NTNU – Trondheim
Norwegian University of
Science and Technology

DESIGN AND ANALYSIS OF TENSION LEG ANCHOR SYSTEMS FOR FLOATING WINDMILLS

Kumaravalavan Sachithanathamoorthy

Marine Technology (2 year)
Submission date: June 2012
Supervisor: Carl Martin Larsen, IMT

Norwegian University of Science and Technology
Department of Marine Technology

M.Sc. thesis 2012

for

Stud.tech. Kumaravalavan Sachithanathamoorthy

DESIGN AND ANALYSIS OF TENSION LEG ANCHOR SYSTEMS FOR FLOATING WINDMILLS

Renewable energy is considered to be the only sustainable way for future energy supply. Norway is blessed with topography and sufficient rainfall that makes it possible to produce sufficient electricity from hydropower. However, future growth in domestic energy demand and export will require unwanted encroachments on rivers and lakes. Alternative energy production is therefore encouraged. Wind energy is an obvious alternative, but wind turbines are not always wanted on land. Offshore windmills have therefore been proposed. For several reasons one would prefer to have such installations at some distance from the coast, but the water depth on the Norwegian continental shelf is too large for the use of bottom fixes turbines. It is therefore proposed to have floating windmills, and the design of cheap but reliable mooring systems for such structures will hence crucial for the economy of this concept.

The purpose of this project is to discuss application of tension leg anchor systems for offshore wind turbines, and methods for design analysis of such systems. A specific design should be defined on the basis of this discussion, and the proposed design should be analyzed by use of existing software. The analysis should focus on extreme environmental conditions.

The work may be carried out in steps as follows:

1. Literature study that should include design aspects of tension leg mooring systems and methods for analysis.

2. Select main parameters for a floating wind turbine and design a tension leg anchor system for this unit.

3. Establish a model for static and dynamic analysis of the system by use of the computer program RIFLEX.

4. Carry out a set of analyses for regular and irregular waves in order to estimate extreme tether forces.

The work may show to be more extensive than anticipated. Some topics may therefore be left out after discussion with the supervisor without any negative influence on the grading.

The candidate should in her/his report give a personal contribution to the solution of the problem formulated in this text. All assumptions and conclusions must be supported by mathematical models and/or references to physical effects in a logical manner.
The candidate should apply all available sources to find relevant literature and information on the actual problem.

The report should be well organised and give a clear presentation of the work and all conclusions. It is important that the text is well written and that tables and figures are used to support the verbal presentation. The report should be complete, but still as short as possible.

The final report must contain this text, an acknowledgement, summary, main body, conclusions and suggestions for further work, symbol list, references and appendices. All figures, tables and equations must be identified by numbers. References should be given by author name and year in the text, and presented alphabetically by name in the reference list. The report must be submitted in two copies unless otherwise has been agreed with the supervisor.

The supervisor may require that the candidate should give a written plan that describes the progress of the work after having received this text. The plan may contain a table of content for the report and also assumed use of computer resources.

From the report it should be possible to identify the work carried out by the candidate and what has been found in the available literature. It is important to give references to the original source for theories and experimental results.

The report must be signed by the candidate, include this text, appear as a paperback, and - if needed - have a separate enclosure (binder, DVD/ CD) with additional material.

Supervisor at NTNU is professor Carl M. Larsen

Trondheim, 16 January 2012

Carl M. Larsen

Submitted:	16 January 2012
Deadline:	15 June 2012

Abstact

Increasing demand for clean and effective energy production turns interests of the world on floating offshore wind technology. To establish floating wind farms, a wind turbine have to be mound on a floating structure. The floating structure has to be carefully design according to sea environmental condition and kept in precise position. Different types of floating structure and stationkeeping systems have been proposed for floating wind turbines.

This project deals with design a spar floater with tension leg mooring system, where the vertical fairlead position located between center of buoyancy and center of gravity. In this project a details study about floater design and tension leg concept was presented. Further, a model was established in computer program RIFLEX and static and dynamic analysis was carried out for two different environmental conditions, one for an operation condition to understand the model behaviour in normal sea state. The second one was for extreme condition to estimate the extreme tether forces and find out slacking possibility.

Preface

Scope behind this project was design a tension leg mooring system for a floating structure. Generally, tethers in tension leg mooring systems are attached at base of the floater. For wind turbine this arrangement makes large overturning moment. In this project the tension leg concept was chose and decided to attach the tethers between center of gravity and center of buoyancy to increase the moment capacity. This arrangement for a tension leg mooring system demanded increased buoyancy compared to a catenary mooring system. It was difficult to find out a model to support tension leg mooring system with stratifying other design criteria. It took a lot of time to find out the model. As a result, I wasn't got enough time to carry out lot of analyses and time domain simulations for enough time. Anyway, I tried to do analyses as far as possible before the deadline.

I would like to tanks my supervisor, Professor Carl Martin Larsen for his guidance during this thesis work.

Kumaravalavan Sachithanathamoorthy

Trondheim, 10.06.2012.

Table of Contents

Table of Figures

List of Tables

List of Symbols

COG - Center of Gravity

COB – Center of Bouyancy

TLP – Tension leg platform

TL – Tension leg

MWL – Mean water level

VIV – Vortex induce vibration

1 Introduction

1.1 Motivation

The energy in the form of electricity is the “blood” for the modern world. The day today life of the mankind is dependent on electric energy and approximately 70 % of electric energy is produces by using fossil fuel nowadays. Same time awareness about disadvantage of fossil fuel (greenhouse gas emissions and fossil fuel are not endless) is increase concededly in modern world. Therefore finding the green energy solution is a major discussion around the global.

On the other hand a report from the United Nations Development programme (UNDP) indicates that around 1.5 billion people in developing countries still have no access to modern electricity [7]. It is mean one fifth of the world’s population are still living under the dark. (Figure 1 shows percentage of people who living without electricity access in developing countries [source: UNDP and WHO [7]]). The electric energy is essential for them to achieve the social and economic development.

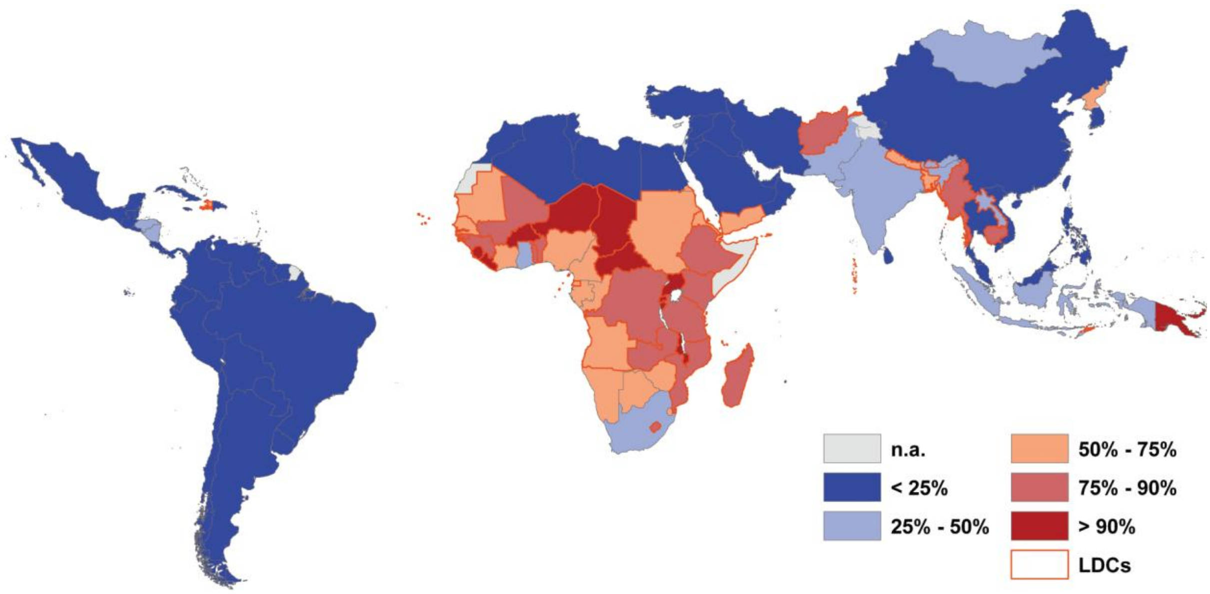


Figure 1: Share of people without electricity access in developing countries, 2008 [7]

The demand for clean and effective energy production is still in height because of reasons which are described above and it will occur with rapidly increasing population. Therefore finding the effective green energy solution is a major discussion around the global. There are many alternative energy method are use in nowadays. One of the more efficient and environmentally friendly (in means of greenhouse gas) method is hydropower, but this method cannot be meet the growing energy demand because this method is already in use in full scale. Wind energy is favourable method after hydropower because it has potential to develop.

1.2 Wind energy

The wind energy is not a new concept for mankind since Man has used wind energy from ancient time. But technology for the electricity generation form wind was developed after the 1970. Since then many land-based wind farms are established and wind turbines technology also developed. Wind energy might be a substitute for fossil fuel because it has no greenhouse gas emissions in operation phase and a renewable source. However it has also some drawback, the main problem is that wind energy is not constant, it is means output of the turbine is strongly dependent on strength of the wind speed. Conflict with life on land and limited land resources also other problems with land-base wind farms. Wind farms at sea may be a solution to overcome these problems. The low sea's surface roughness make higher wind speed at sea than on land and it's turn out to better energy efficiency at offshore than onshore. Locations of the offshore wind farms are far from onshore that reduces the conflict of the life on-land. However offshore wind turbines are considerably expensive than onshore. This can be overcome by developing the technology in future.

1.3 Offshore wind turbines

When moving towards the offshore is a challenge to build or choose the right supporting structure. Gravity base or fixed-bottom supporting structural technologies which are using in marine and offshore oil industry for example jacket-technology may be use for support the wind towers in shallow water. Idea behind the offshore wind farm is capture wind with higher speed than onshore. To ensure capture the wind with sufficient velocity some time it is necessary to move in to the deep water. These bottom fixed structural may be not suitable in economically speaking when water depths is increase [20].

Floating platforms concepts may be sustainable in deep water deployment. Several floating platforms concepts are widely used in offshore oil industry. Some of these concepts may be successfully convert to the offshore floating wind technology, such as spar and semisubmersible platforms.

1.3.1 Spar platform

Spar buoy or spar platform is a vertical cylinder that floats vertically. The concepts had been used in marine field to gather the oceanographic data since 1963 (Chakrabarti, 2005) [2]. But the concepts start to use in oil and gas industry successfully nearly two decades before. The offshore wind technology adapts the concepts relatively quick, and an example for this type wind turbine is Hywind pilot wind turbine owned by Statoil and the turbine is deployed in west Norwegian coast (Figure 3 shows the Hywind – wind turbine). This type of platform is weight stabilized and its mean that center of the gravity located far below the center of the buoyancy. On the other hand the draft of the platforms will increase. This pilot Hywind wind turbine is moored by catenary mooring system.

Figure 3: Spar Type windturbine [11]

Figure 2: Semi-Submerible platform, WindSea windmill [22]

1.3.2 Semisubmersible platform

In this concept, a single wind turbine or more than one wind turbines are mounded on a semisubmersible floater. These types of platforms are column-stabilized which mean large displacement is obtains by big columns or big floaters. The biggest advantage of this platform is better stability for wave loading. Figure 2 shows a semisubmersible platform with three columns and three wind turbines are mounded on it, in many cause a single wind turbine is mounded on this kind of platform. This kind of platforms can be station keeping by cantenary or tension leg mooring system. When we consider the multiple – turbine on single floater, it reduces the mooring line cost. However, W. Musial & et al [20] argued that both the multiple – turbines platform and multi columns platforms are more expensive than mono – column floater. Therefore the spar type platform is economically feasible.

1.3.3 Tension leg platform (TLP)

Another type of platform is known as tension leg platform. This type of platform named after the mooring lines, where the platform is moored by tension legs. Actually this type of platform is a combination of other two type platforms which are discussed above. In this category a wind turbine is mounded on a submerged or fully submerged spar buoys which have small draft and an extended system is attached under the spar buoys (Figure 4). In this design the platform (spar buoys and extend system) is designed to obtain sufficient buoyancy to support to the systems total weight and give the needed pre-tension to the tethers system. An advantage of this platform is the draft is very small, but on the other hand stability again overturning moment is questionable (Larsen, 2010).

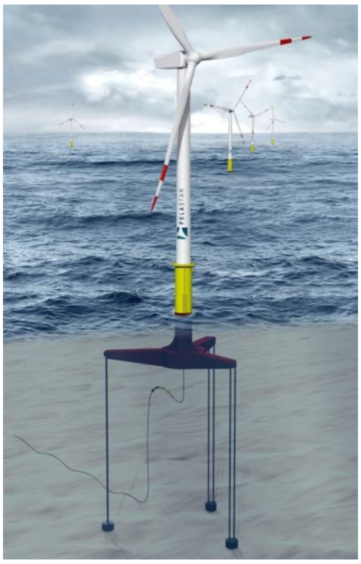


Figure 4 : TLP Windturbine [23]

1.4 Stationkeeping

When its speaking about a floating structure, keep the structure in position is an important characteristic for operation. A floating marine structure in Open Ocean is exposed to environmental loads by wave, wind and current. Mooring systems is used to keep structure in a position again these environmental loads. In offshore industry several concepts of mooring systems are used successfully, some of these principles may be used for floating wind turbines, such as catenary, taut-leg and tensional leg moorings systems.

It was discussed about catenary in pre-project for this project. There it was mentioned that the biggest drawback of the catenary system was the large footprint and large footprints are complicated for wind-farms. Therefore mooring system with small footprint is favourable for wind-turbines. Tension leg mooring systems is vertical anchoring system, that's way the footprint is very smaller than catenary mooring system.

1.4.1 Tension leg mooring system

The tension leg mooring system is a set of parallel tethers attached to the floater to the foundation on the seafloor (Figure 4). The buoyancy of the floater is larger than weight of the total structure and the reserve buoyancy acts tension in the tethers. The platform which moored by tension leg mooring system is relatively restrains from vertical, pitch and roll motions, but allows for horizontal movement with wind and wave disturbances. The anchors at the seabed exposed to large vertical force. Therefore suction anchors are used often to tolerate this large vertical force. A multiple tension legs, commonly three, are used in offshore wind turbine.

In tension legs wind turbine a biggest problem is stability again overturning (Larsen, 2010). Generally the tethers are attached to the bottom of the floating wind turbines for a normal tension leg platform (the type which is described in cha. 1.3.3). Where the center of gravity located above the center of buoyancy or distance between those two points is very small. This critical problem for wind turbine because the weight and horizontal force act above the center of buoyancy so the platform is insufficient against overturning moment.

Every type of platforms has advantage and disadvantage. However, as it discussed above the spar type platform is favourable among them. When they consider mooring system for wind turbine, the tension leg (TL) mooring system has very good performance characteristics. But, nowadays the tension leg mooring system is not in used for spar type wind turbine. So, in this project it will be discuss about feasibility of tension leg mooring system for spar type floating wind turbine.

2 Floating Wind Turbine

2.1 Chosen Wind Turbine

A 5-MW wind turbine has been selected for this case study and turbine and tower properties are given in table below. Actually a 5-MW wind turbine does not excite in offshore currently, but future development in offshore wind technology will demand such a big capacity turbine that is way this model is used in this project. The main parameters of the wind turbine and tower are chosen from (Harald Ormberg, 2011).

Hub Height	90 m
Rotor Diameter / Hub Diameter	126 m / 3 m
Rotor	
Mass	110 Mg
Blades(total)	53.220 Mg
Hub mass	56 .780 Mg
Nacelle	
Mass	240 Mg
Tower	
Tower Mass	249.7 Mg
Base/top diameter	6 m / 3.87mm
Base/top thickness	0.027 m /0.019 m
Young's modulus	210 GPa
Shear modulus	80.8 GPa
Density	8500 kg/m3
Elevation to base	10.0 m
Elevation to top	87.6 m
Elevation to mass centre	43.4 m

Table 1: Wind Turbine properties

2.2 Floater motion

A floating system is subjected to translations and rotations motion due to the wind, wave and current loading. Figure 5 shows the defined coordinate system and motions for the floater, where the surge and sway are horizontal motion respectively along X and Y axes and XY-plane is orientated with mean water level. Heave motion is along the Z- axis and positive Z-axis directed to upward through the centreline of the floater. The motion of rotations about X, Y and Z – axes are referred to as roll, pitch and yaw, respectively.

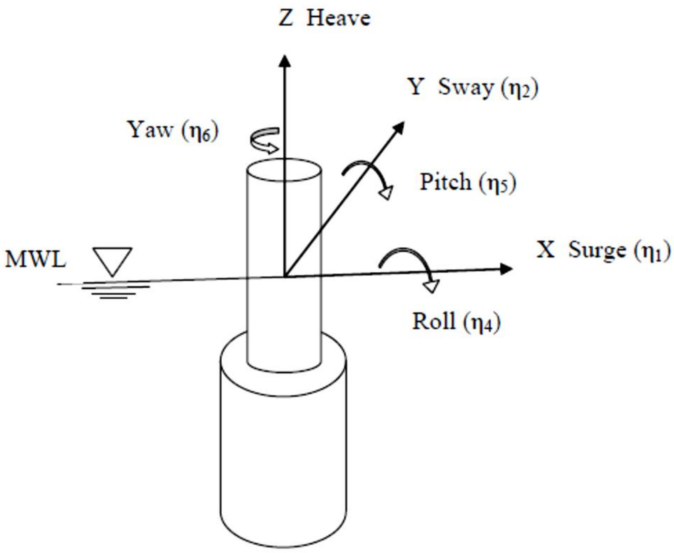


Figure 5 : Floater modes of motion

2.3 Natural periods

Natural periods of an offshore structure are other important design parameters, because the resonance is happed at natural frequency. Therefore natural frequencies of an offshore structure have to be outside of the excitation load frequencies. The Figure 6 shows the wave and wind loads frequency range. For a tension leg floater natural frequency in surge, sway and yaw motion must be shorter than 1/30 Hz in order to avoid the wave load frequency range and it should be more than 1/200 Hz to avoid the wind load spectrum frequency. In heave, pitch and roll motions the natural frequency must be longer than 1/3 Hz (Larsen, 2010; Demirbilek, 1989). A general formula for the natural periods (T_n) can be written according to (Faltinsen, 1990) ;

$$T_{ni} = 2\pi \left(\frac{M_{ii} + A_{ii}}{C_{ii}}\right)^{\frac{1}{2}} \qquad eq. 2.3.1$$

Where, i denote the degree of freedom, M_{ii} is structures mass, A_{ii} is hydrodynamic added mass and C_{ii} is restoring coefficients.

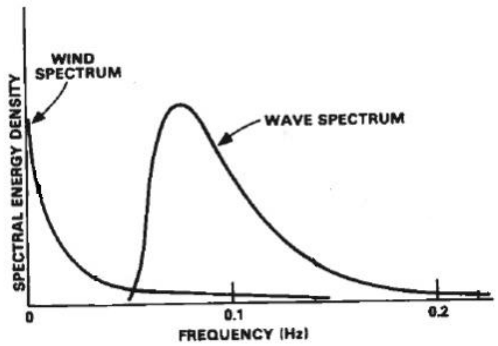


Figure 6 : Wave and wind specrum [3]

2.4 Environmental loads

An offshore structure is exposed wind, waves and current forces. Typically extreme North Sea condition can be represent by a significant wave height (H_s) 15m and wave period (T_p) 16 seconds. The wave load on a slender structure can be calculated by Morison formula. The diameter of the spar cylinder may be between 10-15 m in this project. These diameters are small compare to the wave length ($\lambda = gT^2/2\pi \approx 400m$). Thus the Morison formula is valid to use. The wave load on vertical element can be written as;

$$dF = \frac{\rho_{sw}}{2} C_d D_{spar} u_w |u_w| dz + \rho_{sw} \frac{\pi {D_{spar}}^2}{4} C_m a_w dz \qquad eq. 2.4.1$$

Where the first term is inertia force and second terms is a drag terms. Here, $C_d$and C_m are drag and added inertia coefficients, D_{spar} is the cylinder diameter and ρ_{sw} is the density of the sea water. u_w and a_w are wave horizontal velocity and acceleration. Originally the Morison formula is developed for a fixed structure. Therefore relative velocity and acceleration between water particle and floater have to be use when the formula is using for a floating structure

The wind generate load on the tower and rotor. The wind turbine tower can consider as slender structure. Thus the wind load on tower can be written in term of drag force. The drag forces on the tower per unit length can be written as;

$$dF_{w,tower} = \frac{1}{2}\rho_a C_{D,tower} D_{tower} {V_{air}}^2 \qquad eq. 2.4.2$$

Where; V_{air} is wind speed. $\rho_a$is the air density, $C_{D,tower}$is drag coefficients of the tower, and D_{tower} is the diameter of the tower. The wind forces on the blade elements can be written in terms of lift and drag. However, the momentum theory is used to calculate the total force on rotor in this project and the equation can be written as;

$$F_{blad} = \rho_a A_T v_w (V_{air} - v_w) \qquad eq. 2.4.3$$

Where; A_T is rotor disc area and v_w is wake velocity.

The current loads on cylinder structure can be written as drag and lift forces. The other important phenomenon by current load is vortex induced vibration (VIV). When the vortex shedding frequency is close to natural frequency of the structure, a large vibration will occur and this known as VIV. These vibrations lead the structure to fatigue failure and increasing effective diameter for drag terms. Therefore a tension leg mooring system should be design to avoid the VIV.

2.5 Tension Leg Spar Floater Concept

Scope behind this project is feasibility study of spar type supporting structure for tension leg mooring system. A supporting floating structure with tension leg mooring system must be fulfils the flowing basic requirements:

- Must support its own and wind turbine weight
- Must has excess buoyancy (floater buoyancy > total weight)

The assumed floater has two main parts, see Figure 7 . The upper part is named as tower base and other main part is spar floater. The wind tower will be mounded on the top of the tower base and the tower base has 10m elevation above the sea level, and draft and diameter of this section is determined on base of other facts. The tower base has relatively small diameter near the free surface and it will reduce the wave loading on the floater. The main part of the floater is the spar cylinder, and diameter and draft of this spar cylinder will be determines in design phase to get sufficient buoyancy and center of buoyancy (COB). Simultaneously significant ballast must be added in to the bottom of the spar to get center of the gravity (COG) well below the COB. The vertical position of the fairlead is somewhere between COB and COG, and the vertical potion should be optimized to provide better stability. Not only the arrangement of the fairlead vertical position could give the better stability, but also the horizontal distance of the tethers from center of the floater has also considerable affect on stability. If the tethers attached directly to the main spar cylinder the distance between tethers is insufficient and stability could be critical. To increase distance between tethers its need an extended body for attached to the tethers. In this design a triangle extended body is connected to main spar cylinder, see Figure 8, and the spar vertical center axis (z-axis) and the point of center gravity of triangle meets at same point. Three set of the tethers attached from every corner of the triangle to sea bed. The number of tethers in every set will be determines in design phase of the tension leg.

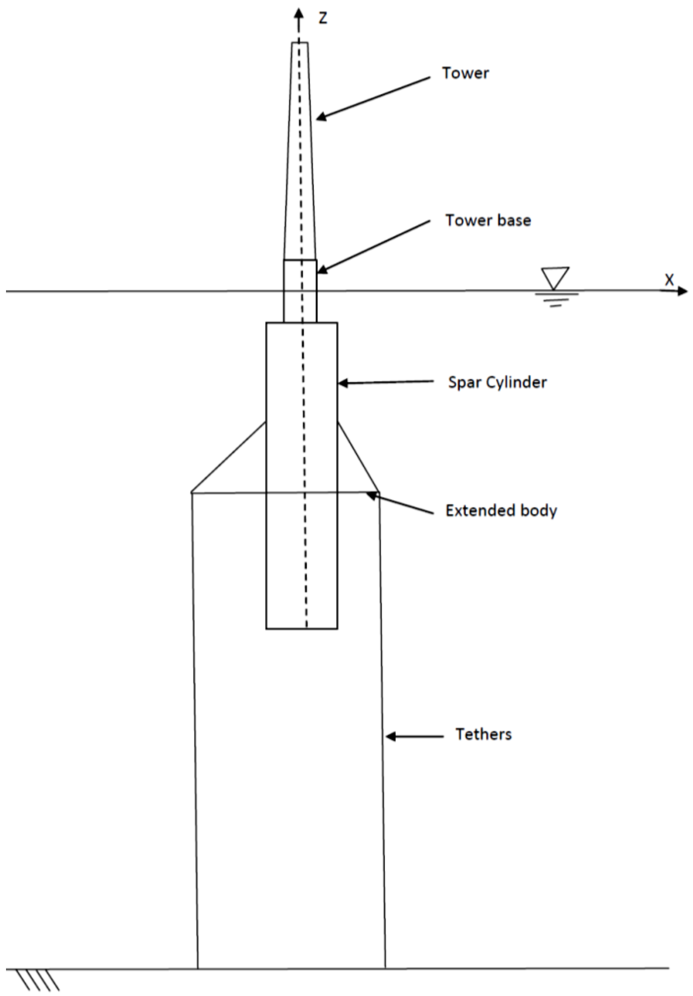


Figure 7: Layout of the floater and TLP

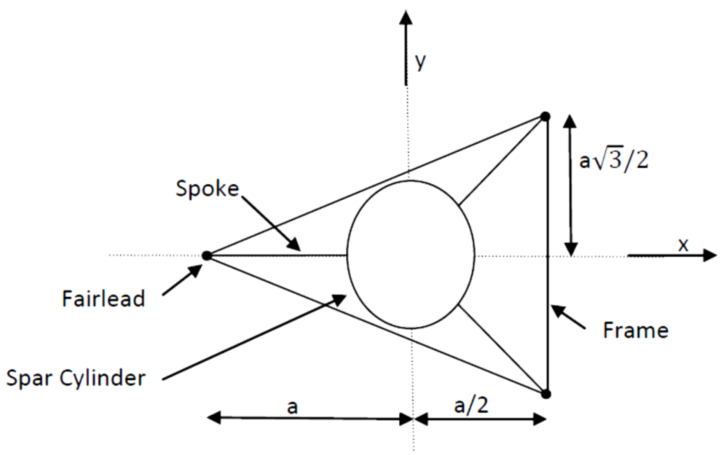


Figure 8 : Over-veiw of the extended system

The reserve buoyancy is a key design parameter in this case. Equation for reserve buoyancy or the static pretension in tethers is given as:

$$F_{tethers} = (\nabla . \rho_{sw} - M_{total})g \qquad eq. 2.5.1$$

Where $\nabla$is total displaced volume by floater, ρ_{sw}density of sea water, $M_{total}$is the total mass of the system and $g$is the acceleration of the gravity. The displaced volume of a spar cylinder is given in following equation.

$$\nabla = \frac{\pi}{4} D_{spar} T \qquad eq. 2.5.2$$

Where $D_{spar}$is spar cylinder diameter and $T$is draft of spar cylinder.

The amount of reserve buoyancy should be enough to prevent the tendons from going slack under the extreme condition. So long tension is remaining in the tethers the systems will prevent from roll and pitch motion. Because, the major rotational stiffness to the system is coming from tethers if tethers going to under slack the system lost the rigid connection with seafloor. So, it may lead overturning. The mass and buoyancy moment also contribute to rotational stiffness and it will be discusses in flowing chapter. The equation for minimum requirement of pretension may be written as;

$$F_{tether\_min}. \sin(\alpha) > \sum F_{Hi} \qquad eq. 2.5.3$$

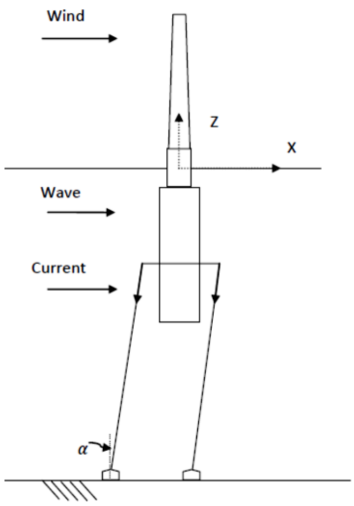


Figure 9 : Horizontal Forces on System

Where; F_{Hi} is horizontal forces which are act on the system and α is the tether angel, see Figure 9. Designing against overturning is an important criterion for a floater. The equation for moment capacity may be written as;

$$F_{tether\_min}.\cos(\alpha).\frac{a}{2} > \sum F_{Hi}Z_i \qquad eq. 2.5.4$$

Where z_i is vertical moment arm for the horizontal forces from the vertical fairlead level, a is distance between tether terminations to center of the spar (ones have to note that the minimum moment arm occurs while horizontal forces are in sway direction). Since $\alpha\ is\ small,$ $\cos(\alpha) \approx 1$, the equation 3.4 may be rewritten as;

$$F_{tether\_min}.a > 2\sum F_{Hi}Z_i \qquad eq. 2.5.5$$

3 Floater Design Process

3.1 Natural Period, Mass, Added Mass and Restoring coefficient

In design phase estimate the system natural periods is an important step. The natural periods can be calculated from equation 2.3.1. To estimate the natural period one need to find out the added mass, inertia and restoring terms. Discussion about these terms will be follow and equations for this calculation are base on (Larsen, 2010) & (Withee, 2004) .

3.1.1 Surge and Sway

When floater is move in surge (as shown in Figure 9) the motion is resisted by a horizontal restoring force which is produced by the tethers. The draft of the floater would be increase in small amount while the floater moves in surge direction and it would also increase tension in tethers. Anyway this small increase in tension can be neglects and assume linearised stiffness in the line. So the restoring coefficient in surge may be written as:

$$C_{11} = \frac{F_{tethers}}{L_{tether}} \qquad eq. 3.1.1$$

Where; $F_{tethers}$ is pre-tension and L_{tether} is length of the tether. The mass M_{11} is the total mass of the structure, but for hand calculation only mass of wind turbine, tower and floater have considered. The added mass of a cylinder spar may be written as;

$$A_{11} = C_m \pi \frac{D_{spar}^2}{4} \rho_{sw} T \qquad eq. 3.1.2$$

Where; C_m - Added mass coefficient, = 1 for circular cross section, D_{spar} - Diameter of the spar cylinder, ρ_{sw} - Density of the sea water and T – Draft of the spar. Horizontal added mass of the triangle extended system may be neglects. The mass, added mass and restoring coefficients for sway motion are also same as in surge motion.

3.1.2 Heave

When consider the heave motion, the restoring force is provides by both tether and hydrostatic effects. As the floater oscillates vertically, the tethers will generate large forces due to the tether's elasticity modulus and that forces will be one of the heave restoring forces. The other part of the heave restoring force is due to the change in water plane area while the floater heaves. However the second part of the restoring force is smaller than the tether restoring force (Withee, 2004). Then the equation of heave restoring coefficient can be written as:

$$C_{33} = \frac{n_{tethers}E_{tether}A_{tether}}{L_{tether}} + \rho_{sw}gA_{wp} \qquad eq. 3.1.3$$

Where; $n_{tethers}$ is number of tethers, E_{tether} is modulus of elasticity, A_{tether} is cross section area of the tether and A_{wp} is the waterplane area. The mass for the heave motion is same as the structure's total mass. The spar and extended spoke system contribute to the heave added mass. Added mass due to the spar is cause by water under the spar bottom and its magnitude may be small. Therefore the contribution from extended system may not negligible. The equation for heave added mass can be written as;

$$A_{33} = \frac{2}{3}\rho_{sw}\pi(\frac{D_{spar}}{2})^3 + \ vertical\ added\ mass\ of\ extended\ system \qquad eq. 3.1.4$$

First part of the above equation indicates contribution from the spar.

3.1.3 Roll and Pitch

The structure is also exposed to roll and pitch moments. In this cause extension and contraction in tether will provide a considerable restoring moment, and tension in tethers, mass and buoyancy also contribute. See Figure 10 for this condition.

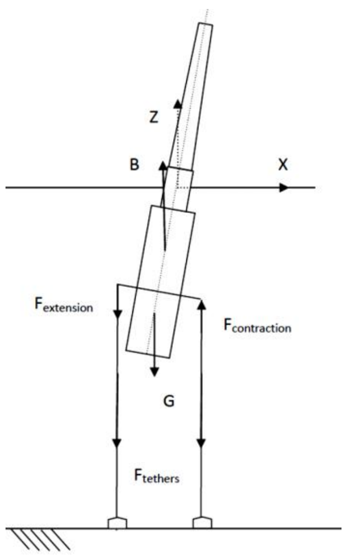


Figure 10 : Diagram for roll and pitch restoring coefficient

First consider about roll motion, the extension and contraction in tethers can be written as;

$$\Delta F = F_{extension} = \frac{E_{tether}A_{tether}}{L_{tether}}\left(\frac{a\sqrt{3}}{2}\right)\sin(\alpha) \qquad eq.3.1.5$$

For small rotation the restoring moment by tethers can written as;

$$\sum M_{tether} = F_{extension}\left(\frac{a\sqrt{3}}{2}\right) + F_{contraction}\left(\frac{a\sqrt{3}}{2}\right) + \frac{1}{3}F_{tehers}\left(\frac{a}{2}\right) - \frac{1}{3}F_{tehers}\left(\frac{a}{2}\right) \qquad \text{eq.3.1.6}$$

Where; a is distance from center to tether termination. The moment by tension in tethers will be cancelling each other. The moment by buoyancy and mass or the uprighting moment can be written as;

$$\sum M_u = -M_{total}gZ_G\sin(\alpha) + \rho_{sw}\nabla gZ_B\sin(\alpha) \qquad eq.3.1.7$$

Where; Z_G is the distance from fairlead to center of the gravity, Z_B is distance from fairlead to center of buoyancy and ∇ is displaced volume by floater. For $\alpha \ll 1, \sin(\alpha) \approx \alpha$. The total restoring moment in roll can be written as;

$$\sum M_R = \alpha\left(2\frac{E_{tether}A_{tether}}{L_{tether}}\left(\frac{a\sqrt{3}}{2}\right)^2 - M_{total}gZ_G + \rho_{sw}\nabla gZ_B\right) \qquad eq.3.1.8$$

So, the roll restoring coefficient can be written as;

$$C_{44} = 2\frac{E_{tether}A_{tether}}{L_{tether}}\left(\frac{a\sqrt{3}}{2}\right)^2 - M_{total}gZ_G + \rho_{sw}\nabla gZ_B \qquad eq.3.1.9$$

In this way the restoring coefficient in pitch written as;

$$C_{55} = \frac{E_{tether}A_{tether}}{L_{tether}}a^2 + 2\frac{E_{tether}A_{tether}}{L_{tether}}(\frac{a}{2})^2 + M_{total}gZ_G + \rho_{sw}\nabla gZ_B \qquad eq.3.1.10$$

These two equations 3.1.9 and 3.1.10 indicate that the restoring coefficients for roll and pitch motions are same and the inertia term will be also remain as same for both motion. The mass term is the mass moment of inertia of the structure about the rotation point; here rotation point is fairlead point. This term and added mass may be written as;

$$M_{44} = M_{55} = \int mz^2 dz = \frac{M_{total}}{3}(Z_g)^3 \qquad eq. 3.1.11$$

$$A_{44} = A_{55} = \int_{-T}^{0} \pi C_M \frac{D_{spar}{}^2}{4} \rho_{Aw} z^2 dz = \frac{\pi}{4} D_{spar}{}^2 C_m \rho_{sw} \frac{T^3}{3} \qquad eq. 3.1.12$$

3.1.4 Yaw

Wind loading on turbine can be a main cause for yaw motion of a wind turbine. The moment of the restoring force by the tether will resist the yaw motion and contribution from extended system may also achieve for counteract to this motion. Anyhow the yaw restoring coefficient on base of tether force moment can be written as;

$$C_{66} = n_{tethers} \frac{F_{tethers}}{L_{tether}} \qquad eq. 3.1.13$$

The yaw motion is around the z-axis, therefore there is no contribution from spar cylinder for added mass. The inertia term is mass moment about z axis.

$$M_{66} = \frac{2\pi}{3} \rho \left(\left(\frac{D_{spar}}{2} \right)^3 - \left(\frac{D_{spar,inn}}{2} \right)^3 \right) T \qquad eq. 3.2.14$$

Where; ρ is density of the spar material and $D_{spar,inn}$ is inner diameter of the spar.

When the mass, added mass and restoring coefficients are determined, one can calculate the natural periods for these motions from equation (eq.2.3.1). However one should note that this calculation will lead to only for an approximate solution.

3.2 Design Parameters

In this section discusses about different parameters, which are involved in spar floater design how to effect on system response. During the design processes water depth and parameters of the tower base (Figure 7) are unchanged. This parameters are given in Table 2. Equations for this calculation are base on which are presented in above chapters. (The significant wave height (H_s) and wave period (T_p) are 8m and 7s for these calculations.)

Water Depth (h)	-200.00
Tower base (TB)	
Diameter of tower base	6.50
Draft of the Tower base	-5.00
Elevation above the sea level	10.00

Table 2: Tower base parameters

3.2.1 Diameter

Nett-buoyancy or pretension is an important for TL- floater. The pretension can be increase by increasing buoyancy. The buoyancy may be increase by increasing diameter or draft of the spar. The Table 3 shows estimated value of the pretension, horizontal force and natural periods of the structure for different diameter of the spar while unchanged the draft. The diameter changed from 10m to 12m.

Spar Cylinder						
Diameter [m]	Pre-tension [kN]	Force-x [kN]	T1/T2 [s]	T3 [s]	T4/T5 [s]	T6 [s]
10.00	4.9819e+004	4.2146e+003	51.6331	1.6250	12.6964	3.3635
10.50	5.9863e+004	4.4574e+003	49.0114	1.6422	13.3592	3.2226
11.00	7.0440e+004	4.7121e+003	46.9536	1.6597	14.0161	3.1129
12.00	9.3193e+004	5.2570e+003	43.9280	1.6960	15.3136	2.9535

Table 3 : Design parameter affect - Diameter

The table above shows that pretension in tethers increase while increasing diameter of the spar, this a good sign for TL floater, but on the other hand the horizontal force on spar also increase with increasing diameter, it mean increasing horizontal offset and overturning moment. Therefore the diameter of the spar is a trade-off between buoyancy and horizontal force (mainly wave force). Sufficiency of the pretension to prevent the tethers from going slack will analyse by RIFLEX.

The Table 3 shows also approximate natural periods of the structure. The surge and sway periods should be more than 30 second. It is clear that surge and sway periods are decreasing while increasing spar diameter. It is very little visible change in heave period while increasing spar diameter. From equation of the heave period one can understand that heave period is mainly depend on axial stiffness of the tethers and water plane area. The yaw natural period should be longer than 30 seconds, but in this calculation it is very small. Anyway its can be acceptable as far as this below the 4 seconds, because this period avoid the wave periods range which is between 4-30 seconds. The table shows that roll and pitch natural periods are in critical state, these are overlaps on wave periods range.

3.2.2 Horizontal Distance

The roll and pitch eigenperiods are not strongly depends on spar diameter. If one look the equations of restoring coefficients for these motions, can understand these are depends on distance of the tethers termination, so changing in distance may be a solution. The Table 4 show the result obtain while change the distance of tether from center of the floater. Natural periods in surge, sway and heave are not depended on distance of the tethers.

a [m]	T4/T5 [s]	T6 [s]
14,50	24,79	3,88
15,00	24,10	3,81
20,00	18,78	3,30
25,00	15,31	2,95
30,00	12,90	2,70
35,00	11,13	2,50
40,00	9,78	2,34
50,00	7,86	2,09
60,00	6,57	1,91
70,00	5,64	1,77
80,00	4,94	1,65
90,00	4,39	1,56
100,00	3,96	1,48

Table 4 : Design parameter- Horizontal distance Vs Natural periods

The Table 4 shows that the roll and pitch eigenperiods are considerably decreasing and going towards favourable range while increasing the distance. The yaw natural periods also reduces with increasing length, but not as for roll and pitch.

From Table 4 it is clear that one can obtain roll and pitch natural periods shorter than 4 second at very long distance, in this cause near to 100 m. However this is an impractical solution, because far distant for tethers from main spar cylinder mean that the extended body system (Figure 8) covers a large area around the spar. This is unwanted situation for a spar type wind turbine.

3.2.3 Number of tethers

One may be overcome the natural periods in roll and pitch by increasing stiffness of tethers, in other word increasing number of tethers.

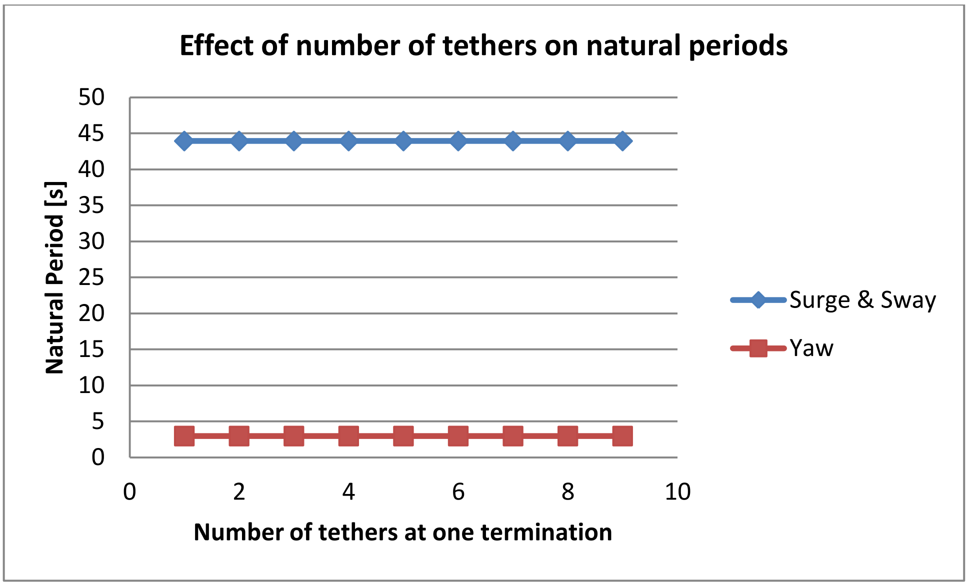


Figure 11: Effect of number of tethers on natural periods - surge, sway and yaw

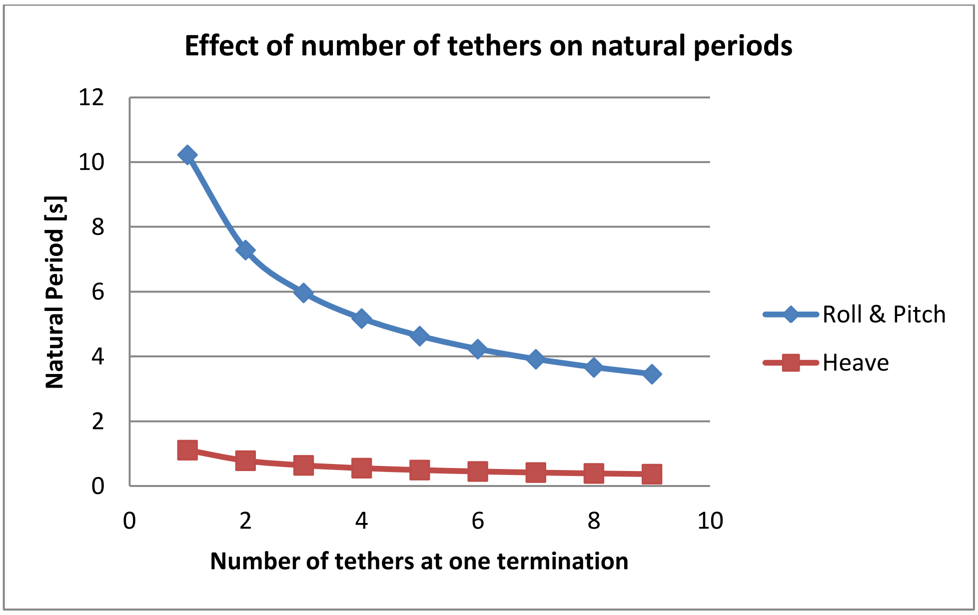


Figure 12 : Effect of number of tethers on natural periods – roll, pitch & heave

The two above graphs (Figure 11 and Figure 12) shows the effect of the number of tethers on natural periods. Figure 11 shows that surge, sway and yaw natural periods are unaffected by changes in number of tethers. Changes in number of tethers is greatly affected on roll and pitch natural periods. The restoring coefficients of roll and pitch motions are increasing while increasing number of tethers because it is increase the stiffness of the tethers, this causes reduces in roll and pitch natural periods. Similarly, the heave natural periods also decreases.

3.2.4 Spar Draft

Other parameter in design of floater is floater draft. Changing in spar draft changes the pretension in tethers (see Figure 13), since the buoyancy of the system increase with increasing draft. Simultaneously the mass and inertia terms of all modes of motions and added mass terms in all DOF, exclude in yaw, are affected by changes in spar draft. At the same time the restoring coefficients in surge, sway and yaw are increases when increasing in pretension. The net result of the increasing draft are decreasing natural periods in surge, sway and yaw are, increasing roll and pitch natural periods and small increases in heave natural period (see Figure 14 and Figure 15).

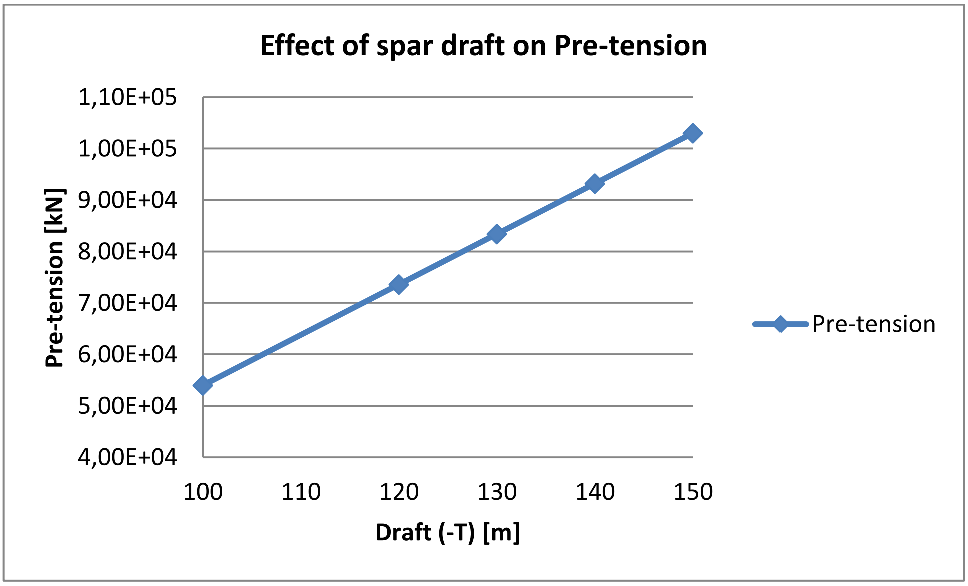


Figure 13 : Effect of draft on pretension

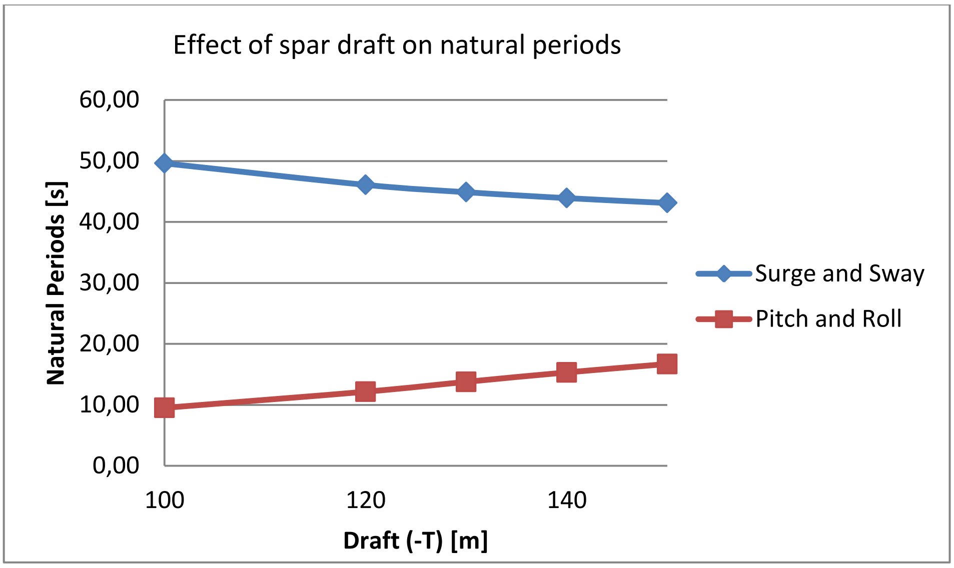


Figure 14 : Effect of spar draft on natural periods - surge, sway & pitch

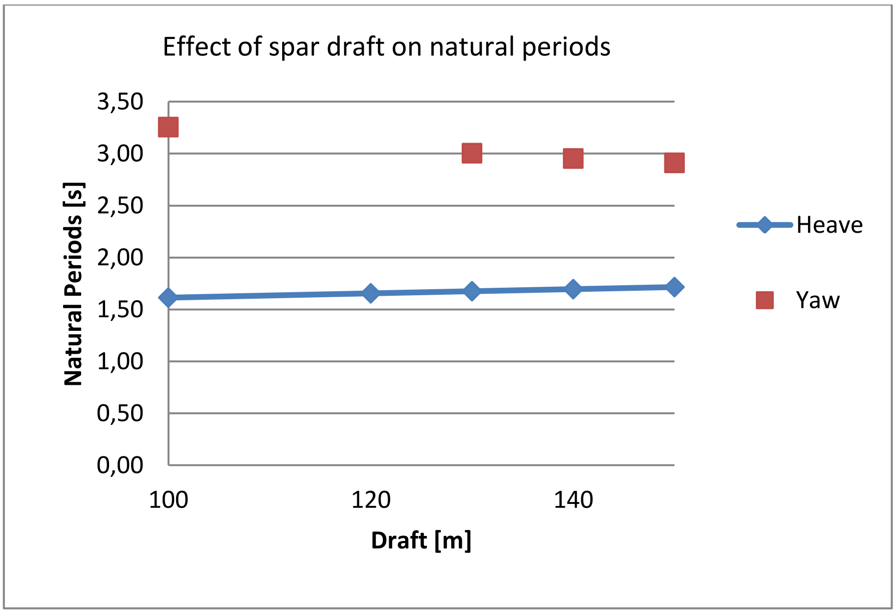


Figure 15 : Effect of spar draft on natural periods- heave & yaw

3.6.5 Vertical fairlead position

Finding the optimized vertical position of fairlead is difficult task. But, if one rewriter the equation of up-righting moment (eq.3.1.7) as follows, a maximum vertical position can be found.

$$B.(KB - KF) > G.(KF - KG) \qquad eq.3.2.1$$

$$KF < \frac{B.KB + G.KG}{(G + B)} \qquad eq.3.2.2$$

Where;

$Z_B = KB - KF, Z_G = KF - KG$ and KF is vertical fairlead position from the bottom of the spar. Assume that buoyancy (B) and total weight (G) are not change while adjusting the KF between KG and KB. The moment of buoyancy reduces when KF go towards to the KB, because it is clear that the moment arm is reducing. At the same time the moment of weight increases. As it is difficult to find the optimized point, so it is better to keep KF as lower as possible. At the same time, it's necessary to understand the changes in KF which affect have on system. Changes in KF position mean in other word changes in length of the tethers. Parameter of the tether length is involved in all modes of the restoring coefficients. All natural periods are slightly increasing with increases in tether length or KF. The Figure 16 and Figure 17show that.

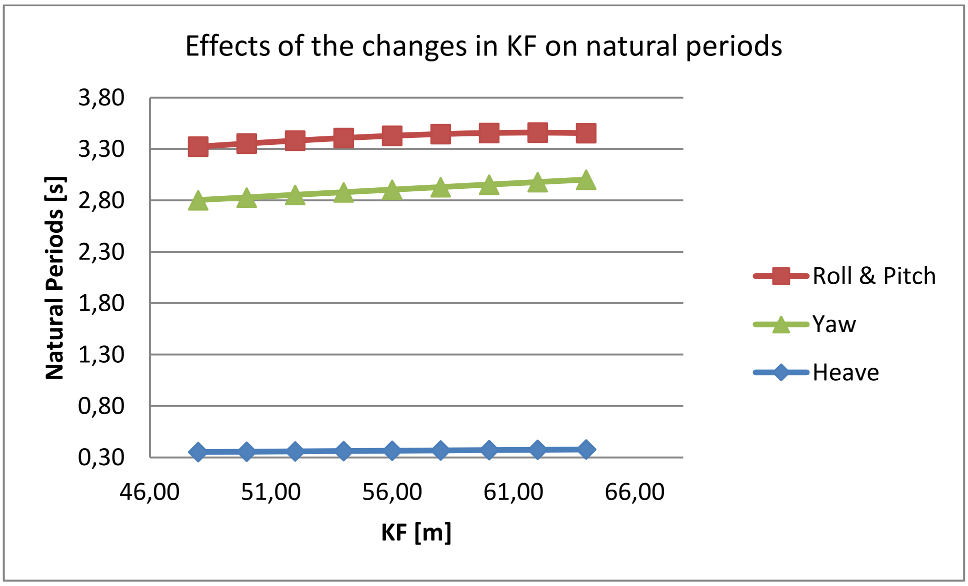


Figure 16:Effects of the changes in KF on natural periods - roll, pitch, yaw and heave

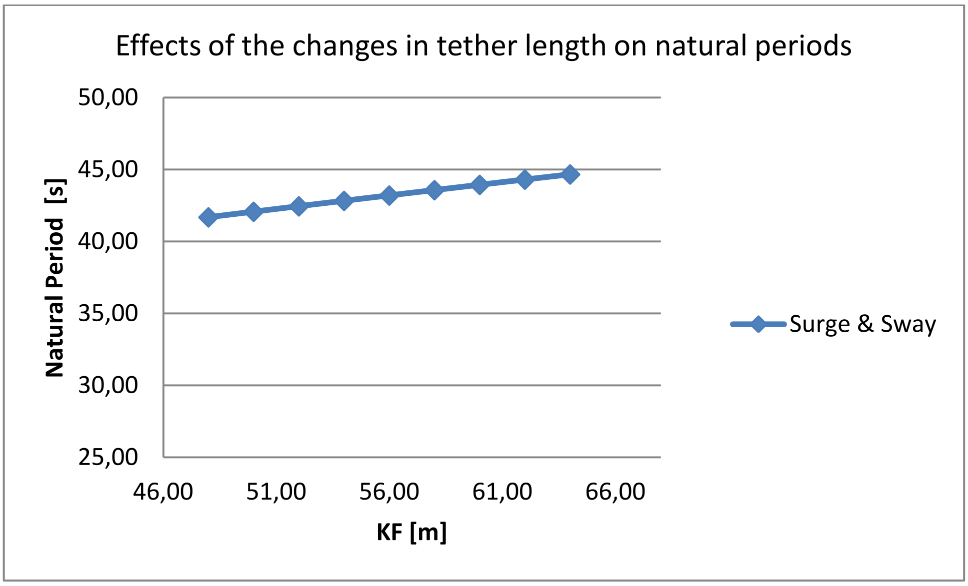


Figure 17 :Effects of the changes in KF on natural periods - surge and sway

4 Computer model

The wind turbine system with floater and tension leg mooring is modelled in computer program RIFLEX. Then static and time domain dynamic analyses are carried out. RIFLEX is a computer program for analysis of slender marine structure and developed by MARINTEK. This program can handle the nonlinear time domain analysis based on finite element method. The figure below shows the basic progress in RIFLEX; first one has to write and run an INPMOD module for input data, then STAMOD and DYNMOD modules for static and dynamic analyses. Finally OUTMOD module for post-processing of selected results. In this cause the FREMOD module which is for frequency domain analyses is not dons.

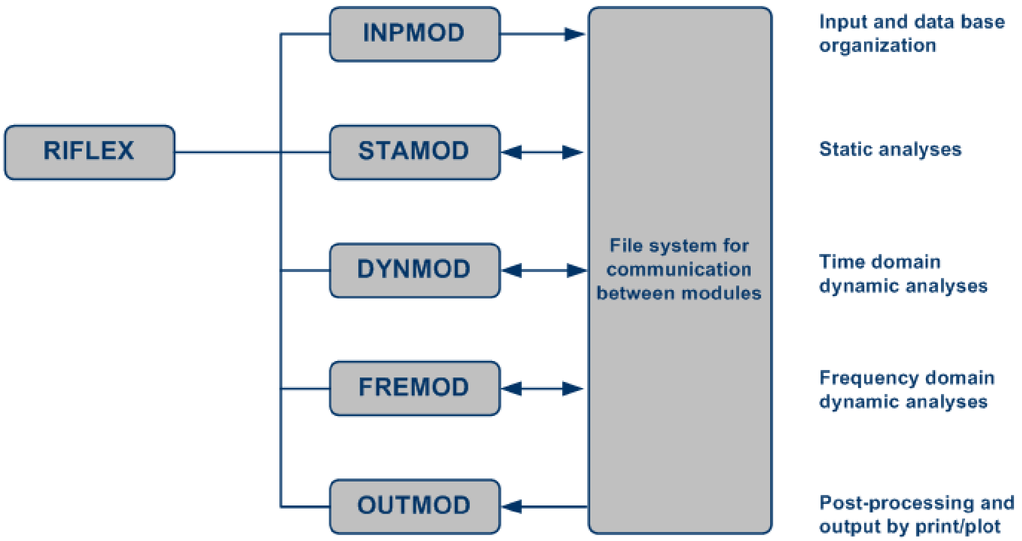


Figure 18 : RIFLEX main parts [14]

4.1 INPMOD module

In input file whole wind turbine with floater and mooring lines are modelled. In addition the wave and current also modelled in environmental conditions.

4.1.1 Structure model

In input file all components are modelled as circular cross-section beam elements. Figure-A 17 and Figure-A 18 in appendix B show proposed model global topology, where all super nodes and lines are named. One should note that these figures are not scaled.

The shaft is modelled as two circular beam elements with total turbine weight and connection between shaft and tower top is defined as master-slave connection. The shape of the tower is almost conical shape i.e. the diameter of the tower is decreasing consistently from top to bottom. Only circular cylinder sections can be models in RIFLEX, therefore the tower is divided into ten cylindrical segments, as show in Figure 20, with average diameters, where the top and bottom segments diameters are 3.86 m and 6.3 m respectively.

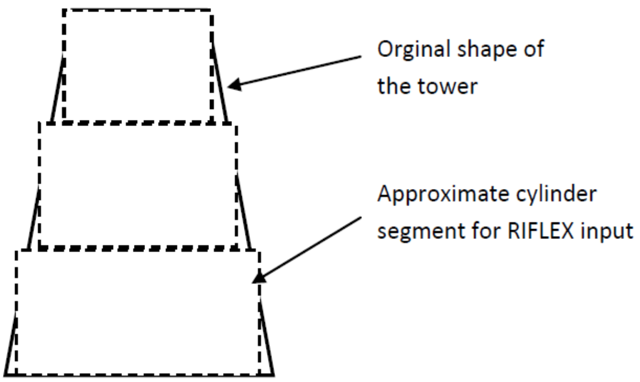


Figure 20 : Tower model in REFLEX input

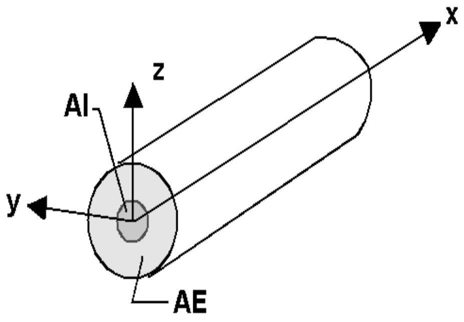


Figure 19 : Cross section for RIFLEX input []

While a cylindrical cross-section (as show as in Figure 19) is defining in INPMOD the flowing properties also have to be input. These are unit mass, external and internal cross-sectional area (AE and AI), axial, bending and torsion stiffness and hydrodynamic coefficients. The tower properties are used in this INPMOD as it's used by Harald Ormberg etal. (Harald Ormberg, 2011)

The floater with spar cylinder and tower base has circular cylinder cross-section, so it is modelled as it is. The suitable diameter, thickness and draft of these sections are to be determines after many analysis run. In addition the ballast section included at the bottom of the spar. The extended body system for mooring lines connection point is also included in the model. Actually it should be sets of tethers at every termination point to sea bed for safety consequence in cause of loss of one tether. But, to avoid the difficulty in design phase, it is modelled only single tethers from each fairlead to fixed point sea bed. One should note that every line type is divided into many numbers of elements for FEM analysis.

4.1.2 Environmental loading

The environmental loads are modelled in environmental model. The sea state can be model as regular and irregular wave condition. But, only one type of wave condition, i.e. irregular or regular, can be run in dynamic analysis at one time. Two type regular sea state run with different type of wave height and period. The irregular sea state is modelled with JONSWAP wave spectrum and two type of irregular sea state will be run, one for normal operation condition and other for extreme condition. The current load is modelled with defining the current velocity in x-direction at different depth levels. One should note that the wind load is note modelled in this analysis, because there is no option to model the wind load in RIFLEX.

4.2 Static (STAMOD) and Dynamic (DYNMOD) analyses

The finite element method (FEM) is selected to static analysis in RIFLEX. This analysis is base on non-linear formulation. Further four load types are activated, such as volume forces, global spring, boundary change and current forces. The super node "sparloc" (see Figure-A 17), which located at sea level, is defined as fixed super node in all DOF in INPMOD. While running the load type "boundary change" in STAMOD the super node "sparloc" is allows to be free in all translation and two rotation DOF, but yaw motion is continue to be fixed in this analysis. If this node is allowed to be free in all DOF, the analysis will be fail.

Dynamic analysis is couple of regular and irregular wave analyses are carried out. The regular wave analysis is base on Airy linear wave theory. Time domain analysis in nonlinear analysis and the procedure is base on Newmark's β-family methods.

5 Results

5.1 Chosen Floater

The Table 5 shows the parameters of the chosen floater and mooring line for supporting the 5MW wind turbine. Process of the floater design is combination of the Matlab calculation and RIFLEX analyses. The step by step design process in RIFLEX in is found in Appendix A. The chosen spar has diameter for 14m and 100m draft.

Water Depth (h)	-200	m
Draft (T)	-100	m
Diameter of tower base	6,5	m
Draft of the tower base	-5	m
Elevation of tower base above the sea level	10	m
Diameter of spar	14	m
Thickness of floater	0.01	m
Material	Steel	
Density	7.85	Mg/m^3
Displaced Volume	15160	m^3
Position of buoyancy	-51.94	m
Total Mass (including ballast)	4,31E+03	Mg
Position of mass center	-84.83	m
Pretension	1,07E+05	kN
Mooring lines		
Number of tethers	3	
Vertical position of fairlead	-60	m
Horizontal distance (a)	25	m
Diameter of tether	0.45	m
Thickness of tether	0.3	m

Table 5: Chosen Flaoter Parameters

The Table 6 shows the chosen structure natural periods. The natural periods in surge and sway are in well above the 30 seconds. The natural periods in heave is very small, it's mean the structure is very stiff in heave motion. At the same time, the natural periods in roll and pitch may not under the range of 3-4 second, but a lot of analyses done to find out the right model which give roll and pitch natural periods under 3 seconds, but it was difficult to find out. Due to the time consent the above model is chosen for further analyses. In addition, natural period in yaw motion is very small, according to Larsen (2010), the yaw natural period should be longer than 30 seconds. Anyway its can be acceptable as far as this below the 3-4 seconds, because this period avoid the wave periods range which is between 4-30 seconds. The tether diameter and thickness seem to be unrealistic, but these parameters are used in hence about RIFLEX input, where only one tether is modelled at one termination point.

Natural Periods	
Surge & Sway	42.39 s
Heave	0.56 s
Roll & Pitch	3.66 s
Yaw	0.93 s

Table 6 : Natural periods of chosen floater

The center of buoyancy is well above the center of gravity and the fairlead position is between COG and COB. The Extended body systems properties are not included in this table. This system contributes to increase the pretension with 2,22E+03kN and it is not affected on center of gravity and buoyancy, because the system is fully submerged. In Table-A 10 (in appendix A) one can find the whole systems mass and buoyancy details including the “Extended body system”.

5.2 Static and dynamic Analysis

To study the chosen model response and maximum and minimum value tether forces, it’s necessary to carry out static and dynamic analyses. In analyses two types of environmental conditions are considered, first one for operation condition and second one is extreme condition. These environmental conditions are show in table, where the extreme condition for wave is 100-year return periods and current is 10-year return period.

	Operation condition	Extrem condition
Wave		
Hs [m]	1.00	15.00
Tp [s]	7.00	16.00
Current velocity [m/s]		
Water Depth [m]		
0.00	0.50	1.60
-20.00	0.40	1.10
-40.00	0.30	1.10
-60.00	0.20	0.70
-80.00	0.10	0.70
-100.00	0.00	0.60

Table 7 : Environmental conditions

5.2.1 Operation condition

First the static analysis is done in operation conditions with current. The following figures (Figure 21and Figure 22) show result of the static analysis. The first one show effective tension in tether 1 while second one is for tether 2 and 3. The static effective tension for tether 2 and 3 is same, because the floater is symmetric about x-z plane. TheTable 8: Effective tension – give the maximum and minimum value in tethers, where a maximum value for 2.08 MN is read in tether 2 and 3 while a minimum 0.64 MN read in tether 1. Different between these values are not very height.

EFF. TENSION [kN]	Moor-1	Moor-2
Max	2,035E+03	2,080E+03
Min	6,441E+02	6,890E+02

Table 8: Effective tension –(Hs=1, Tp=7)

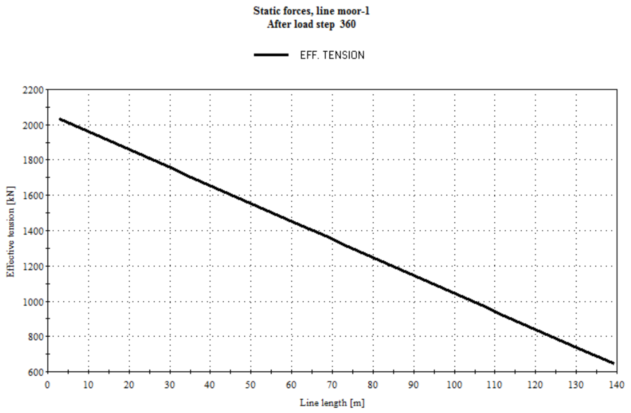


Figure 21 : Effective tension in tether-1 –(Hs=1, Tp=7)

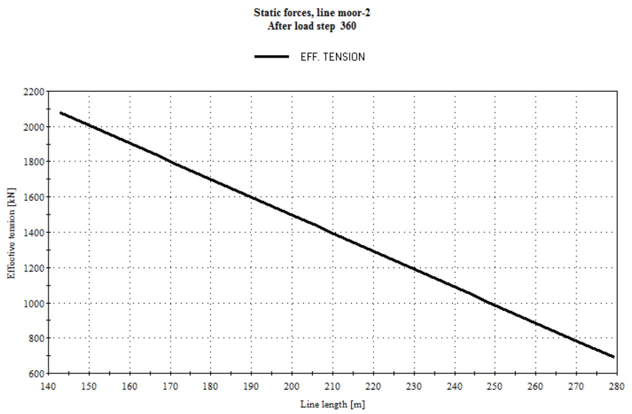


Figure 22 : Effective tension in tether-2 –(Hs=1, Tp=7)

After that, a time domain dynamic analysis with a regular wave in operation condition is carried out for ten different wave propagating direction. The maximum and minimum forces value in tethers from analysis is given in Table 9. From the table one can see that values of the forces are positive all time. Further, a tether is exposed to maximum and minimum force when the wave propagation direction is parallel to tether, where the maximum force act for head seas while the minimum force obtain for following seas. Overall the maximum and minimum force act on tether -1 in this situation.

Direction (deg.)	Moor-1		Moor-2		Moor-3	
	F-MIN [kN]	F-MAX [kN]	F-MIN [kN]	F-MAX [kN]	F-MIN [kN]	F-MAX [kN]
0	2,578E+04	4,158E+04	3,005E+04	3,901E+04	3,005E+04	3,901E+04
30	2,677E+04	4,064E+04	3,274E+04	3,573E+04	2,756E+04	4,167E+04
60	2,946E+04	3,813E+04	2,986E+04	3,840E+04	2,673E+04	4,264E+04
90	3,295E+04	3,524E+04	2,711E+04	4,079E+04	2,776E+04	4,166E+04
120	2,969E+04	3,887E+04	2,601E+04	4,166E+04	3,028E+04	3,896E+04
150	2,724E+04	4,166E+04	2,694E+04	4,080E+04	3,280E+04	3,568E+04
180	2,635E+04	4,270E+04	2,965E+04	3,850E+04	2,965E+04	3,850E+04
210	2,724E+04	4,166E+04	3,280E+04	3,568E+04	2,694E+04	4,080E+04
240	2,969E+04	3,887E+04	3,028E+04	3,896E+04	2,601E+04	4,166E+04
300	2,946E+04	3,813E+04	2,673E+04	4,264E+04	2,986E+04	3,840E+04
MIN/MAX	2,578E+04	4,270E+04	2,601E+04	4,264E+04	2,601E+04	4,264E+04

Table 9 : Max and Min forces in tethers, Regular wave – (Hs=1, Tp=7)

Other important parameter is displacement of the line and systems. For above regular wave analyses the max displacement values of tethers are collected for each sea state. The Figure 23 shows the max value of displacement in x-direction. A maximum displacement 0,73m is read in tether 1 for wave from 180^0 direction. This displacement is not big. In other tethers also maximum displacement is read when the wave direction is parallel to them.

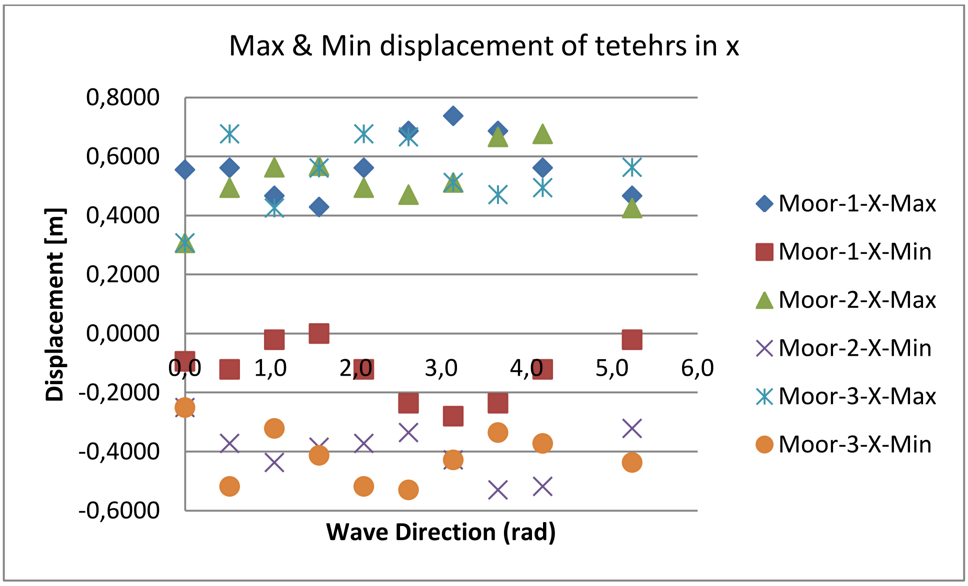


Figure 23: Max & Min displacement of tetehrs in x-dir (Hs=1, Tp=7)

The Figure 24 shows the tethers max displacements value in y-direction for each sea state. The max displacement in y-direction is observed in tether 2 and 3 for wave heading 90^0 and the value near to +/- 0,75m.

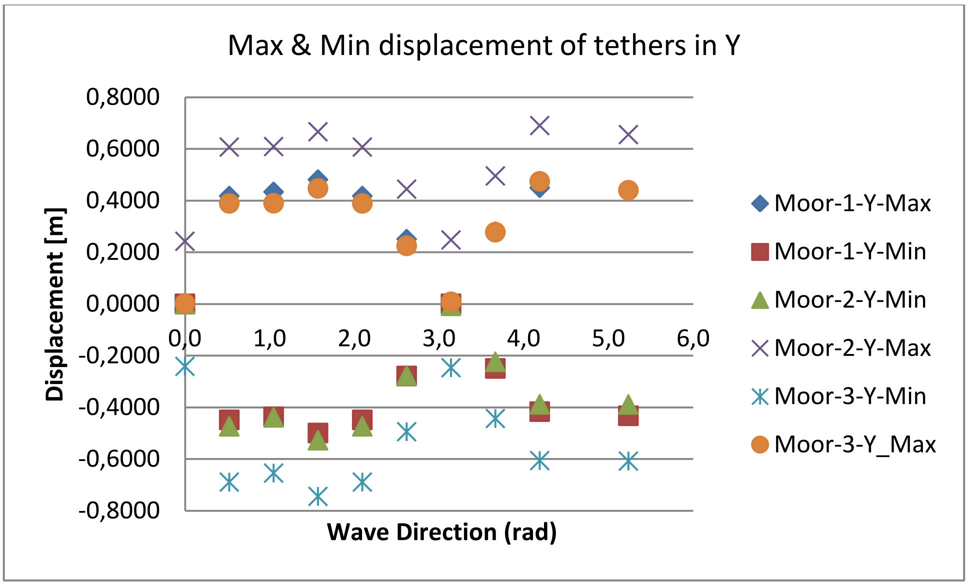


Figure 24 :Max & Min displacement of tethers in Y-dir. (Hs=1, Tp=7)

Above to displacement graphs indicate that the mooring lines horizontal offset amplitudes are under the 1m. In addition a figure below shows the displacement along tether-1 for sea state 180^0, where the blue and black lines indicate the displacement in x-direction.

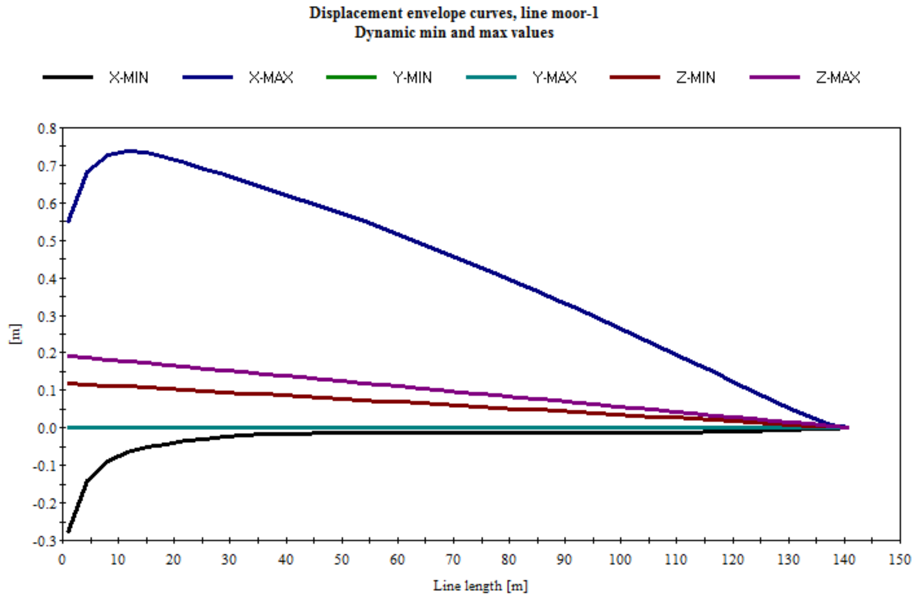


Figure 25 : Displacement envelope- tether-1 (Hs=1, Tp=7)

At the same time it is necessary to study the platform response. The figures (Figure 27 and Figure 26) below show surge and heave motion of the spar cylinder in time series. The amplitude of the surge motion is below the 1m, but the motion is not come to the steady state. In heave, the platform oscillates heavily in beginning, after some time step the motion coming to steady state.

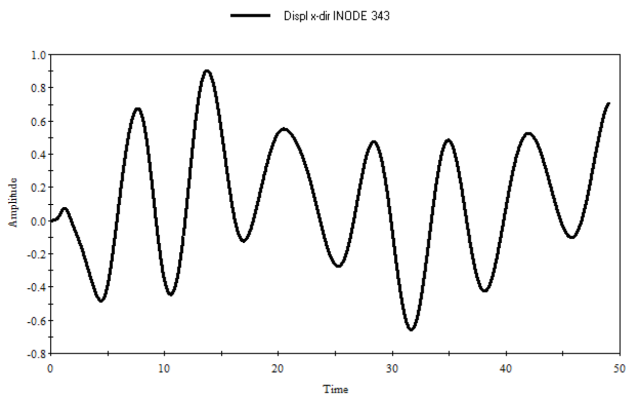


Figure 27 : Floater surge motion (Hs=1, Tp=7)

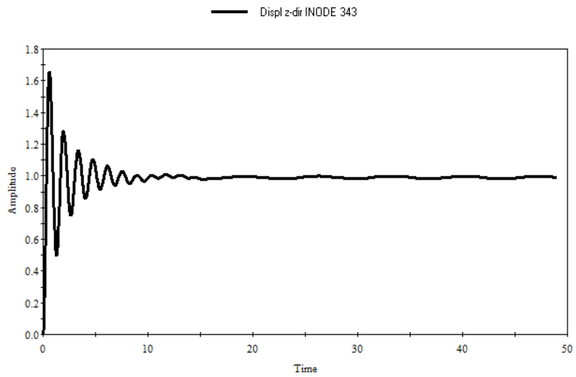


Figure 26 : Floater heave motion – (Hs=1, Tp=7)

The tower motion may be study from Figure 28; INODE-285 shows the surge motion of platform at sea level, while the INODE-284 shows surge motion at tower tops. From these figure one can study the angle of the tower top. Height surge displacement of the tower base is 0.6m at the same stage tower displacement is near 2m.

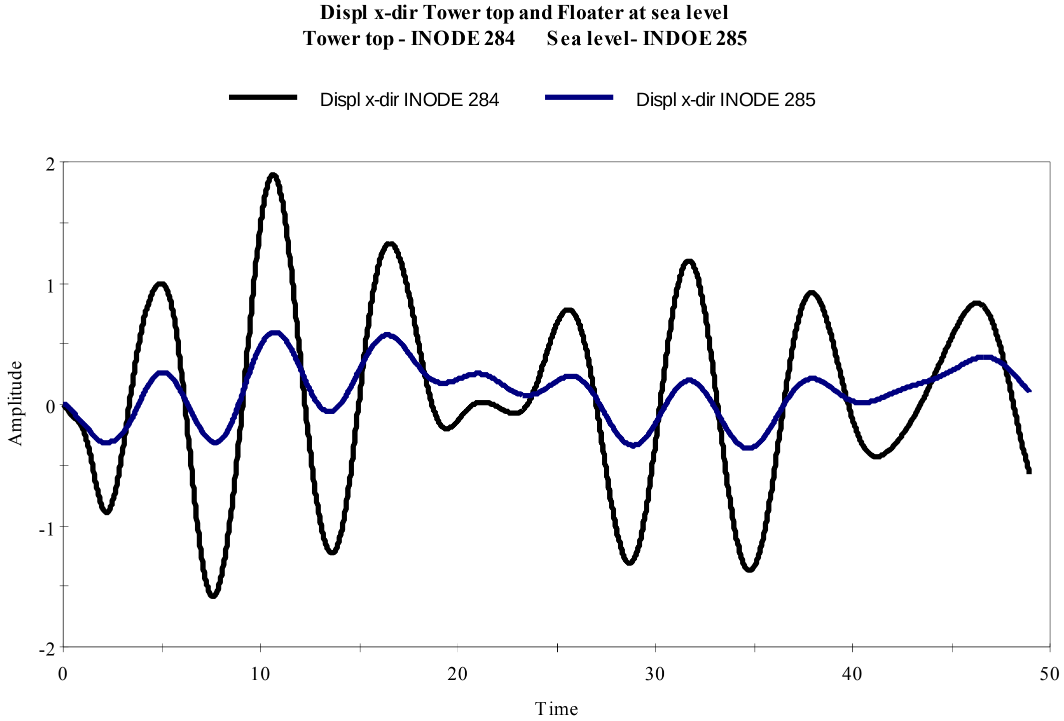


Figure 28 : Surge motion- Comparison between tower base and top (Hs=1, Tp=7)

5.2.2 Extreme condition

An extreme conditions sea state analysis also carried out. The wave and current input value used as show in Table 7. The Table 10 shows the max and min effective tension from extreme condition analyses. The maximum and minimum effective tensions are read in respectively tether 2 and tether 1, as same as for operation condition analysis. But the max and min tension values are different compare with first condition, max effective tension in second condition is higher than first condition and the minimum value lower than first one.

EFF. TENSION [kN]		Moor-1	Moor-2
	Mni	1,627E+02	9,514E+02
	Max	1,554E+03	2,342E+03

Table 10 : Effective tenstion (Hs=15, Tp=16)

The table below shows the max and min tethers forces from dynamic analyses for 10 different wave propagation directions. In this cause also max and min tension values obtain while wave are parallel to tethers and max and min value are read in tether-2 and-3 and the minimum value is higher than zero.

Direction (deg.)	Moor-1		Moor-2		Moor-3	
	F-MIN [kN]	F-MAX [kN]	F-MIN [kN]	F-MAX [kN]	F-MIN [kN]	F-MAX [kN]
0	2,141E+04	4,617E+04	2,563E+04	4,184E+04	2,563E+04	4,184E+04
30	2,296E+04	4,465E+04	3,046E+04	3,621E+04	2,155E+04	4,635E+04
60	2,682E+04	4,085E+04	2,797E+04	4,076E+04	2,101E+04	4,810E+04
90	2,952E+04	3,789E+04	2,355E+04	4,374E+04	2,289E+04	4,689E+04
120	2,704E+04	4,194E+04	2,161E+04	4,428E+04	2,615E+04	4,270E+04
150	2,361E+04	4,616E+04	2,308E+04	4,290E+04	3,036E+04	3,689E+04
180	2,236E+04	4,803E+04	2,744E+04	4,019E+04	2,744E+04	4,019E+04
210	2,361E+04	4,616E+04	3,036E+04	3,689E+04	2,308E+04	4,290E+04
240	2,704E+04	4,194E+04	2,615E+04	4,270E+04	2,161E+04	4,428E+04
300	2,682E+04	4,085E+04	2,101E+04	4,810E+04	2,797E+04	4,076E+04
MIN/MAX	2,141E+04	4,803E+04	2,101E+04	4,810E+04	2,101E+04	4,810E+04

Table 11: Max and min tethers forces – (Hs=15, Tp=16)

In this cause the displacements are very high. For direction 180^0 maximum horizontal displacement is observed. The Figure 29 shows the displacement of the tether-1 for wave direction 180^0, where the max horizontal displacement (X-MAX) at top point is near to 23m, but if one take close look of the time series (Figure 31) of tether-1 top node, that maximum value occurs at once in beginning after that it’s oscillate steady with a amplitude around 15m. For a higher value in beginning may be a reason from of transient effecting on structure by wave for first time. Actually, results from time domain analysis should be taken after few seconds to avoid this effect, unfortunately in this cause it has taken from beginning.

The Figure 29 shows also tether displacement in vertically. The curves for vertical direction (Z-MIN) indicate tethers displace in downwards. This situation have to be carefully study, Figure 30 shows the tether top node heave motion with time.

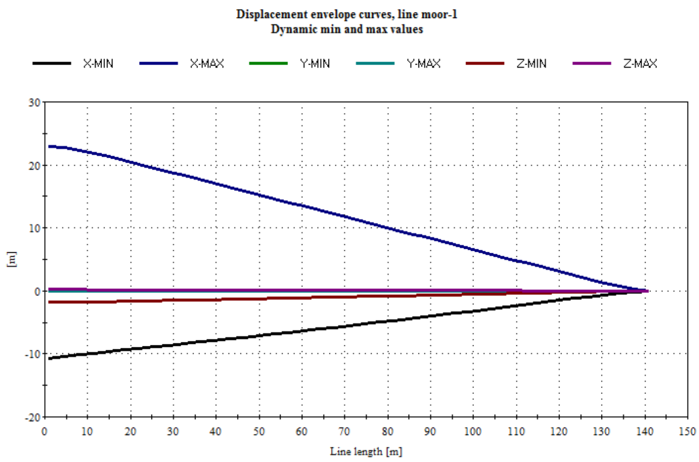
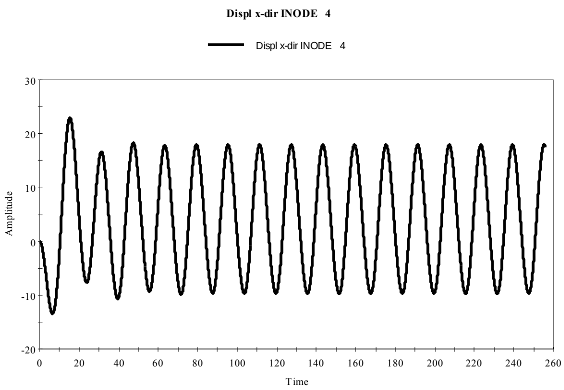


Figure 29: Displacement envelope, tether-1(Hs=15, Tp=16)



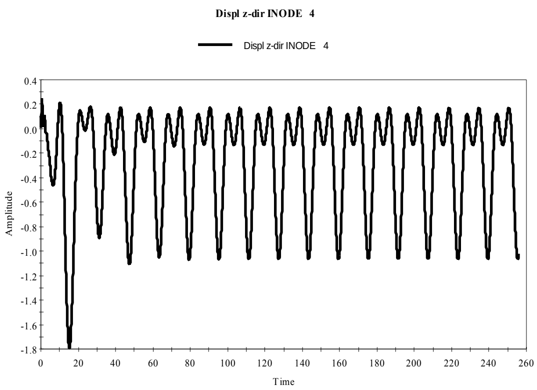


Figure 31 : Surge motion (Hs=15, Tp=16)

Figure 30 : Heave motion (Hs=15, Tp=16)

It is has also similar effect as said for surge motion in beginning after that changes in tether are 0.2m upward oscillate with nearly 1m amplitude. In this cause, one has to look also the tension condition for tether. Figure 32 shows the force time series on tether top. From this figure on can see that force is always positive, so it's clear that no slack in tether. The Figure 33 shows the heave time history at MWL. From thesis two figures (Figure 33 Figure 30) one can say that the platform has nearly 1m set-down for extreme wave condition. It may be explain that in extreme condition more forces effect on platform and surge displacement will increase. In this situation a TL- platform has to go set-down. Thus daft also increasing, as result tension will increase in tethers. Actually a tension leg is designed to have minimum heave motion. But, in this situation surge induced nearly one meter set-down.

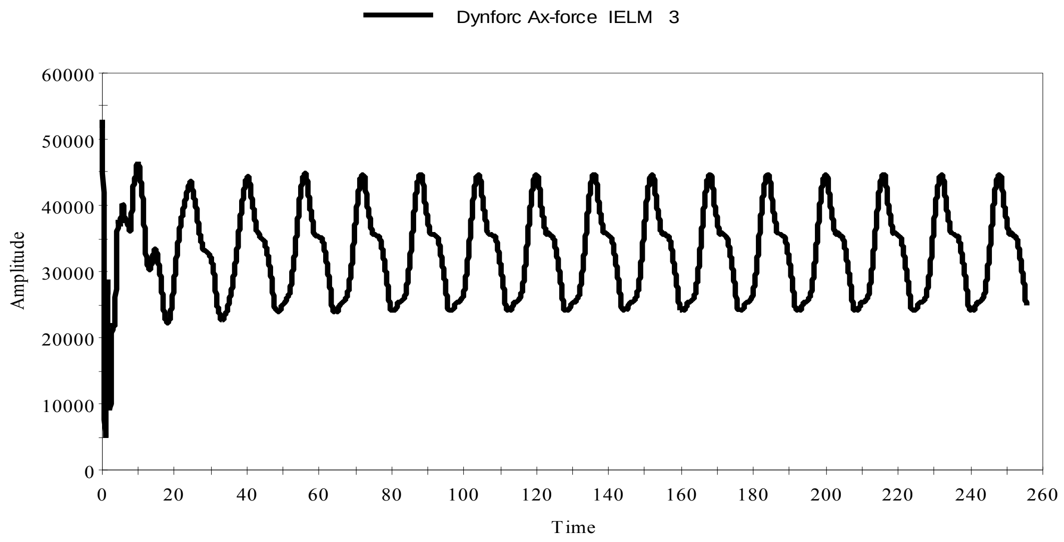


Figure 32 : Force Time series in tether-1 (Hs=15, Tp=16)

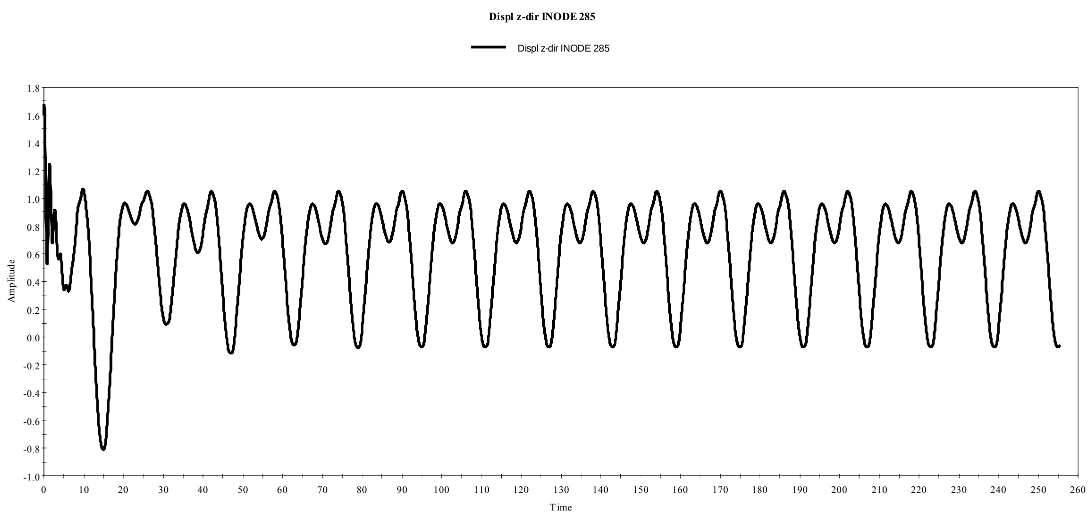


Figure 33 : Floater heave motion in time series (Hs=15, Tp=12)

Surge motions time history of the platform for extreme condition is shown in Figure 31. The platform surge motion at mean water level (MWL) and nacelle level is same. It is mean there is no pitch rotation for tower and whole system move together with a amplitude around 15m.

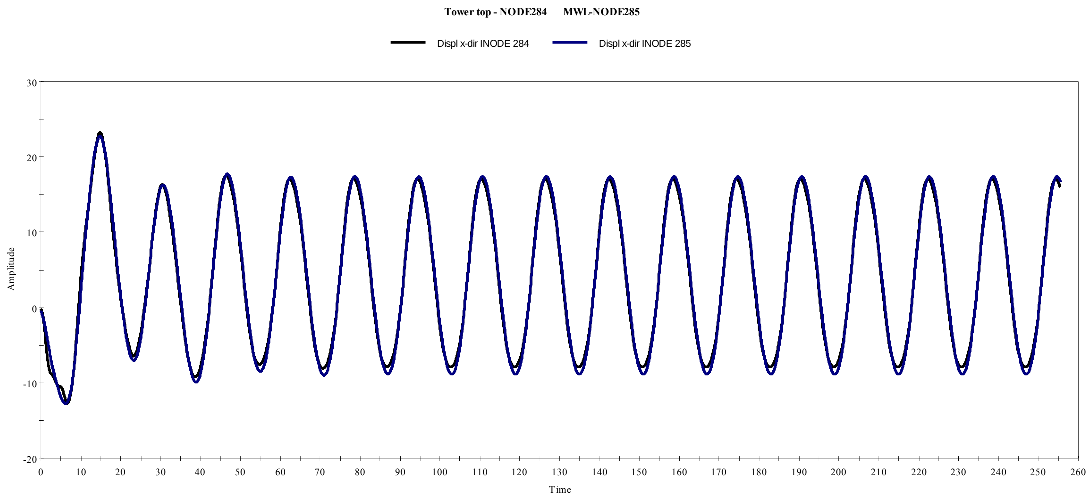


Figure 34 : Surge Time history (Hs=15, Tp=12)

5.3 Irregular wave analyses

Three irregular waves, one for operation condition and two for extreme condition carried out in two seed. In this analysis the static conditions are same as for regular waves. So only dynamic results will be discusses below. The figures below show the force envelope for tether-1, Figure 35 is for operation condition and Figure 36 for extreme condition. The max and min value for both condition given in Table 12 . From these figures and table, one can say that there is no slacking and the min value is 2,880MN, well above the zero.

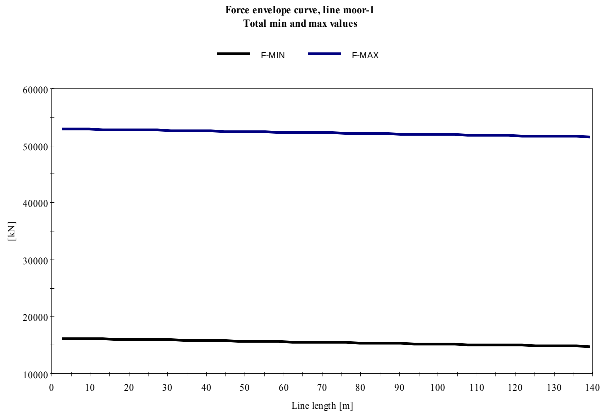


Figure 35 : Force envelope, Irregular wave (Hs=1)

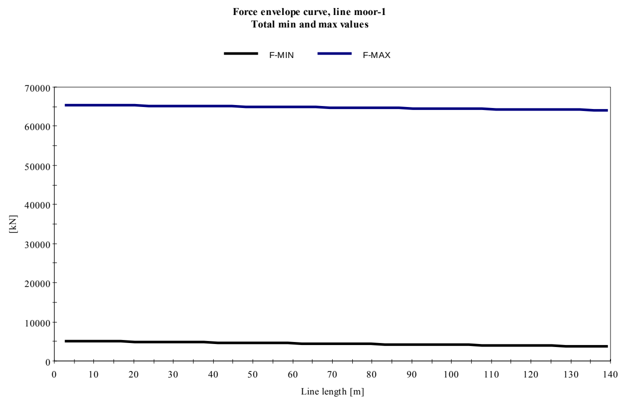


Figure 36 : Force envelope- Irregular wave (Hs=15, Tp=16)

Irregular wave condition	Moor-1		Moor-2		Moor-3	
	F-MIN [kN]	F-MAX [kN]	F-MIN [kN]	F-MAX [kN]	F-MIN [kN]	F-MAX [kN]
Opration	1,483E+04	5,290E+04	2,412E+04	4,432E+04	2,412E+04	4,432E+04
Extreme	3,749E+03	6,544E+04	1,635E+04	4,970E+04	1,635E+04	4,970E+04
	2,880E+03	6,209E+04	1,799E+04	5,205E+04	1,799E+04	5,205E+04

Table 12 : Max and min forces, Irregular wave

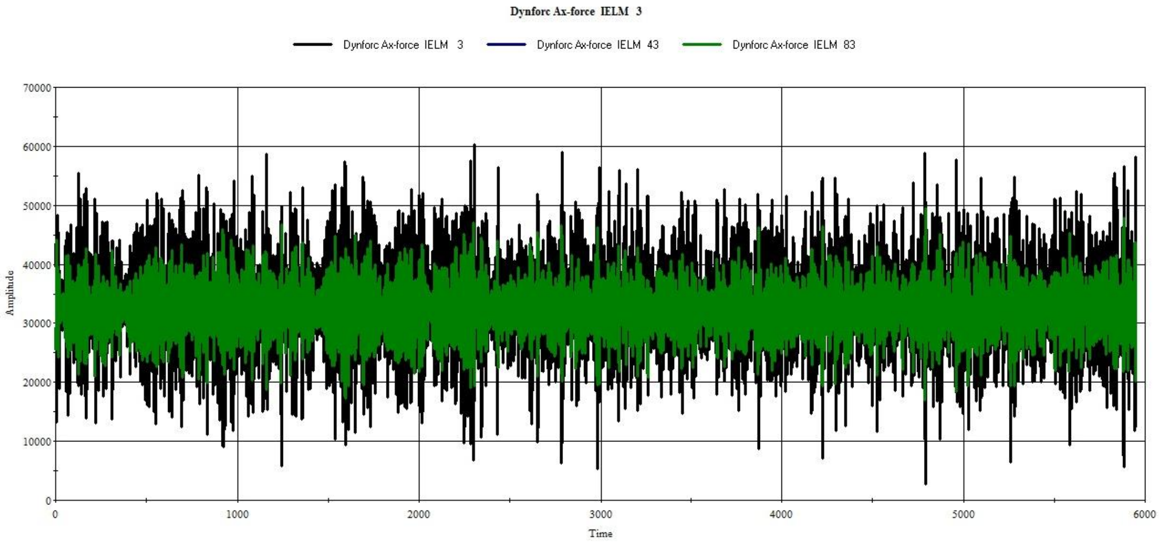


Figure 37: Force time history - Irregularwave

The axial tension time history in extreme wave condition for all three tethers present in Figure 37, from that one can see that tension in tether always positive. But, the maximum value is very high. The Figure 38 shows the heave motion of the platform, this time series is a long simulation and the start value taken after 200 time step. That figure show that a critical value near 0.8m occur nearly in one hour retune periods. The Figure 39 shows the surge response of the floater in extreme condition. It is show that surge motion is critical one.

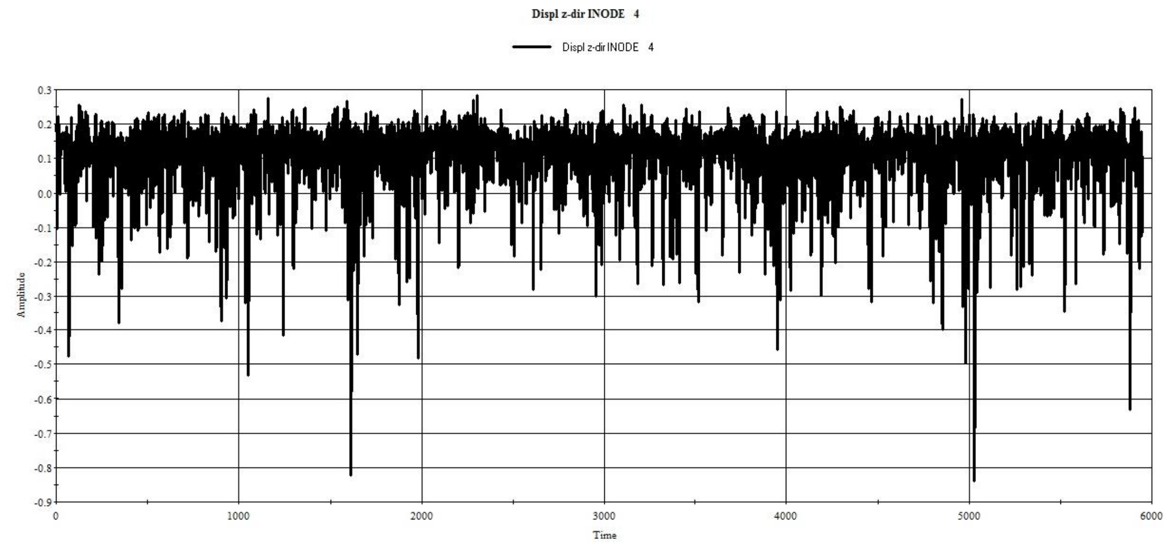


Figure 38 : Heave motion - Irregular wave

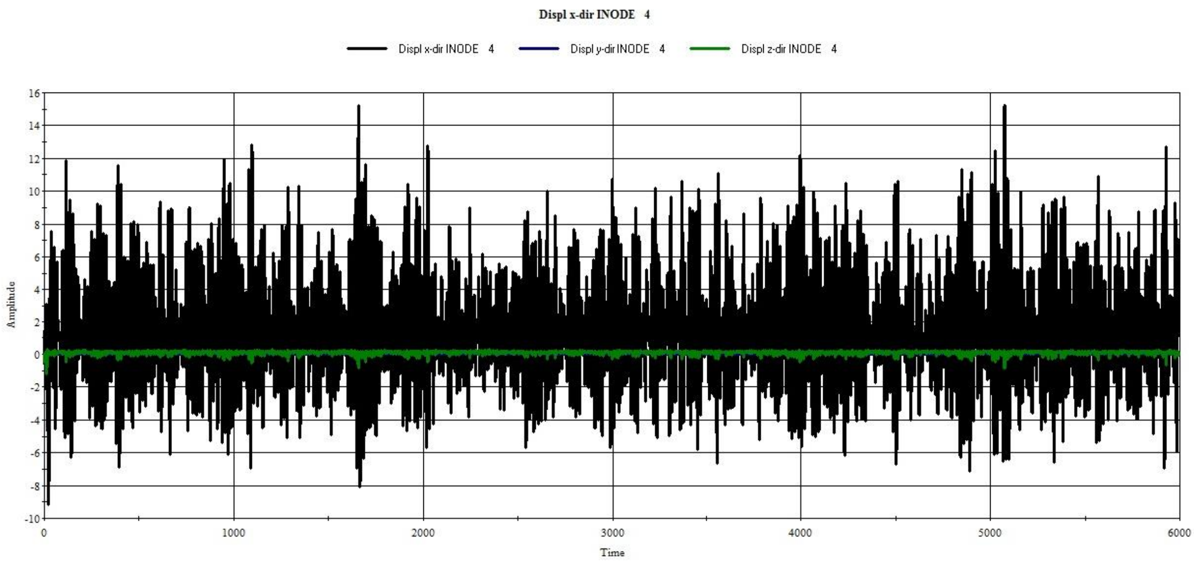


Figure 39 : Surge motion - Irregular wave

Finally, two time series (Figure 40 and Figure 41) show the pitch and yaw motion of the system. It is clear that the pitch motion is almost zero. It is mean that the platform is well resisted by tethers. Figure 41present the yaw motion at tower top, where the maximum motion found. The tower top undergoes a big yaw motion, because of the shaft at top.

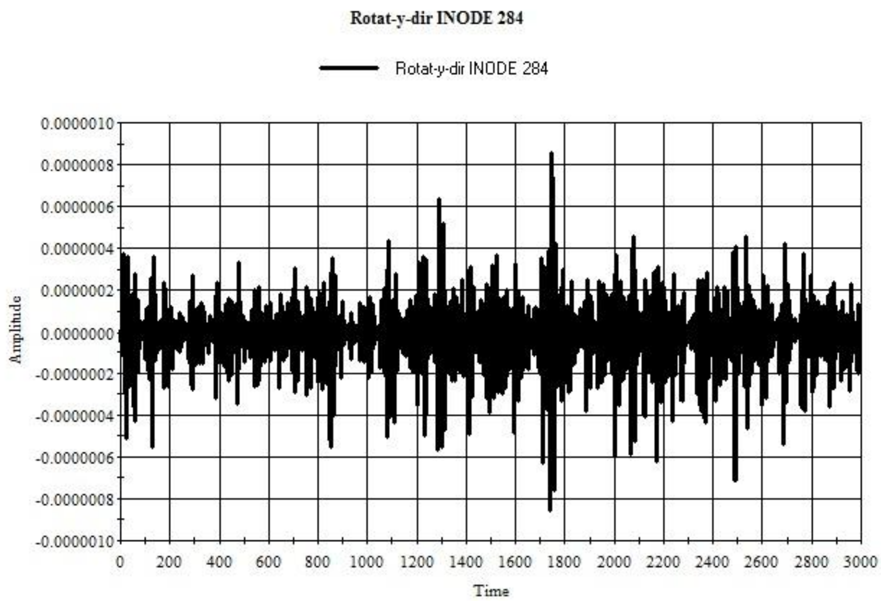


Figure 40 : Pitch motion of the floater

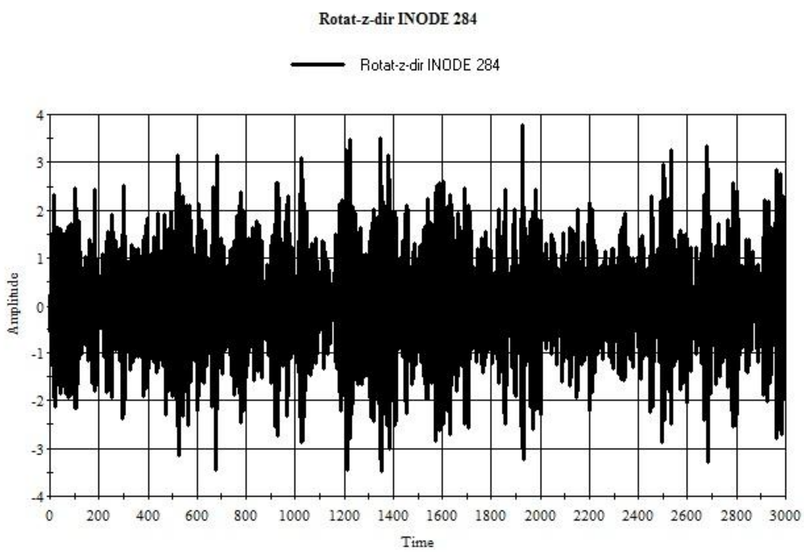


Figure 41 : yaw motion at tower top

5.4 Discussion on results

		F-MIN [kN]	F-MAX [kN]
Opration	Static	6,44E+02	2,08E+03
	Regular	2,58E+04	4,27E+04
	Irregular	1,483E+04	5,290E+04
Extreme	Static	1,63E+02	2,34E+03
	Regular	2,10E+04	4,81E+04
	Irregular	2,880E+03	6,209E+04

Table 13 : Compare the Max and Min Force results

The analyses mainly consider about tension in tethers. The Table 13 shows the obtain max and min forces value from each analyse. The results show that the static analysis gives the critical value. The static value from extreme conditions is smaller one. Other ways it can say that tethers never went to slacking. In dynamic analysis minimum force value in extreme condition is 2.88MN. This seems to be not near to zero. So, it can say that the selected floater can prevent the tethers from going slack. However, the problem in static analysis is current load.

The critical results are response of the structure. The Figure 39 show the maximum surge response amplitude is near to 15m it is almost near with wave amplitude. Any wave the tethers saved in this extreme condition also. If one compare the Figure 39 and Figure 38, heave and surge time series, one can tell that a maximum set-down occur in heave is surge induce. In this project the allowable off-set and set-down or angular was not calculated. So, this maximum off-set and set-down have to be carefully consider in future.

The pitch motion is well resisted by tethers, while the yaw motion is in critical condition. From yaw and surge results one can say that the pretension is not enough on the tethers, because restoring coefficients of these motions are depended on pretension. Finally, we can say that the wind turbine never overturn and survived during this analyses by comparing the tower top motion with tower base motion (Figure 28 and Figure 34) and no slacking in tether even in extreme condition.

6 Conclusions and

Scope behind this thesis was design and analysis of tension leg mooring system for floating windmills. The first goal was that design a spar floater for tension leg mooring system. The second one was estimate the extreme tether forces.

In design phase focused on for design a spar floater which had the center of the gravity well below the center of buoyancy and the vertical fairlead position located between center of buoyancy and center of gravity. Thus, it was differed from other tension leg wind turbine floaters which have center of gravity above the center of buoyancy and the fairlead was attached bottom of the floater. The idea behind the design was to get better stability. In order to bring down the center of gravity below the fairlead it needed to add additional ballast. The design demanded more displacement to support its own weight plus ballast and to give sufficient pretension in tethers. Either diameter or draft or both were changed to achieve the demanded displacement. These changing affect on the system natural period. The surge, sway and yaw natural periods depended on pretension, while the heave, roll and pitch natural periods depended on tethers stiffness. It was difficult to find out the right model with consider about system natural periods and pretension. The pitch and roll natural periods were most difficult one to keep out of the wave frequency range. Finally a floater with margin natural period range was chosen to carry out the analyses. The chosen floater had 14m diameter and 100m draft. This diameter dimension was large when they compare with the spar type wind turbines which use the catenary mooring system [12], while the draft is almost same. It is mean the material costs will be higher. However, this model reduces the footprint.

The static and dynamic analyses are carried out in RIFLEX for two environmental conditions one for an operation condition to understand the model behaviour in normal sea state. The second one was for extreme condition to estimate the extreme tether forces and find out slacking possibility in tethers. A set of regular wave and irregular wave analyses was carried out and results were presented. The results showed that the selected model survived during the extreme wave analysis. However, static analyses indicated that current profile could be a problem.

The platform was well resisted in pitch and roll motion even though it was difficult to get sufficient stiffness for pitch and roll. But, the surge and yaw motion was critical. These modes of restoring coefficients are depended on pretension. So, to limit the surge and yaw motion one needs to increase the pretension. It is mean increase the diameter or draft to get sufficient buoyancy. On the other hand it will be problem for surge natural periods, because the surge natural period decreases while increasing the diameter or draft. So, the design will get problem again. In conclusion, to design a spar floater with tension leg mooring system where the fairlead located above the COG was not seem to be a promising design.

7 Future Work

First of all, it is better to done an eigenvalue analysis by RIFLEX, because the natural periods which are present in this project are approximate calculation and they are near to wave frequency range. During the design phase, the roll and pitch natural periods were in critical margin. These natural periods are depended on tether stiffness. To decrease the roll and pitch natural periods, one has to increase the axial stiffness of the tether. Since the elastic modulus is material constant, one needs to increase the cross-section area of the tether. In design phase it was found that the demanded cross-section area will lead to a big diameter, near to one meter, this dimension is big and will lead to increasing current load. So, it is better to find out a material which has high elastic modulus.

In this project only two irregular wave analyses were carried out in extreme condition. It is recommended to do more irregular wave analyses. The allowable off-set and set-down or angular was not calculated in this project. So, recommended to carry out these calculations to ensure the maximum off-set and set-down

References

[1] API. (2010). *Planing, Designing, and Constructing Tension Leg Platforms.* American Petrolum Insitiute.

[2] Chakrabarti, S. (2005). *Chapter 8, Mooring System.* I *Handbook of Offshore Engineering, Volumes 1-2.* lllinois: Elsevier Ltd.

[3] Demirbilek, Z. (1989). *Tension Leg Platform, A State of the Art Review.* New York: American Society of Civil Engineers.

[4] DNV-OS-J101. (2011). *Design of Offshore Wind Turbine.* DNV.

[5] Faltinsen, O. (1990). *Sea Loads on the ships and offshore structures.* Cambrige: Cambridge University Press.

[6] Fylling, I. J. (1992). *Deep water mooring.* Trondheim.

[7] Gwénaëlle Legros, I. H. (November 2009). *The Energy Access Situation in Developing Countries A Review Focusing on the Least Developed Countries and Sub-Saharan Africa.* UNDP andWorld Health Organization.

[8] Harald Ormberg, E. P. (2011). Global analysis of a floating wind turbine using an AERO-HYRO-ELASTIC Model. Part 1: Code development and case study. *Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering.* oceedings.

[9] Haver, S. K. (2010). *TMR4159, Design of offshore structures, Lecure notes.*

[10] Herbich, J. B. (1999). *Developments in offshore engineering: Wave phenomena and offshore topics.* Houston: Gulf Publishing Company.

[11] Hordvik, T. (2010). *Alternative Design of Anchore Systems for Floating Windmills; Project Thesis at NTNU.* Trondheim.

[12] Hordvik, T. (2011). *Design analysis and optimisation of mooring system for floating wind turbines; MSc Thesis.*

[13] Karimirad, M. (2011). *Stochastic Dynamic Response Analysis of Spar-Type Wind Turbines with Catenary or Taut Mooring Systems; Doctoral theses at NTNU.* Trondheim: Tabir Uttrykk.

[14] Larsen, C. M. (2010). *Tension leg anchor system, Internal document, NTNU.*

[14] *RIFLEX User's Manual - Rev.8, 2010.* (2010).

[16] S. Butterfield, W. M. (2007). *Engineering challenges for floating offsdore wind turbines. National Renewable Energy Laboratory.* Copenhagen.

[17] Sclavounos, P. D. (2010). *Floating offshore wind turbnes: Tension leg platform and taught leg bouy concepts suppoting 3-5MW wind turbines. European Wind Energy Conference. Warsaw, Poland.*

[18] Vågen, R. Å. (2010). *Alternative desigen of anchor systems for floating windmills; Project thesis.* Trondheim.

[19] Vågen, R. Å. (2011). *Design Of Tension Leg Anchor Systems for Floating Windmills - M.Sc.Thesis.* Trondheim.

[20] W. Musial, S. B. (2004). *Feasibility of Floating Platform Systems for Wind Turbines*. *Proceeding of the 23rd ASME Wind Energy*. Golden: National Renewable Energy Laboratory.

[21] Withee, J. E. (2004). *Fully Coupled Dynamic Analysis of a Flaoting Wind Turbine System.* Massachusetts: Massachusetts Institute of Technology.

[22] WindSea http://www.windsea.no/ (16/12/2011)

[23] (2011, 12 15). Retrieved from http://wacleantech.org/2011/08/new-platform-would-let-wind-farms-float/

Appendices

Table of figures in Appendices

List of Tables in Appendices

Appendix A – Floater Design in RIFLEX

After some calculation in Matlab the following parameters are selected for floater design in RIFLEX (Table-A 1, Table-A 2, Table-A 3). The tether diameter and thickness seem to be unrealistic, but these parameters are used in hence about RIFLEX input, where only one tether is modelled at one termination point (To ensure the roll and pitch natural periods under the 4 seconds). The first consideration in RIFLEX model analysis is tension in mooring lines, because as it discussed before tension in mooring lines should be positive always. And the displacement of the mooring line also considered.

.

Water Depth (h)	-200	m
Draft (T)	-120	m
Tower base (TB)		
Diameter of tower base	6.50	m
Draft of the TB	-5.00	m
Elevation above the sea level	10.00	m
Spar Cylinder		
Diameter of Spar	10.00	m
Thickness of Spar	0.01	m
Displaced Volume	9427.90	m^3
Position of buoyancy center	-61.42	m
Total Mass (including ballast)	4.281E+03	Mg
Position of mass center	-101.61	m
Pretension	5.049E+04	kN

Table-A 1 : Step-1 selected parameters for floater design

Natural Periods		
Surge & Sway	44,28	s
Heave	0,35	s
Roll & Pitch	2,62	s
Yaw	0,93	s

Table-A 2: Step-1 Natural periods of selected system

Mooring lines	
Number of tethers	3
Vertical position of fairlead	-91,61 m
Horizontal distance (a)	25,00 m
Diameter of tether	0,60 m
Thickness of tether	0,40 m

Table-A 3: Step-1 selected mooring line

Step 1,D=10m, T=-120m

For first model the spar diameter selected as 10m and draft is -120m. And mooring line properties are as show in Table-A 3. This system's natural periods ranges are out of the wave periods range, see Table-A 2. The static analysis is dependent on current profile and the Table-A 4 shows also the current profile which is used in floater design procedure.

Current properties	
Depth [m]	Velocity in x-dir.[m/s]
0	1,00
-50	0,50
-100	0,15
-150	0,03

Table-A 4: Step-1 Current profile

The graph below (**Error! Reference source not found.**) shows tension in mooring line 1 form of the static analysis. It's clear that line goes to negative tension at some stage. It is mean the buoyancy is not enough. So, nest step is increasing buoyancy. While increasing draft without changes in diameter, failed to fulfill the roll and pitch natural periods requirements. So, next step is increasing diameter.

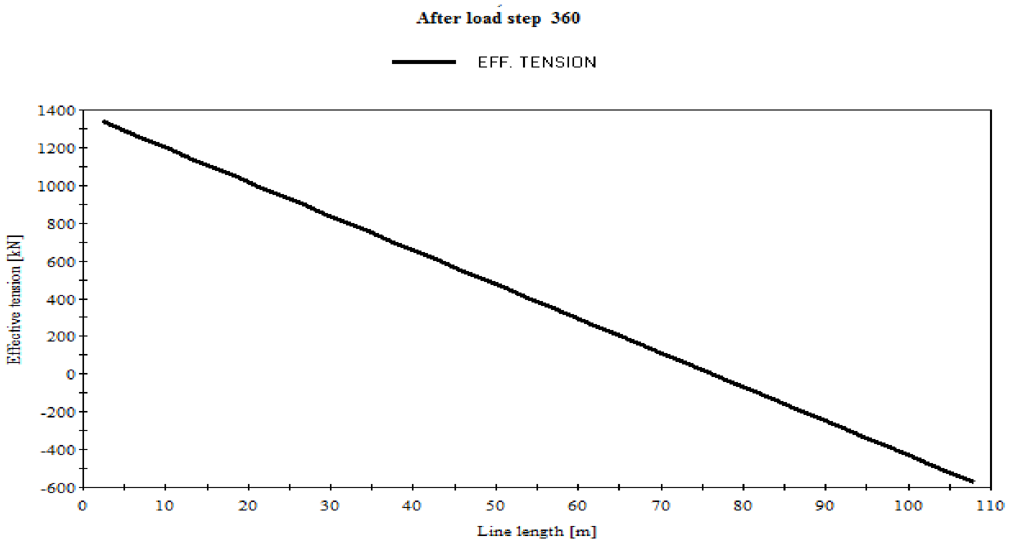


Figure-A 1: RIFLEX result, D=10m, T=-120

Step 2,D=12m, T= -80m

Now the spar diameter is 12 m and draft -80 m tested in RIFLEX, it's also failed, see Figure-A 2 below.

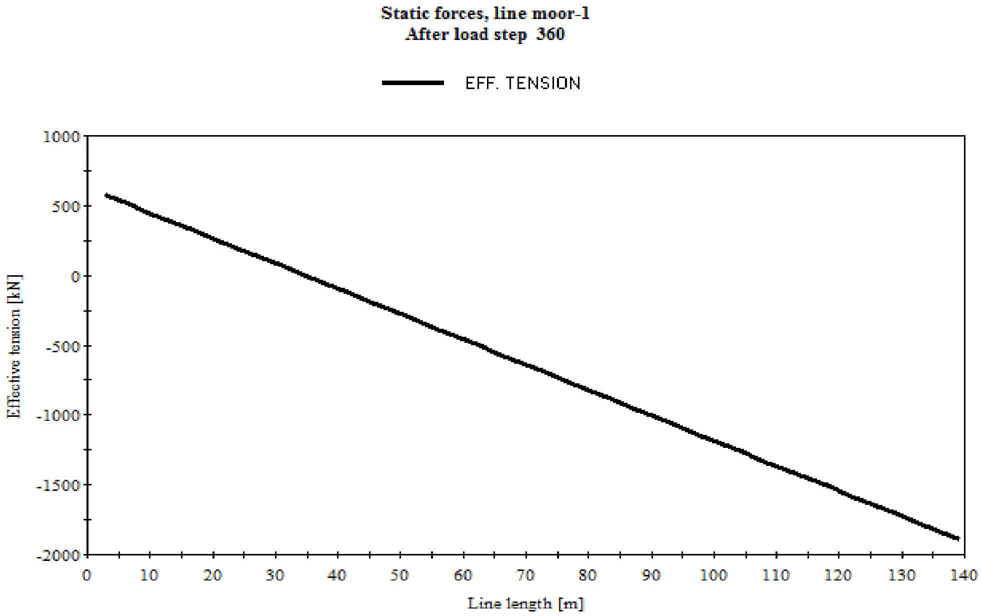


Figure-A 2: RIFLEX static result, D=12m, T=-80m

Step 3, D=12m, T=-100m

Now the draft is increased without changing the diameter. But it also filed, see Figure-A 3 below.

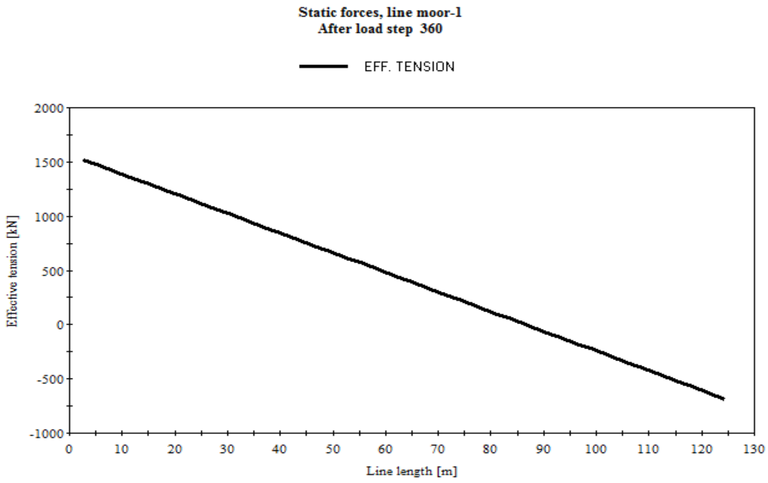


Figure-A 3: Static forces in mooring line 1, D=12m, T=-100m

Step 4, D=12m, T=-140m

In step 4, to get better buoyancy the draft in increased to 140m. In this stage the roll and pitch natural periods are near to 4 seconds (see Table-A 5). The result from static analysis is positive (see Figure-A 4), anyway in dynamic analysis with a regular wave height 4 m and period is 7 second, the lines are failed and they goes to negative (see Figure-A 5, Figure-A 6).

Natural Periods	
Surge & Sway	37,26 s
Heave	0,36 s
Roll & Pitch	3,82 s
Yaw	0,82 s

Table-A 5: Step-4 Natural periods

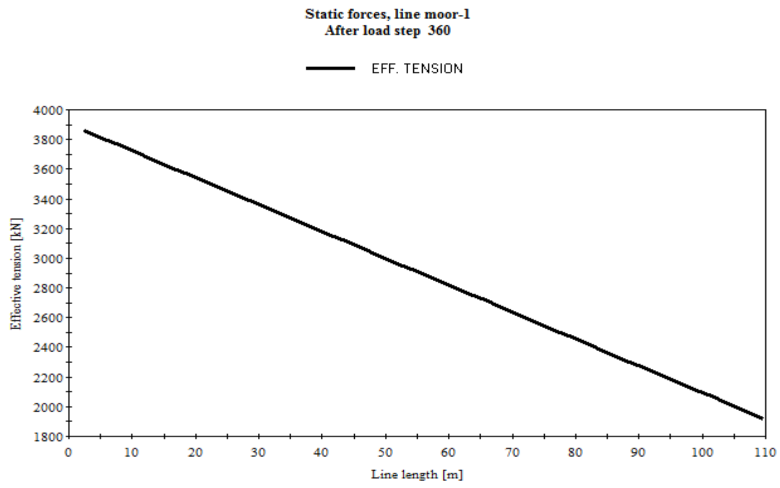


Figure-A 4: Static forces in mooring line 1, D=12m, T=-140m

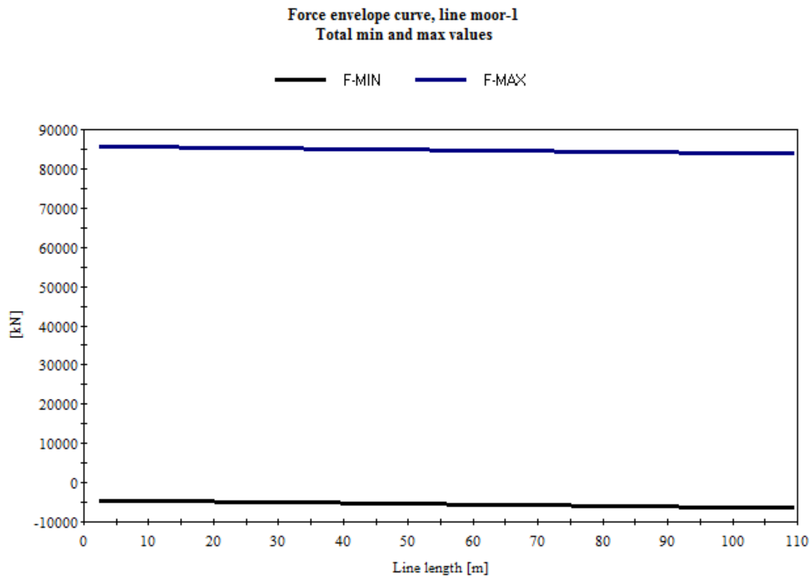


Figure-A 5: Dynamic max & min forces in mooring line 1, D=12m, T=140m

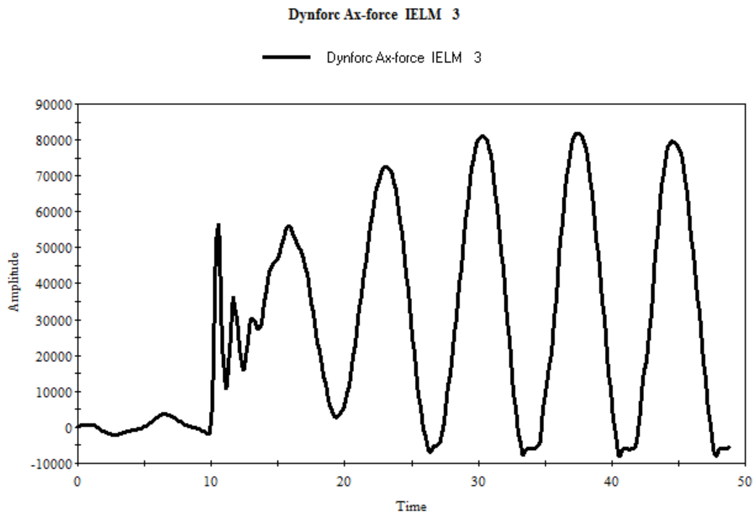


Figure-A 6: Dynamic force in mooring line 1 with time step, D=12m, T=-140m

Step 5, D=14m, T=-80m

Still, the needed buoyancy is not obtained. Now it's decided to increase the diameter to 14m and hence about natural periods first the draft for 80 m chosen and a small changes in tethers diameter also did (see Table-A 6). Anyway it is also failed, see Figure-A 7.

Diameter	14,00 m
Draft	-80,00 m
Pretension	75895,00 kN
Mooring lines	
Number of tethers	3
Vertical position of fairlead	-60,00 m
Horizontal distance (a)	25,00 m
Diameter of tether	0,45 m
Thickness of tether [m]	0,30 m
Natural Periods	
Surge & Sway	45,38 s
Heave	0,56 s
Roll & Pitch	2,90 s
Yaw	0,98 s

Table-A 6: Step 5- Spar parameters

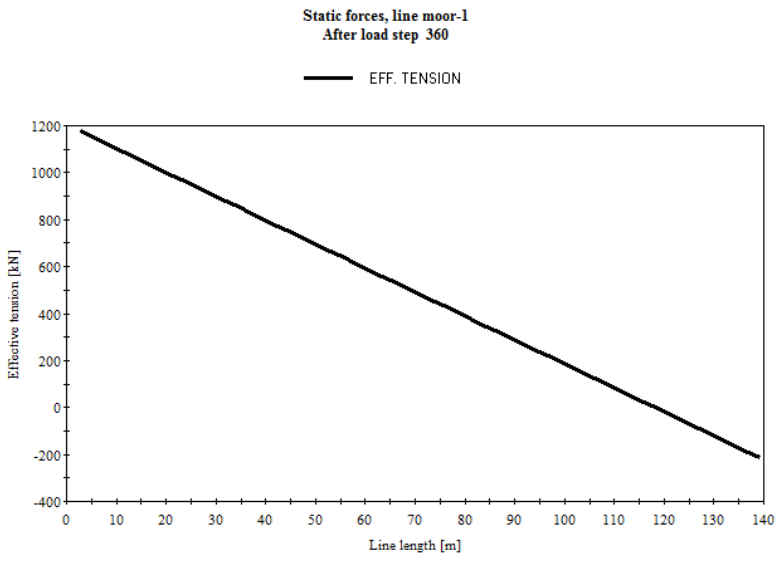


Figure-A 7: Static forces in mooring line 1, D=14m, T=-80m

Step 6,   D=14m, T=-100m

Now the draft is increases to 100m, as discussed before increasing draft results increasing roll and pitch natural periods, these periods are just below the 4 second. Anyway analyses is done the Figure-A 8 shows the static force in mooring line 1, during static analysis tension in line is always positive. So, next, the dynamic analysis don with Hs=4m and Tp=7m. The results from dynamic analyses show in figure 9 and 10.

Diameter	14,00	m
Draft	-100,00	m
Pretension	1,065E+05	kN
CB	-51,94	m
CG	-84,83	m
Mooring lines		
Number of tethers	3	
Vertical position of fairlead	-60,00	m
Horizontal distance (a)	25,00	m
Diameter of tether	0,45	m
Thickness of tether [m]	0,30	m
Natural Periods		
Surge & Sway	42,39	s
Heave	0,56	s
Roll & Pitch	3,66	s
Yaw	0,93	s

Table-A 7: Step-6 Spar parameters

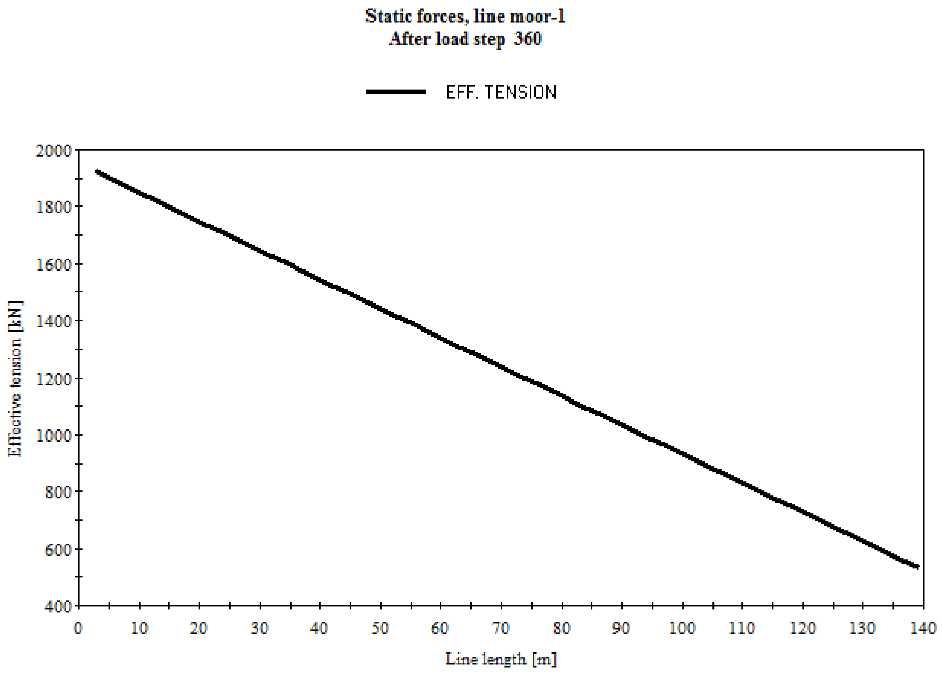


Figure-A 8: Static forces in mooring line 1, D=14m, T=-100m

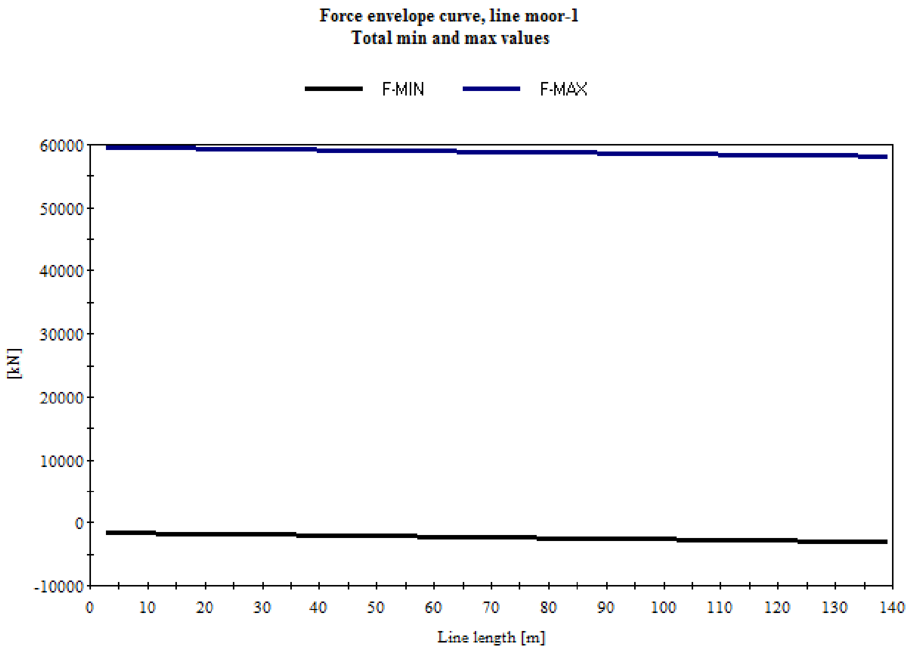


Figure-A 9:Dynamic max & min forces in mooring line 1, D=14m, T=100m

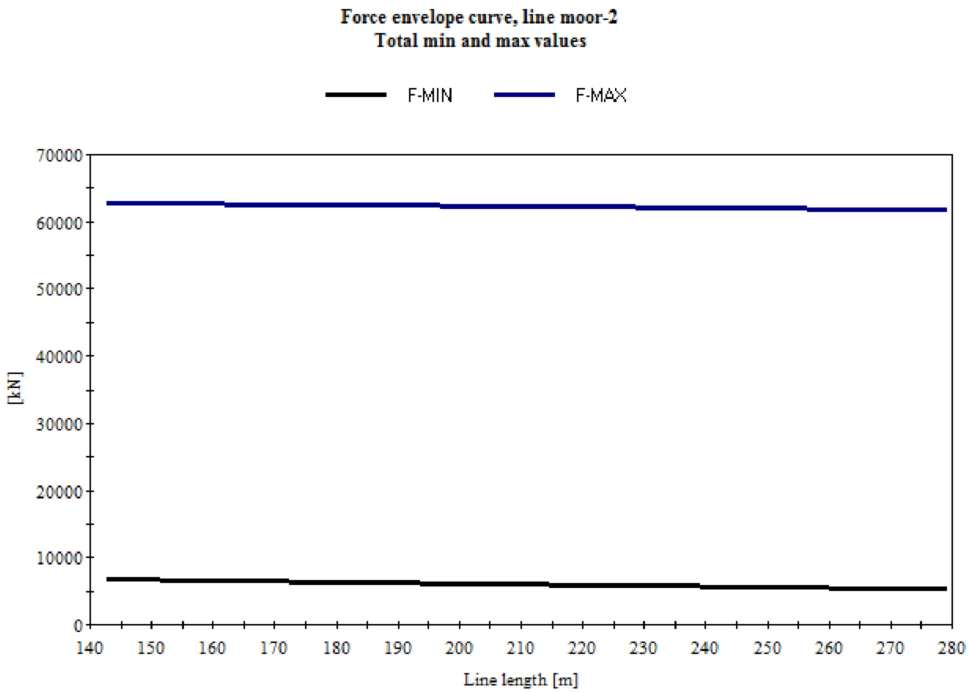


Figure-A 10 : Dynamic max & min forces in mooring line 2, D=14m, T=100m

The Figure-A 9 and Figure-A 10 show the max and min dynamic forces in mooring line -1 and 2. In mooring line-1 it shows negative force, but if look the time series of the line-1 (Figure-A 11), it is clear that the negative tension in line is within 10 seconds after that the line affected by an enormous force. The series of the line 2 also has similar affect, Figure-A 12. It assumed that, in dynamic analysis the boundary changes of the fixed super node ("sparloc", see **Error! Reference source not found.**) start to release in free in all direction after 10 seconds. The reason may be the big axial stiffness of the mooring line and structure behaves as fixed structure during the first 10 seconds. Therefore it's decided to release the super node to be free immediately (at 0 second). The Figure-A 13 and Figure-A 14 show the result of the dynamic forces in line 1 and 2 after the super node released immediately. It's visible that there is no slacking during the analyses.

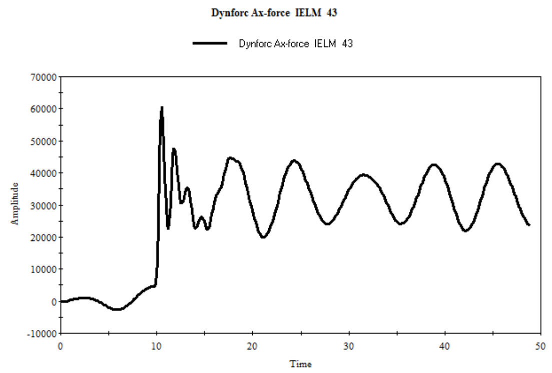


Figure-A 11 : Dynamic force time series for mooring line 1, release after 10s

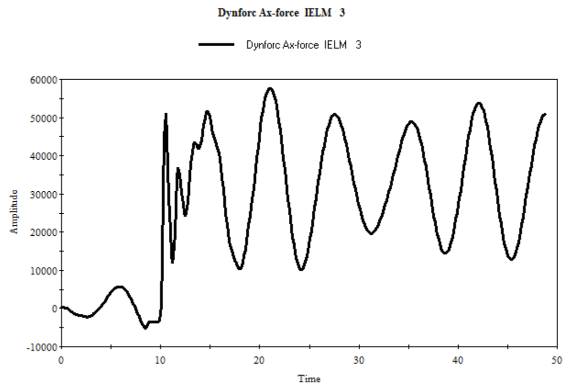


Figure-A 12 : Dynamic force time series for mooring line 2, release after 10s

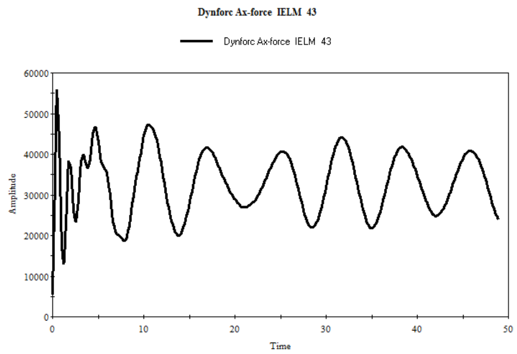


Figure-A 14: Dynamic force time series for mooring line 1, release after 0s

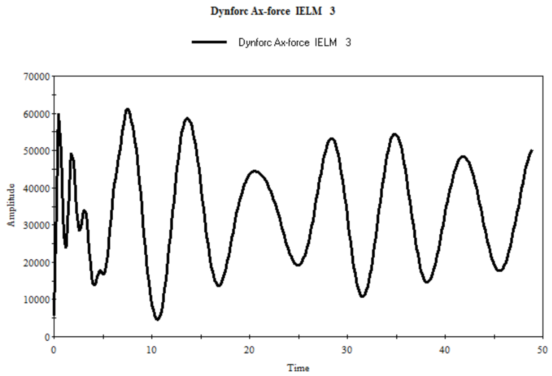


Figure-A 13 : Dynamic force time series for mooring line 2, release after 10s

So, now this model may be used for further analyses, but when they consider about roll and pitch natural periods it is better to have below the 3 seconds. To reduce these periods, may one can reduce the draft between 100m to 80m. When reduces the draft to 90m, the natural period is decreasing slightly and all forces are positive. However displacements of the mooring line in x-direction is very long (see Figure-A 15) compare with result of 100m draft, see Figure-A 16. Other ways the stiffness of the tethers has to increases. Its mean increases in total weight, so it is needs increase buoyancy again. A lot of analyses done including increasing the distance “a” to find out the right model which give the wishing roll and pitch natural periods, but it was difficult to find out. Due to the time consent the model in step 6 decided to keep for further analyses.

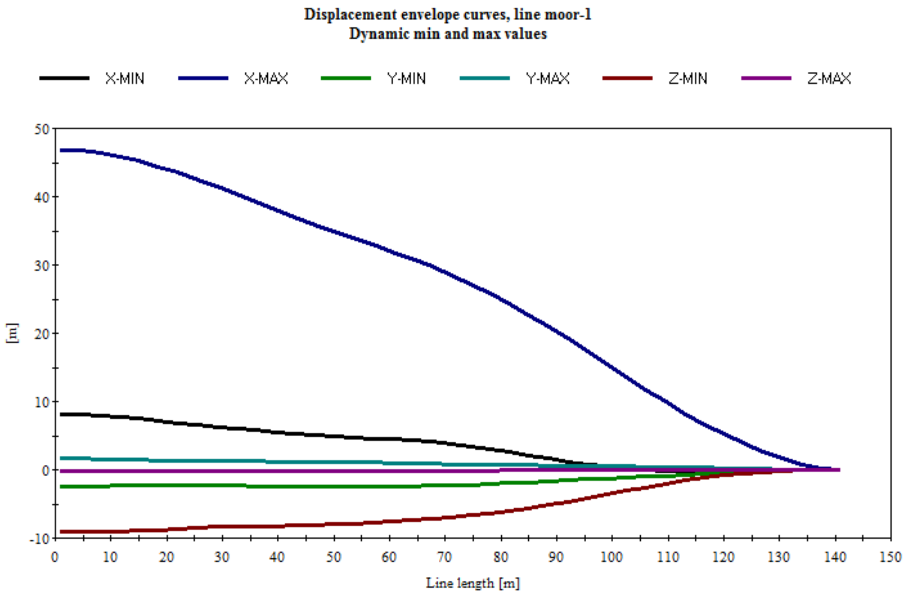


Figure-A 15 : Displacement of mooring line 1, D=14m, T=-90m

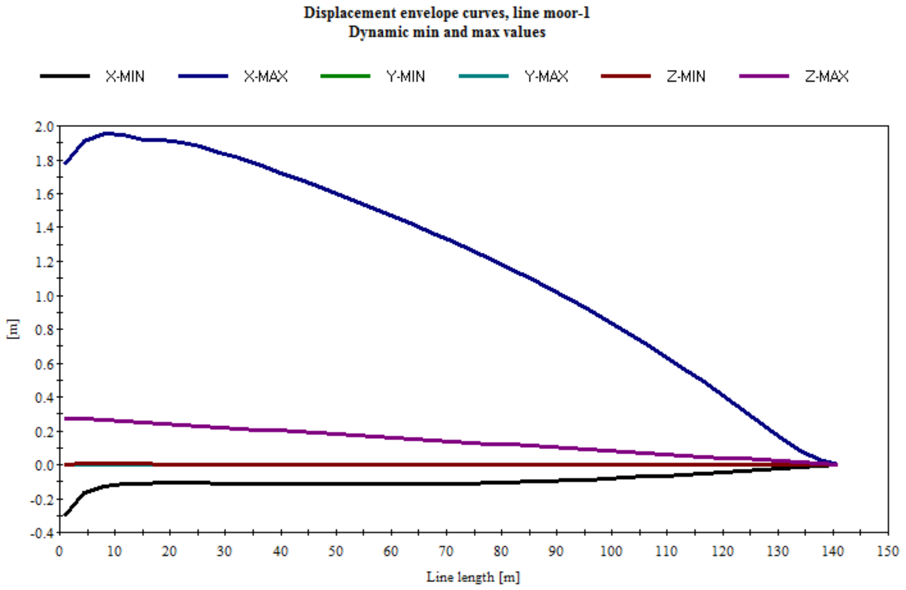


Figure-A 16 : Displacement of mooring line 1, D=14m, T=-100m

Results

Finally, as it discuses above the model in step 6, decided to keep for further analyses. So, the main parameters of the floater are given in Table-A 8 and Table-A 9 below.

Water Depth (h)	-200	m
Draft (T)	-100	m
Tower base		
Diameter of tower base	6,50	m
Draft of the tower base	-5,00	m
Elevation above the sea level	10,00	m
Spar Cylinder		
Diameter of spar	14,00	m
Thickness of floater	0,01	m
Displaced Volume	15160,00	m^3
Position of buoyancy	-51,94	m
Total Mass (including ballast)	4,305E+03	Mg
Position of mass center	-84,83	m
Pretension	1,065E+05	kN
Mooring lines		
Number of tethers	3	
Vertical position of fairlead	-60,00	m
Horizontal distance (a)	25,00	m
Diameter of tether	0,45	m
Thickness of tether	0,30	m

Table-A 8 : Final Model properties

Natural Periods		
Surge & Sway	42,39	s
Heave	0,56	s
Roll & Pitch	3,66	s
Yaw	0,93	s

Table-A 9 : Final Model Natural periods

Final Model Mass and Buoyancy including Extended body

Line	segment	Externa Cross-section AE	Mass/ Length AMS	Length SLGTH	Weight/ Lenght [Mg/L]	Total Weight [Mg]	Buoyancy / Length	Total buoyancy
Spar	Spar	153,900	1,715	85,00	16,82	1,43E+03	1548,00	1,32E+05
	Ballast	153,900	351,200	10,00	3446,00	3,45E+04	1548,00	1,55E+04
Towe base	Above sea level	33,180	2,338	10,00	22,94	2,29E+02	0,00	0,00E+00
Towe base	Submerged	33,180	2,338	5,00	22,94	1,15E+02	333,70	1,67E+03
Spoke	1	0,283	1,803	18,00	17,68	3,18E+02	2,84	5,12E+01
	2	0,283	1,803	18,00	17,68	3,18E+02	2,84	5,12E+01
	3	0,283	1,803	18,00	17,68	3,18E+02	2,84	5,12E+01
Frame	1	0,283	1,803	43,30	17,68	7,66E+02	2,84	1,23E+02
	2	0,283	1,803	43,30	17,68	7,66E+02	2,84	1,23E+02
	3	0,283	1,803	43,30	17,68	7,66E+02	2,84	1,23E+02
Incline element	sup-1	0,126	0,074	34,98	0,72	2,52E+01	1,26	4,42E+01
	sup-2	0,126	0,074	34,98	0,72	2,52E+01	1,26	4,42E+01
	sup-3	0,126	0,074	34,98	0,72	2,52E+01	1,26	4,42E+01
Tower						6,00E+02		
Total						4,02E+04		1,49E+05
Pretension [kN]								1,09E+05
Pretension - by Matlab calculation [kN]								1,07E+05
Different in pretension calculation [kN]								2,22E+03
Total buoyancy from Extended body system								1,49E+05
Contribution for the buoyancy from Extended body system								6,55E+02

Table-A 10 : Final Model properties including Extended body

Appendix B: Global Topology/ FE Model with super nodes and line

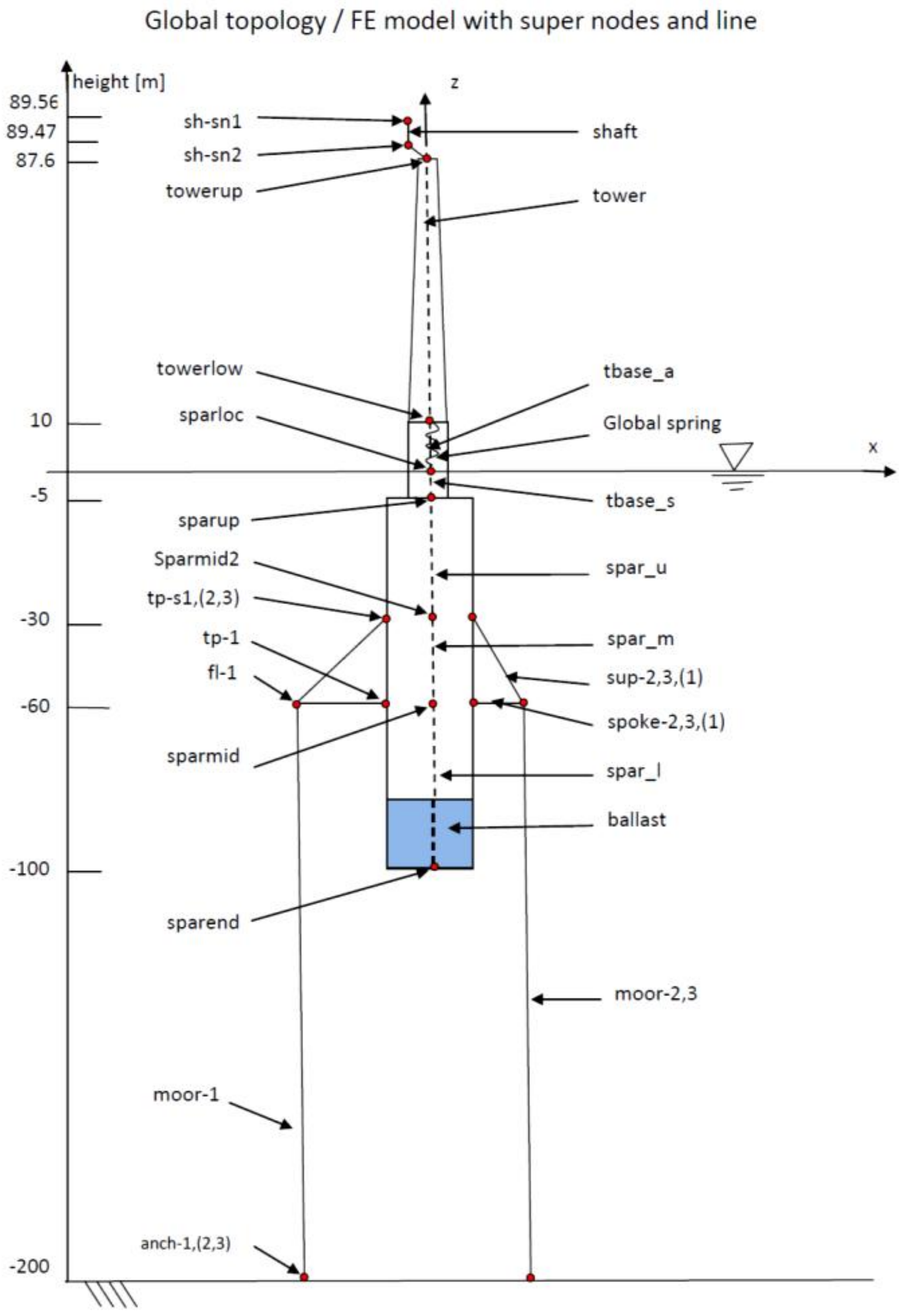


Figure-A 17: Global Topology/ FE Model with super nodes and lines

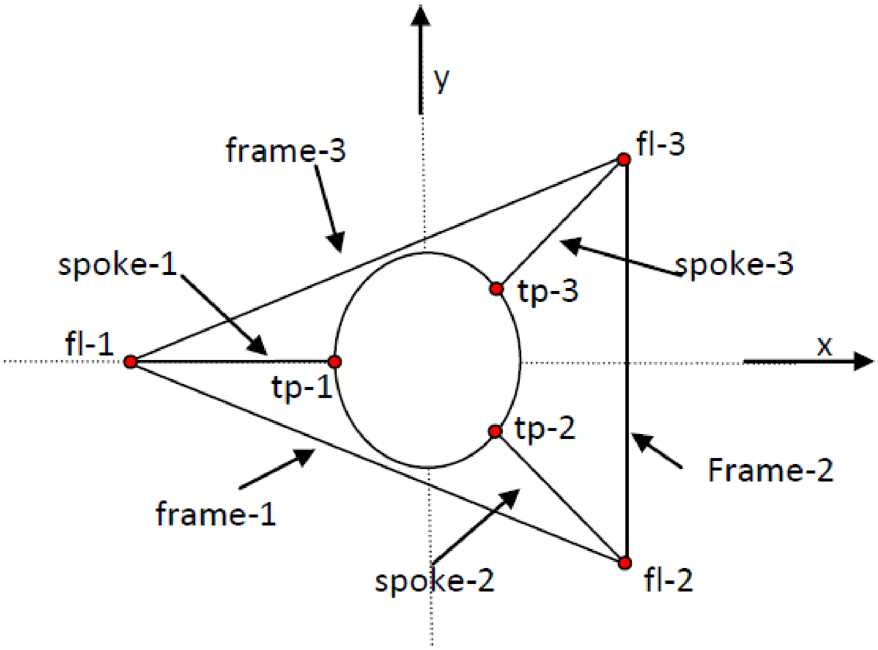


Figure-A 18: Global topology, over view- at fairlead

Appendix C : Content in attached File

1. Matlab script file
2. RIFLEX
   2.1 RIFLEX – INPMOD
   2.2 RIFLEX – STADMOD
   2.3 RIFLEX – DYNMOD
   2.4 RIFLEX - OUTMOD