The influence of offshore floating foundations to the wind turbine generator
A study using aNySIMPHATAS

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December 2016
ECN-E—16-032
Acknowledgement

The authors would like to express their gratitude to Sebastien Gueydon of MARIN, Richard Bakker of NLR and Bo Paulsen of Deltares for their input in this work. A special thanks to the TO2 foundation for providing the financial means to collaborate with our partner TO2 organizations.

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Summary

In this report, three floating wind turbine foundation concepts are modelled; a Semi-submersible, Spar and tension leg platform type. The floating foundations are modelled with an NREL 5 MW reference turbine on top, and a monopile reference is included to act as a baseline model. An extensive set of 828 loadcases is simulated using the combined aero-elastic behaviour of PHATAS and hydrodynamic interaction from aNySIM. The floating structures are modelled as rigid bodies due to numerical solving limitations of the combined code. The environmental conditions simulated in the loadcases are applied equally to all floater types. Only the water depth differs for the models. The result is a large set of dynamic response data for the different floating foundations that can be compared directly. The Spar type foundation is shown to result in the largest loads on the turbine. However, sharp peaks in the load response are visible, likely caused by the dynamic stall model.

For the tension leg platform, a more detailed analysis is carried out for determining the tendon stiffness. This effort is finalized by proposing an integrated tendon design method for tension leg platforms.

Finally, an analysis is carried out for three mooring line configurations of the Semi-submersible floating foundation. Here a three line spread mooring configuration is compared with a three line hybrid configuration (applying chain and wire rope) and a six line configuration. The displacement and mooring line tension of all configurations remains within acceptable limits. The costs of the configurations have been estimated and a 25 % cost reduction can potentially be achieved when choosing the hybrid mooring line configuration over the other options.
Introduction

Over the last years, a multitude of concepts have been introduced for application as floating wind turbine foundations. With the commission of the Hywind Spar in 2009 the first commercial wind turbine was installed on a floating substructure. Today, demonstration projects of other floating concepts are commissioned or in pre-commissioning phase. In this development, designs of floating foundations originating from the offshore oil and gas industry have been adjusted and optimized for the different loading regime of an offshore wind turbine generator (OWTG). In previous experimental campaigns, such as those carried out by the DeepCwind consortium, the dynamic response of the most common floating concepts has been modelled and tested on model scale [1]. This report aims to complement the existing simulation efforts by focussing on the effect of different floating foundation concepts to the loads and dynamics of the wind turbine.

Publicly available reference designs for a 5 MW offshore wind turbine and the most common floating foundations have been modelled (Figure 1). The turbine model is known as the NREL 5 MW Reference Wind Turbine (RWT) [2]. The Spar, Semi-submersible and tension leg platform (TLP) are defined in respectively the IEA OC3, OC4 and DeepCWind projects [3], [4], [1]. These floating foundations are compared to a bottom-fixed monopile design as specified in the Upwind study [5]. All foundation types are modelled with the same turbine on top.

For the simulations, the code aNySIMPHATAS has been used in the modular software package FOCUS6. aNySIMPHATAS is a combination of the aero-elastic modelling tool PHATAS, developed by ECN and WMC and the hydrodynamic response modelled by aNySIM, developed by MARIN. To cover the design driving loadcases, a loadset of 828 loadcases has been selected from the IEC 61400-3 norm [6], comprising power production, extreme turbulent conditions, fault causes, shut-down and extreme wind conditions with a parked turbine. The same environmental conditions are applied to all the modelled offshore wind turbine structures. Only the water depth is equal to design conditions for all concepts.
Modelling of the tendons is worked out following a methodology from literature in chapter 4. An integrated design procedure is proposed, to optimize the TLP design process including the tendon stiffness.

The mooring design has been investigated further by comparing three mooring configurations for a Semi-submersible in chapter 5. The motion response for the three configurations is determined with the aNySIMPHATAS model. Also the costs of the mooring line configurations is discussed.

Figure 1: Most common floating foundations (from left to right): Spar, Semi-submersible, Tension leg platform [7]
In this chapter, the main model parameters are presented for the turbine, the floating foundations and the monopile reference. In section 2.6 the software tool used for the simulations is discussed and in section 2.7 the selection of loadcases is presented.

2.1 Turbine model

The NREL 5MW reference wind turbine has been modelled according to the specifications in as described in [2]. The tower as defined in [2] has a total length of 87.6 m. For the offshore models used in this report, the tower is truncated 10 m from the bottom, resulting in a tower length of 77.6 m. The tower is mostly tapered starting from 6.0m outer diameter, 7.76 m above the platform, to 3.87m diameter 77.6 m above the platform. Main particulars of the turbine model are shown in Table 1 below.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass tower</td>
<td>250 tons</td>
</tr>
<tr>
<td>Mass rotor (including hub)</td>
<td>110 tons</td>
</tr>
<tr>
<td>Mass nacelle</td>
<td>240 tons</td>
</tr>
<tr>
<td>Rated rotor speed</td>
<td>12.1 rpm</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>126 m</td>
</tr>
</tbody>
</table>
2.2 Reference bottom fixed monopile foundation

As a reference case, a bottom fixed support structure is modelled in Focus6. The configuration is taken as presented in the Upwind project, in which the NREL 5MW machine is modelled on top of a monopile (MP) foundation for the location of interest [5]. The monopile is straight with an outer diameter of 6.0 m until the platform height, 30 m above the mudline.

![Upwind Monopile foundation](image)

The soil-pile interaction is simplified by a set of coupled springs described by a foundation stiffness matrix, as displayed in Equation 1. Here \( w \) is the (static) lateral deflection and \( \phi \) the rotation of the pile at the mudline due to shear force \( F \) and overturning moment \( M \).

\[
\begin{bmatrix}
  k_{11} & k_{12} \\
  k_{21} & k_{22}
\end{bmatrix}
\begin{bmatrix}
  w \\
  \phi
\end{bmatrix} =
\begin{bmatrix}
  F \\
  M
\end{bmatrix}
\]

Equation 1

Patrick Passon ([8]) determined the values of the stiffness matrix for three soil layers.

\[
\begin{align*}
  k_{11} &= 2.575E+09 \text{ N/m} \\
  k_{12} &= k_{21} = -2.253 E+10 \text{ N/rad or Nm/m} \\
  k_{22} &= 2.629E+11
\end{align*}
\]
2.3 Semi-submersible floater

The Semi-submersible is a naturally buoyant structure because of the large volume displacement. Large cylinders on the outer corners of the structure are subjected to a restoring buoyancy force when pushed further into the water. The Semi-submersible design is selected from the OC4 project and will be further be denoted as the OC4 Semi. In the design, three cylinders with heave plates are present at the corners of a triangular structure. The turbine is fixed atop a central cylinder. Bracings supply the stiffness of the floating structure. For an overview of the main dimensions, see Figure 3 and Table 2.

Figure 3: Semi-submersible main dimensions [4]

![Figure 3: Semi-submersible main dimensions](image)

Table 2: OC4 Semi main dimensions

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draft</td>
<td>20 m</td>
</tr>
<tr>
<td>Total displacement volume</td>
<td>13917 m³</td>
</tr>
<tr>
<td>Distance COG from keel (ex turbine)</td>
<td>6.54 m</td>
</tr>
<tr>
<td>Dry mass floater</td>
<td>13473 tons</td>
</tr>
</tbody>
</table>
2.4 Spar floater

The Spar floater type is a long slender buoy that features a very low centre of gravity. This creates a large restoring moment when the structure is tilted due to environmental loads. The design as defined in phase IV of the IEA OC3 project [9] will be used that is modelled alike the Hywind Spar buoy.

![Figure 4: OC3 Spar [9]](image)

<table>
<thead>
<tr>
<th>Table 3: OC3 Spar main dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
</tr>
<tr>
<td>Draft</td>
</tr>
<tr>
<td>Total displacement volume</td>
</tr>
<tr>
<td>Distance COG from keel (ex turbine)</td>
</tr>
<tr>
<td>Dry mass floater</td>
</tr>
</tbody>
</table>
2.5 Tension leg platform

The tension leg platform is moored by the use of vertical tethers or tendons with a high axial stiffness. These tendons are used to pull the floating foundation deeper in the water, thereby restricting the movement of the floater. The TLP is not always naturally buoyant and finds its stability by the tension force from the tendons on the structure. The design of the TLP as investigated in the DeepCWind project is based on the Pelastar concept, see Figure 5.

Figure 5: DeepCWind tension leg platform [10]

Table 4: DeepCWind TLP – main dimensions

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draft</td>
<td>30 m</td>
</tr>
<tr>
<td>Total displacement volume</td>
<td>2771 m³</td>
</tr>
<tr>
<td>Distance COG from keel (ex turbine)</td>
<td>18.8 m</td>
</tr>
<tr>
<td>Dry mass floater</td>
<td>661.6 tons</td>
</tr>
</tbody>
</table>
2.6 Simulation software

For the simulations, the code aNySIMPHATAS has been used in the modular software package FOCUS6. aNySIMPHATAS is a combination of the aero-elastic modelling tool PHATAS, developed by ECN and WMC and the hydrodynamic response modelled by aNySIM, developed by MARIN. Coupling of the two codes has been reported in [11].

The floating foundations are modelled as rigid structures in aNySIM. Due to numerical solving issues between aNySIM and PHATAS, no tower flexibility could be included in the simulations. The blades however can deflect under the aerodynamic loading. The reference bottom-fixed monopile model (section 2.2) has a fully flexible tower to allow for realistic dynamic response in the tower top and nacelle.

The implications of the rigid tower modelling of the floating offshore wind models entail the loss of the tower modes in the dynamic response. Also the interaction and potential resonance between the movements and dynamic loads of the floater to the vibrations in the tower are lost. Accelerations of the tower top and nacelle should therefore be considered with caution.

2.7 Loadcase selection

A loadset is created according to the IEC 61400-3 norm [6] based on the wind, wave and current characteristics for the IJmuiden shallow water site, described in the Upwind study [5]. The site can be categorized as a II-B site according to the IEC classes. The reference wind speed is 42.73 m/s, the reference turbulence intensity is 14% and the average water depth is 20 m.

From the loadset, a subset of 828 loadcases has been selected for simulation. The 828 loadcases comprise power production, extreme turbulent conditions, fault causes, shut-down and extreme wind conditions with a parked turbine.

The loadcases are given a 5 digit id which includes the design load case for the first two digits (ie 13 for DLC 1.3). For the power production loadcases DLC 1.2 and DLC 1.3 the third and fourth digit describe the average wind speed and the last the seed number (ie 12214 is DLC 1.2, average wind speed of 21 m/s, turbulence seed 4).

- DLC 1.2
  - Power production,
  - Normal sea state
  - Normal wind speed model.
  - Average wind speed ranging 3 – 25 m/s, in steps of 1 m/s.
  - Misalignment is varied -8,0,+8°.
  - Two seeds per misalignment position (six per wind speed bin)
• DLC 1.3  
  o Power production,  
  o Normal sea state  
  o Extreme turbulence model  
  o Average wind speed ranging 3 – 25 m/s, in steps of 1 m/s.  
  o Misalignment is varied -8,0,+8°.  
  o Two seeds per misalignment position (six per wind speed bin)

• DLC 2.1  
  o Pitch runaway & blocked pitch of blade 2  
  o Normal sea state  
  o Normal turbulence model  
  o Six seeds at sub-rated wind, rated wind, rated wind+2 and cut-out wind speed.

• DLC 2.2  
  o Short circuit, failed pitch controller, negative and positive yaw runaway  
  o Normal sea state  
  o Normal turbulence model  
  o Six seeds at sub-rated wind, rated wind, rated wind+2 and cut-out wind speed.

• DLC 2.3  
  o Extreme operating gust with grid-loss  
  o Normal sea state  
  o Six seeds at sub-rated wind, rated wind, rated wind+2 and cut-out wind speed.

• DLC 2.4  
  o Operation with negative and positive failed yaw and larger delay for pitch of blade 2  
  o Normal sea state  
  o Normal turbulence model  
  o Two seeds at sub-rated wind, rated wind, rated wind+2 and cut-out wind speed.

• DLC 5.1 – Emergency stop  
  o Normal turbulence model  
  o Normal sea state  
  o Six seeds at sub-rated wind, rated wind, rated wind+2 and cut-out wind speed.

• DLC 6.1  
  o Idling rotor, upwind  
  o Extreme sea state  
  o Extreme wind model  
  o Severe sea state

• DLC 6.2  
  o Idling rotor, failed yaw control  
  o Extreme sea state  
  o Wind direction variation  
  o Extreme wind model

• DLC 6.3 – EWM  
  o Idling upwind  
  o Extreme sea state  
  o One year extreme wind  
  o ±20° yaw error
Because of the longer natural periods of the floater models compared to the vibration modes of a bottom-fixed structure, the time duration for the loadcases is increased to 2200 s for the floaters in order to capture a sufficient number of cycles.
In this chapter, the results of the aNySIMPHATAS calculations are presented. The modelling input and environmental conditions have been described in Chapter 2. The response parameters selected from the output are selected first in section 3.1. The extremes values for motion and load response is shown next. The range of displacements and rotations is given in section 3.3 for wind velocities of 3-25 m/s. This range displays a different motion sensitivity of the floater types to commonly occurring environmental conditions. The dynamic response is investigated in more detail in section 3.4, where the time series response for a single loadcase is plotted and the differences analysed. In 3.5 the dynamic content of the time signals is shown, i.e. spectral analyses were carried out. In a previous model created earlier in the project, the hydrodynamic interaction was found to be using a scaled model of the TLP. The influences this has had on the results are discussed in section 3.6. Finally, the extremes response of the Spar floater is zoomed into, on page 33.

### 3.1 Output parameters

The following parameters are used to monitor the loads on the wind turbine:

- Xflap1: flapwise displacement of the blade in the rotor plane
- Fx, Fy, Fz: internal force according to GL coordinate system (see Figure 6)
- Mf1, Ml1, Ml1: flap-wise, lead-wise, torsion moment in blade root
- Mraf, Msid, Mrtos: fore-aft, sideward, torsion moment in tower base
- Tsh: torque in rotor shaft
- Fax: axial rotor force
The following parameters are monitored for the operation of the turbine:

- \( V_{\text{hub}} \): wind speed at hub height
- \( P_e \): electric power supplied by the generator
- \( N_{\text{rpm}} \): rotor speed
- \( \theta_1 \): pitch angle of blade 1

The motions of the floater and turbine are written in 6 degrees of freedom. Surge, sway, heave, pitch, roll and yaw.

Statistics of the helideck motion were derived from the aNySIMPHATAS output. In Appendix B (page 59 - 65) this derivation is worked out. The statistical tables have been shared with NLR to aid in the analysis of helicopter movements within floating wind farms.

Figure 6: Coordinate definition PHATAS [12]
3.2 Extreme values

The extreme values are determined for both loads and motion response for the 828 loadcases. A clear trend is found in Figure 7 where the load response of the Spar is dominating. The axial rotor force is however similar for all four support structures, so the source of the large difference in loading must be found in the dynamic response of the floater.

Figure 7: Bar graph of load response maxima (scale y-axis is logarithmic)

In Figure 8 the maximum motion response is given. The restriction of certain degrees of freedom by the mooring lines is apparent. Roll and pitch is almost non-existent for the TLP. Surge and sway are largest for the Spar. Maximum acceleration in the tower top is largest for the Spar, though maximum acceleration at interface level is of a similar magnitude for both Spar and monopile.
A more detailed overview of the statistical maxima and minima of the load indicators over all 828 loadcases are shown in Table 16 in Appendix A (page 57). It is clear from the table that most of the extremes can be found in loadcase 2.2 and 6.2 which represent failed pitch controller at cut-out wind speed (2.2) and failed yaw control for an idling turbine under extreme wind from a variation of directions (6.2).
3.3 Range of displacement and rotation

For normal power production (DLC1.2), the range (max-min) of the surge, sway, heave, roll, pitch and yaw is displayed in the following scatter plots. These plots indicate the difference in motion response of the floating concepts, i.e. how much they are displaced for wind velocities in the operational range.

**Figure 9**: DLC 1.2 – Normal Production – range of surge motion at interface level

![Range Surge Motion](image)

**Figure 10**: DLC 1.2 – Normal Production – range of sway motion at interface level

![Range Sway Motion](image)
Figure 11: DLC 1.2 – Normal Production – range of heave motion at interface level

Figure 12: DLC 1.2 – Normal Production – range of roll rotation at interface level
In Figure 9 surge is most prominent for the Spar and TLP, where the TLP only shows a larger surge (wrt Semi-sub) for wind velocities above 10 m/s. Largest surge range for the Spar is found slightly under rated wind speed, and for the TLP this maximum is found above rated wind speed. The difference in lateral mooring stiffness the most likely cause as the Spar uses catenary mooring lines versus the tendons of the TLP. The surge of the Spar is however much larger than the Semi-submersible model with similar mooring line type.

Heave, roll and pitch are virtually non-existent for the tension leg platform because of restrictions the tendons pose to the degrees of freedom of the floater.

The range of pitch and heave are larger for the Spar than the Semi-submersible. The large inertia and the larger hydrodynamic surface area of the Semi-submersible is the
likely cause of the smaller motion response. The differences are however not as large in sway and roll degrees of freedom.
3.4 Time series comparison

This section zooms in on some interesting events by comparing time series of the dynamic response of the different concepts.

3.4.1 Spar maximum pitch and surge

For loadcase 22360, a maximum in the roll and surge response of the OC3 Spar is found (see Table 17). For this reason it is an interesting loadcase to learn what is causing the increased response by looking at a selection of time series plots. In this loadcase a pitch error occurs at rated +2 m/s wind speed (average 14 m/s, see Figure 15).

![Figure 15: Loadcase 22360: wind speed at hub](image1.png)

![Figure 16: Loadcase 22360: blade pitch angle](image2.png)

The pitch angle of all blades is suddenly dropped to -1° at 450 seconds, as seen in Figure 16. This causes an increase in pitch of the floaters. The Spar shows a higher pitch angle, but the magnitude is comparable to the Semi-submersible (Figure 18).
Figure 17: Loadcase 22360 - Roll

Figure 18: Loadcase 22360 - Pitch

Figure 20 shows how the surge of the Spar is much higher than the surge of the TLP and Semi-submersible. The Spar (and Semi-sub) surge changes in a more irregular way than the regular surge harmonics of the TLP. This is likely due to the interaction of the large pitching motion in the Spar and Semi-submersible, which is not present for the TLP. Because of this effect, the larger surge range of the Spar in Figure 9 can be explained.

Figure 19: Loadcase 22360 – surge

Figure 20: Loadcase 22360 – sway

3.5 Spectral comparison

Plotting the response of the floating offshore wind turbines in a spectral plot allows for the identification of the various harmonics in the signal. In this section, the power spectral density plots are shown for the floating models during operating conditions (Section 3.5.1). In section 3.5.2, the contribution of lead-wise blade vibrations in the dynamic response is determined. In section 3.5.3, the response amplitude operator is plotted to understand dynamic response of the floating substructure to the wave climate better.
3.5.1 Operational turbine at rated wind speed (12121)

In Figure 21, the roll acceleration at interface level is shown for the Semi-sub, Spar and TLP. The frequency peaks at low frequency can be led back to the rigid body modes of the floating structure. The calculated natural frequencies by aNySIM are displayed in Figure 21 as vertical lines in the plot. The OC4 Semi and OC3 Spar show dominant motion at this natural frequency. The TLP displays very little roll and pitch motions, which is to be expected with the tendon configuration that allows very little movement in heave, pitch and roll. However, the 3P response is largest for the TLP. This is likely due to the higher effective eigenfrequency of the TLP including the tendons. The rigid body mode of the TLP shown by the yellow line in Figure 21 displays a rather low eigenfrequency, but the stiffness of the tendons would increase the eigenfrequency closer to the 3P region. Therefore, the acceleration response at 3P for the TLP is higher than the other floating concepts.

Figure 21: Power spectral density plot of roll, pitch and yaw acceleration at interface level for loadcase 12121, power production at rated wind speed (straight lines are floater natural periods, upwards triangle is 1P, downward triangle is 3P frequency)
3.5.2 Blade resonance

A high contribution of the natural side-side blade frequency is found throughout all loadcases in the spectrum of the leadwise bending moment in the blade root. The magnitude for power operation in rated wind speed is shown in Figure 22.

Figure 22: Power spectral density of leadwise blade root bending moment for power production at rated wind speed (12 m/s)
3.5.3 Response Amplitude Operator

To map the response of the fore-aft bending moment at the interface to the wave climate, a RAO plot can be constructed. In Figure 23 the spectral response of fore-aft bending moment is divided by the power spectral density of the wave height signal.

Figure 23: Response amplitude operator of fore-aft bending moment at interface level
3.6 Investigation of hydrostatic scaling

If the displacement in the configuration input (ini file) is not equal to that from the hydrodynamic database (hyd file), aNySIM will scale the provided hydrodynamic properties given in the HYD file to a different body size. It became clear that such scaling has indeed been applied during the comparative aNySIMPHATAS calculations as carried out earlier in the project. The water displacement of the configuration file was set at 2771 m$^3$. The HYD file however was created for a displacement of 1328 m$^3$. As such, the scaling factor reported by aNySIM was $1.28 = \sqrt{2771/1328}$. This means that the hydrodynamic properties of the TLP used in creating the results of this chapter were scaled for a larger body. The correct scaling and displacement value has been used for the resulting statistics and graphs in 3 and further in the report. However, the effects of hydrostatic scaling are further investigated in this section for learning purposes.

In the following graphs, the difference of surge, sway, pitch and roll is shown in time series and power spectral density plots.

Figure 24: Time series surge response TLP - power production at rated wind speed. Comparison in hydrostatic scaling.
Figure 25: Time series sway response TLP - power production at rated wind speed. Comparison in hydrostatic scaling.

Figure 26: PSD pitch response TLP - power production at rated wind speed. Comparison in hydrostatic scaling.
Figure 27: PSD roll response TLP - power production at rated wind speed. Comparison in hydrostatic scaling.

Table 5: Comparison floater properties due to scaling

<table>
<thead>
<tr>
<th></th>
<th>Scaling factor 1.28</th>
<th>Scaling factor 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displaced volume</td>
<td>1327 m³</td>
<td>2840 m³</td>
</tr>
<tr>
<td>Vessel draft equilibrium</td>
<td>11.73 m</td>
<td>-13.44 m</td>
</tr>
<tr>
<td>Water plane area</td>
<td>54.24 m²</td>
<td>33.22 m²</td>
</tr>
<tr>
<td>Hydrostatic restoring matrix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Heave</td>
<td>545.4 kNms</td>
<td>334.0 kNms</td>
</tr>
<tr>
<td>- Roll</td>
<td>-1784909.5 kNms</td>
<td>-1784909.8 kNms</td>
</tr>
<tr>
<td>- Pitch</td>
<td>-1784909.5 kNms</td>
<td>-1784909.8 kNms</td>
</tr>
<tr>
<td>Natural period</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Heave</td>
<td>21.12 s</td>
<td>20.81 s</td>
</tr>
<tr>
<td>- Roll</td>
<td>18.65 s</td>
<td>15.64 s</td>
</tr>
<tr>
<td>- Pitch</td>
<td>18.66 s</td>
<td>15.64 s</td>
</tr>
<tr>
<td>Added mass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Heave</td>
<td>4.85 kton</td>
<td>2.32 kton</td>
</tr>
<tr>
<td>- Roll</td>
<td>11.95 Mtonm²</td>
<td>7.28 Mtonm²</td>
</tr>
<tr>
<td>- Pitch</td>
<td>11.95 Mtonm²</td>
<td>7.28 Mtonm²</td>
</tr>
</tbody>
</table>

An increased water plane area is taken into account when the scaling factor is applied (Table 5). The implications of the larger body means a larger buoyancy force and thus higher equilibrium draft. In the hydrostatic restoring matrix the largest difference is seen in the heave direction. The pitch and roll hydrostatics barely change, but will be affected most by the increased stiffness of the tendons.

As mentioned at the start of this section, the results shown elsewhere in this report include the model results of the correct dimensions.
3.7 Investigating the extreme Spar response

In section 3.2 and 3.3, the Spar foundation type shows the largest movements and loads. There are two things at play.

First, as shown in Figure 22, the lead-wise eigenfrequency of the blade contributes significantly to the lead-wise bending moment at the blade root. The larger movements of the floating structure, combined with a large blade pitch angle in idling causes a large angle of attack. The combination of blade flexibility and the dynamic stall model causes a 1Hz lead-lag resonance which ends in extremely high blade torsion and deflections. This extreme response is not expected in practise and is likely caused by the dynamic stall model at high angles of attack.

Second, glitches are found for simulations such as power production where a limited number of loadcases include an extreme value much higher than other similar simulations. This is likely a numerical convergence error. In order to determine whether turning off the dynamic stall model could prevent this calculation instability a loadcase of an operating floating wind turbine at rated wind speed is simulated with dynamic stall turned on and off.

Figure 28: Graph of fore-aft shear force at interface level for Spar, power operation at rated wind speed, with and without dynamic stall

From the time series of the axial shear force at interface level, the turbine with included dynamic stall model shows a sharp peak around 415 seconds. Without dynamic stall this peak does not occur, resulting in more reliable statistics. In general, the magnitude of shear force is similar in the two conditions, though the model with no dynamic stall is slower in following the load response of the model with dynamic stall enabled, e.g. a phase lag is visible.

In the spectrum of the axial shear force at the tower top (Figure 29), less broadband excitation is present in the model without dynamic stall enabled. It is advised to keep
the dynamic stall model enabled, but investigate the occurrence of sharp peaks further in follow-up research.

**Figure 29**: PSD axial rotor force, showing influence of dynamic stall modelling at rated wind velocity.
4

Tension Leg Platform

4.1 Introduction

In the past, the focus of ECN has been on the coupling of the aero- and hydroelastic tools. Models of a Spar and Semi-submersible have been created as part of the IEA OC3 and OC4 studies.

In the TO2-project on floating wind turbines the dynamic behaviour of a Tension Leg Platform, TLP, is investigated as well. Unlike a Spar and a Semi-submersible having a spread mooring, a TLP is vertical restrained by so-called tethers. These are vertical anchor lines that are tensioned by the platforms buoyancy [13].

In this chapter the design of the tendon mooring system is described as part of the system integration. First the general design consideration for a TLP platform are presented followed by a (simple) model of the tendon stiffnesses.

After applying the model for the tendon stiffness, the resulting mooring stiffness is compared to the aNySIM input as used for the DeepCwind TLP platform. Finally the chapter is concluded with a proposal to integrate the tending design with the TLP wind turbine platform.

4.2 TLP design and modelling

4.2.1 General considerations

In their retrospective of the tension leg platform, D'souza et.al. [14], pay attention to the design considerations for the TLP hull and tendon design. Although the focus is on TLP's for the oil and gas sector, it is thought that the basic ideas also apply for tension leg floating wind turbines.
• The TLP natural periods of the heave, roll and pitch motion must be less than 4.5 seconds to avoid dynamic resonant response in waves;
• The maximum (mean plus wave and wind induced) offset in the 100 year metocean conditions must be less than 8% of water depth primarily due to mechanical limitations of production riser and tendon top and bottom connectors. This also limits the maximum setdown of the hull;
• Tendon pre-tension to hull displacement ratio increases with water depth. In the Gulf of Mexico (GoM) the ratio ranges from 0.15 to 0.40;
• The tendon diameter to wall thickness \( \frac{d_t}{t_t} \) ratio, is designed so that each tendon is neutrally or positively buoyant, so as not to increase hull buoyancy requirements or tendon axial stresses. A \( \frac{d_t}{t_t} \) greater than 32 will achieve this requirement for steel tubular tendons;
• Column centre to centre separation and diameter for "self stable" TLPS determine the capacity of the TLP to transit to site with fully integrated topsides as well as its pitch stiffness. Column separation must strike a balance between hydrostatic stability tendon pitch stiffness and deck structure weight;
• Freeboard is the sum of setdown, maximum wave elevations and required air gap (5 feet) in 100 year metocean events.

4.2.2 Modelling of tendons

The tendon model of Bachynski et. al. [15] is applied to determine the tendon characteristics and can be used to model the mooring stiffness in aNySIM. The mooring system stiffnesses are defined as follow:

For the individual tendon the stiffness \( k_{11} \) and \( k_{33} \) are for the surge and heave direction respectively.

\[
k_{11} = \frac{T_0}{l_0} \quad \text{Equation 2}
\]

With \( T_0 \) the pre tension and \( l_0 \) the unstretched tendon length.

\[
k_{33} = \frac{E_t A_t}{l_0} \quad \text{Equation 3}
\]

Here \( E_t \) is the tendon Young’s modulus and \( A_t \) is the tendon cross-sectional area.

\[
K_{11} = \sum_{j=1}^{n_t} k_{11} \quad \text{Equation 4}
\]

\[
K_{33} = \sum_{j=1}^{n_t} k_{33} \quad \text{Equation 5}
\]
\[ K_{51} = K_{15} \approx \sum_{j=1}^{n_t} k_{1j} z_j \quad \text{Equation 6} \]

With \( z_j \) is the vertical location of pontoons.

\[ K_{55} \approx \sum_{j=1}^{n_t} k_{1j}^2 z_j^2 + k_{33} r_p^2 \cos \theta^2 \quad \text{Equation 7} \]

Where \( r_p \) is the pontoon radius measured from the TLP hull centre line and \( \theta \) the angle between the pontoons.

\[ K_{66} = \sum_{j=1}^{n_t} k_{1j} r_p^2 \quad \text{Equation 8} \]

Dependent on the symmetry of the system the following relations hold.

\[ K_{22} = K_{11} \quad \text{Equation 9} \]
\[ K_{24} = K_{42} = -K_{51} \quad \text{Equation 10} \]
\[ K_{44} = K_{55} \quad \text{Equation 11} \]

### 4.2.3 Frequency considerations

To understand the dynamics of a tension leg platform floating wind turbine it is of importance to know the natural frequencies of the system. Also for the mooring system. It is not trivial to decide whether the tendon should be considered to be a simply supported pre-tensioned string or beam. Therefore the natural frequencies are presented here both for a tendon represented by a string or a beam. The natural frequencies of a string are according to [16]

\[ \omega_i = \frac{i \pi}{l_0} \sqrt{\frac{T_0}{\mu_1 + m_a}} \quad \text{Equation 12} \]

According to Rao [17] the natural period for a beam with pretension is

\[ \omega_i = \frac{\pi^2}{l_0^2} \sqrt{\frac{E_t l_t}{\mu_1 + m_a}} \left( t^4 + \frac{i^2 T_0 l_0^2}{\pi^2 E_t l_t} \right)^{\frac{1}{2}} \quad \text{Equation 13} \]

Where \( M_a \) is the added mass/m and \( \mu_1 \) is mass/m

### 4.2.4 Characteristics of DeepCwind TLP

In this section the characteristics of the DeepCwind TLP are studied using the tendon modelling described above together with the aNySIM hydrodynamic model of the TLP platform as supplied by Marin. The results are compared with data presented in papers by Robertson et. al. [1] and Gueydon et. al. [18] and the aNySIM model input and
output. First the mooring stiffness is compared, followed by the natural periods of the motions.

The mooring stiffness applied in the model tests are compared with the ones calculated using the above equations.

### Table 6: Mooring stiffness

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Model test</th>
<th>ECN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{11}$ [kN/m]</td>
<td>84.6</td>
<td>85.4</td>
</tr>
<tr>
<td>$K_{33}$ [kN/m]</td>
<td>1.45E5</td>
<td>1.45E5</td>
</tr>
<tr>
<td>$K_{55}$ [kNm/rad]</td>
<td>6.5E7</td>
<td>6.54E7</td>
</tr>
</tbody>
</table>

The natural period of the platform motions can be determined using the mass, added mass and hydrostatic stiffness of aNySiM together with the mooring stiffness. It should be noted that the added mass is frequency dependent. In this case the added mass at 0.35rad/s is selected from the aNySiM hyd-file. The natural frequencies for a rigid body are:

### Table 7: Natural frequencies of the rigid body motions

<table>
<thead>
<tr>
<th>Frequency [rad/s]</th>
<th>Model test</th>
<th>ECN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>0.15</td>
<td>0.16</td>
</tr>
<tr>
<td>Heave</td>
<td>6.3</td>
<td>6.4</td>
</tr>
<tr>
<td>Pitch</td>
<td>3.1</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Bachynski et. al. [15] also describe how the added mass of a TLP platform can be estimated. However it turned out that the difference with the aNySiM data is to large at the moment. Further study is needed.

### 4.3 Proposal for an integrated tendon design method.

Based on the above presented tendon stiffness model a design method is described to estimate the mooring system and the dimensions of a steel tendon. It is assumed that the dimensions of the TLP platform are determined first, depending on the TLP design philosophy. For instance transport with the completed turbine installed. The hull displacement will be increased by the pre-tension of the tendons.

Assuming the masses, hydrodynamic and hydrostatic properties are known the design of the tendon is as follows.
1. For a given pre-tension hull displacement ratio, for instance 0.3, the pre-tension is known;
2. With the known pre-tension the surge stiffness of the mooring system can be determined;
3. For a maximum axial load the surge offset is estimated and checked with the maximum allowed offset of 8% of the water depth;
4. A heave natural frequency less than 4.5s is selected to determine the heave mooring systems stiffness using the known mass, added mass and hydrostatics;
5. The tendon heave stiffness is used to determine the tendon area $A_t$;
6. The tendon area $A_t$ together with the tendon to wall thickness ration $d_t/t_t = 32$ are used to determine the tendon diameter and wall thickness;
7. The natural periods of the tendon modes are calculated and checked with the wind turbine eigenfrequencies;
8. Check the natural frequencies of the platform motions.

The steps for the tendon design can be repeated together with an update of the TLP dimensions.
5

Mooring line analysis

5.1 Mooring system configurations

For the mooring system, several options are open. However for the Semi-submersible floating platform a system with catenary mooring lines is normally used. Often three mooring lines are used, symmetrically spread around the platform vertical axis. This configuration is based on experience from Semi-submersibles as used for oil and gas applications. For a Semi-submersible used as a support structure for a wind turbine, the optimal choice might be different. The analysis as done by GustoMSC [19] shows that the location/height of the fairleads has an important effect on the stability and motions of the platform which may result in significant cost reductions. In this paragraph some other configurations have been evaluated.

5.1.1 Base line configuration

For this task the initial mooring configuration was chosen in line with the baseline (Semi-submersible) concept of the project [4].
For the baseline the location of the anchor point is clarified in Figure 31. The fair leads are 14 m below sea level at a radius of 40 m from the Y-axis. The touch down point for all lines is at a radius of 592 m in the equilibrium position.

5.1.2 Configuration alternatives

Initially some static calculations were executed in order to gather insight in the behaviour of the system. These calculations were done with the aNySIMPHATAS simulation tool. The tool was used in the equilibrium position mode, which implied that the mooring forces are calculated for the given equilibrium positions.

Apart from the base case, options considered are:
1. High fair leads instead of low fair leads
2. High fair leads instead of low fair leads with increased line length
3. 6 mooring lines instead of 3 mooring lines

The high fair lead options might be an attractive alternative for reasons of stability and costs. The 6-line mooring system might be attractive for reasons of redundancy and safety.

For the two 3-line configurations with a high fair lead position, only the length of the mooring line is increased, while the anchor positions does not change.

For the 6-line configuration, the mooring line lengths are not changed while the anchor positions are modified (see Figure 32).

Figure 32: Anchor positions for 6-line configuration

In this configuration the mutual distance between 2 anchors is only 80 m. This will probably not the optimum configuration, but should be considered as a starting point.

5.2 Equilibrium positions

For the equilibrium calculations, deviations are considered in surge and sway directions.
In Figure 33 the tensions in 3 mooring lines are given for displacements in surge direction (a) and sway direction (b). The purple line indicates whether there is a touch down point detected in each of the mooring lines. For large deviations from the equilibrium, a mooring line can become loose from the bottom, which results in strong increase of the line tension. In order to avoid high line tensions, the motions should be limited within a range so that a touch down point in each of the lines is ensured. For certain configurations, it is necessary to increase the line length in order to ensure a touch down point. In general, the displacements of the centre of gravity are limited to a radius of around 18 meter for this configuration.

From previous studies, high placement of the fair leads might be attractive. When only the fair leads positions are modified (the height is increased from z=6 to z=36 m), the lines become loose from the bottom earlier (Figure 33a). The line lengths can be increased to overcome this (Figure 33b).
Figure 35: Six line configuration

For the six line configuration, the line tension are about the same, as well as the range within which a line touch down is ensured. This is in line with which can be expected.

5.3 Simulation of load cases

In order to dimension the mooring lines, the expected loads should be known. The highest loads during normal operation are expected for rated wind speed with the wind direction in line with one of the mooring lines. A simulation run under rated conditions resulted in the following loads as summarized in Table 8.

<table>
<thead>
<tr>
<th>signal</th>
<th>average</th>
<th>min</th>
<th>max</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td>abs windspeed [m/s]</td>
<td>12.3</td>
<td>6.5</td>
<td>18.2</td>
<td>11.7</td>
</tr>
<tr>
<td>Wind-wave direction [deg]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>xCoG [m]</td>
<td>6.8</td>
<td>0.0</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td>yCoG [m]</td>
<td>-1.3</td>
<td>-4.2</td>
<td>1.8</td>
<td>6.0</td>
</tr>
<tr>
<td>zCoG [m]</td>
<td>0.0</td>
<td>-0.2</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>roll [deg]</td>
<td>0.6</td>
<td>-0.5</td>
<td>1.7</td>
<td>2.3</td>
</tr>
<tr>
<td>pitch [deg]</td>
<td>2.6</td>
<td>-0.9</td>
<td>5.4</td>
<td>6.2</td>
</tr>
<tr>
<td>yaw [deg]</td>
<td>0.0</td>
<td>-5.2</td>
<td>5.0</td>
<td>10.3</td>
</tr>
<tr>
<td>Line1 Node6 tension [kN]</td>
<td>1538</td>
<td>1099</td>
<td>2142</td>
<td>1044</td>
</tr>
<tr>
<td>Line2 Node6 tension [kN]</td>
<td>915</td>
<td>781</td>
<td>1099</td>
<td>318</td>
</tr>
<tr>
<td>Line3 Node6 tension [kN]</td>
<td>1002</td>
<td>877</td>
<td>1150</td>
<td>272</td>
</tr>
<tr>
<td>FxMooring [kN]</td>
<td>-583</td>
<td>-1297</td>
<td>0</td>
<td>1297</td>
</tr>
<tr>
<td>FyMooring [kN]</td>
<td>77</td>
<td>-127</td>
<td>279</td>
<td>407</td>
</tr>
</tbody>
</table>
The maximum line tension which occurs during the simulation is 2142 kN. With the mooring system used in this simulation, the deviation out of the equilibrium are less than 13 m. This is considered as acceptable, compared with the mutual distance between the turbine (=7*D=880m).

The maximum line tension was used to dimension the mooring lines. Rules for dimensioning of catenary mooring lines are based on [20].

For chains the following rules are used:

\[
\begin{align*}
\text{w} & = 0.1875*D^2 \quad \text{[N/m]} \\
\text{AE} & = 90000*D^2 \quad \text{[N]} \\
\text{CBS or proof load} & = c*(44-0.08*D)*D^2 \quad \text{[N]}
\end{align*}
\]

with

\[
\begin{align*}
\text{w} & = \text{Submerged weight per unit length} \\
\text{AE} & = \text{Axial stiffness per unit length} \\
\text{D} & = \text{diameter in mm} \\
\text{c} & = \text{factor depending on material grade} \\
& \quad \text{For CBS, material grade 4, c = 27.4} \\
& \quad \text{For proof load, material grade 4, c=21.6}
\end{align*}
\]

For the material data was used:

Chain grade 4

Yield strength = 580 N/mm^2
Ultimate tensile strength = 860 N/mm^2

An alternative for chain is a wire rope. There are more types of wire ropes on the market. For floating constructions operating at one location, a spiral strand type is normally used for several reasons. For spiral strand wire rope the following rules are found:

\[
\begin{align*}
\text{w} & = 0.043*d^2 \quad \text{N/m} \\
\text{AE} & = 9000*d^3 \quad \text{N} \\
\text{CBS} & = 900*d^2 \quad \text{N}
\end{align*}
\]

with

\[
\begin{align*}
\text{w} & = \text{Submerged weight per unit length} \\
\text{AE} & = \text{Axial stiffness per unit length} \\
\text{d} & = \text{Nominal diameter in mm}
\end{align*}
\]

For the material data was used:

Ultimate tensile strength = 1570 N/mm^2
5.3.1 Base line

The break load for the chains, as used in previous simulations, based on the chain diameter and grade 4 material, used the above-mentioned rules is:

\[ \text{CBS} = c \times (44 - 0.08 \cdot D) \times D^2 \, [\text{N}] \]
\[ = 27.4 \times (44 - 0.08 \cdot 76.6) \times 76.6^2 \times 10^6 \, [\text{N}] \equiv 6088 \, [\text{kN}] \]

During the simulations, the maximum tension was 2142 kN. The current chain is probably dimensioned for another load case (for instance 50yrs extreme wave) with some degree of safety. But this is less important for mutual comparison of different systems. So, for the other configurations the same value will be used.

The results of the calculations, using the above-mentioned rules, can be found in Table 9 under the column Chain / cf1&cf2b. These parameters are used as input in the simulation.

5.3.2 Hybrid mooring lines

A wire rope is used as an alternative for a chain. Initially the wire rope was used with chains at both ends. The chain parts are conform the base line (cf1). For the wire rope the properties are calculated using the rules above, The results can be found in Table 9, column Wire Rope / cf2b.

The mooring line is defined by the vectors LineSegmentType and Length. In order to be flexible, the line is divided in 5 parts and the lengths of the parts are defined in the vector:

\[ \text{Length} = \{50, 258.5, 258.5, 258.5, 10\} \]

For each segment of the line, different properties can be defined. In our situation:

Chain : LineSegmentType = 1
Wire Rope : LineSegmentType = 2

The composition of the line is defined by the vector:

\[ \text{LineSegmentType} = \{1, 2, 2, 1\} \]

In this example, the line exist of:
anchor <> 50 m Chain <> 3x258.5 m Wire Rope <> 10 m Chain <> fair lead.

A first simulation learned that the weight of the mooring line did not result in sufficient mooring forces. The line came loose from the bottom at rated conditions, which is not in accordance with the principle of a catenary mooring. For this reason, the chain at the side of the fair lead was extended, which resulted in the following line definition (cf2b):

\[ \text{LineSegmentType} = \{1, 2, 2, 1, 1\} \]
\[ \text{Length} = \{50, 258.5, 258.5, 258.5, 10\} \]

This configuration is used for the simulations.
5.3.3 Additional mooring lines

For reasons of redundancy and safety it might be attractive to add some lines so that in case of calamities drifting of a platform with the risk of collision. With a three line system, failure of 1 line causes unfavourable loads on the other anchors. At least 5 lines are necessary to keep the loads on the anchors in the same direction. In this case 6 lines has been chosen, so that the same fair leads can be used. The mutual distance between the anchors belonging to the lines attached to the same fair lead is 80 meters (Figure 32).

Because the loads at a fair lead are divided over 2 mooring lines, the chain parameters were adapted (Table 9, chain/cf3).

Table 9: Mooring line data

<table>
<thead>
<tr>
<th>Mooring line data</th>
<th>Chain</th>
<th>Wire Rope</th>
<th>Chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>cf1 &amp; cf2b</td>
<td>cf2b</td>
<td>cf3</td>
</tr>
<tr>
<td>D</td>
<td>mm</td>
<td>76.6</td>
<td>82.0</td>
</tr>
<tr>
<td>c</td>
<td>-</td>
<td>27.4</td>
<td>0.0</td>
</tr>
<tr>
<td>CBS</td>
<td>kN</td>
<td>6089</td>
<td>6052</td>
</tr>
<tr>
<td>w</td>
<td>N/m</td>
<td>1100</td>
<td>289</td>
</tr>
<tr>
<td>m</td>
<td>kg/m</td>
<td>112</td>
<td>29</td>
</tr>
<tr>
<td>AE</td>
<td>kN</td>
<td>528080</td>
<td>605160</td>
</tr>
<tr>
<td>A</td>
<td>mm²</td>
<td>4608</td>
<td>5281</td>
</tr>
<tr>
<td>UTS</td>
<td>N/mm²</td>
<td>860</td>
<td>1570</td>
</tr>
<tr>
<td>Yield strength</td>
<td>N/mm²</td>
<td>580</td>
<td>0</td>
</tr>
<tr>
<td>Hydrodynamic drag coeff</td>
<td>-</td>
<td>2.6</td>
<td>1.8</td>
</tr>
</tbody>
</table>

5.3.4 Mooring line definition aNySIM

In Table 10 the definition of the mooring line system is given for the three configurations.

Table 10: Mooring definition for aNySIM for three configurations

<table>
<thead>
<tr>
<th>Mooring configuration</th>
<th>cf1</th>
<th>cf2b</th>
<th>cf3</th>
</tr>
</thead>
<tbody>
<tr>
<td>[MooringSystem1]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comment</td>
<td>3 lines spread mooring</td>
<td>3 hybrid lines spread mooring</td>
<td>6 lines spread mooring</td>
</tr>
<tr>
<td>MooringSystemType</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>IsDynamic</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Nline</td>
<td>3</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>LineDef</td>
<td>{ 1, 1, 1 }</td>
<td>{ 1, 1, 1 }</td>
<td>{ 1, 1, 1, 1, 1 }</td>
</tr>
</tbody>
</table>
5.3.5 Simulation results for three configurations

Simulations have been carried out for the three mooring system configurations as described above. The load cases are summarized in Table 11.
**Table 11: Load cases**

<table>
<thead>
<tr>
<th>Condition</th>
<th>rated</th>
<th>cut out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean wind speed</td>
<td>11.4</td>
<td>25</td>
</tr>
<tr>
<td>Wave peak period</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Significant wave height</td>
<td>4.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Turbulence intensity</td>
<td>14.7</td>
<td>13.1</td>
</tr>
<tr>
<td>Spectrum peak enhancement factor</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Yaw misalignment</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 36 shows the motions of the centre of gravity for 2 configurations at rated conditions. The motions for the third configuration (cf3) are in line with cf1.

Due to the lower mass of the wire rope part of the hybrid mooring lines and resulting reduced mooring stiffness, the displacements of the centre of gravity of cf2b are much larger than cf1/cf3. However, compared with the mutual distance between the turbines, the values are acceptable. This is also the case for cut out conditions.
The line tensions found during the simulations are as expected and at an acceptable level for both configurations. Only during the initialisation, the tension is significantly larger for the hybrid configurations due to the lower mooring stiffness and increased dynamic response.

**Figure 38**: Displacement of turbine top for 2 configurations at rated conditions

![Turbine top displacement](image)

The displacements of the turbine top (**Figure 38**) are also as expected. The motions are larger for the hybrid mooring system. Although the values are not excessive, further analysis in combination with turbine control are necessary.

The simulation runs were done over a period of 670 seconds. For the calculation of the statistical values, the time interval up to 350 seconds was neglected because the simulations did not start in the equilibrium position.

**Table 12**: Statistics of 6 simulation runs (350-670 sec)

<table>
<thead>
<tr>
<th>Load case</th>
<th>cf 1, rated</th>
<th>cf 2b, rated</th>
<th>cf 3, rated</th>
<th>cf 1, cut out</th>
<th>cf 2b, cut out</th>
<th>cf 3, cut out</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{CoG}$ [m]</td>
<td>6.8 8.8 12.8 10.0 6.8 11.9</td>
<td>4.8 6.9 10.7 7.7 4.7 6.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$y_{CoG}$ [m]</td>
<td>-0.1 1.1 -0.6 5.4 -0.1 1.1</td>
<td>-0.6 2.1 -1.2 7.7 -0.6 2.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$z_{CoG}$ [m]</td>
<td>0.0 0.9 0.0 0.9 0.0 0.9</td>
<td>0.0 2.2 0.0 2.2 0.0 2.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fairlead [kN]</td>
<td>1533 624 1137 981 774 467</td>
<td>1389 419 979 407 692 211</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fairlead [kN]</td>
<td>963 163 566 95 484 102</td>
<td>986 101 573 103 494 63</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fairlead [kN]</td>
<td>974 146 580 93 480 109</td>
<td>1035 191 601 110 511 118</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_x$ Mooring [kN]</td>
<td>-569 788 -597 1048 -589 1156</td>
<td>-363 545 -423 466 -381 589</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_y$ Mooring [kN]</td>
<td>10 108 7 165 10 112</td>
<td>34 160 15 187 35 199</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_z$ Mooring [kN]</td>
<td>-52 90 -89 235 -55 133</td>
<td>-28 70 -47 90 -28 73</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_x$ Mooring [kNm]</td>
<td>-364 1228 -256 1135 -361 1211</td>
<td>-851 3235 -444 1645 -849 3451</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_y$ Mooring [kNm]</td>
<td>58965 53940 60111 54834 59057 57385</td>
<td>39411 73487 39807 72778 39494 73753</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_z$ Mooring [kNm]</td>
<td>-306 10164 -322 9817 -296 10054</td>
<td>-2142 17925 -2217 18029 -2142 17640</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The results are given in Table 12. This table does not show any excessive values. Whether all motions are within an acceptable range should be confirmed by further analysis.

5.4 Mooring systems costs

5.4.1 Cost model

Costs estimates for the mooring system were based on [21].

**Anchor:**

\[ C_{\text{anchor}} = M \cdot C_1 \cdot C_2 \]

with:

- \( M = 17 \times 10^3 \text{ [kg]} \) Mass of the anchor
- \( C_1 = 670 \text{ [%]} \) Complexity factor
- \( C_2 = 1.00 \text{ [€/kg]} \) price steel

The product \( C_1 \cdot C_2 \) (≈ 6.70 €/kg) can be seen as the steel price for this specific application. According to [22], the material price for anchors should be 5 €/kg. So the material price of 6.70 €/kg is considered as “good enough” for this purpose.

**Chain:**

In [21], the following cost were mentioned:

- Mass: 126.5 kg/m
- Diameter: 76 mm
- Cost: 250 €/m

This results in a material price of 1.97 €/kg.

**Strand steel wire:**

In [21], the following cost were mentioned:

- Mass: 29 kg/m
- Diameter: 61 mm
- Cost: 45 €/m

This results in a material price of 1.55 €/kg

According to [22], the material price for chains should be 2.5 €/kg.

5.4.2 Cost estimates

For the cost estimates, the following parameters are used:
Table 13: Cost parameters for three mooring line configurations

<table>
<thead>
<tr>
<th>Cost parameters</th>
<th>cf1</th>
<th>cf2</th>
<th>cf3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chain length m</td>
<td>835.5</td>
<td>318.5</td>
<td>835.5</td>
</tr>
<tr>
<td>Specific mass kg/m</td>
<td>126.5</td>
<td>126.5</td>
<td>61.5</td>
</tr>
<tr>
<td>Steel wire m</td>
<td>517.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific mass steel wire kg/m</td>
<td>52.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anchor weight kg</td>
<td>17000</td>
<td>17000</td>
<td>8500</td>
</tr>
</tbody>
</table>

The weight of the anchor was chosen identical to [21] for the three line systems. For the six line system, the mass was halved. Other parameters were chosen conform the input as used for the aNySIMPHATAS simulations.

Table 14: Material price for mooring application

<table>
<thead>
<tr>
<th>Material cost</th>
<th>Anchor material €/kg</th>
<th>Chain material €/kg</th>
<th>Wire rope ,material €/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchor material €/kg</td>
<td>6.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chain material €/kg</td>
<td>1.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wire rope ,material €/kg</td>
<td>1.55</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The material prices were chosen in accordance with [21].

Based on these parameters, the cost of the mooring system are estimated (Table 15).

Table 15: Cost estimates for three mooring line configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>anchor [€]</th>
<th>chain [€]</th>
<th>steel wire [€]</th>
<th>total line [€]</th>
<th>total system [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>cf1</td>
<td>113,900</td>
<td>208,875</td>
<td>322,775</td>
<td>968,325</td>
<td></td>
</tr>
<tr>
<td>cf2b</td>
<td>113,900</td>
<td>79,625</td>
<td>42,041</td>
<td>235,566</td>
<td>706,697</td>
</tr>
<tr>
<td>cf3</td>
<td>56,950</td>
<td>101,581</td>
<td>158,531</td>
<td>951,184</td>
<td></td>
</tr>
</tbody>
</table>

The costs of the steel wire are much lower than for the chains. This results in a cost saving of more than 25% for the hybrid configuration compared with the baseline. So further design of alternative configurations with hybrid lines in combination with other mooring line length and fair lead positions is recommended.

The six-line configuration does not differ very much from the baseline, which can be expected. Most of the scaling and cost estimated has been done by linear relationships And installation of the mooring line and anchors has not been taken into account. Advantages of systems with more than 4 mooring lines come from redundancy and safety considerations.
Conclusion and recommendations

In this report, the dynamic behaviour of a Semi-submersible, Spar and tension leg platform has been simulated using aNySIMPHATAS for a large number of load cases. The Spar has shown the largest range of pitch, heave and surge response for power production cases. The tension leg platform has a similar range of surge response near rated wind speed as the Spar. Pitch, heave and roll however are restricted by the tendon configuration. The Semi-submersible shows large pitch response, but the range of heave remains below 1 m.

The Spar also shows the largest extreme values for most motion response parameters and all loads on the turbine. From this it can be concluded that a turbine will be loaded most severely on a Spar foundation. However, there are some reservations to this conclusion. First, the Spar has been designed for very deep water sites. The wave climate that was used for generating the set of loadcases is based on a more shallow water site. For the design of a Spar foundation, it is advised to choose a wave climate that is more representative for a deep water site, containing longer waves. However, the response to the loadcases subjected to the model is still considered valid. Second, some very sharp peaks in the load response have been found which are likely caused by the dynamic stall model for increased angles of attack. Next to the glitches, a lead-lag resonance is found when the blade is pitched to feather in idling conditions. It is recommended to look better into the cause of these instabilities and solutions to prevent them.

The effect of hydrostatic scaling in aNySIM has been investigated. The displaced water plane area of a scaled structure is larger, hence a larger (heave) restoring force is the effect and the equilibrium position is higher. The model response given in this report is however simulated without the scaling effect.

In Chapter 4, the model for the tendon stiffness of Bachynski et. al. [15] is used for the DeepCwind TLP platform. Good agreement is found with the mooring system as applied
in aNySIM. A design procedure is proposed to integrate the tendon design with the TLP wind turbine platform.

Finally, three mooring line configurations have been investigated for a Semi-submersible foundation. A three line spread mooring configuration has been compared with a three line hybrid configuration (applying chain and wire rope) and a six line configuration. An increase of drift in surge direction and a larger mooring line tension is found for the hybrid mooring line configuration. However, the displacement and mooring line tension of all configurations is considered acceptable as the breaking load is not surpassed by a wide margin. The costs of the configurations were estimated and a 25% cost reduction can potentially be achieved when choosing the hybrid mooring line configuration over the other options.


[20] “Floating structures, a guide for design and analysis.”
Appendix A. Statistical load and motion response

Table 16: Statistical maxima and minima loads – all 828 loadcases

<table>
<thead>
<tr>
<th></th>
<th>Monopile reference</th>
<th>OC4 Semi-submersible</th>
<th>OC3 Spar</th>
<th>DeepCWind TLP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>max</td>
<td>min</td>
<td>max</td>
<td>min</td>
</tr>
<tr>
<td>Fax [N]</td>
<td>2238a</td>
<td>3.71E+06</td>
<td>2238a</td>
<td>-2.45E+06</td>
</tr>
<tr>
<td>Mside Interface [Nm]</td>
<td>61133</td>
<td>7.96E+07</td>
<td>62485</td>
<td>-1.02E+08</td>
</tr>
<tr>
<td>Mfraf Interface [Nm]</td>
<td>62522</td>
<td>1.18E+08</td>
<td>23625</td>
<td>-1.30E+08</td>
</tr>
<tr>
<td>Mtors Interface [Nm]</td>
<td>62485</td>
<td>2.64E+07</td>
<td>62485</td>
<td>-3.27E+07</td>
</tr>
<tr>
<td>Fx_Interface [N]</td>
<td>62371</td>
<td>1.95E+06</td>
<td>23624</td>
<td>-1.59E+06</td>
</tr>
<tr>
<td>Fy_Interface [N]</td>
<td>62485</td>
<td>1.78E+06</td>
<td>62485</td>
<td>-1.09E+06</td>
</tr>
<tr>
<td>Fz Interface [N]</td>
<td>2238a</td>
<td>-4.97E+06</td>
<td>2238a</td>
<td>-6.78E+06</td>
</tr>
<tr>
<td>Fx_Top [N]</td>
<td>2238a</td>
<td>1.36E+06</td>
<td>23625</td>
<td>-1.48E+06</td>
</tr>
<tr>
<td>Fy_Top [N]</td>
<td>62485</td>
<td>1.28E+06</td>
<td>61153</td>
<td>-9.37E+05</td>
</tr>
<tr>
<td>Fz_Top [N]</td>
<td>2238a</td>
<td>-2.65E+06</td>
<td>2238a</td>
<td>-4.45E+06</td>
</tr>
<tr>
<td>M11 [Nm]</td>
<td>61145</td>
<td>1.40E+07</td>
<td>62490</td>
<td>-1.56E+07</td>
</tr>
<tr>
<td>M11 [Nm]</td>
<td>2238a</td>
<td>1.11E+06</td>
<td>2238a</td>
<td>-1.36E+06</td>
</tr>
<tr>
<td>M11 [Nm]</td>
<td>62485</td>
<td>2.94E+06</td>
<td>62485</td>
<td>-2.94E+06</td>
</tr>
</tbody>
</table>
### Table 17: Statistical maxima and minima motions – all 828 loadcases

<table>
<thead>
<tr>
<th></th>
<th>Monopile reference</th>
<th>OC4 Semi-submersible</th>
<th>OC3 Spar</th>
<th>DeepCWind TLP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>max</td>
<td>min</td>
<td>max</td>
<td>min</td>
</tr>
<tr>
<td></td>
<td>LC value</td>
<td>LC value</td>
<td>LC value</td>
<td>LC value</td>
</tr>
<tr>
<td>Roll [°]</td>
<td>62331</td>
<td>6.72</td>
<td>62581</td>
<td>-5.42</td>
</tr>
<tr>
<td>Pitch [°]</td>
<td>62541</td>
<td>15.11</td>
<td>51403</td>
<td>-5.33</td>
</tr>
<tr>
<td>Yaw [°]</td>
<td>13155</td>
<td>11.56</td>
<td>13253</td>
<td>-11.73</td>
</tr>
<tr>
<td>Disp_interface_x [m]</td>
<td>62372</td>
<td>25.71</td>
<td>62530</td>
<td>-22.51</td>
</tr>
<tr>
<td>Disp_interface_y [m]</td>
<td>62480</td>
<td>13.92</td>
<td>62534</td>
<td>-17.68</td>
</tr>
<tr>
<td>Disp_interface_z [m]</td>
<td>62451</td>
<td>2.20</td>
<td>62355</td>
<td>-2.44</td>
</tr>
<tr>
<td>Acc_Top_x [m/s²]</td>
<td>2238a</td>
<td>4.01</td>
<td>2238a</td>
<td>-3.62</td>
</tr>
<tr>
<td>Acc_Top_y [m/s²]</td>
<td>2238a</td>
<td>3.79</td>
<td>62485</td>
<td>-3.81</td>
</tr>
<tr>
<td>Acc_Interface_x [m/s²]</td>
<td>2238a</td>
<td>7.64</td>
<td>2238a</td>
<td>-8.09</td>
</tr>
<tr>
<td>Acc_Interface_y [m/s²]</td>
<td>2236a</td>
<td>10.35</td>
<td>2236a</td>
<td>-9.91</td>
</tr>
</tbody>
</table>
Appendix B. Transforming motion to helideck

The motions of the tower top and helideck are desired output from the aNySIMPHATAS simulations. However, aNySIM only provides motion at the interface of the floater and the tower. These displacements, velocities and accelerations in 6 DOF must be transformed to a different location in space.

The first assumption is that the rotation angles $\phi$ (roll), $\theta$ (pitch) and $\psi$ (yaw) are equal in the interface, in the tower top and at the helideck. In Matlab, a vector is created containing the roll, pitch and yaw angles at the tower bottom in degrees. The rotational velocity and acceleration are determined by numeric differentiation. This creates vectors with a length that is respectively one and two samples shorter than the vector containing the roll, pitch and yaw timeseries. In order to plot the velocity and acceleration versus the time vector, the last element is repeated in case of the angular velocity vector, and the first and last element are repeated for the angular acceleration vector.

The displacement in the tower top and at the helideck can be described as the sum of the interface displacement ‘Disp_interface’ and a component describing the displacement due to rotation. For the helideck an extra component ‘Disp_yaw_heli’ is added describing the displacement from the neutral position due to the yaw angle of the nacelle.

$$\text{Disp}\_\text{top} = \text{Disp}\_\text{interface} + \text{Disp}\_\text{rot}\_\text{top}$$
$$\text{Disp}\_\text{heli} = \text{Disp}\_\text{interface} + \text{Disp}\_\text{rot}\_\text{heli} + \text{Disp}\_\text{yaw}\_\text{heli}$$

Velocity and acceleration at the tower top and helideck is found by adding the derivative of the individual components.

$$\text{Vel}\_\text{top} = \text{Vel}\_\text{interface} + \text{Vel}\_\text{rot}\_\text{top}$$
$$\text{Vel}\_\text{heli} = \text{Vel}\_\text{interface} + \text{Vel}\_\text{rot}\_\text{heli} + \text{Vel}\_\text{yaw}\_\text{heli}$$

$$\text{Acc}\_\text{top} = \text{Acc}\_\text{interface} + \text{Acc}\_\text{rot}\_\text{top}$$
$$\text{Acc}\_\text{heli} = \text{Acc}\_\text{interface} + \text{Acc}\_\text{rot}\_\text{heli} + \text{Acc}\_\text{yaw}\_\text{heli}$$
A.1. Displacement due to rotation of tower base

In [11] the transformation of global rotation into local motion is described. The motion in the tower top and helideck due to rotation of the base is found by applying the following equations.

The global position vector $GP$ at time $t$, in the coordinate system of $GP$ at time $t = 0$, can be determined by multiplying the transformed rotation matrix $R\text{trans}(\phi, \theta, \psi)$ with $GP_{t=0}$.

$$GP_t = R\text{trans}(\phi, \theta, \psi) \cdot GP_{t=0}$$

Let:

$$R_\phi = \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_\theta = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix}$$

$$R_\phi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & \sin \phi \\ 0 & -\sin \phi & \cos \phi \end{bmatrix}$$

Then:

$$R\text{trans}(\phi, \theta, \psi) = [R_\phi^T \cdot R_\theta^T \cdot R_\phi^T]$$

$$= \begin{bmatrix} \cos \psi \cos \theta & -\sin \psi \cos \phi + \cos \psi \sin \theta \sin \phi & \sin \phi \sin \psi + \cos \psi \sin \theta \cos \phi \\ \sin \psi \cos \theta & \cos \psi \cos \phi + \sin \psi \sin \theta \sin \phi & -\cos \psi \sin \phi + \sin \psi \sin \theta \cos \phi \\ -\sin \theta & \cos \theta \sin \phi & \cos \theta \cos \phi \end{bmatrix}$$

The displacement is the difference of new position $GP_t$ with respect to the old position $GP_{t=0}$. So for the tower top this can be given as:

$$\text{Disp}_{\text{rot top}} = (R\text{trans}(\phi, \theta, \psi) - I) \cdot GP_{\text{top}}$$

$$\text{Disp}_{\text{rot heli}} = (R\text{trans}(\phi, \theta, \psi) - I) \cdot GP_{\text{heli}}$$

Global position tower top wrt interface:

$$GP_{\text{top}} = \begin{bmatrix} 0 \\ 0 \\ 77.6 \end{bmatrix}$$

Global position helideck wrt interface (for zero yaw angle):

$$GP_{\text{heli}} = \begin{bmatrix} 12 \\ 0 \\ 84.1 \end{bmatrix}$$
To include the yaw position of the turbine (shown in Figure 41), the global position of the helideck must be updated for every time interval. This results in the following equation for the global position helideck with respect to the interface level.

\[
GP_{heli} = \begin{bmatrix}
12 - 12 \cdot \cos(yaw\_angle) \\
12 \cdot \sin(yaw\_angle) \\
84.1
\end{bmatrix}
\]

The velocity and acceleration are approached through a finite difference calculation.

Velocity:

\[
Vel_{rot\_top,\ heli} \approx \frac{\Delta Disp_{rot\_top,\ heli}}{\Delta t} \quad \Delta t = \text{sample interval}
\]

Acceleration:

\[
Acc_{rot\_top,\ heli} \approx \frac{\Delta^2 Disp_{rot\_top,\ heli}}{\Delta t^2} \quad \Delta t = \text{sample interval}
\]
A.2. Motion of helideck due to nacelle yaw

The displacement of the helideck with respect to the neutral position (yaw_angle=0) is included in the component ‘disp_yaw_heli’. The derivation for disp_yaw_heli, vel_yaw_heli and acc_yaw_heli can be found in section A.4.

\[
\text{Disp}_{\text{yaw_heli}} = \begin{bmatrix} -12 \cdot \cos(\text{yaw_angle}) + 12 \\ 12 \cdot \sin(\text{yaw_angle}) \\ 0 \end{bmatrix}
\]

\[
\text{Vel}_{\text{yaw_heli}} = \begin{bmatrix} -12 \cdot \frac{d \text{yaw_angle}}{dt} \cdot \sin(\text{yaw_angle}) \\ 12 \cdot \frac{d \text{yaw_angle}}{dt} \cdot \cos(\text{yaw_angle)} \\ 0 \end{bmatrix}
\]
\[
\text{Acc}_{\text{yaw\_heli}} = \begin{bmatrix}
12 \cdot \left( \frac{d}{dt} \text{yaw\_angle} \right)^2 \cdot \cos(\text{yaw\_angle}) - 12 \cdot \frac{d^2 \text{yaw\_angle}}{dt^2} \cdot \sin(\text{yaw\_angle}) \\
12 \cdot \left( \frac{d}{dt} \text{yaw\_angle} \right)^2 \cdot \sin(\text{yaw\_angle}) + 12 \cdot \frac{d^2 \text{yaw\_angle}}{dt^2} \cdot \cos(\text{yaw\_angle}) \\
0
\end{bmatrix}
\]

**Figure 41:** Definition nacelle orientation in Phatas [12]

For a loadcase representing a yaw runaway, the time series of \text{disp\_yaw\_heli} is displayed in **Figure 42**.
A.3. Total displacement of helideck

As previously mentioned, the displacement at the helideck is comprised of the displacement of the interface, the displacement due to tilting/rotation of the floater and displacement due to the nacelle yaw angle. These separate components are shown in Figure 43.
A.4. Derivation of helideck motion due to nacelle yawing

In this section, the motion of the helideck due to nacelle yaw angle (here $\theta$) is derived. The assumption is that the $x$ and $y$ vectors are parallel to the global $X$ and $Y$ directions i.e. that the $x$-$y$ plane is not tilted.

In Figure 44 the vector $r$ is drawn from the tower center axis to the helideck.

Figure 44: Top view diagram of a nacelle under a yaw angle.

Position of the helideck, at distance $r$ from the tower centre can be described as:

$$\text{pos}_{\text{heli, x}} = r \cdot \cos(\theta)$$
$$\text{pos}_{\text{heli, y}} = r \cdot \sin(\theta)$$

As in the neutral position, $x = 12$ m and $y = 0$ m, ‘Disp_yaw_heli’ is written as:

$$\text{disp}_{\text{yaw, x}} = r \cdot \cos(\theta) - r$$
$$\text{disp}_{\text{yaw, y}} = r \cdot \sin(\theta)$$

Tangential velocity $v = \omega \cdot r = \frac{d\theta}{dt} \cdot r$

Centripetal acceleration $a_c = \frac{v^2}{r} = \omega^2 r = \left(\frac{d\theta}{dt}\right)^2 \cdot r$

Tangential acceleration $a_t = \frac{dv}{dt} = \frac{d^2\theta}{dt^2} \cdot r$

Separated into x and y components

$$v_x = -v \cdot \sin(\theta) = -\frac{d\theta}{dt} \cdot r \cdot \sin(\theta)$$
$$v_y = v \cdot \cos(\theta) = \frac{d\theta}{dt} \cdot r \cdot \cos(\theta)$$
$$a_{c,x} = a_c \cdot \cos(\theta)$$
$$a_{c,y} = a_c \cdot \sin(\theta)$$
$$a_{t,x} = -a_t \cdot \sin(\theta)$$
$$a_{t,y} = a_t \cdot \cos(\theta)$$

$$a_x = a_{c,x} + a_{t,x} = \left(\frac{d\theta}{dt}\right)^2 \cdot r \cdot \cos(\theta) - \frac{d^2\theta}{dt^2} \cdot r \cdot \sin(\theta)$$
$$a_y = a_{c,y} + a_{t,y} = \left(\frac{d\theta}{dt}\right)^2 \cdot r \cdot \sin(\theta) + \frac{d^2\theta}{dt^2} \cdot r \cdot \cos(\theta)$$