

TENSION LEG PLATFORM TURBINE: A UNIQUE INTEGRATION OF MATURE TECHNOLOGIES

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Concept rendering of a tension-leg platform supporting a 5-MW offshore wind turbine in 55 m water depth (fish-eye view) – The Glosten Associates

ABSTRACT

The TLTP (Tension-Leg Turbine Platform) is a floating, permanently moored structure designed to support a utility-scale offshore wind turbine in water depths of 40 meters and greater. This paper discusses the design tools and unique design process used for this novel structure. Reasons for selecting a tension-leg platform (TLP) are discussed. Motivations to apply TLP technology to relatively shallow water depths are explained. The requirements for supporting a wind turbine, which are fundamentally different than the requirements for supporting a typical oil and gas payload, are discussed.

KEYWORDS

Wind turbine; floating; tension leg platform; chain mooring; design spiral.

INTRODUCTION

The Tension Leg Turbine Platform (TLTP) is the integration of many mature technologies including tension-leg platforms (TLP), offshore utility-scale wind

turbines, permanent chain mooring systems and high-vertical-load anchors. Together, they form a unique solution to the intermediate and deep water¹ challenges inherent in the next generation of offshore wind farms. This paper provides a general overview of our TLTP design concept, a description of the environmental and design criteria, and a discussion of the reasons for choosing a three-armed tension leg platform.

The TLTP is fundamentally different from offshore oil and gas tension leg platforms in its payload, loading, target water depth, and tendon materials. Siting the TLTP in water depths of 40 to 100 meters requires the mitigation of design challenges not fully realized by either traditional ship or tension-leg platform design processes. Consequently, our unique TLTP design process, along with a discussion of the tools used for design and analysis, is presented as well.

DESIGN CONCEPT OVERVIEW

The TLTP design concept is based on requirements for a generic 5-MW offshore wind turbine to be sited in environmental conditions found in the United Kingdom Round 3 Development Area. As with most wind turbine foundations and offshore platforms, this design is highly site-specific. Offshore wind turbine characteristics, environmental criteria, and details of the supporting tension leg turbine platform are discussed below.

Wind Turbine Characteristics

The offshore 5-MW wind turbine used for the present design is a hybrid between the REPower 5-MW and Multibrid 5-MW turbines. It is similar to the 5-MW NREL Reference Wind Turbine described in Jonkman, *et al.* [2], but with a heavier nacelle/rotor and a shorter, and thus lighter, tower. The interface between wind turbine tower and hull is 18.0 meters above the mean sea level (MSL). The hub height is 95.5 m above MSL. As shown in Figure 1, a 5-MW TLTP positioned next to the Seattle Space Needle would be comparable in height.

Principal characteristics of the wind turbine are provided in Table 1.

For the coupled dynamic modeling discussed later in this paper, the 5-MW NREL Reference Wind Turbine, as described in Jonkman, *et al.* [2], is used for definition of controls and operating parameters.

Environmental Criteria

The offshore wind industry has, in general, chosen a 50-year return period to define the extreme environmental conditions. This differs significantly

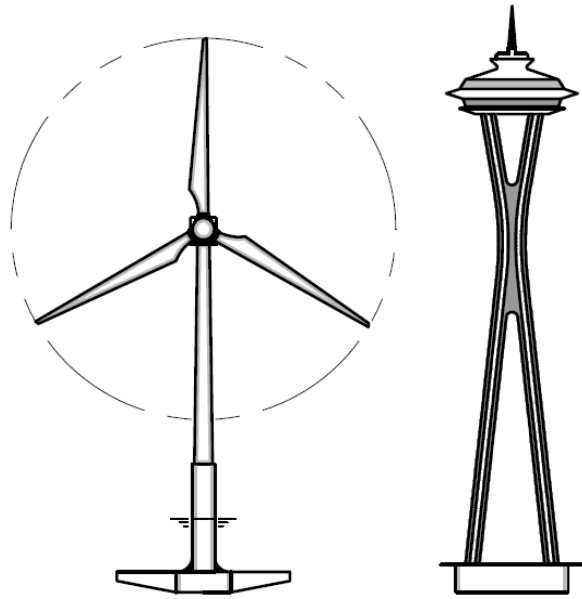


Figure 1: 5-MW TLTP and Seattle Space Needle

Table 1: 5-MW offshore wind turbine characteristics

Turbine Characteristics	
Tower Weight	300 tonnes
Nacelle and Rotor Weight	410 tonnes
Hub Height above Tower Interface	77.5 m
Rotor Diameter	126.0 m
Cut-Out Wind Speed	25 m/s

from the offshore oil and gas industry, which uses a 100-year return period. As onshore and offshore wind turbines are unmanned and typically have a shorter design life, the ultimate limit state return period can be lowered.

The specific location of interest in the UK Round 3 Development Area has a 50-year, 3-hour significant wave height of 8.5 meters, with an associated peak period of 12.5 seconds. Wave loads are modeled using a JONSWAP sea spectrum with a peak enhancement factor of 3.3. The 1-year statistics are listed in Table 2 for the site of interest.

For operational (wind turbine operating) load cases, significant wave height and peak periods are developed as a function of the wind speed taken at 10 m above the sea surface. For example, the cut out hub wind speed of 25 m/s has a significant wave height of 4.5 meters, and a peak period of 9.0 seconds. The correlation is based on ten years of hindcast data.

The 50-year, 3-second gust, at 100 meters above the sea surface, is 55 m/s. Using logarithmic scaling, this correlates to a 1-hour average wind speed of 33 m/s, at a height of 10 meters above the sea surface.

The turbulence intensity for the maximum wind condition is 12%, which gradually increases to 20.7% as the wind speed approaches zero. The maximum wind speed standard deviation is, therefore, 5.6 m/s.

The Kaimal spectrum, as recommended by DNV OS-J101², is used to develop the spectral density.

For wind spatial coherence, the Davenport spectrum is used as described in DNV RP-C205. This spatial variation is used to calculate the yaw moment by modeling each blade with varying instantaneous wind velocities.

Current speed is taken as 4% of wind speed at the sea surface, which is typical analytical practice for a Gulf of Mexico hurricane. A vertical profile of the current velocity is implemented.

For ultimate limit state analysis (50-year conditions), wind, waves, and current are assumed to be collinear. Operational states consider both aligned and misaligned wind, waves, and current.

Water depths for UK Round 3 sites range from 35 to 60 meters. The chosen water depth for this TLTP design is 55 meters. Water depths as shallow as 40 meters are possible with the TLTP, but a more benign wave environment and/or a smaller wind turbine is needed in comparison to the design presented here.

Table 2: Environmental summary

Environmental Summary	
H_s / T_p (50 year, 3 hr storm)	8.5 m / 12.5 sec
H_s / T_p (1 year, 3 hr storm)	6.7 m / 11.1 sec
U_{100m} (50 year, 3 sec. gust)	55.0 m/s
U_{100m} (50 year, 10 min. avg)	47.0 m/s
Current (surface)	1.3 m/s
Tidal Variation	4.0 m
Water Depth	55.0 m

TLTP Overview

The TLTP hull is comprised of several main components, which are shown in Figure 2 and described as follows:

1. Upper Hull – This central column is essentially an extension of the turbine tower. Like the tower, it is designed to support the wind turbine, but has additional hydrostatic and dynamic loading. The upper hull, at 7.2 meters in diameter, is the only portion of the TLTP that pierces the waterplane,

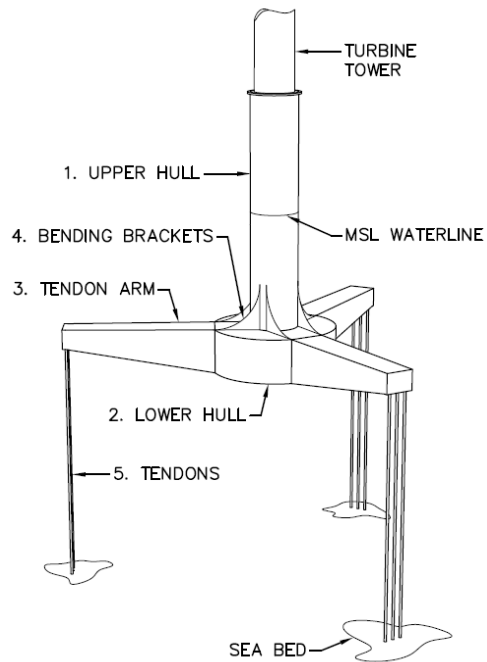


Figure 2: TLTP primary geometry

even during extreme wave events. The mean sea level (MSL) waterline is shown in Figure 2 for reference. The upper hull is made of rolled steel with internal ring frames. Watertight bulkheads are used to subdivide the upper hull to limit flooding in damage conditions.

2. Lower Hull – The primary purpose of this component is to provide sufficient pretension to the TLTP moorings, and to achieve cancellation of the hydrodynamic forces between the various buoyant components. The lower hull is not in the direct load path, but still sees considerable hydrostatic and dynamic pressures. Like the upper hull, it is made of cylindrical rolled steel with internal ring frames. The lower hull is subdivided with vertical watertight bulkheads that are designed as tank boundaries.
3. Tendon Arms – Three tendon arms connect the upper hull to the tendons. The tendon arms experience significant bending loads, hydrostatic and hydrodynamic pressures. They are made of flat plate with internal stiffeners running the length of the arms (i.e., longitudinal). Transverse web frames and cross ties, similar to those in ship tank structures, break up the span of the stiffeners. The tendon arms are buoyant, and subdivided with vertical watertight bulkheads.
4. Bending Brackets – Large external brackets are used to reduce stresses in the upper hull to tendon

arm connection.

5. Tendons – Although unusual for a tension leg platform, the TLTP has tendons comprised of offshore studless chain. Three chains make up each tendon group, for a total of nine tendons per platform³. Upper terminations are made with adjustable chain stoppers. Lower terminations to the single anchor chain are made with a custom “tri-plate”.
6. Anchors (not shown) – Either driven plate or drilled and grouted anchors can be used to secure the tendon groups to the soil. This choice is largely dependent on water depth and soil conditions.

A preliminary steel weight design margin for small vessels is typically 8%; however, due to the lack of industry experience with wind turbines mounted on tension-leg platforms, a higher 15% margin, consistent with concept design, is used.

The TLTP is designed to withstand damaged chain tendons, in accordance with API-RP-2SK. The TLTP is also designed to withstand single compartment flooding, and has subdivision to permit survival in a reduced extreme environment.

A small amount of fixed water ballast can be incorporated into the lower hull. This allows the pretension to be adjusted and increases the flexibility of the design. As the platform will be unmanned and has no ballast system, a tank level monitoring system is required.

The TLTP presented herein is designed to a combination of guidelines and rules that best suit a first principles “working stress design” approach and a quick design cycle. These include American Petroleum Institute (API) and American Bureau of Shipping (ABS) publications: API RP-2A, API RP-2T, API RP-2SK, ABS Floating Production Installation, ABS MODU and ABS Steel Vessel rules.

Det Norske Veritas (DNV) publishes a set of rules specific to the support structures of offshore wind turbines, but these rules are more onerous (load resistance factor design method) to apply in concept and preliminary design. It is envisioned that DNV or Germanischer Lloyd (GL) rules will be used as the design progresses towards a prototype for a site-specific location. Saigal *et al.* [3] discusses the various differences of the offshore wind turbine design guidelines for United States waters, and Roddier *et al.* [4] discusses standards applicable to floating wind turbines.

DESIGN DRIVERS

At its inception, the design concept required a floating turbine foundation that facilitates complete quayside assembly, thereby precluding costly at-sea turbine assembly and enabling the economical development of wind power in vast stretches of deep offshore areas previously thought to be “undevelopable”.

Numerous floating wind turbine concepts have been proposed. Spar installation vessel concepts along the lines of the Research Vessel *Flip* [5] have been proposed, but to date have been dismissed by major turbine manufacturers. *HyWind* [6] is a full-scale demonstration of spar technology applied to offshore wind power. *WindFloat* [4], a semi-submersible platform, is presently under development. *Blue H* [7] is developing a tension-leg platform, albeit with a proprietary turbine.

A tension-leg platform, in addition to facilitating complete quayside assembly, has the potential to satisfy intermediate water depths and provides a platform suitable for currently available offshore wind turbines, without requiring major modification. The tension-leg concept is vertically constrained, and thus its heave, roll, and pitch motion are minimal. This fits particularly well with current offshore wind turbines, which lose efficiency as the blades move away from vertical. Minimizing roll and pitch also reduces gyroscopic forces that develop with a pitching, spinning body, such as yaw induced pitch.

Earlier research indicated high potential for tension-leg platforms, but warned that complexity and costs typically associated with their mooring systems were the primary design challenge; i.e., Musial *et al.* [8].

To simplify and reduce the cost of the typical TLP mooring system, chain tendons are used along with driven-plate anchors. For relatively shallow water applications, the simple installation and inexpensive cost of chain far outweighs the small weight penalty. Driven plate anchors are fabricated from widely available flat plate and wide flange beams, and can be designed to have very high holding capacities. They must be hammered and jettied into position, and thus their application water depth is limited. Alternatively, drilled and grouted or suction pile anchors can be installed. Anchor choice is largely a function of water depth, site specific soil conditions and cost.

Each TLTP will have a fully erected and commissioned wind turbine installed while floating at its staging site. The TLTP will be towed to the site and installed, which eliminates the need for costly jack-up installation crane vessels. These vessels will become

increasingly expensive at greater water depths.

Because of the large overturning moment of a wind turbine, significant horizontal separation between the tendons is required. This minimizes pitch and roll, while keeping the tendon tensions reasonably low. For this reason, tendon arms are proportionately longer than what is seen on offshore oil and gas TLPs.

Three tendon arms spaced 120 degrees apart provide the minimum number of stabilizing legs to resist overturning moments from any direction. The three-arm system has the added benefit of symmetry around two axes, as the moment of one arm is equal to the moment contribution of the other two arms [$1 = 2 \times \cos(60^\circ)$].

Unlike most offshore tension leg platforms, which are “one-off” structures⁴, 30 to 100 or more TLTPs will be produced for one wind farm. This scale requires the TLTP to be designed specifically for high-production assembly, with an installation methodology that strives for speed and minimal cost. Steel weight and structural complexity are the primary components to minimize, as they will be the most prominent drivers of the foundation cost.

The overall size of the TLTP is substantial, as shown in Figure 1; however, it is small when compared to even the smallest offshore oil and gas tension leg platform. The TLTP has less than half the displacement, hull weight, and operating depth of the smallest (Morpeth and Allegheny) and the shallowest (Hutton) oil and gas TLPs [9]. This relatively small scale allows for fabrication in smaller and even multiple facilities to meet the installation demand.

To make the TLTP as cost competitive as possible, the largest wind turbine currently available is used in the design to take advantage of economies of scale. When 7- and 10-MW wind turbines are available, the TLTP will likely be modified.

The near-term challenges, and therefore opportunities, in the offshore wind sector center around intermediate depths. For example, sites in the UK Round 3 Development Area primarily have water depths of 35 to 60 meters. There is a gap in cost-effective foundation technology at these water depths. Rather than determining how *deep* a bottom-fixed foundation could go, we set out to determine how *shallow* a floating foundation could go.

The TLTP concept has been shown to be cost competitive when compared with bottom-fixed turbine foundations in water depths of around 50 meters and greater. To become a central solution to the intermediate water depths, the TLTP must operate in a *shallow a water depth* as possible.

DESIGN AND ANALYSIS PROCESS

This section describes the unique, analysis-intensive design process developed for the TLTP concept. Design challenges are identified, a unique design spiral is presented, and design tools are discussed.

Design Challenges

The three most notable design challenges encountered with the TLTP are: 1) determination of the hydrodynamic loads, aero-servo-elastic loads, and their coupling effects; 2) development of a platform mooring system with sufficient pre-tension to balance large overturning moments and prevent slack lines, while remaining sufficiently soft, or compliant, in surge, sway, and yaw; and 3) development of a design process that facilitates solving challenges 1 and 2 in an efficient manner.

The first challenge is inherent with any floating turbine system. The second challenge is unique to the TLTP concept in shallow water. The natural frequencies in surge, sway, and yaw increase (i.e., system becomes stiffer) with increasing pre-tension and with decreasing water depth. For shallow water, a low pre-tension is needed to avoid surge, sway, and yaw resonance with wave excitation forces. However, a high pre-tension is needed to balance the large overturning moments, regardless of water depth.

To address this shallow water challenge, the primary forcing functions on the TLTP can first be decoupled and analyzed separately. Hydrodynamic loading primarily occurs between 0.06 Hz and 0.2 Hz, or 5 seconds to 17 seconds. The TLTP should have natural periods greater than 17 seconds, at a minimum, in the horizontal-plane motions (surge, sway, and yaw).

Turbine-induced loading occurs at the rotor rotational frequency and its third harmonic, where there is blade-tower interaction similar to a ship’s propeller blades rotating past a strut. These frequencies are known as “1P and 3P, respectively. The TLTP natural frequencies should be higher than the 1P and 3P frequencies in the vertical-plane modes (heave, roll, and pitch). Figure 3 illustrates the primary forcing frequencies, with the TLTP natural periods superimposed. Interestingly, bottom-fixed towers are generally designed with natural frequencies that “sneak in” between the 1P and 3P frequency ranges, or from 0.22 Hz to 0.30 Hz.

The first design requirement is development of a system that avoids resonance with environmental and turbine-induced excitation. Note that in Figure 3, the yaw natural period is coincident with wave energy. Ensuing analysis confirmed that the yaw mode is

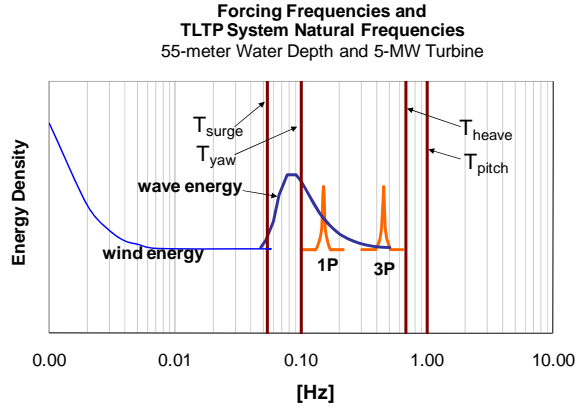


Figure 3: Forcing frequencies and TLTP system natural frequencies.

sufficiently damped by viscous hydrodynamic forces on the arms, and therefore the yaw natural period is not problematic.

The discussion now shifts to the challenges inherent in coupling hydrodynamics, aerodynamics, and control systems. As stated in Nielsen *et al.* [6], the turbine can be an effective damping mechanism against hydrodynamic responses at lower wind speeds, but can lead to “negative damping” when the turbine is in the power-regulated mode (higher wind speeds).

Figure 4 illustrates the relationship between wind speed, rotor thrust, and power. At higher wind speeds, the turbine control system maintains constant RPM to regulate power and avoid excessive tip speeds. When a turbine blade experiences an increase in apparent wind speed, the control system feathers the blade (reduces blade pitch).

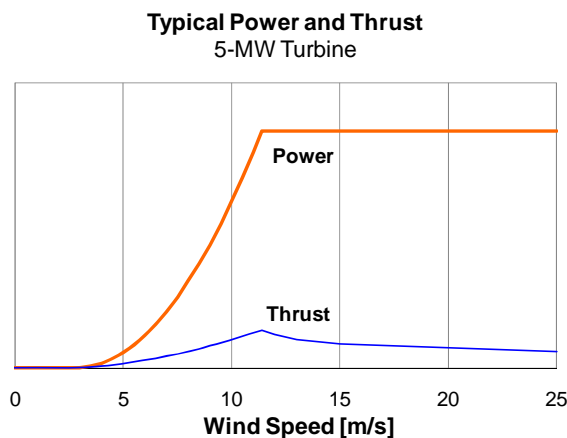


Figure 4: Wind Turbine Thrust and Power, as a function of Wind Speed

Nielsen *et al.* [6] addressed the issue of coupling between surge/pitch motion and blade pitch control by

implementing an additional control algorithm aimed at avoiding negative surge damping. This algorithm uses tower velocity as an input.

In a sense, the TLTP faces the same challenge as HyWind [6], though in this case the root cause is pure surge motion as opposed to pitch-induced surge. When the TLTP surges upwind, the apparent wind speed increases slightly and the blades are feathered, which reduces the aerodynamic damping just as it is needed most. Fortunately, the TLTP demonstrates significant hydrodynamic damping in surge. A similar controls-based solution to the surge-blade coupling can be envisioned for this TLTP design as is implemented in HyWind.

Yaw resonance was found to be problematic for a circular barge-type floating wind turbine foundation, especially in the parked condition Jonkman [10]. The TLTP concept demonstrates sufficient hydrodynamic yaw damping to avoid yaw response problems.

DNV OS-J101 gives a comprehensive set of load cases to be analyzed. Jonkman [10] makes a compelling case for analyzing a sub-set of cases including normal operating conditions (“1.X cases”), parked/idling conditions (“2.X”), and extreme sea state conditions (“6.X”). The 6.X load cases are used to optimize the hull form and mooring system based on strength of materials and global platform responses. During optimization, a close eye is kept on the 6-DOF system natural frequencies. Solutions that resonate with normal operating and parked conditions are rejected. The complete set of load cases in DNV OS-J101 will be analyzed in contract design.

Design Process

The TLTP design process is highly simulation-based due to the complex coupling of loads from aerodynamics, control systems, hydrodynamics, and tendons.

A ship design spiral approach simply does not work for the TLTP as it assumes the solution space is smooth. Optimization routines are necessary to find feasible solutions at the beginning of the design cycle, because the solution space is not smooth. Without computer based exploration of the solution space, it is entirely possible (and likely in some cases) that a seemingly good starting point takes the designers along a negative design spiral (spinning outward to an infeasible solution).

A traditional ship design spiral is shown in Figure 5. The first and outermost spiral can be thought of as concept design. This spiral may be repeated many times, until a viable concept that meets all of the design requirements is produced.

Note that in Figure 5 there are no high level

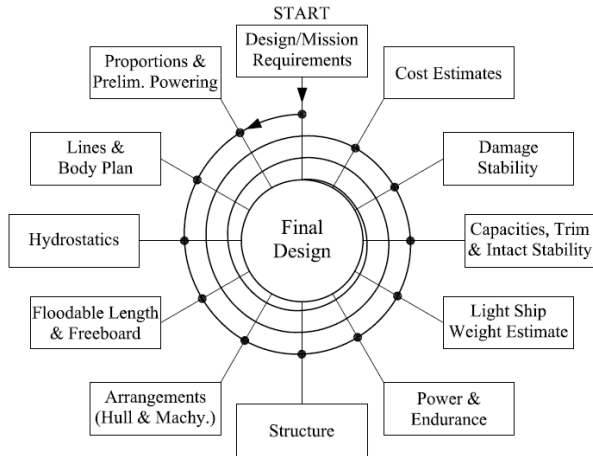


Figure 5: Traditional ship design spiral

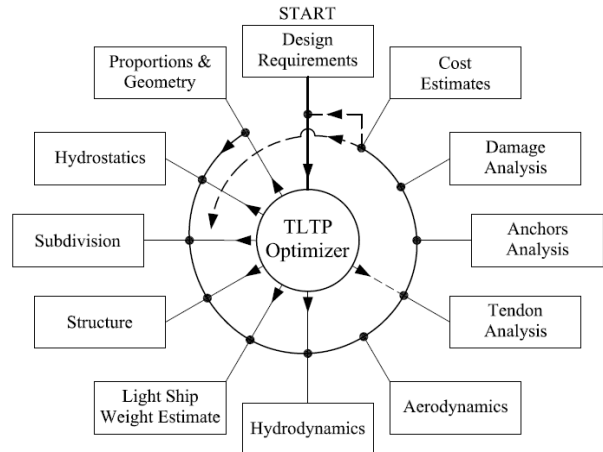


Figure 6: TLTP design spiral

computations required in the concept design phase. As the design progresses from simple to complex (spiraling inward), so do the calculations. Often in the preliminary, and certainly in the contract design phases (inner spirals), hydrodynamic calculations are performed for motions, dynamic positioning, and other investigations such as CFD⁵ analysis. The design, however, is typically well detailed at this stage and changes should be relatively minor.

While the authors are not designers of oil and gas TLPs, they observe that the concept design of an oil and gas TLP hull is based significantly on the minimization of hydrodynamic heave forces.

Since the TLTP is designed for relatively shallow water, the relationship between total pre-tension and tendon length can establish a system surge natural period that resonates with wave energy. At the scale of the TLTP, where both inertial and viscous forces govern hydrodynamic loading, there is not an intuitive buoyancy distribution that simultaneously minimizes wave excitation and avoids system resonance with the various forcing functions described above, especially at the target water depths. In other words, it is not sufficient to simply minimize the amplitude of hydrodynamic heave forces at the concept design level for the TLTP.

A unique design spiral (and design tools) was developed for the TLTP concept, which is illustrated in Figure 6. This design spiral is dramatically different from a ship design spiral and more closely resembles the Simulation-Based Design discussed recently in Campana, *et al.* [11]. The TLTP design spiral calls for a significant analysis effort in the early stages of design. Indeed, the determination of a feasible *starting point* requires simultaneous optimization of hydrodynamic loading, system stiffness, and weight.

Similar to the ship design spiral, the TLTP design

spiral starts with a clear definition of the design requirements. Moving inward, constraints and objectives are chosen and the optimization is started. The optimizer then radiates the design outward to the outer design elements, whence the design spiral is continued to the last design element: cost. A decision is made at this point to either revisit the design requirements and reenter the optimization, or to proceed with the design spiral. Ideally, solid lines (indicating direct calculations) emanating radially outward from the TLTP Optimizer would be implemented to each design element.

The *art* of design has, therefore, shifted slightly from intuition and experience to creative code writing. This code must contain the flexibility to allow an optimization routine to search, not only unexplored territory, but to perform local searches to achieve an optimal solution.

Design Tools

With the design process established, appropriate design tools must be identified. The present TLTP design was accomplished with a combination of commercial design tools, established research codes, and custom design tools developed specifically for the platform sizing and optimization tasks.

In addition to the typical design tools that naval architects and marine engineers use for ship design, such as 2D drafting, 3D modeling, spreadsheets, word processing, and finite element analysis tools, the following tools are specific to the TLTP design.

Hydrodynamic and Weight Optimization is completed using an in-house tool developed specifically for the TLTP. As with any optimization problem, the objective function and constraints must be well defined. Furthermore, the ability to evaluate the objective in a closed-form manner significantly

improves the computational efficiency of the optimization routine. To that end, a simplified model of the TLTP was developed that captures excitation and responses.

The structural weight calculation uses a “rules” based approach, along with first principle combined loads, structural natural frequencies, and simple fatigue, to produce structural scantlings. Intelligent decisions about subdivision are made and weight is calculated.

The optimization has two objectives: minimize structural steel weight and minimize extreme tendon loads.

Constraints on the optimization include: maintain sufficient tendon pre-tension (i.e., do not allow slack tendons), avoid system resonance with excitation forces, and maintain reasonable structural proportions.

With a well defined objective function, well defined constraints, and a closed-form evaluation of the objective function, an evolutionary solver was applied to the optimization problem. Since the evaluation of the objective function involves finite depth wave kinematics and structural step functions, the optimization problem is linear but not smooth.

With an optimized solution that satisfied the design requirements, the feasibility of the solution was verified using a more robust analytical tool.

HARP [12] is a fully coupled, 6-DOF, non-linear, time-domain software capable of modeling the TLTP and its mooring system. *HARP* was used to validate our simplified 3-DOF model and to verify the validity of the optimized solution. For all its strengths, *HARP* is limited to modeling wind loads on “passive” superstructures and rigid bodies. The complex aerodynamics, control systems, and structural dynamics of a wind turbine are not modeled in *HARP*.

FAST [13] is an aero-servo-elastic wind turbine analysis code that captures the lifting surface aerodynamics, control systems, and structural dynamics of a wind turbine. Jonkman [10] made a major breakthrough in developing a hydrodynamic and mooring module for *FAST*, known as *HydroDyn* [10]. *HydroDyn* captures hydrodynamic radiation and diffraction responses, as well as viscous effects on the submerged section of the turbine tower. Even so, *FAST* with *HydroDyn* requires further modification to model the TLTP, since horizontal-plane Morison members (needed to model the TLTP arms) cannot be implemented in the current version of *HydroDyn*.

CONCLUSIONS

The tension-leg turbine platform as presented in this paper is a feasible foundation for utility-scale

offshore wind turbines sited in water depths of 40 meters and greater. The concept can be modified to suit a wide range of turbine sizes, water depths, and metocean conditions.

The TLTP design spiral presented herein lays out a path for developing an optimal solution where the interaction of hydrodynamics, weight, and natural periods dominate the solution space, and where a traditional design spiral fails.

Although *HARP* and *FAST* both have many strong points, neither is the “one-stop” software solution to the design challenges presented here. The *Hydrodynamic and Weight Optimization* would ideally incorporate either *FAST* or *HARP* in the optimization loop to compute the hydrodynamics. A more accurate structural and weight calculation can be incorporated as the structural design is progressed.

Additional analytical modeling and physical modeling are needed to better understand the TLTP system responses, especially during the power production mode. Further development of the TLTP will benefit from the experience and lessons learned from the HyWind project [6], especially with respect to physical model testing and wind turbine control systems.

While initial design phases require optimization of environmental loads and steel weight, ensuing design phases should include optimization based on cost and power production, which are the real design drivers of wind farms.

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NOTES

1. Deep water for offshore wind turbines is greater than 50 m. See Pearce et al. [1] for a discussion of shallow water (0 to 30 meters) foundation technology.
2. Det Norske Veritas, Design of Offshore Wind Turbine Structures
3. Cost of end terminations may drive the number of tendons to be decreased.

4. TLPs Morpeth and Allegheny, as well as Kizomba A and Kizomba B, are the only TLPs that claim “sister” status.
5. Computational Fluid Dynamics

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