UC axis
upwards
nfact: 1 source: UC1DU1Fx         scale:  .001          unit: [kN]  !
nfact: 1 source: UC1DU1Fy         scale:  .001          unit: [kN]  !
nfact: 1 source: UC1DU1Fz         scale:  .001          unit: [kN]  !
nfact: 1 source: Fair1Ten         scale: -.001          unit: [kN]  ! Positive when in
tension
nfact: 1 source: Fair2Ten         scale: -.001          unit: [kN]  !
nfact: 1 source: Fair3Ten         scale: -.001          unit: [kN]  !
nfact: 1 source: Fair1Ang         scale: 0.             unit: [deg]  ! Angle from
horizontal
nfact: 1 source: Fair2Ang         scale: 0.             unit: [deg]  !   POSITIVE value
nfact: 1 source: Fair3Ang         scale: 0.             unit: [deg]  !
nfact: 1 source: Anch1Ten         scale:  .001          unit: [kN]  ! Positive when in
tension
nfact: 1 source: Anch2Ten         scale:  .001          unit: [kN]  !
nfact: 1 source: Anch3Ten         scale:  .001          unit: [kN]  !
nfact: 1 source: Anch1Ang         scale: 0.             unit: [deg]  ! Angle from
horizontal
nfact: 1 source: Anch2Ang         scale: 0.             unit: [deg]  !   POSITIVE value
nfact: 1 source: Anch3Ang         scale: 0.             unit: [deg]  !
nfact: 1 source: Fair1_xz         scale: -1.            unit: [sin]  !
nfact: 1 source: Fair2_xz         scale: -1.            unit: [sin]  !
```

```
nfact: 1 source: Fair3_xz       scale: -1.          unit: [sin]  !
nfact: 1 source: Anch1_xz       scale: -1.          unit: [sin]  !
nfact: 1 source: Anch2_xz       scale: -1.          unit: [sin]  !
nfact: 1 source: Anch3_xz       scale: -1.          unit: [sin]  !


!================================================================================
=================================

!Stivhetsmatriser for egenfrekvens og draft (hvor i vannet vi flyter)

!Restoring moment due to buoyancy

add_node_stiffness  find  0.  0. 0.
f_lin  0. 0. 1.26e8    0.  0.  0.
x_lin  0. 0. 0. 0. 0. 0.
1    1     0 !Stiffness from mooring
2    2     0 !Stiffness from mooring
3    3     2890422.558
4    4     4.182e8
5    5     4.182e8
6    6     0 !Stiffness from mooring




!_____

!For egenfrekvensene

damping type ratio2rayl  ratio_1 0.05  ratio_2 0.05  omega_1  0.05  omega_2   1.

!
! plotting with Python script plot_geo.py

monitor_element_b1  type plot nmonitor 10 file turb1.plot

!
newmark dt 0.025  nassemble 1 nnewton 50 nsubmin 1  rwilson 0.9
relax 0.0  resid_newton  1e-06  nmonitor 100

step nstep 50 method gen_alpha

eigen_analysis old nfreq 20 amplitude 10 filename frekvenser.txt

!_____

!printing og plotting til outputfiler

!print_nodes
nodes.txt
-1  -1

!print_b1_elements
elements.txt
-1 -1
 3 2 3 2


! Tecplot
!
monitor_element_b1  type tecplot nmonitor 10
file turb1.dat
```

```
print_solution
solution.txt

END
!_____
```

```
print_solution
solution.txt


END
```

Appendix

5

My on the shaft
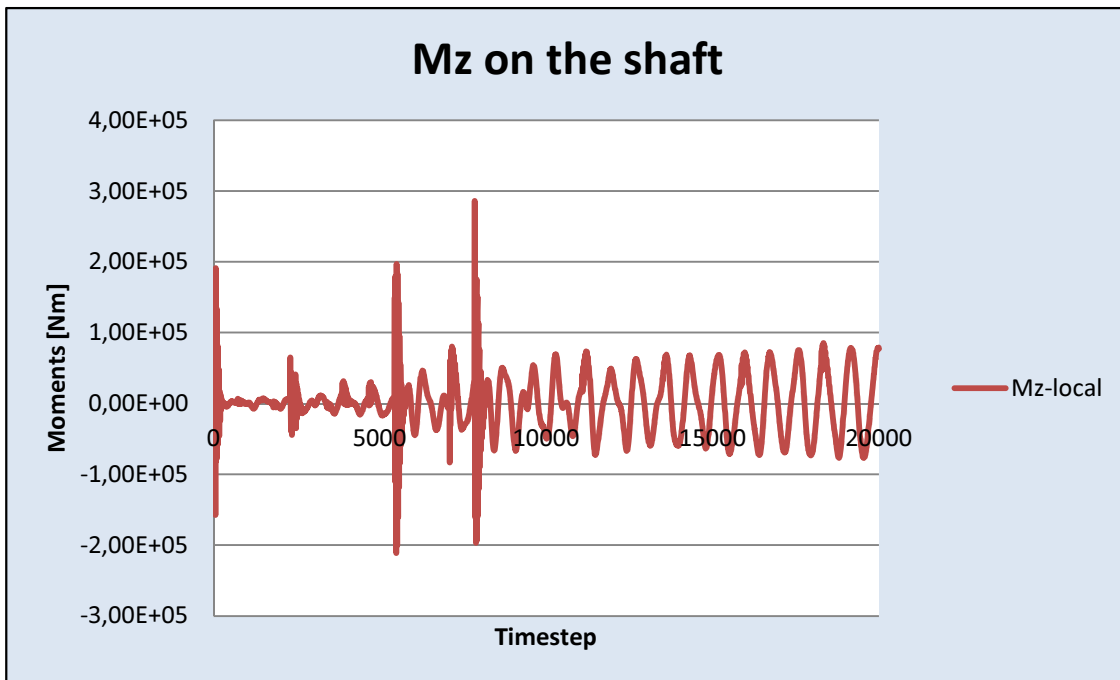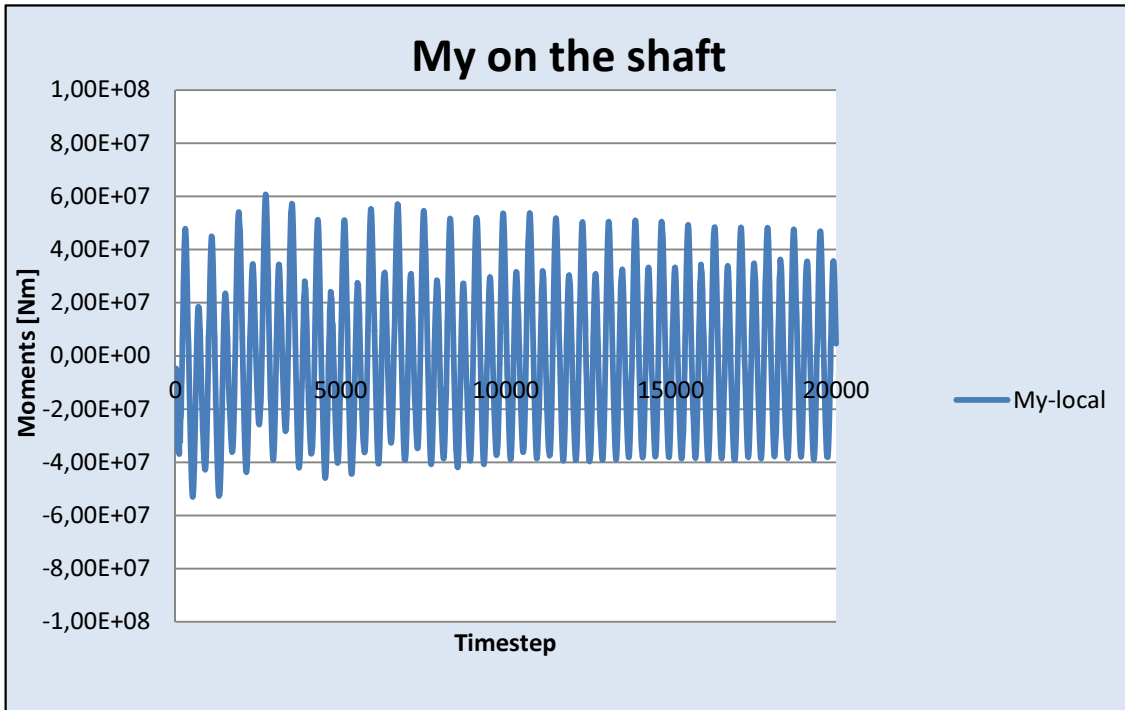
Mz on the shaft
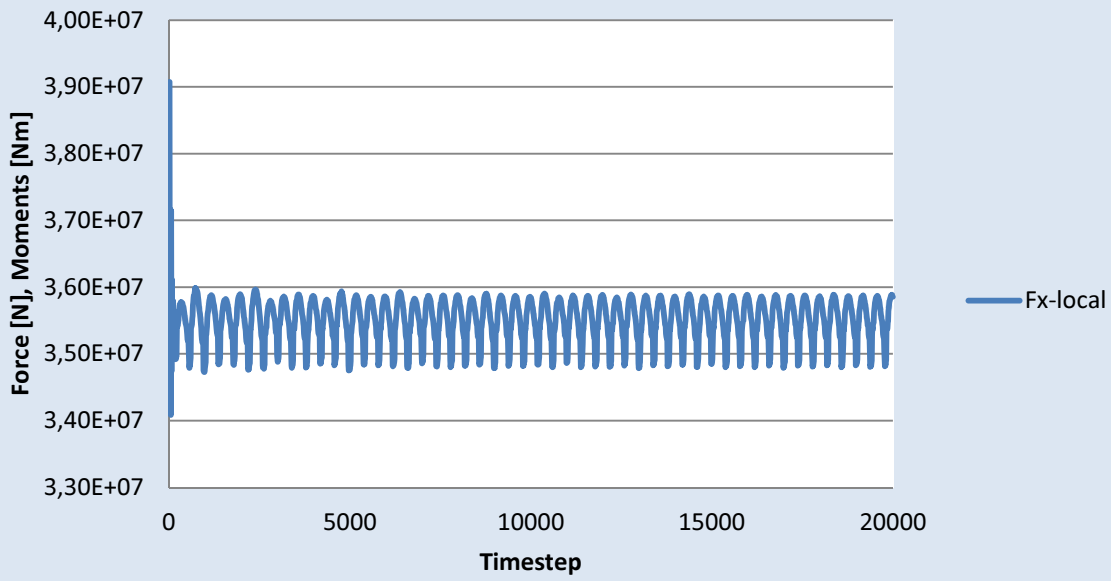
Fx in the shaft

My on the shaft cylinder from the pontoon
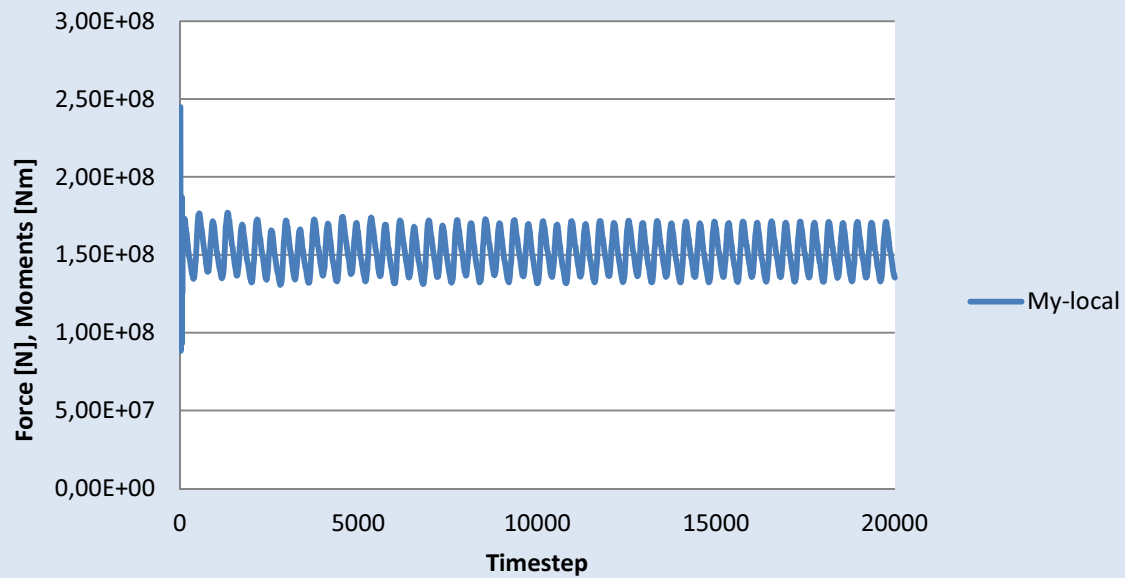
Mz on the shaft cylinder from the pontoon

Fx on the shaft cylinder from the pontoon
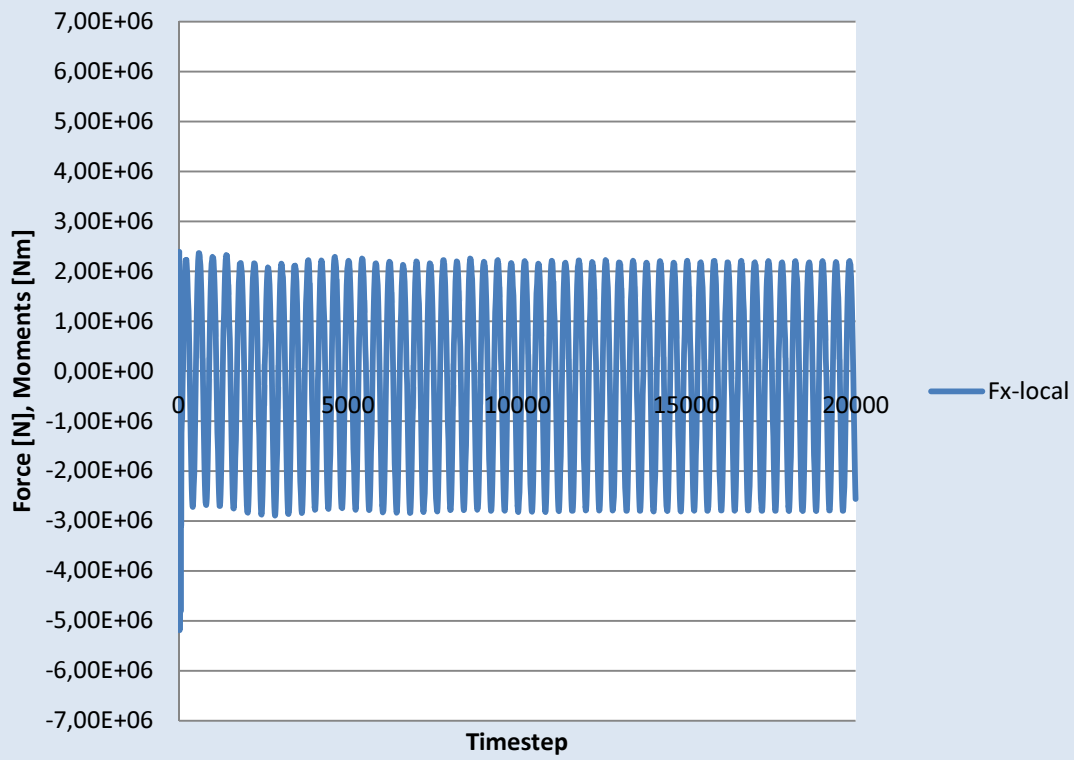
My on the shaft cylinder from the pontoon
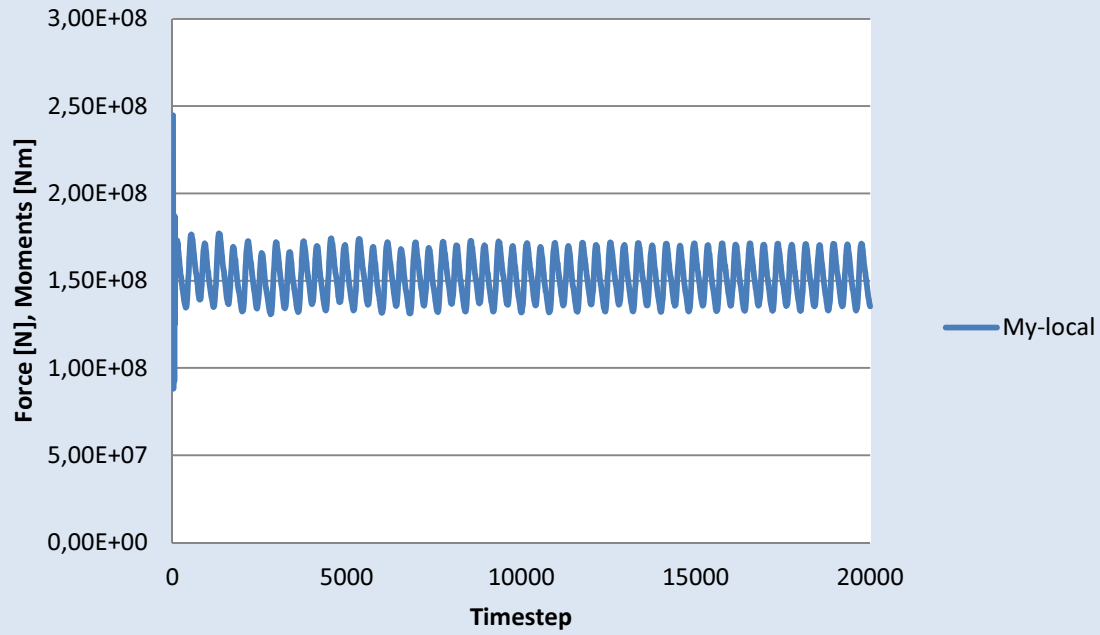
Mz on the shaft cylinder from the pontoon
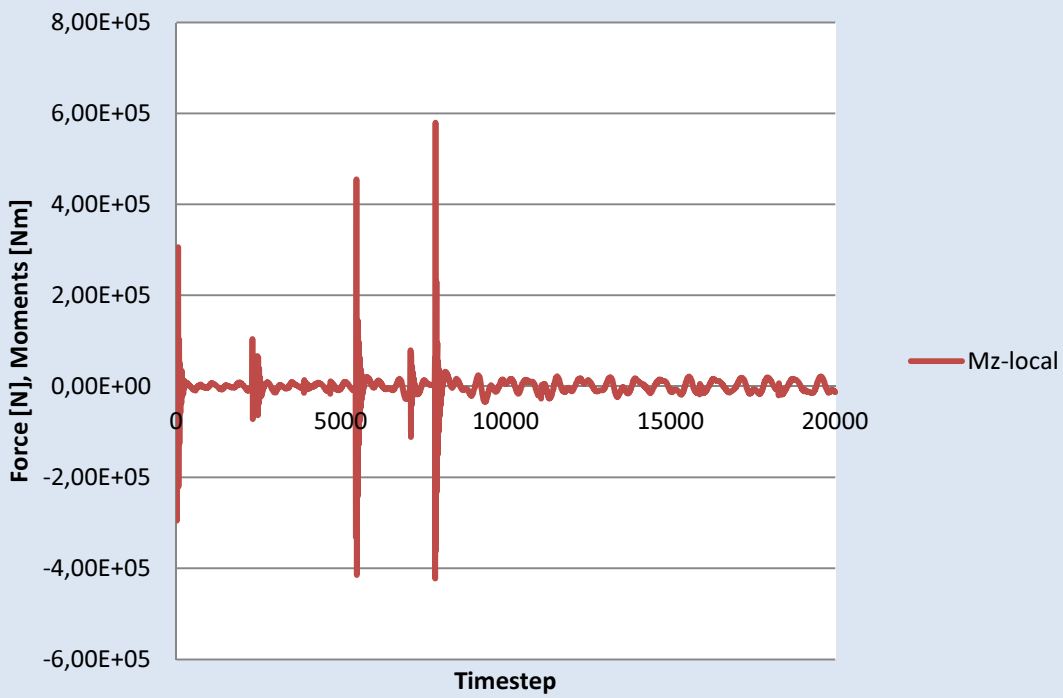
Fx on the corner cylinder from the pontoon
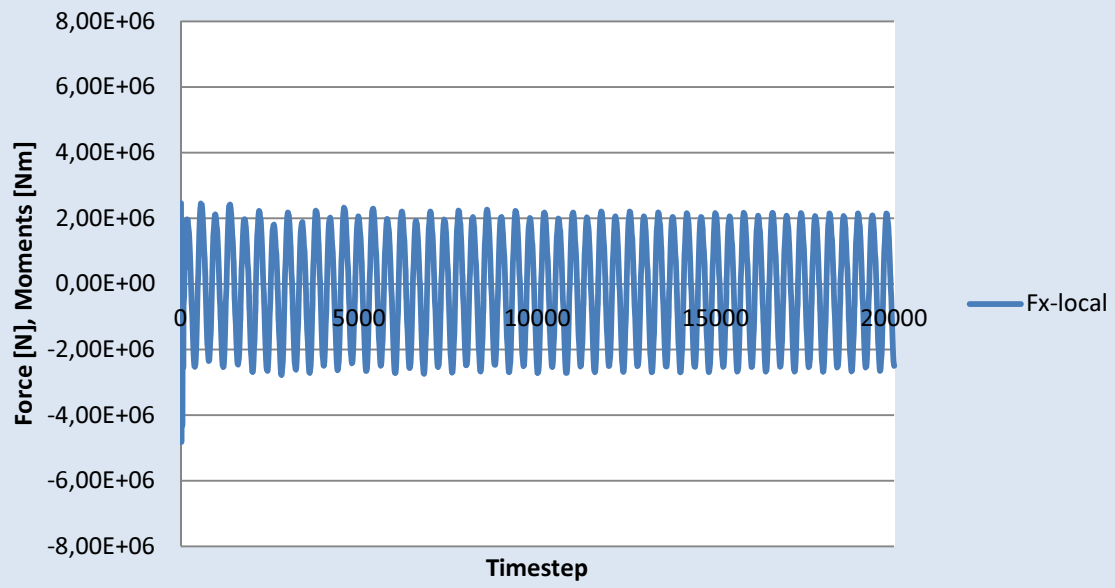
Appendix

6

Inputvalues:

$kNm := kN \cdot m$

$Nm := N \cdot m$

$$\rho_1 := 2000 \cdot \frac{kg}{m^3} \qquad \rho_2 := 2200 \cdot \frac{kg}{m^3}$$

Normalized concrete strength: $\quad F_c := 41.6 \cdot \dfrac{N}{mm^2}$

Reduction factor: $\qquad \eta := 0.15 + 0.85 \cdot \dfrac{\rho_1}{\rho_2} = 0.923$

Partial factor: $\qquad \gamma_c := 1.35$

Capacities:

$$F_{cn} := F_c \cdot \eta$$

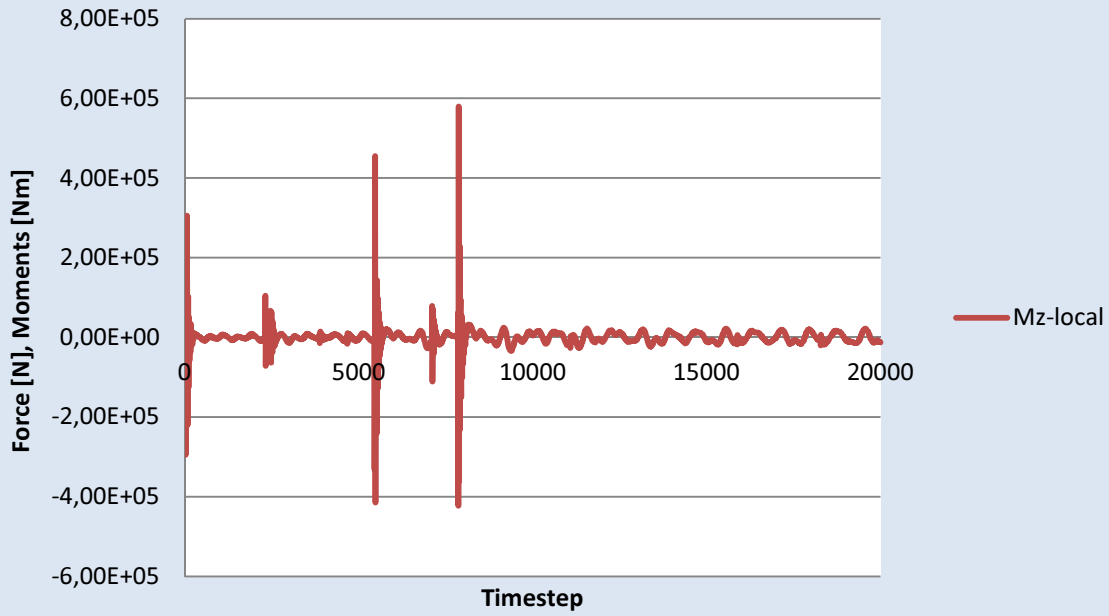$$F_{Rd.compression} := \frac{F_{cn}}{\gamma_c} = 28.43 \, MPa$$

Cross-section 1: Shaft base

$$r_y := 5.5 \cdot m \qquad r_i := 5.1 \cdot m$$

$$y_{maks.1} := r_y \qquad z_{maks.1} := r_y \qquad A_{concrete.1} := \pi \cdot r_y^2 - \pi \cdot r_i^2 = 13.32 \, m^2$$

Forces

$$F_{x.1} := 3.6 \cdot 10^7 N = 36000 \, kN$$

$$M_{y.1} := 5.04 \cdot 10^7 \cdot Nm = 50400 \, kNm$$

$$M_{z.1} := 1 \cdot 10^5 \cdot Nm = 100 \, kNm$$

Calculated values:

$$I_{ytre.1} := \frac{1}{4} \cdot \pi \cdot r_y^4 \qquad I_{indre.1} := \frac{1}{4} \cdot \pi \cdot r_i^4$$

$$I_{y1} := I_{ytre.1} - I_{indre.1}$$

$$I_{z1} := I_{y1}$$

$$W_{y.1} := \frac{I_{y1}}{2 \cdot r_y} \qquad\qquad W_{z.1} := \frac{I_{z1}}{2 \cdot r_y}$$

Tensions

$$F_{Ed.Comp.1} := \frac{F_{x.1}}{A_{concrete.1}} = 2.703 \cdot MPa$$

$$F_{Ed.My.1} := \frac{M_{y.1}}{W_{y.1}} = 2.959 \cdot MPa$$

$$F_{Ed.Mz.1} := \frac{M_{z.1}}{W_{z.1}} = 0.006 \cdot MPa$$

Combinations:

$$Combo_{1.1} := F_{Ed.Comp.1} + F_{Ed.My.1} \qquad\qquad Combo_{1.2} := F_{Ed.Comp.1} + F_{Ed.Mz.1}$$

$$Utilization_{1.1} := \frac{Combo_{1.1}}{F_{Rd.compression}} = 0.199 \qquad \text{Value:} \qquad Combo_{1.1} = 5.662\,MPa$$

$$Utilization_{1.2} := \frac{Combo_{1.2}}{F_{Rd.compression}} = 0.095 \qquad \text{Value} \qquad Combo_{1.2} = 2.709\,MPa$$

Cross-section 2: Pontoon at cylinder

$\text{Width}_2 := 11 \cdot m$ $\qquad$ $T_z := 0.35 \cdot m$

$\text{Height}_2 := 6 \cdot m$ $\qquad$ $T_x := 0.4 \cdot m$

$A_{\text{concrete}.2} := \text{Width}_2 \cdot \text{Height}_2 - \left[\left(\text{Width}_2 - 2T_z \right) \cdot \left(\text{Height}_2 - 2 \cdot T_x \right) \right] = 12.44 \, m^2$

Forces

$F_{x.2} := 2 \cdot 10^6 \cdot N = 2000 \, kN$

$M_{y.2} := 1.75 \cdot 10^8 \cdot Nm = 175000 \, kNm$

$M_{z.2} := 3 \cdot 10^5 \cdot Nm = 300 \, kNm$

Calculated values:

$I_{y.2.\text{outer}} := \dfrac{1}{12} \cdot \text{Width}_2 \cdot \text{Height}_2^{\,3}$ $\qquad\qquad$ $z_{\text{maks}.2} := \text{Width}_2$

$I_{z.2.\text{outer}} := \dfrac{1}{12} \text{Height}_2 \cdot \text{Width}_2^{\,3}$ $\qquad\qquad$ $y_{\text{maks}.2} := \text{Height}_2$

$I_{y.2.\text{inner}} := \dfrac{1}{12} \cdot \left(\text{Width}_2 - 2 \cdot T_z \right) \cdot \left(\text{Height}_2 - 2T_x \right)^3$

$I_{z.2.\text{inner}} := \dfrac{1}{12} \cdot \left(\text{Height}_2 - 2 \cdot T_x \right) \cdot \left(\text{Width}_2 - 2 \cdot T_z \right)^3$

$I_{y.2} := I_{y.2.\text{outer}} - I_{y.2.\text{inner}}$

$I_{z.2} := I_{z.2.\text{outer}} - I_{z.2.\text{inner}}$

$W_{y.2} := \dfrac{I_{y.2}}{y_{\text{maks}.2}} = 12.885 \cdot m^3$ $\qquad\qquad$ $W_{z.2} := \dfrac{I_{z.2}}{z_{\text{maks}.2}} = 17.453 \cdot m^3$

Tensions

$$F_{Ed.Comp.2} := \frac{F_{x.2}}{A_{concrete.2}} = 0.161 \cdot MPa$$

$$F_{Ed.My.2} := \frac{M_{y.2}}{W_{y.2}} = 13.581 \cdot MPa$$

$$F_{Ed.Mz.2} := \frac{M_{z.2}}{W_{z.2}} = 0.017 \cdot MPa$$

Combinations:

$$Combo_{2.1} := F_{Ed.Comp.2} + F_{Ed.My.2} \qquad Combo_{2.2} := F_{Ed.Comp.2} + F_{Ed.Mz.2}$$

$$Utilization_{2.1} := \frac{Combo_{2.1}}{F_{Rd.compression}} = 0.483 \qquad \text{Value:} \qquad Combo_{2.1} = 13.742\,MPa$$

$$Utilization_{2.2} := \frac{Combo_{2.2}}{F_{Rd.compression}} = 0.006 \qquad \text{Value} \qquad Combo_{2.2} = 0.178\,MPa$$

Cross-section 3: Pontoon at shaft

$\text{Width}_3 := 11 \cdot m \qquad \text{Height}_3 := 6 \cdot m$

$A_{concrete.3} := \text{Width}_3 \cdot \text{Height}_3 - \left[\left(\text{Width}_3 - 2T_z \right) \cdot \left(\text{Height}_3 - 2 \cdot T_x \right) \right] = 12.44 \, m^2$

Forces

$F_{x.3} := 2 \cdot 10^6 \cdot N = 2000 \, kN$

$M_{y.3} := 1.66 \cdot 10^8 \cdot Nm = 166000 \, m \, kN$

$M_{z.3} := 9.1 \cdot 10^3 \cdot Nm = 9.1 \, kNm$

Calculated values:

$I_{y.3.outer} := \dfrac{1}{12} \cdot \text{Width}_3 \cdot \text{Height}_3{}^3 \qquad\qquad z_{maks.3} := \text{Width}_3$

$I_{z.3.outer} := \dfrac{1}{12} \text{Height}_3 \cdot \text{Width}_3{}^3 \qquad\qquad y_{maks.3} := \text{Height}_3$

$I_{y.3.inner} := \dfrac{1}{12} \cdot \left(\text{Width}_3 - 2 \cdot T_z \right) \cdot \left(\text{Height}_3 - 2T_x \right)^3$

$I_{z.3.inner} := \dfrac{1}{12} \cdot \left(\text{Height}_3 - 2 \cdot T_x \right) \cdot \left(\text{Width}_3 - 2 \cdot T_z \right)^3$

$I_{y.3} := I_{y.3.outer} - I_{y.3.inner}$

$I_{z.3} := I_{z.3.outer} - I_{z.3.inner}$

$W_{y.3} := \dfrac{I_{y.3}}{y_{maks.3}} = 12.885 \cdot m^3 \qquad\qquad\qquad W_{z.3} := \dfrac{I_{z.3}}{z_{maks.3}} = 17.453 \cdot m^3$

Tensions

$$F_{Ed.Comp.3} := \frac{F_{x.3}}{A_{concrete.3}} = 0.161 \cdot MPa$$

$$F_{Ed.My.3} := \frac{M_{y.3}}{W_{y.3}} = 12.883 \cdot MPa$$

$$F_{Ed.Mz.3} := \frac{M_{z.3}}{W_{z.3}} = 0.001 \cdot MPa$$

Combinations:

$$Combo_{3.1} := F_{Ed.Comp.3} + F_{Ed.My.3} \qquad Combo_{3.2} := F_{Ed.Comp.3} + F_{Ed.Mz.3}$$

$$Utilization_{3.1} := \frac{Combo_{3.1}}{F_{Rd.compression}} = 0.459 \qquad \text{Value:} \qquad Combo_{3.1} = 13.044 \, MPa$$

$$Utilization_{3.2} := \frac{Combo_{3.2}}{F_{Rd.compression}} = 0.006 \qquad \text{Value} \qquad Combo_{3.2} = 0.161 \, MPa$$

Appendix

7

```
!Set Environment her:

set_environment  gravity on  buoyancy on  hydro_force morison
wind_force ndrg  waves extrapolated_airy  norder -1  wind no_mean_profile
pre_computed_waves_file off  random_mode write_file  randomfile  rho_water 1025.
rho_air 0.001  nu_water 1.e-5  nu_air 1.e-6  wave_amplitude 3.
wavelength 156.07768226721353  wave_direction 0.  current_speed 0.  current_direction
0.
tsweeps 0.  tsweepe -1  stretch 0.  wind_speed  0.
wind_ref_height 90.  wind_exponent 0.  wind_direction 0.  spectral_peak 10.
seed .3  nfreq 64.  wave_ramps  0.  wave_rampe  20.  depth 200.0
tshift_waves 800  tshift_wind 0.

wave_forces cm_morison 1.63


!for egenfrekvenser; oppdrift off.
!!! Defining materials needed to construct model:
!
define_material  name betong  rho 2276.25  e 0.55e+11  g 21.15e+9
define_material  name betong0  rho 0.001  e 0.55e+11  g 21.15e+9


!================================================================================
=============================
!--------------------------------------------------------------------------------
--------------------------------
!
!!! SEMI-SUBMERSIBLE
!================================================================================
=============================
!
!!    Sentersoyle
!
new_body  name   Sentersoyle   parent   inertial   reftype   inertial
axes normal

new_elements_beam1  nelem 1  material betong  connect_mode auto
x1 0.0 0.0 -20.0  dcyl1 12.2  tcyl1 0.03  pre_strain_long  0.0
x2 0.0 0.0 -5  dcyl2 12.2  tcyl2 0.03  btype beam_lid1 pointmass 8000
frac_stiff 1.0   cdn 0.56 cma 1.0



!================================================================================
=============================
!
!!    Leg 1
!
new_body  name   Leg1   parent   Sentersoyle   reftype   refnode   xfind   0.0 0.0 -20.0

rotorder 123  rotation   0. 0. 0.0   axes normal

! Leg Column
new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 0.0  dcyl1 8  tcyl1 0.06  pre_strain_long  0.0
x2 6.1 0.0 0.0  dcyl2 8.0  tcyl2 0.06  btype beamwb pointmass 0
frac_stiff 1.0   cdn 0 cda 0 cma 1

!================================================================================
=============================
!
!!    Leg 2
!
```

```
new_body  name  Leg2  parent  Sentersoyle  reftype refnode xfind  0.0 0.0 -20.0

rotorder 123  rotation   0.0 0.0 120.0   axes normal

! Leg Column
new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 0.0  dcyl1 8  tcyl1 0.06  pre_strain_long  0.0
x2 6.1 0.0 0.0  dcyl2 8.0  tcyl2 0.06  btype beamwb pointmass 0
frac_stiff 1.0   cdn 0 cda 0 cma 1


!================================================================================
================================
!
!!    Leg 3
!
new_body  name  Leg3  parent  Sentersoyle  reftype refnode xfind  0.0 0.0 -20.0

rotorder 123  rotation   0.0 0.0 240.0   axes normal

! Leg Column
new_elements_beam1  nelem 1  material betong0  connect_mode auto
x1 0.0 0.0 0.0  dcyl1 8  tcyl1 0.06  pre_strain_long  0.0
x2 6.1 0.0 0.0  dcyl2 8.0  tcyl2 0.06  btype beamwb pointmass 0
frac_stiff 1.0   cdn 0 cda 0 cma 1



!================================================================================
================================

!Define sea bed

apply_nodal_bc find 0.  0.  0.  wall  idofs 3 idofe 3  displ -200.0  1.    dstat 0.01


!================================================================================
================================
!--------------------------------------------------------------------------------
---------------------------------
!! !  Apply gravitational force to pointmasses:
!
!apply_nodal_bc find 0 0.0 -20.0 apply_force 0.0 0.0 -78453.2 0. 0. 0.

!! her må alle pointmasser som er satt inn settes inn igjen i globale koordinater!
dette er i M*g !!! g er her 9,80665. de tre siste er rotasjon.

sensors:
nfact: 1 source: WindVxi        scale: 1.             unit: [m/s]  ! header as source
label
nfact: 1 source: WindVyi        scale: 1.             unit: [m/s]  !
nfact: 1 source: WindVzi        scale: 1.             unit: [m/s]  !
nfact: 1 source: WaveElev       scale: 1.             unit: [m]    !
nfact: 1 source: GenPwr         scale: 0. .001            unit: [kW]   !
nfact: 1 source: GenTq          scale: 0. 1.030927835e-5       unit: [kNm] !
1./97.e3
nfact: 1 source: Azimuth        scale: 0. 57.295779513082323    unit: [deg]  !
180./rpi
nfact: 1 source: RotSpeed       scale: 0. 60.          unit: [rpm]  !
nfact: 1 source: RotSpeed       scale: 0. 5820.        unit: [rpm]  header:
GenSpeed    ! 60*97
nfact: 1 source: OoPDefl1       scale: 0. 1.           unit: [m]    !
nfact: 1 source: IPDefl1        scale: 0. 1.           unit: [m]    !
nfact: 1 source: Twst_yx        scale: 0. 57.295779513082323  unit: [deg]  header:
TwstDefl1
nfact: 1 source: BldPitch1      scale: 0.             unit: [deg] ! ???
nfact: 1 source: TTDspFA        scale: 1.             unit: [m]    !
```

```
nfact: 1 source: TTDspSS        scale: 1.               unit: [m]    !
nfact: 1 source: TTDsp_yx       scale: 57.295779513082323 unit: [deg]  header:
TTDspTwst
nfact: 1 source: PtfmSurge      scale: 1.               unit: [m]    ! rel. inertia
nfact: 1 source: PtfmSway       scale: 1.               unit: [m]    !
nfact: 1 source: PtfmHeave      scale: 1.               unit: [m]    !
nfact: 1 source: Ptfm_yz        scale: 57.295779513082323 unit: [deg]  header:
PtfmRoll
nfact: 1 source: Ptfm_xx        scale: 57.295779513082323 unit: [deg]  header:
PtfmPitch
nfact: 1 source: Ptfm_yx        scale: -57.295779513082323  unit: [deg]  header:
PtfmYaw
nfact: 2 source: blrootfx blrootfxi scale:  0.   0.   .001  .001 unit: [kN] header:
RootFxc1   !
nfact: 2 source: blrootfy blrootfyi scale:  0.   0.   .001  .001 unit: [kN] header:
RootFyc1   !
nfact: 2 source: blrootfz blrootfzi scale:  0.   0.   .001  .001 unit: [kN] header:
RootFzc1   !
nfact: 2 source: blrootmx blrootmxi scale:  0.   0.   .001  .001 unit: [kN] header:
RootMxc1   !
nfact: 2 source: blrootmy blrootmyi scale:  0.   0.   .001  .001 unit: [kN] header:
RootMyc1   !
nfact: 1 source: RootMzc1       scale:  0.              unit: [kNm] !
nfact: 1 source: RotTorq        scale: 0.  -.001        unit: [kNm] !
nfact: 1 source: LSSGagMya      scale: 0.  -.001        unit: [kNm] !
nfact: 1 source: LSSGagMza      scale: 0.  -.001        unit: [kNm] !
nfact: 1 source: YawBrFxp       scale: -.001           unit: [kN]  ! Nacelle coord.syst.
nfact: 1 source: YawBrFyp       scale:  .001           unit: [kN]  !
nfact: 1 source: YawBrFzp       scale: -.001           unit: [kN]  !
nfact: 1 source: YawBrMxp       scale:  .001           unit: [kNm] !
nfact: 1 source: YawBrMyp       scale:  .001           unit: [kNm] !
nfact: 1 source: YawBrMzp       scale:  .001           unit: [kNm] !
nfact: 1 source: TwrBsFxt       scale:  .001           unit: [kN]  ! Tower base
coord.sys.
nfact: 1 source: TwrBsFyt       scale:  .001           unit: [kN]  !
nfact: 1 source: TwrBsFzt       scale: -.001           unit: [kN]  !
nfact: 1 source: TwrBsMxt       scale: -.001           unit: [kNm] !
nfact: 1 source: TwrBsMyt       scale: -.001           unit: [kNm] !
nfact: 1 source: TwrBsMzt       scale:  .001           unit: [kNm] !
nfact: 1 source: UC1YU1Fx       scale:  .001           unit: [kN]  ! Local element
coord.sys.
nfact: 1 source: UC1YU1Fy       scale:  .001           unit: [kN]  ! x-axis beam axis
nfact: 1 source: UC1YU1Fz       scale:  .001           unit: [kN]  ! z-axis UC axis
upwards
nfact: 1 source: UC1DU1Fx       scale:  .001           unit: [kN]  !
nfact: 1 source: UC1DU1Fy       scale:  .001           unit: [kN]  !
nfact: 1 source: UC1DU1Fz       scale:  .001           unit: [kN]  !
nfact: 1 source: Fair1Ten       scale: -.001           unit: [kN]  ! Positive when in
tension
nfact: 1 source: Fair2Ten       scale: -.001           unit: [kN]  !
nfact: 1 source: Fair3Ten       scale: -.001           unit: [kN]  !
nfact: 1 source: Fair1Ang       scale: 0.              unit: [deg]  ! Angle from
horizontal
nfact: 1 source: Fair2Ang       scale: 0.              unit: [deg]  !   POSITIVE value
nfact: 1 source: Fair3Ang       scale: 0.              unit: [deg]  !
nfact: 1 source: Anch1Ten       scale:  .001           unit: [kN]  ! Positive when in
tension
nfact: 1 source: Anch2Ten       scale:  .001           unit: [kN]  !
nfact: 1 source: Anch3Ten       scale:  .001           unit: [kN]  !
nfact: 1 source: Anch1Ang       scale: 0.              unit: [deg]  ! Angle from
horizontal
nfact: 1 source: Anch2Ang       scale: 0.              unit: [deg]  !   POSITIVE value
nfact: 1 source: Anch3Ang       scale: 0.              unit: [deg]  !
nfact: 1 source: Fair1_xz       scale: -1.             unit: [sin]  !
```

```
nfact: 1 source: Fair2_xz      scale: -1.           unit: [sin]  !
nfact: 1 source: Fair3_xz      scale: -1.           unit: [sin]  !
nfact: 1 source: Anch1_xz      scale: -1.           unit: [sin]  !
nfact: 1 source: Anch2_xz      scale: -1.           unit: [sin]  !
nfact: 1 source: Anch3_xz      scale: -1.           unit: [sin]  !


!material_specific_damping  material wire_OC4  type  rayleigh   alpha  0.0   beta  0.02


!add_node_stiffness  find   0.  0.  0.    ! mooring, LINEARIZED only
f_lin  0. 0. 0  0. 0. 0.
x_lin  0. 0. 0. 0. 0. 0.
 1    1      70.8e1
 2    2      70.8e1
 3    3      19.1e1
 4    4      87.3e4
 5    5      87.3e4
 6    6      117.e4
 1    5      -108.e1
 5    1      -107.e1
 2    4       108.e1
 4    2       107.e1

!!!!add_node_stiffness  find  0.  0.  0.  !!!!! -13.174633020736458   ! buoyancy
!!!f_lin  0. 0. 139.6e6     0.  0.  0.    ! only for eigenfreq. calculations
!!!x_lin  0. 0. 0. 0. 0. 0.
!!! 3    3      3.836e6
!!! 4    4     -377.6e6
!!! 5    5     -377.6e6
!!!
!!!!add_node_stiffness  find   0.  0.  0. ! restoring moment due to gravity
!!!f_lin  0. 0. 0.  0. 0. 0.              ! only for eigenfreq. calculations
!!!x_lin  0. 0. 0. 0. 0. 0.              ! this is included in RHS for time stepping
!!! 4  4      1390486670.2850199      !mgL, L is -9.943... overall systems CM
incl. mooring weight.
!!! 5  5      1390486670.2850199
!!!
!_____
!For equilibrium run
!--------
damping type ratio2rayl  ratio_1 0.71  ratio_2 0.71  omega_1  0.1  omega_2   1.

newmark dt 0.05  nassemble 1 nnewton 50 nsubmin 1  rwilson 0.9
relax 0.0  resid_newton  1e-06  nmonitor 100

step nstep 1 method gen_alpha
!print_nodes
nodes.txt
-1  -1

!print_b1_elements
elements.txt
-1 -1
 3 2 3 2



! plotting with Python script plot_geo.py
!
monitor_element_b1  type plot nmonitor 10
file turb1.plot

! Tecplot
```

```
!
monitor_element_b1  type tecplot nmonitor 10
file turb1.dat


damping type ratio2rayl  ratio_1 0.05  ratio_2 0.05  omega_1  0.1  omega_2   1.
step nstep 2000 method gen_alpha

print_solution
solution.txt

END
!_____

! for egenfrekvenser
! eigen_analysis old nfreq 20 amplitude 10 filename frekvenser.txt
```