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OFFSHORE WIND TURBINES ON TLPS – ASSESSMENT OF FLOATING SUPPORT STRUCTURES FOR OFFSHORE WIND FARMS IN GERMAN WATERS

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Summary

Appropriately designed floating support structures for offshore wind turbines need not be more massive nor costly than the jackets or tripods currently being deployed in German waters. However a number of significant challenges remain in the development of this technology, including the verification of design tools and the demonstration of safe, cost-effective installation methods. This paper assesses the prospects for floating support structures suitable for deployment in the German sectors of the North and Baltic Seas in terms of technology principles, challenges and the potential wind resource.

1. Introduction

The most promising type of floating support structure for offshore wind turbines for typical depths in German waters in the longer term would appear to be tensioned leg platforms (TLPs), however overall experience of fabricating and operating this technology to date has been limited. Since the first TLP was installed at the Hutton Field in the North Sea in 1984, the offshore oil and gas industry has installed only approximately twenty units worldwide.

This paper examines the technical merits and challenges of applying TLP support structures in offshore wind farms and uses the results of outline design methods and load analysis calculations using BLADED to present preliminary candidate configurations suitable for German conditions.

This paper attempts to explain why floating support structures for offshore wind energy in intermediate depth waters are more attractive than at first apparent and how efforts could be focused to realise the benefits in the near future.

2. Floating Concepts

Floating foundations can broadly be catagorised in to three classes of vessels, Fig. 1:

- Spar Class: using a weight deep under the surface to provide a counter balance, for example a long and slender cylinder,
- Semi-Sub Class: Using a framework structure with a combination of buoyant sections and ballast to provide dynamic stability.
- TLP Class: using mooring arrangements to keep the structure stable, specifically tensioned moorings.

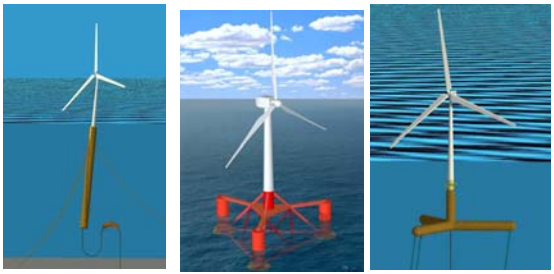
Spar Class SemiSub Class TLP Class

Fig. 1: Support Structure Classes

The spar floater concept benefit of utilising widely used and proven technology although the number of spars worldwide are again relatively few, spar buoys are restricted to sites with water depths of greater than approximately 125-150m.

SemiSub class vessels can be utilized in shallow waters, and are arguably lower risk than TLP class vessels; the principal challenge will be to develop a light weight and hence cost effective structure and a number of concepts are currently under development, with prototype demonstration units planned in the medium term, hence in the medium the SemiSub technology could arguably be the more attractive concept.

The TLP has the benefit of providing highly stiff restraint to pitch and roll motion of the platform with heel angles for a TLP anticipated to be of the order of 10 times lower than for a spar or semi-sub. This is achieved with a structure which is more compact than a spar and simpler than a semi-sub. The challenges lie in trying to make the mooring system economic; and design the system so that a simple installation procedure can be executed with assembly taking place in the harbour.

2.1 German Market Overview

The German sectors of the North and Baltic Seas are relatively shallow with most potential offshore wind farm sites shallower than 50m. This depth excludes Spar-class concepts and mooring design for both TLP and catenary moored semi-sub structures is more challenging at these depths than in deeper waters, for example 50 to 100m.

2.2 TLP Support Structure

As argued above, TLP's are arguably the most suitable floating concept for German waters in the longer term.

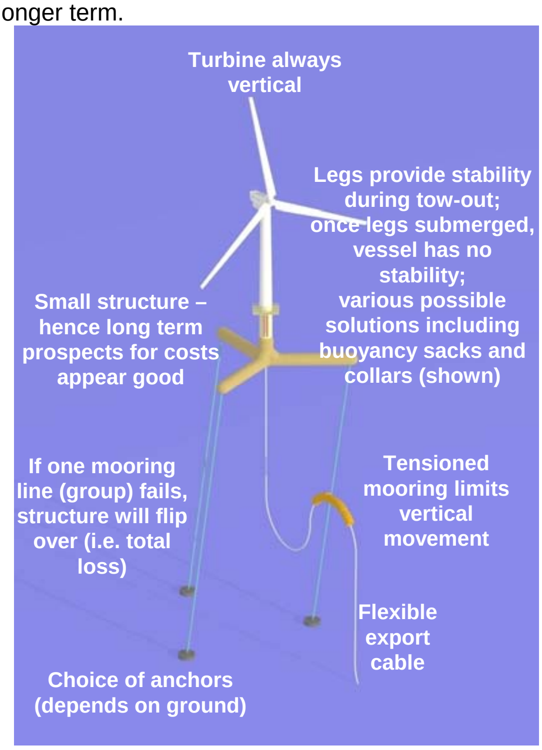

Fig. 2 TLP - Overview of the Technical Features

Features of the TLP

- Stability achieved from mooring
- low motion response, in particular in the roll, pitch and heave degrees of freedom
- small seabed footprint

The challenges in developing a successful design are significant, in particular:

- high cost and uncertainty in this cost of the mooring lines,
- installing the structure safely, reliably and cost-effectively;
- developing anchoring for ground conditions at the site; numerous technical solutions have been proposed including gravity anchors (a large concrete block), piled anchors and suction anchors, however none are particularly easy to design or cheap to handle and involve a degree of technical innovation and hence risk;
- potentially prone to yaw motion,
- sensitive to water level (tidal) variations
- limited experience with the detail design, including fatigue loading at joints.

3. Design

Preliminary design assessments of the TLP was made using first principals analyses. Turbine properties were based on the NREL 5MW model [5], Tab. 1. The dimensions of the platform neck and arms as well as the tendon diameter were chosen to minimise the overall cost of the structure while maintaining constraints on structural dimensions, heel angle, natural frequencies and necessary strength.

Turbine Rated Power	5MW
Rotor-Nacelle Mass ^{1}	350 tonnes
Tower Mass	288.5 tonnes
Height of Nacelle ^{2}	85 m
Rated Thrust	728 kN
Extreme Thrust ^{3}	1,500 kN

1. total tower top
2. above MWL
3. Extreme load condition

Tab. 1 Wind Turbine Design Characteristics

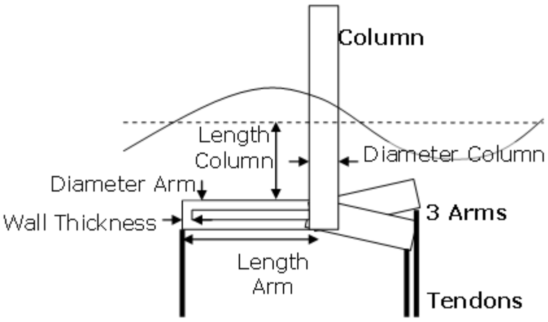

Fig. 3 TLP - TLP Design Overview

Turbine Rated Power	5MW
Arm Length ^{1}	32.5m
Arm Diameter ^{1}	4.5m
Column Diameter ^{2}	5m
Column Length ^{2}	20m
Steel Wall Thickness (average)	50 mm
TLP-WTG Total Mass ^{3}	1,338 t
TLP Submerged Structure Mass ^{3}	700 t
Tendon Mass ^{4}	21 t
Tendon diameter	0.167m

1 optimised
2 assumed
3 excluding tendons
4 each

Tab. 2 Indicative TLP Concept

The tension leg platform is constrained tightly in the vertical direction to within ±0.25m by the tension in the tendons. However it is relatively flexible in surge and sway displacements. The operational range of surge is presented in Figure 1. In contrast, the pitch and roll motion of the structure is held to within ±1˚.The TLP is more flexible in yaw and this can vary by up to ±5˚ in normal, turbulent wind and wave conditions while the turbine is operational.

3.1 Global Analysis

The TLP concept was modelled in Bladed [1] by using an existing model of the NREL 5MW rotor-nacelle-assembly (RNA) and replacing the onshore tower below the waterline by the tension leg structure described above. The floating structure is implemented by considering a free joint at the intersection of the three arms. The system is then constrained by applying mooring line forces according to a wire with resistance only in tension proportional to it's extension consistent with Tab. 3. Bladed then takes account of both the rigid body motion associated with displacement of the mooring, as well as the modal deflections of the steel support structure.

Fig. 4: TLP Model in BLADED

A fully coupled analysis is critical to a developing a viable and plausible design, the importance raised by the soft structural response and the design process needs to include consideration of:

- Aeroelastic-hydrodynamic coupling
- Model Coupling (i.e. fore-aft with side-side)
- Turbine controller, reaction to soft low frequency motion

Other issues to be considered:

- Influence of slowly varying (second order) wave drift forces
- Whether the application of the Morison equation is appropriate, if structure is large
- Impact of all of the full range of design load cases, it being difficult to identify in advance which are likely to be most onerous, i.e.:
- turbine faults (Blade pitch failure for one blade)
- Blade flapwise – TLP torsion coupling

3.2 Natural Frequencies

Natural frequencies of motion neglecting the turbine flexibility were calculated using the MathCad model of the TLP. These were compared with results from Bladed in two ways i) without turbine flexibility to validate the model and ii) with turbine flexibility to determine its importance. For the fully-coupled results, two frequencies have been shown for the roll and pitch modes. The roll and pitch motion couples with the tower flexibility to give a low frequency tower motion-dominated mode as well as a mooring dominated mode which has a slightly higher frequency than the rigid roll/pitch mode. The low frequency surge, sway and yaw modes are relatively unaffected by the flexibility of the TLP.

It is apparent that the tendons required to react to large buoyancy forces are relatively stiff in tension, hence natural frequencies of the TLP structure are affected by the structural design and a first principal rigid-body analysis is insufficient, Tab. 3.

Mode	Preliminary Model	Bladed (no turbine flexibility)	Bladed (fully-coupled structure)
Surge	25.6	25.6	25.6
Sway	25.6	25.6	25.6
Heave	0.60	0.60	1.02
Roll	1.04	1.04	4.20 / 0.99
Pitch	1.04	1.04	4.26 / 0.99
Yaw	-	13.7	13.7

Tab. 3 TLP natural periods [s]

3.3 Motion Response

Bladed [1] was used to carry out the operational load cases according to the IEC61400-3 standard [4].

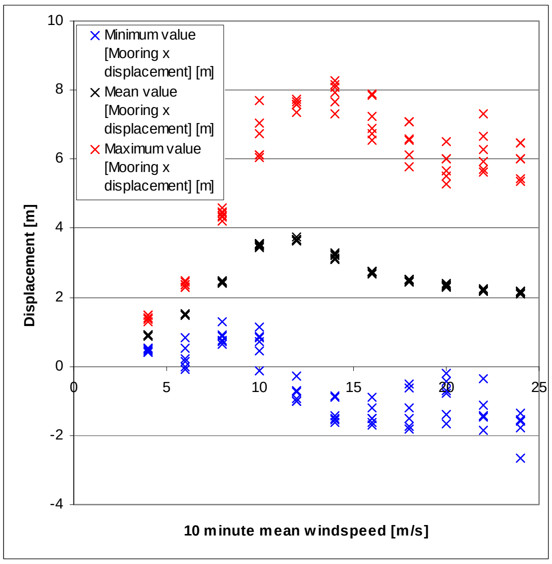

Fig. 5: TLP Motion Response

3.4 Extreme Events

A selection of non-operational extreme events were modelled in Bladed [1]. Bladed allows the effect of wind and waves to be modelled concurrently with the interaction fully coupled with motion of the blades, tower and floating platform.

One of the major concerns for floating turbines is that the design fault case of having one blade with failed pitch could be disastrous for systems which are as flexible in yaw as floating wind turbines. The failure mode is the azimuth angle of the failed blade coupling with the yaw motion to induce motion. However, for the TLP, the yaw stiffness seems large enough to avoid instability.

The other case which could be dimensioning for the structure is load case 6.1 of the IEC61400-3 standard [4] or GL Guidelines [3] which can be implemented in Bladed by using a background stochastic extreme sea state along with an embedded stream function wave with the extreme wave height. The overturning moments generated by this wave are not allowed to make any of the three tendons go slack (see Section 3.5). This constraint is a challenge for design as increasing the TLP size increases the static tension. However it also increases the applied wave loading as well as making the structure more expensive.

3.5 Mooring

There are fundamental differences in the mooring system design requirements for WECs compared to those of conventional offshore moorings. These are driven in particular by the dynamic loading from the wind turbines and the need for a low cost implementation of the TLP concept.

TLP moorings are a design critical component. Failure of any group of lines will cause the structure to capsize and hence result in the total loss of the turbine as survival moorings are unlikely to be cost effective for offshore wind. This is in contrast to the consequences of a failure of spar or semi-sub moorings, which does not necessarily result is catastrophic damage. In addition, mooring lines must avoid loss of tension, i.e. becoming slack, as the snap loads when tension is reengaged will risk failure. For this to be applicable during 50-year wave climate and turbine fault conditions, high initial buoyancy is required.

The mooring system consists of two principal components:

- Mooring lines;
- Anchoring.

3.6 Mooring Lines

Mooring lines can be fabricated from a choice of materials:

- Chains
  - Not susceptible to corrosion;
  - Poor elastic properties, thus not able to absorb dynamic load.
- Wire rope:
  - Flexible material; easily coiled on to the drum of a winch; easily changed;
  - However susceptible to abrasion, i.e. sand or corrosion;
  - tends to become stiffer over time, this modifying natural frequencies as well as dynamic loads
- Synthetic fibre lines, i.e. nylon, polypropylene, polyester, Kevlar
  - light weight, flexibility and low modulus;
  - very susceptible to abrasion and damage from fish (encasing the lines may eliminate this problem);
  - subject to reduction in strength when wet and fatigue
  - highly elastic, susceptible to resonant vibrations, in particular nylon;
  - Polyester and Kevlar ropes generally preferable
  - Carbon fibre lines are very stiff but costly.
- Pipes.
  - can be utilised instead of ropes in very deep waters;
  - present better fatigue behaviour than steel wires or synthetic cables.
  - Combinations are also possible, i.e. Kevlar together with chains or steel wire.

Other issues to be considered include:

- Vortex induced vibrations of cables, due to currents and waves
- Non-linear dynamic loading and response of the cables;
- Load transfer with the TLP structure at the connection
- Avoidance of any physical contact of the lines, with each other or with vessels
- Designing the moorings to a 20 year operational life; if this is not possible, developing a safe method to exchange mooring lines
- Ability to monitor and adjust cable tension during the lifetime to compensate for creep (extension of the lines)
- Mooring and anchor forces can be determined according to Rules for Offshore Installations [2]

3.7 Anchoring

Similarly there are a number of technologies that can be utilised for anchoring the TLP, the suitability of each depending on ground conditions:

- Vertically loaded anchors (VLA)
  - Design of connection points critical
  - Chains are used at the ends (abrasion) and to reduce tension on the anchor)
- Piled anchors; challenges include:
  - Achieving penetration depth
  - installation in high depth.
- Suction pile anchors
  - can be used in clays and sand soil
- Gravity base anchors
  - Similar issues with soft round conditions as GBFs (gravity base foundations) used for offshore wind turbines

4. Fabrication, Installation and Operation

4.1 Fabrication

The fabrication of the TLP floater can be performed using existing facilities e.g. of the shipyards placed in Northern Europe. It is proposed to use classic steel fabrication methods for the floating body. The tendons used will be of bespoke offshore grade as used in the oil and gas industry, while the anchors will be of conventional design, appropriate to the loads and the soil characteristics. Special care has to be taken for the fabrication of the detail where the mooring lines are attached to the structure and anchor, due to the high fatigue loading at this location.

4.2 Installation

Installation sequence can be described as follows:

- Tow out of TLP
- Installation of mooring
- attachment of mooring
- submergence of TLP

Installation is arguably the key challenge for TLP structures in general and for wind turbines especially. Optimally the floating structure including wind turbine will be assembled at the yard and towed as one piece to the wind farm site, thus requiring that sufficient water depth is available within the whole transport and installation procedure. The stability requirements stipulated in the SPS- [9] and SOLAS Codes [10] shall be complied with during the tow-out, depending on configuration. Extra water ballast and in most cases additional buoyancy and stability appendages to the structure will be required.

This float-out supporting structure could consists of additional floating bodies connected to the main TLP body via steel arms. The size of these structures and hence the loads imparted to the TLP will depend on the available water depth, with higher additional buoyancy needed for shallower water depths. The design can be optimized for the governing metocean conditions along the tow-out route and at the installation site.

The anchors and the mooring lines can be installed at the site using conventional offshore engineering procedures. One alternative would be simple gravity anchors, preferably without major ground preparation. The mooring lines would be preattached to the anchors and held in place by buoys. The critical phase is the attachment of the lines to the TLP, presumably utilising ROV's or other specialist equipment. After attachment, the tendons would be tensioned over several stages by ejecting water ballast from the TLP. A critical point will be the disconnection of the buoyancy supporting structures.

Alternatively the complete assembly could be transported to site on barges and launched. Such procedures are well proven within the offshore engineering industry but will need high capacity.

4.3 Operational Issues

In the event of water ingress in to the TLP structure being detected, there is likely to be a need to investigate the cause of leakage immediately. Confirmed through thickness cracks in these members will normally require immediate repair.

5. Certification

The certification of wind turbines on TLP platforms can be in principal be performed using existing procedures however specialized rules and Guidelines are not available as yet. In German waters the BSH standards [11] would be applicable, which stipulate that all floating equipment shall be class approved. It is assumed that the same requirement would apply for the TLP once in permanent position.

In common with all floating structures, TLPs have the advantage over fixed structures that they can be designed for generic conditions and thus type certified. The design of the anchors and the mooring lines will need to be site specific as for every fixed offshore wind turbine support structure. This feature may reduce the time and effort required to gain permissions.

The wind turbine, the tower and in all likelihood the floater as well can be designed on the basis of the existing GL Guidelines [2] although some adjustment and additional load cases are needed to fully assess the motion response of the floating structure. In this case the GL Rules for offshore installations are applied [3]. In the longer term, the Guidelines for floating offshore wind turbines planned by GL within the IEC framework would be applicable, with a timeline of 2013 anticipated.

New requirements will need to be drafted for transport and installation procedures since these may result in design driving conditions for the structure. Finally stability criteria have to be fulfilled. Since the offshore wind turbine is an offshore structure with low environmental impact it is proposed to use the same requirements as for barges according to IS-Code [8].

A major deviation from the requirements in Germany will be the structural design of the support structure consisting of the floater and the mooring. As German standards to be applied do not exist e.g. for the assessment of the tendons and anchors a special agreement with BSH will be needed. The design of the mooring, including anchors, lines and attachment points can be performed on the basis of the GL Rules for offshore installations [3].

6. Further Discussions and Conclusions

The structural buoyancy generates the tension necessary for this type of structure and it will be essential to control this buoyancy over the life time of the structure. The risk of leaks must be minimised and robust detection systems included in the design It will also be necessary to be able to compensate for long term changes of mass over the life time of the structure.

Experience has shown that flooded member detection in watertight tubular bracing members in can be a valuable aid to the prevention of failure of these critical structural members and stability of the whole system.. Attention needs to be given to the following issues during the design process:

- Bracing members normally submerged at operating draught are watertight and kept dry whenever possible, at least in way of critical connections (e.g. brace/column, brace/brace) and other areas containing significant stress concentrations or lower fatigue life details.
- Facilities are provided to enable internal inspection of these void spaces whilst the unit is afloat at operating draught, with access from within the unit wherever possible.
- Facilities are provided and operating procedures implemented to ensure prompt detection of any significant ingress of water which might indicate a through thickness crack in the wall of the tubular.
- The stability requirements as stipulated for non-manned structures shall apply. Wind turbines can be treated as a pontoon. Relevant is IMO intact stability code IS-Code 2008. For the transport ship that brings personal to the site, the SPS-Code is to be applied, if no national regulations are mandatory. The IS-and the SPS-codes refer to the SOLAS document (definitions, etc…) [8]/[9]/[10].

The main challenges to be overcome are:

- modelling capability, to design and optimise the complete system including the controller. The paper presents results from a new version of the GH Bladed code, based on multibody dynamics, which accurately models the large deflections associated with floating wind turbines;
- engineering solutions to performance issues, such as those potentially due to the softness of the foundations;
- reliable installation and repair procedures,
- maintaining stability throughout the process, including during tow-out, preparation work and while the moorings are being tensioned and the structure is being submerged,
- developing a low-cost tensioned-mooring system; to date applications have been for large high-performance systems;
- developing a concept able to resolve all these issues and result in the demonstration of a successful grid-connected prototype.

7. References

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