FINAL REPORT

Design Guideline for Stationkeeping Systems of Floating Offshore Wind Turbines

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Executive Summary

The main objectives of this project are to:

- Conduct a state-of-the-art review of the design concepts, methodologies and technologies that are relevant to stationkeeping systems and global performance analyses of floating offshore wind turbines (FOWTs)
- Explore technical challenges and critical design parameters of FOWT stationkeeping systems
- Propose a design guideline for FOWT stationkeeping systems and global performance analyses

This project starts with a state-of-the-art review of existing knowledge relevant to FOWT stationkeeping systems and global performance analyses. The subjects of interest include existing design concepts, design standards and guidelines, simulation tools, and global performance analysis methodologies and procedures.

Extensive case studies are conducted to evaluate FOWT load and response characteristics and applicable global performance analysis methodologies. The scope of case studies is not limited to examine global responses of the FOWT stationkeeping system alone. Rather, each FOWT under consideration is modeled and evaluated as an integrated system such that dynamic interactions of the main FOWT subsystems and the effect of such interactions on global responses of FOWT stationkeeping systems can be accounted for. The design load cases proposed in the BSEE TA&R Project 669 final report are further evaluated in the present case studies. Emphasis is given to the modeling approaches relevant to FOWT global performance analyses. Three representative design concepts, which include a Spar-type, a TLP-type, and a Column-Stabilized (Semi-submersible)-type floating support structure and their associated stationkeeping systems, are selected for the case studies. The turbine installed on each of these design concepts is the NREL 5-MW baseline offshore wind turbine developed by the National Renewable Energy Laboratory (NREL). The representative operational and extreme environmental conditions of the East, West and Gulf of Mexico coastal regions on the US Outer Continental Shelf (OCS) are applied. The case studies are performed using the state-of-the-art simulation software for the fully coupled aero-hydro-servo-elastic analysis for the integrated simulation model that comprises the turbine Rotor Nacelle Assembly (RNA), the turbine control system, the floating support structure and the

stationkeeping system. Sensitivity studies are performed to assess and verify various modeling strategies and simulation methods for FOWT global performance analyses.

Technical challenges and critical design parameters in the design of FOWT stationkeeping systems are identified based on the results of the state-of-the-art review and the case studies as well as experience in designing stationkeeping systems for floating oil and gas offshore structures. A draft guideline is developed to provide recommended design methods and acceptance criteria for FOWT stationkeeping systems. Guidance on FOWT global performance analyses is also developed. The main subjects addressed in the proposed design guideline include:

- Overall design considerations
- Design environmental conditions
- Design load conditions and load calculations
- Recommended global performance analysis methods
- Strength and fatigue criteria
- Stationkeeping system hardware and material selection

Recommendations are made for future research on software validation, model testing method and design load cases for FOWT stationkeeping systems.

1 Introduction

Over the past fifteen years, many design concepts for floating offshore wind turbines (FOWTs) have been proposed. It was not until 2008 that the first scaled prototype, Blue H, was installed offshore Italy where the water depth is about 113 m (Bastick, 2009). Since then, several small-scale prototype FOWTs have been installed for field testing and two full-scale FOWTs have been deployed for concept demonstrations, including the Hywind FOWT installed offshore Norway in 2009 (Bratland, 2009, Thygeson, 2010) and the WindFloat FOWT installed offshore Portugal in 2011 (Andrus, 2011, Aubault, et al., 2012, Cermelli, et al., 2012).

To support the development of design guidelines for FOWTs, the American Bureau of Shipping (ABS) recently completed a study funded by the Bureau of Safety and Environmental Enforcement (BSEE) of the U.S. Department of the Interior under the Technology Assessment and Research (TA&R) Project 669 "Floating Wind Turbines" (Yu and Chen, 2012). In that study, extensive literature reviews and case studies were conducted, and a draft design guideline for FOWTs was proposed. In addition to the design load cases and acceptance criteria for FOWT floating support structures, an essential part of design requirements for FOWT stationkeeping systems was proposed in that design guideline. It was concluded that the FOWT stationkeeping systems behave, to some extent, in a similar way to those designed for oil and gas floating offshore structures. Existing experience from the offshore oil and gas industry, as formulated in a number of design criteria and guidelines published by American Petroleum Institute (API), International Organization for Standardization (ISO) and classification societies, can be adapted for application to FOWTs, provided the differences between stationkeeping systems for FOWTs and those for floating oil and gas offshore structures are appropriately addressed. Recommendations were made for further research on more comprehensive design guidance on FOWT stationkeeping systems.

This project is aimed to provide a thorough review of existing technologies relevant to the design of FOWT stationkeeping systems; to identify critical technical areas and design parameters; and to evaluate the global performance analysis methodologies using the latest simulation methods. A draft design guideline for FOWT stationkeeping systems and for global performance analyses of FOWTs is proposed based on the research findings and applicable experience adapted from the offshore oil and gas industry.

The report is organized into five main sections, which present:

- results of the state-of-the-art review;
- case studies for three FOWT conceptual designs assumed to be installed on the US OCS;
- discussions of critical technical areas and design parameters in designing FOWT stationkeeping systems; and
- a proposed design guideline.

Section 2 presents the results of the state-of-the-art review, with the primary focus on:

- existing design concepts;
- existing design standards and guidelines;
- design tools and software verifications; and
- global performance analysis procedures and methodologies for FOWTs.

The results of the literature review are categorized into these four subjects in order to establish a general overview of available information and where past research effort has been directed.

Section 3 is dedicated to the case studies using the conceptual FOWT designs. The ABS in-house capability of performing advanced global performance analyses is leveraged to tackle one of the major challenges in the design of FOWTs, i.e. the dynamic interactions of the wind turbine rotor, floating support structure and stationkeeping system subjected to the combined actions of turbine's control systems and environmental conditions. Three representative design concepts, which include a Spar-type, a TLP-type, and a Column-Stabilized (Semi-submersible)-type FOWT assumed to be installed in the East, West and Gulf of Mexico coastal regions on the US OCS, are selected for the case studies. The modeling, methodology and results of the global performance analyses are described in Section 3. Conclusions are also provided about the global performance analysis methodologies and global response characteristics of FOWT stationkeeping systems and floating support structures.

Section 4 provides a discussion of critical technical areas and design parameters for FOWT stationkeeping systems. The discussion is primarily based on the results from the state-of-the-art review and the case studies performed in this project. It is also partially based on common practices of the offshore oil and gas industry and the offshore wind industry. Although design considerations for stationkeeping systems of oil and gas floating offshore structures are in many cases still valid, the uniqueness of FOWT stationkeeping systems does exist and has to be appropriately accounted for.

Section 5 presents a draft design guideline for FOWT stationkeeping systems and global performance analyses. The main contents of this draft design guideline cover:

- overall design considerations;
- environmental conditions;
- design load conditions and load calculations;
- global performance analysis;
- strength and fatigue design criteria of mooring lines and tendons; and
- stationkeeping system hardware and material selection criteria.

Recommendations are made in Section 6 for future research on software validation, model testing method and design load cases for FOWT stationkeeping systems.

2 State-of-the-Art Review

A state-of-the-art review is conducted for various subjects relevant to the design of FOWT stationkeeping systems and global performance analyses. Numerous publications have been collected, reviewed and commented upon. Emphasis is given to the following technical areas:

- Existing design concepts of FOWTs and their stationkeeping systems (Section 2.1)
- Relevant design codes and standards (Section 2.2)
- Design tools and software verifications (Section 2.3)
- Global performance analysis procedures and methodologies for FOWTs (Section 2.4)
- FOWT model testing (Section 2.5)

2.1 Existing Designs and Design Concepts

2.1.1 Existing Designs and Design Concepts of FOWTs

Based on the literature review summarized in BSEE TA&R Project 669 final report (Yu and Chen, 2012) and the literature review performed in the current study, existing designs and design concepts for FOWTs are summarized in the following subsections:

- Full scale and scaled prototype FOWTs (Section 2.1.1.1)
- FOWT conceptual designs (Section 2.1.1.2)

These concepts can be categorized into the following six groups:

- Spar-based FOWTs
- Tension Leg Platform (TLP-based) FOWTs
- Monohull (barge-based) FOWTs
- Column-Stabilized (Semi-submersible-based) FOWTs
- Multiple-unit design concepts
- Other innovative design concepts (such as vertical axis wind turbines)

2.1.1.1 FOWT Prototypes

There are currently two full-scale prototype FOWTs deployed for concept demonstrations. These are the Spar-type Hywind (Bratland, 2009, Thygeson, 2010) and the Semi-submersible-based WindFloat (Andrus, 2011, Aubault, et al., 2012, Cermelli, et al., 2012). The Hywind was installed offshore Norway in 2009. The WindFloat was installed offshore Portugal in 2011. The mooring system for the Hywind Spar is a 3-point spread mooring system, while the WindFloat uses a 4-point spread mooring system. In addition to the full-scale prototypes, several scaled prototype FOWTs have also been installed for field testing (Yu and Chen, 2012). In summary, the stationkeeping systems for these FOWTs are of the follow types:

- Tension leg system with gravity anchor (Blue H)
- Turret mooring system (Poseidon Hybrid Wave-Wind Energy Converter)
- Single articulated tension leg (Sway)
- Spread mooring system (Hywind and WindFloat)

2.1.1.2 FOWT Conceptual Designs

A comprehensive review of conceptual designs of FOWTs is provided in BSEE TA&R Project 669 final report (Yu and Chen, 2012). The literature survey performed in the current study identified a number of new or additional design concepts as described below in this subsection.

Korogi, et al. (2009) presented a study on a new concept of floating wind power plant that does not have a traditional mooring system, but moves with sails and thrusters. With the mobility, the structure can move toward a favorable direction to maximize the power generation. Mobility gives another benefit that the floating support structure can shelter from high seas, thus structural weight can be reduced. This concept is called VLMOS (Very Large Mobile Offshore Structure), which is a semi-submersible floating structure composed of a slender lower-hull, an upper-hull and vertical struts. The sizes of VLMOS are 1,880 m in length, 70.2 m in width and 20m in draught. Eleven 5-MW class wind turbines are mounted on the floating support structure.

Resistance test and oblique towing tank test were carried out using a 1/100 scale model of VLMOS for investigating the effect of the interaction among the struts and between the lower hull and the struts. An experiment to test the stability of station keeping was performed. Navigation performance of the floating support structure was also demonstrated with model sails.

Delpeche (2009) described a hybrid concept called Toroidal, which is a semisubmersible platform with a torus-shaped lower hull and three columns. The structure is designed to weathervane by means of a turret mooring system. Incoming wave energy is captured by water turbines on the water surface. On the triangular deck structure, three wind turbine towers are mounted. The submerged toroidal pontoon is expected to provide favorable motion characteristics. The concept has an active ballast system to allow the hull to be submerged below the water surface in storm conditions.

A 1/200 scale model was fabricated and model tests were performed. The model tests were conducted in regular waves for a range of wave heights and periods with and without current. The mooring system was changed to a spread mooring system in the model test using three linear springs. The effect of wave-current interaction was noted and mooring line forces were measured. Numerical analysis was performed and the results were compared with the experimental results. The experimental and calculated heave response showed an amplification factor of less than one, which indicates for an incident wave height of 1 m, the structural response is not amplified but rather reduced. The author considered this as a key benefit of using a toroidal shaped hull, although the low frequency responses in mooring line loads indicates that the mooring system will be susceptible to wave drift loads.

Chabert (2011) introduced the WinFlo project initiated in France in 2008. The project is to develop a multi megawatts floating offshore wind system for deep water coasts at about 50 m depth. A semi-submersible floating platform with a catenary anchoring system was chosen for the project. A prototype is expected to be tested and demonstrated at sea around 2013 – 2014 and full industrial production is anticipated by 2020.

Pascual (2011) presented the EOLIA project in Spain conducted between 2007 and 2010. Three different FOWT concepts, including a Spar-type, a semi-submersible-type and a TLP-type FOWT, were studied. The design concepts used a 5-MW wind turbine and were assumed being deployed in a 200 m water depth. Design software was calibrated and new mooring analysis tools were developed.

Timofeev, et al. (2011) presented the results of developing floating offshore power farms (FOPF) with the capacity to harness up to 25 MW from ocean renewable energy sources (wind, wave, current and solar). The proposed concept consists of a hull in the form of a hollow triangle with one wind turbine located at each of the three corners. The underwater current turbines are located under the hull. The hull is connected by a spread mooring system to the seabed. In the FOPF concept demonstration phase, it is planned to perform detailed design, construction and pilot operation of a 150 KW FOPF unit. Preliminary assessments for offshore Murmansk in the Barents Sea confirmed the design concept's economic viability.

Tang, et al. (2011) proposed a concept design of a floating foundation for a small wind turbine. A semi-submersible foundation supporting a 600 KW horizontal axis wind turbine, a tower and a mooring system are designed for the water depth of 60 m. The mooring system is a 6-point catenary spread mooring system. Finite element models of the FOWT system were created, consisting of the mooring lines, floating foundation, tower and wind turbine. Wave-induced dynamic responses of the floating foundation were evaluated in the frequency domain.

Myhr and Nygaard (2012) addressed design considerations, such as excess platform buoyancy and mooring line layout, associated with the Tension-Leg-Buoy (TLB) FOWT. The authors indicated that excess buoyancy was required to keep the mooring lines taut throughout all events, and was therefore strongly influenced by the wave loads. Due to the taut mooring lines and excess buoyancy, the anchors are subjected to relatively high mean horizontal and vertical loads. Furthermore, load variations due to wind and waves are transferred directly to the anchors. This leads to higher anchor costs than for designs using a catenary mooring line system. The TLB system currently uses drag embedded plate anchors.

The main issue addressed in the paper was on the reduction of mooring force amplitudes and steel mass. An attempt to reduce the wave loads with a space-frame section in the wave action zone was presented. Optimization routines were utilized to adjust the geometry and mooring line layout to reduce the cost. The tools and procedures used for the optimizations and the resulting TLB conceptual design improvements were presented.

Hong, et al. (2012) conducted a feasibility study for a novel floating structure concept supporting a 5-MW wind turbine. The design targets were to achieve cost effectiveness, a smaller draft than traditional Spars, simple construction and installation. The hull design was based on the truss Spar with heave plates. Parametric analyses were carried out to identify a new floating substructure for FOWTs. A simple box shape floater with pitch and heave plates was chosen such that heave and pitch natural periods were outside of the wave periods. A preliminary model test was conducted and the numerical and model test results were compared with the traditional Spar-type FOWT design. The authors concluded that the proposed design had some merits regarding construction cost savings.

Ren, et al. (2012) developed a conceptual floating support structure with a square buoy and a combination of tension legs and a catenary spread mooring system for a 5-MW wind turbine. 1/60 scale model tests for investigating the coupled wind-wave effect on the FOWT system were conducted in the wind tunnel & wave flume joint laboratory. The results of model tests and numerical simulations showed good agreement. 1/60 scale model tests using a circular buoy also were conducted and the test results were compared to those tests using the squared buoy. The difference in the surge responses of the tested models of the two different buoys was small, which indicated that the square buoy shape was acceptable. The test results of traditional TLP-type FOWT without additional catenary mooring lines were compared with those of the new concept. It was found that the motion responses of the new concept and the loads of the tension legs were reduced by the additional spread mooring system.

Shin and Dam (2012) developed an FOWT concept that is moored by a single spring-tensioned leg for installation where the water depth is 50 m. The hull has an inverted conical cylinder shape with four weight ballast plates at the bottom. 1:128 scale models with 3 different types of appendage plate were tested in regular waves to estimate their motion characteristics. The motions of the FOWT models were measured and the Response Amplitude Operators (RAOs) were compared. The proposed conceptual design appeared to have good stability and relatively small motion responses in waves.

Copple and Capanoglu (2012) described a conceptual design of a positively buoyant Tension Leg Wind Turbine (TLWT) suitable for both moderate and deep water. The TLWT consists of three inclined water-piercing columns, each of which is restrained by a pre-tensioned vertical tether and an inclined tether. The tethers are connected to the seafloor by either suction piles or gravity anchors. Although the TLWT is similar to traditional tension leg systems and has restrained heave, pitch and roll motions, it is also largely restrained in surge, sway and yaw motions by the inclined non-pretensioned restraining system. Vertical tethering alone could be made adequate for a TLWT at a deepwater site. However, in relatively shallow water, an appreciable set down due to combined wind, wave drift and current loading may require additional lateral restraints. Inclined columns preclude the ‘lock-in’ effect of vortex-induced motions. The restricted heave motions can also minimize potential cable fatigue damage at the interface. In addition to these design issues, the authors also addressed fabrication and installation options as well as applied ocean environment loads affecting the design of tethering system.

Zhao, et al. (2012) proposed an FOWT concept based on a multi-column TLP foundation (Windstar TLP). The hull has three corner columns, two groups of horizontal pontoons and one center column. The tower is mounted on the center column. At each corner of the corner column, there is one pair of tendons consists of two wire ropes arranged to secure redundancy and connected to seabed through gravity anchors. The tendon bodies were made of spiral strand ropes protected by polyethylene sheath. Aero-hydro-servo-elastic coupled analyses for selected IEC-61400-3 design load cases were performed using NREL's time-domain numerical analysis program FAST. Statistics of the key parameters were obtained and analyzed.

Mayilvahanan, et al. (2012) conducted a numerical study to investigate the hydrodynamic performance of Deep Draft Column Structures (DDCS) with different aspect ratios supporting a 5-MW offshore wind turbine. The conceptual designs were assumed to be deployed in an Indian coastal area having a water depth of 100 m. The floating support structure consists of a circular pontoon at the base and four columns supporting a circular deck where the wind turbine is mounted. The floater is moored by a slack (catenary) mooring system. Global response analyses were performed using the best design option selected based on the test results of six models. The interaction between the wind turbine (with the control system) and the floating support structure was incorporated into the frequency-domain equation of motion by considering the damping and restoring properties of the 5-MW wind turbine. However, the effect of mooring system interaction was not included in the numerical analysis and the wave and wind were treated independently.

Berthelsen, et al. (2012) presented a preliminary conceptual design of a floating support structure and mooring system for a 5-MW vertical axis offshore wind turbine (VAWT). The design was also known as DeepWind concept, which consists of a Darrieus rotor mounted on a Spar buoy support structure. The authors indicated that the mooring lines should be designed to provide sufficient yaw stiffness in order to withstand large yaw moments exerted by the rotating turbine. The yaw stiffness should also be selected to avoid possible resonance responses excited by periodic loads from the rotating turbine. Minimum yaw stiffness could be achieved by using a large horizontal pretension and a large fairlead radius, a so-called crowfoot delta-line connection, or increased number of mooring lines.

The conceptual design was formulated as an optimization problem solvable using analytical mooring and motion analysis tools. Two different mooring system configurations were considered: chain systems with 3 and 6 lines, respectively. A simplified aerodynamic load model was used where the floater was modeled as a single rigid-body. This approach did not account for the correct dynamical effects from the rotating turbine; aerodynamic loads were assumed to be proportional to the relative wind velocity squared. Only extreme load conditions were considered in the study.

In a parallel paper by Vita, et al. (2012), the design process and results of the DeepWind VAWT concept development were presented. The concept evaluation was divided into various levels of simplification associated with the degrees of freedom of the system. The numerical simulations were carried out with consideration of the fully coupled aerodynamic and hydrodynamic loads on the structure due to wind, waves and currents.

Collu, et al. (2012) presented the conceptual designs of the floating support structure for the NOVA (NOvel Vertical Axis wind turbine) project, which was intended to perform a techno-economic feasibility assessment of 5 to 10 MW novel VAWTs on a fixed and on a floating support structure assumed to be deployed at a representative UK North Sea wind farm site. The paper presented the evolution of two FOWT concepts to illustrate how geometrical and inertial characteristics influence dynamic responses to waves. The two concepts include a barge-type and a semi-submersible-type floating support structure. The barge concept evolved to the ‘triple doughnut-Miyagawa’ concept, consisting of an annular cylindrical shape with an inner (to control the damping) and outer (to control added mass) bottom flat plates. The semisubmersible was optimized to obtain the balance between dynamic behavior and amount of material needed.

Muliawan, et al. (2012) presented a concept that combined a Spar-type FOWT and a Torus (donut-shaped) point absorber-type wave energy converter (WEC) and named it ‘Spar-Torus Combination’ (STC). The feasibility study was carried out through numerical simulations to demonstrate the positive synergy between wind and wave energy generation.

An overview of recent studies on the floating offshore structures for use in the offshore wind industry, with primary focus on Spar, TLP and semi-submersible based FOWTs, was provided by Thiagarajan and Dagher (2012).

2.1.1.3 Existing and Conceptual Designs of Stationkeeping Systems for FOWTs

Based on the design concepts reviewed in Section 2.1.1.1 and Section 2.1.1.2 and those presented in the BSEE TA&R Project 669 final report (Yu and Chen, 2012), stationkeeping systems of existing FOWT prototype and conceptual designs belong to the following types:

- Spread mooring system with catenary or taut lines
- Tension leg system
- Single point mooring with turret
- Single point mooring with articulated leg
- Thruster mooring system
- Combined tension legs and spread mooring system

Applicable anchoring systems include:

- Gravity anchor
- Drag anchor
- Pile anchor
- Suction anchor
- Vertical loaded anchor
- Other types (for example, torpedo anchor)

2.1.2 Existing Designs of Stationkeeping Systems for Floating Offshore Structures

Experience in designing stationkeeping systems for floating oil and gas offshore structures can provide valuable information to the development of the design guidelines for FOWTs. A major part of the state-of-the-art review carried out in this project was therefore devoted to the existing mooring and anchoring systems for 18 Spars, 24 TLPs and selected semi-submersible platforms, as well as buoy-based single point mooring systems and disconnectable buoy mooring systems. The review was based on published papers and information available in the public domain. The results are presented in the following Subsections:

- Spars (Section 2.1.2.1)

- TLP (Section 2.1.2.2)
- Semi-submersibles (Section 2.1.2.3)
- Buoys (Section 2.1.2.4)
- Anchoring system (Section 2.1.2.5)

2.1.2.1 Mooring and Anchoring Systems for Spar

According to "2012 Deepwater Solutions & Records for Concept Selection" (Offshore magazine poster, 2012) and "2012 Worldwide Survey of Spar, DDCV and MinDOC Vessels" (Offshore magazine poster, 2012), there are 18 Spars (including 3 Classic Spars, 13 Truss Spars, 1 Cell Spar and 1 MinDOC deep draft floater) installed worldwide by the middle of 2012. The Spar poster also provides general information about the Spar mooring and anchoring systems. A more detailed review of relevant data available in the public domain is performed in this study. Table 2.1 summarizes the Spar mooring and anchoring systems based on the literature review presented in this subsection.

Bangs, et al. (2002) described the design of the first two Truss Spars for the Nansen/Boomvang Field Development. The paper reviewed the Truss Spar concept, past development work, and comparison with the Classic Spar concept; as well as the specific Nansen/Boomvang project requirements and design criteria and how they influenced the platform configuration. The paper also introduced unique design features, including heave plates, Steel Catenary Riser (SCR) pull tubes, hard tank-to-truss connections, and top-tensioned riser guides. The design of a semi-taut mooring system was discussed. The system is composed of 9 lines which are arranged into 3 groups of 3 lines (a so-called "3x3" system). Each taut-catenary mooring line is primarily composed of 5.0 in jacketed spiral strand connected to the driven pile anchor and the fairlead through 250 ft of 5.5 in studless chains.

Bugg, et al. (2004) summarized the regulatory approval process for the polyester mooring system in the GoM for the Mad Dog project, which received the first approval for the permanent use of polyester moorings in the GoM. The mooring system of the Mad Dog project is composed of 11 lines arranged into three groups: two groups with four lines and one group with three lines. Suction piles are used for the mooring line foundations. Each line comprises 146 mm K4 ground and platform chain and 270 mm Marlow Superline polyester rope. The polyester segments and the top polyester to platform chain are connected with specially designed H-link connectors. A subsea mooring connector links the ground chain to the pile anchor chain. The water depth is approximately 1348 m at the Spar's nominal position.

Table 2.1 Mooring and Anchoring Systems for Existing Spars

Platform Type	*Water Depth (ft)*	*Mooring Systems*	*Anchoring Systems*
Spar	1930	6 chain-wire-chain	6 84in×180ft anchor pile
	2223	3-3-4 chain-wire-chain	n/a
	2599	3-4-3-4 chain-wire-chain	14 96in anchor pile
	3150	3×3 chain-wire-chain	9 84in×220ft anchor pile
	3330	3×3 chain-wire-chain	n/a
	3453	3×3 chain-wire-chain	9 84in×232ft anchor pile
	3678	3×3 chain-wire-chain	9 84in×232ft anchor pile
	4000	3×4 chain-polyester-chain	driven pile
	4100	4-4-5 chain-polyester-chain	13 84in×254ft driven pile
	4344	4×4 chain-wire-chain	16 216in×126ft suction pile
	4364	2-3-3-2 chain-wire-chain	n/a
	4420	4-3-4 chain-polyester-chain	7 216in×85ft 1 216in×49.2ft 1 299in×46.6ft 1 299in×51.8ft 1 299in×53.8ft suction pile
	4800	4×3 chain-wire-chain	12 252in×105ft suction pile
	4970	3×3 chain-wire-chain	anchor pile
	5300	6 chain-polyester-chain	6 216in×78ft suction pile
	5423	3×3 chain-wire-chain	6 216in×90ft 3 216in×95ft suction pile
	5610	3×3 chain-wire-chain	9 228in×114ft suction pile
	7817	3×3 chain-polyester-chain	9 216in×87-103ft suction pile

Petruska, et al. (2004a) discussed the prototype test plan for the polyester ropes for the Mad Dog truss Spar. The test plan mainly followed API RP 2SM but with several modifications, in particular regarding using more dynamic stiffness data and static drift stiffness (extension) data over various mean loads, load ranges and rates of loading. In addition, axial tension-compression fatigue testing of the mooring line was conducted by applying the loading conditions and number of cycles expected to occur during the service life. A stiffness model was developed for the polyester mooring system design and global performance analyses. The inspection plan throughout the service life of the polyester mooring is reviewed by Petruska, et al. (2004b). The authors also discussed the quality control measures for rope manufacturing with a particular emphasis on splicing the end terminations.

Thurmond, et al. (2004) presented the challenges in planning and executing the four major GoM deepwater projects in the Holstein, Mad Dog, Atlantis, and Thunder Horse fields at water depths of 4344 ft, 4420 ft, 7100 ft, and 6300 ft, respectively. The truss spars were selected for the Holstein and Mad Dog fields, while the semi-submersibles were selected for the Thunder Horse and Atlantis fields. The Holstein Spar was the largest spar built to date, with a hull diameter of 149.3 ft, a hull length of 744 ft, and a payload capacity of 47,000 tons. It comes with a 16-line mooring system comprising 171 mm studless RQ4 chains and each suction pile weighs about 300 tons. The Mad Dog Spar's polyester mooring system was designed to cope with severe seafloor topography issues. Some of the mooring system's suction anchors, which are as large as 25 ft in diameter, were positioned on an escarpment slope with poor soil conditions.

Tahar, et al. (2005) discussed the measurements of the Horn Mountain production Spar and comparisons with analytical predictions of mooring tension during Hurricane Isidore in September 2002. The Horn Mountain Spar is located in the GoM where the water depth is 5,425 ft. The spar's hard tank is 106 ft in diameter with bottom depth of 176 ft. The total hull length is 555 ft and the draft is 505 ft. The mooring system features three groups of three semi-taut chain-wire-chain mooring lines and the fairleads located 12 ft above the bottom of the hard tank and 164 ft below the mean water line. Mooring tensions were measured at chain jack location (inboard tension), while analytical models were developed to compute those tensions at the fairlead location (outboard tension). Special attention was placed on the effect of Coulomb friction between wire chain and the fairlead bearing on the dynamic tension of mooring lines. The authors concluded that there was good agreement between the field measurements and the computed tensions at the chain jacks when fairlead friction was included and the vessel motions were accurately predicted. Ignoring fairlead friction could result in a slightly conservative estimation of the mooring line tension at the chain jack. This has been the standard practice in all Spar designs to date.

Haslum, et al. (2005) described the design and testing of the polyester mooring system for the Red Hawk Spar installed in the GoM Garden Banks area where the water depth is approximately 5,300 ft. The mooring system consists of six evenly spread taut legs comprising chain-polyester-chain. Segments are connected with H-link connectors. Each leg is anchored to the seafloor by a suction pile with a diameter of 18 ft and a length of 78 ft. A subsea mooring connector connects the ground chain to the pile chain. The mooring system design was found to be governed by the extreme Loop Current conditions. A new test plan was developed and used to evaluate polyester rope stiffness under extreme Loop Current conditions. It was found that the line stiffness under extreme Loop-Current conditions was dependent on the amount of “construction stretch” removed during installation.

Tule, et al. (2005) presented rope test results for the Red Hawk Spar after one rope accidentally contacted the seabed during installation. A two-phase test plan was established and conducted to demonstrate that the polyester rope retained 100% of new rope break strength, modulus, and fatigue life after contact with the seabed. It also demonstrated that the strand jacket provided sufficient protection from adverse effects caused by seabed contact. The results of the two-phase testing were intended to provide technical justification for relaxing the current practice requiring line replacement when touchdown occurs. The regulatory agencies concurred with the request to allow the section of polyester that touched the seabed to remain in service.

Jatar and Dove (2005) described the planning and installation of the Red hawk Spar and the polyester mooring system using a Construction and Anchor Handling Tug (CAHT). Red Hawk Spar is the first Spar that was upended and attached to mooring lines without the involvement of derrick barges or construction vessels. Another key design decision was to minimize the amount of platform mooring equipment to be installed on the Spar. All previously installed Spars have chain jacking equipment located at every mooring leg. Since the Red hawk Spar is not required to offset for drilling and other operations it was decided that a single chain windlass located at one position on the Spar deck, which can access the six mooring stations, would suffice for periodic mooring adjustments. The anchorages with pile chains were first installed several months before other parts of the preset mooring were installed. The preset mooring consists of grounded chain and the lower segments of polyester ropes were then installed, while the upper segments of polyester ropes were installed during the hook-up to the hull before the topside installation. The polyester rope construction stretch was removed using the CAHT, and the design mooring tension was applied to the system using the windlass.

Hendriks and Lange (2005) addressed the lessons learned from the installation of Spars in deepwater using Heerema's Deepwater Construction Vessel (DCV) Balder and Semi-Submersible Crane Vessels (SSCV) Hermod and Thiaf. The installations of the Horn Mountain, Gunnison, Holstein and Mad Dog Spars were reviewed.

Jenkins, et al. (2008) presented a general overview of the Kikeh project located where the average water depth is 1,320 m in the South China Sea offshore east Malaysia. The Kikeh Spar was the first Spar installed outside the GoM.

Varnado (2009) provided an overview of the development of the Tahiti Spar which was moored using a taut mooring configuration at water depth ranging from 4,100 ft to 4,300 ft. Each mooring line consists of chain and polyester rope segments and is terminated at a driven anchor pile with a diameter of 84 in and a length of 254 ft. The mooring system was designed to meet strength and fatigue requirements with consideration of the integrated mooring and riser responses to the wave frequency loading, low frequency loading and Vortex Induced Motion (VIM) excitation.

Lohr and Smith (2010) reviewed various aspects of the design, fabrication, transportation and installation of the Perdido Spar and its mooring system. The Perdido mooring system comprises nine chain/polyester lines averaging more than two miles in length. The nine taut lines are oriented in a 3x3 pattern and consist of 9.68 in (24.6 cm) polyester rope main sections, 5.28 in (13.4 cm) chain at each end of the mooring lines, and suction piles with diameters of 18 ft (5.5 m). The top of each mooring line is a short length of chain (i.e. the platform chain) connected to the Spar. The platform chain runs through a below-water fairlead, which is mounted on the outside shell of the Spar. The lower end of the platform chain is connected to the polyester mooring rope above the mudline. The ground chain's top segment is connected to the bottom segment by a subsea mooring connector. The other end of the ground chain bottom segment is connected to the foundation suction pile by a mooring shackle. A number of records were set during the installation campaign in 2008, including the world's deepest Spar installed at 7,817 ft water and the world's deepest permanent mooring pile at 8,631 feet water depth.

Veselis, et al. (2010) discussed the challenges in the design and installation of the mooring system for the MinDOC deep draft floating platform. This was the first permanent mooring designed to the post Hurricane Katrina and Rita metocean conditions. The MinDOC platform is located where the water depth is approximately 4,000 ft. The mooring design consists of a 12-point chain-polyester-chain taut leg system where each mooring line is terminated with a driven anchor pile. H-link connectors connect individual polyester sections as well as the polyester section to the adjacent chain. The mooring system was designed to provide the required performance and maintain the desired flexibility to accommodate non-predefined installation vessel(s) options. A significant part of such flexibility was achieved by prelaying the polyester mooring on the seabed. Since this had not been previously done for a permanent polyester mooring system in the GoM and, an extensive testing was carried out.

Herman, et al. (2010) discussed the effects of hull form selection, mooring design and riser interaction on the global performance of the MinDOC platform. The MinDOC's global performance was modeled experimentally and numerically with good correlation. The Vortex-induced Motion (VIM) behavior was studied through model testing, and suppression was achieved by adding strakes to the interior portion of the upper columns, which simplified horizontal construction.

Petruska, et al. (2010) introduced the latest revision of API RP 2SM. The authors discussed the major changes including: sections on elongation and stiffness testing; contact with the seafloor; creep rupture; and axial tension compression fatigue, and the positive impact of those changes on the design, installation and operation of synthetic fiber mooring systems.

2.1.2.2 Mooring and Anchoring Systems for Tension Leg Platforms (TLP)

According to "2012 Deepwater Solutions & Records for Concept Selection" (Offshore magazine poster, 2012) and "2010 Worldwide Survey of TLPs, TLWPs" (Offshore magazine poster, 2010), there were 24 TLPs or TLWPs (Tension Leg Wellhead Platforms) installed worldwide by the middle of 2012 (Hutton and Typhoon TLPs have been decommissioned). The TLP poster provides general data of the TLP mooring and anchoring systems. A more detailed review of the published information is performed in this study.

Table 2.2 summarizes the collected data of existing mooring and anchoring systems for TLPs based on the literature review presented in this subsection.

Table 2.2 Mooring and Anchoring Systems for Existing TLPs

Platform Type	*Water Depth (ft)*	*Mooring Systems*	*Anchoring Systems*
TLP	482	16 10.23in	n/a
	889	4×2 24in	8 64in×173ft Individual pile
	1100	4×4 32in	Concrete foundation templates
	1132	4×4 32in	Concrete foundation templates
	1490	4×2 24in×.812in	8 64in×320ft Individual driven pile
	1650	4×2 24in	8 64in×198ft Individual pile
	1699	3×2 26in	6 84in×340ft Individual driven pile
	1759	4×3 24in×.812in	piled foundation templates
	2097	3×2 28in×.881in	Individual driven pile
	2816	3×2 32in ×1.143in	6 96in×418ft Individual driven pile
	2862	4×3 26in×1.3incombined with a lateral mooring	4 piled templates
	2933	4×3 28in×1.2in	12 84in×375ft Individual driven pile
	2985	4×3 32in×1.25in	12 82in×340ft Individual pile
	3216	4×3 28in ×1.2in	12 84in×349ft Individual pile
	3236	4×3 28in	Individual pile
	3310	3×2 28in	6 84in Individual driven pile
	3349	4×2 26in	8 72in×251ft Individual pile
	3800	4×4 32in×1.5in	16 96in×417ft Individual driven pile
	3863	4×2 32in	Individual pile
	3863	4×2 32in	Individual pile
	4200	3×2 36in×1.36in	6 96in×414ft Individual pile
	4300	4×2 28in×1.2in	8 76in×390ft Individual pile
	4375	4×2 36in×1.55in 44in×1.44in	n/a
	4674	4×2 32in	8 96in×315ft Individual driven pile

Hauch and Haver (1998) demonstrated how full scale measurements of the Heidrun TLP could be used in assessing the platform behaviors. The Heidrun TLP is the only TLP having a concrete hull structure. It has sixteen tendons with four tendons at each of its four corners. The quality of the measurements were evaluated by comparing the responses determined using simultaneously acquired time series from hydro acoustic position sensors, accelerometers and tether tension sensors. Examples of the low, wave, and high frequency response components were shown. The authors concluded that the measurements met expectations and that the TLP motions obtained from the analyzed time series were within the allowable values.

Rainey (2002) provided a general overview of the Brutus TLP, which is located in the Green Canyon 158 block in the GoM where the water depth is about 2,985 ft. A tendon system similar to that of the Ursa TLP was adopted along with modifications to accommodate a new design of the connector and the associated testing and certification requirements. Because of its much larger size, the Ursa TLP required four tendons per column while the Brutus TLP required only three per column.

Matten, et al. (2002) described the design, fabrication, installation and hook-up and commissioning of the Typhoon SeaStar TLP, which is located in the Green Canyon 236/237 block in the GoM where the water depth is approximately 2,097 ft. Typhoon SeaStar TLP is the third SeaStar TLP installed in the GoM after the Sir Douglas Morpeth Seastar TLP (installed 1998) and the Allegheny SeaStar TLP (installed 1999). The SeaStar TLP design features a mono-column hull with 3 pontoons radiating outwards at the base. The platform stability against overturning is provided by 6 near neutrally buoyant tendons running vertically from the top connectors mounted on the tendon porches at the extremities of each pontoon to the piles driven into the seabed. The tendon system also acts as the stationkeeping system. In order to minimize the moment transfer at the pontoon/column connection, the buoyant pontoons are designed to provide tension in the tendons, and the column buoyancy supports the topsides payload.

Kibbee and Snell (2002) summarized the four projects using the SeaStar TLPs and the continuing evolution of this technology. The SeaStar Mono-column TLP concept had been deployed in the GoM for AGIP's Morpeth Field, AGIP's Allegheny Field, Chevron's Typhoon Field, and TotalFinaElf's Matterhorn Field. The primary geometric difference between a SeaStar TLP and a conventional TLP is the former's single column. The single column allows the deck and the hull to be separately optimized, resulting in a versatile and cost-effective solution.

The Morpeth platform is located where the water depth is 1,670 ft. The platform is vertically moored by six 26-in neutrally buoyant, pre-installed tendons. Each tendon is connected directly to an independent driven pile. Notwithstanding an increase in the water depth from Morpeth's 1,670 ft to Allegheny's 3,350 ft, Allegheny TLP is similar in many respects to Morpeth TLP. The platform is also vertically moored by 6 pre-installed tendons. Tendon weight increases associated with Allegheny's deeper water were managed by the use of stepped wall thickness tendons. Each tendon is connected directly to an independently driven pile. The Typhoon platform was installed where the water depth is approximately 2,097 ft. The platform is vertically moored by six 26-in neutrally buoyant, pre-installed tendons, each of which is connected directly to an independent driven pile. Matterhorn TLP is vertically moored by six 32-in preinstalled tendons. Each tendon is connected to an independent driven pile.

Koon, et al. (2002) presented the development of the MOSES TLP in the Prince Field in the GoM where the water depth is approximately 1,490 ft. The MOSES TLP is the first deployment of a new generation of TLP designs that introduces a new hull configuration. The mooring system consists of 8 tendons that connect the hull to the foundation piling. Each tendon consists of a 24-in tubular, a top connector assembly, and a bottom connector assembly. The length of each tendon is approximately 1,428 ft and varies to accommodate the sea bottom slope. Three spare main body sections were fabricated in case of damage to the primary sections.

Brock (2003) addressed the challenges faced and actions taken in navigating the transition of the Auger TLP. With first production in 1994, the Auger TLP was transformed from a TLP focused on field development to an infrastructure hub serving as a subsea tie-back host for fields in the surrounding area. The Auger TLP is a four column floating structure with a displacement of 73,000 mt and is held in place by three 26-in steel tendons attached to each column. The field in the GoM has a water depth of 2,862 ft.

Korloo, et al. (2004) presented the design of the West Seno A TLP, which is a conventional TLP with four columns and four pontoons. Total displacement at the mean design draft is about 23,000 mt. The TLP is moored by 8 tendons, each of which has an outer diameter of 660 mm. A fully coupled time-domain analysis approach was adopted for the TLP design. The paper summarized the numerical simulations and the comparison with the model test results.

Hurel and van der Linden (2004) and Leverette, et al. (2004) discussed the development of the Matterhorn SeaStar TLP located in the GoM where the water depth is about 2,816 ft. The TLP main hull is 84 ft in diameter, 125 ft in height, and 179 ft in radius to the tip of the three pontoons. The hull dry weight is 5,500 mt, which is approximately double the size of the previous SeaStar TLPs. The hull is moored by 6 32-inch tendons composed of 290 ft long tendon joints, each of which is a 32-in neutrally buoyant pipe. Each tendon is anchored by a driven pile which is 418 ft long and 96 in in diameter. The tendons are connected to the piles by flex-joint connectors. The upper 1,100 ft of each tendon is covered by fairings to reduce vortex-induced vibration (VIV) response in current. The adopted global analysis methods and techniques were first developed for the Morpeth SeaStar TLP in 1997, and evolved through subsequent designs, multiple model test programs, and evaluations of 5 years of field measurement data. The authors concluded that metocean data, model test calibration, coupled analysis of hull, tendon and riser systems, and mitigation of vortex induced vibration of tendons and risers were critical to the TLP design.

Perego, et al. (2005) presented measured response data for the Marlin TLP during the Hurricane Ivan in September 2004. The Marlin TLP was installed in the GoM in 1999 where the water depth is approximately 3,250 ft. The TLP consists of a four column hull connected by ring pontoons and is moored using two tendons per corner. The TLP has a displacement of approximately 52,000 kips. The Marlin TLP uses an extensive monitoring system to measure the environmental and platform responses. These measurements were used to assist platform operations and to verify analytical models of platform global performance. Marlin's measurements include a comprehensive, high quality dataset recorded during Hurricane Ivan. The eye of Ivan passed directly over Marlin resulting in wind and wave conditions substantially greater than the 100-year design hurricane. Measured data were compared to both the design level responses and to predicted responses from a fully coupled frequency-domain simulation of the TLP, including all tendons and risers, using hindcast environmental conditions as input.

Bates, et al. (2006) highlighted the installation phase of the Kizomba A and B Tieback projects located offshore Angola and within 7 miles from each other. Kizomba A and B share the same field development concept, which contains a wellhead TLP tied back to a FPSO and an offloading buoy. The main challenge of installation was to moor the FPSO in close proximity to the TLP.

van Dijk and van den Boom (2007) described the instrumentation of the Marco Polo TLP and presented characteristic results of the monitoring campaign. The Marco Polo field is located in Green Canyon block 608, 160 miles south of New Orleans where the water depth is about 1300 m. The purpose of the full scale monitoring campaign was to evaluate the TLP performance under hurricanes and loop-current conditions. The measured parameters comprised the high and low frequency modes of motion, the fatigue loading of the platform and the dynamic behavior of the tendons and risers with special attention paid to vortex induced vibrations. Wind, wave and current conditions were also measured simultaneously. The monitoring system was in operation during the hurricanes Ivan, Katrina and Rita and therefore acquired valuable measurements. Although Marco Polo was very close to the center of these severe hurricanes, with wind speeds in excess of 138 mph and maximum wave heights over 28 m were measured, no significant damage was inflicted to the platform.

2.1.2.3 Mooring and Anchoring Systems for Semi-submersibles

According to "2012 Deepwater Solutions & Records for Concept Selection" (Offshore magazine poster, 2012) and "2011 Worldwide Survey of Semi-FPSs and FPUs" (Offshore magazine poster, 2011), there are 51 semi-submersible based FPSs (Floating Production Systems) or FPUs (Floating Production Units) installed, or to be installed, worldwide by the middle of 2012. Some of the units have been in service for more than 20 years. This subsection presents a review of recent designs of the mooring and anchoring systems for production semi-submersibles. Table 2.3 summarizes the results of the review.

Table 2.3 Mooring and Anchoring Systems for Existing Production Semi-submersibles

Platform Type	*Water Depth (ft)*	*Mooring Systems*	*Anchoring Systems*
Semi-submersibles	1050	16 catenary	Piles
	1115	12 wire chain	12 192in×49ft suction piles
	2998	4×3 chain-polyester-chain	Suction Embedded Plate Anchor (SEPLA)
	3100	4×3 chain-polyester-chain	suction piles
	6050	4×3 chain-polyester-chain	12 84in×215ft driven pile
	6065	4×4 chain-wire-chain	16 216in×91ft suction piles
	6340	4×4 chain-wire-chain	16 168in×83ft suction piles
	6494	8 polyester chain	Piles
	7072	4×3 chain-wire-chain	suction piles
	8000	4×3 chain-polyester-chain	12 216in×90ft suction piles

Thurmond, et al. (2004) discussed the primary challenges in planning and executing four major GoM deepwater projects, of which Thunder Horse and Atlantis are semi-submersibles. Thunder Horse is the world's largest production semi-submersible with a 130,000-mt displacement. Suction anchors are employed in the anchoring system.

Paton, et al. (2004) described the development of the Na Kika semi-submersible located where the water depth is approximately 1,936 m (6,350 ft). The platform is moored by a semi-taut mooring system with steel spiral strand wire ropes and consisting of 16 lines in 4 groups of 4 lines at each corner of the platform. The grounded and platform chains are R4 studless chains. Forged shackles are used for chain to wire and chain to pile connections. The mooring wires are spiral strand wire ropes terminated with open cast sockets. The selected fairlead is a bending shoe design, above which the chain tensioner with permanent chain stopper is installed. The anchoring system comprises suction piles, each of which has an outer diameter of 14 ft and a length of 83 ft with a design penetration of 78 ft. The mooring lines are connected to the padeyes on the pile wall located at 54 ft below the mudline.

Mikkelsen, et al. (2005) described the development of the Troll West field offshore Norway at the water depth of 315-340 m. Two semi-submersibles were deployed as floating production systems. Troll B is a concrete semi-submersible, while Troll C is a steel semi-submersible.

Kindel, et al. (2007) presented an overview of the major design and construction activities of the hull and the mooring system of a deep draft semi-submersible. Special attention was placed on the hull vortex induced motions, hull air gap during design hurricane events, effects of wave run-up during design hurricane events, topside-to-hull integration interface, multi-cable transits and shipyard safety program.

Couch, et al. (2007) reviewed the planning, preparation, and execution of the installation of the Independence Hub semi-submersible in Mississippi Canyon Block 920 in the GoM. The transport and installation of the suction piles and the installation of the polyester moorings in a record water depth of 8,000 ft were presented. The mooring system consists of 12 taut leg polyester mooring lines anchored by suction piles.

Flory, et al. (2007) reviewed the experience and issues with the use of polyester fiber ropes as mooring lines in deepwater applications. Polyester and other fiber ropes were studied for deepwater moorings in several Joint Industry Projects in the early 1990s. These studies provided vital information and answered many critical questions. They showed that polyester rope has desirable stretch characteristics and very good durability for use as mooring lines. The use of polyester mooring systems for semi-submersibles was pioneered by Petrobras in the late 1990s. Mobile Offshore Drilling Units (MODU) began using polyester mooring lines in the GoM in the early 2000s. The first permanent applications of deepwater polyester mooring systems in the GoM were the Mad Dog and Red Hawk Spars installed in early 2004. The use of polyester and other fiber rope mooring systems in even deeper water depths could present new challenges. More knowledge of the properties of the alternative, high-modulus, high-strength fiber ropes was needed.

Todd and Replogle (2010) and Cramond, et al. (2010) presented the similarities and key differences between the Thunder Horse and Atlantis semi-submersibles. Thunder Horse is the largest production semi-submersible in the GoM with a displacement of 130,000 mt, while Atlantis is also a large semi-submersible with a displacement of 88,600 mt. Both platforms are equipped with instrumentation to measure metocean conditions and platform and riser responses. The authors presented the measurements taken when several major hurricanes passed close to these two platforms. Even though the metocean conditions exceeded design values, no major hull, mooring or riser damage occurred. Comparisons of the measured platform responses to the numerical analysis results showed that, in general, the numerical analysis tended to be conservative.

Miller, et al. (2011) summarized observations and lessons learned from the first quinquennial (every 5 years) mooring system inspection for the Thunder Hawk semi-submersible, which is located in Mississippi Canyon Block 736 in the GoM where the water depth is approximately 1800 m (6,000 ft). The mooring system is composed of 12 taut-line chain-polyester-chain mooring legs in 4×3 groups. The anchors are driven piles. Rope and chain segments are connected using a ball-grab, or H-Link connector appropriately sized to exceed the strength of the mooring rope. The first quinquennial inspection was performed by Remotely Operated Vehicle (ROV) in 2010. The inspection required the ROV to fly both sides of the mooring leg while oriented normal to the axis of the mooring line. This allowed the inspectors to observe the amount of twist in the mooring chains and ropes. It also made it possible to see any damage to the cover, splice area, or eye of the mooring ropes. By the end of the inspection, nearly 40 miles of rope and chain were observed. Based on the inspection findings, the authors concluded that current industry standard corrosion allowances should not be removed or reduced for steel chain or wire until the corrosion processes in low Oxygen environments are better understood and quantified.

Mullett, et al. (2012) presented the design, analysis, and installation of the suction piles and polyester mooring system for OPTI-EX semi-submersible production facility installed in Mississippi Canyon area in the GoM where the water depth is about 3,100 ft. The mooring system is a 12 line chain-polyester-chain configuration arranged into 4 groups of 3 lines, each of which comprises 107mm R4 studless platform and ground chain. The polyester rope is Whitehill's VETS 370 construction rope with a minimum breaking load of 1,100 mt and an average overall diameter of 205 mm. Delmar's subsea connector was used to connect the ground chain to the suction piles. The mooring system was designed using dynamic analyses with consideration of both mooring line dynamics and six DOF vessel dynamics. The design metocean condition was based on the 100-year return hurricane event. A survivability check was analyzed at the 1,000-year return event to ensure safety factors were in excess of 1.0. The mooring analysis of the polyester rope mooring systems incorporated the actual nonlinear tension-elongation characteristics of the polyester rope as well as the rope's permanent non-recoverable elongation. The nonlinear stiffness properties of the polyester rope and permanent elongation data were derived from the load-elongation data obtained from the rope testing.

2.1.2.4 Mooring and Anchoring Systems for Buoys

According to "2012 Worldwide Survey of Floating Production, Storage and Offloading (FPSO) Units" (Offshore magazine poster, 2012), there are 156 FPSOs operating worldwide by the middle of 2012. Mooring systems for FPSOs include single point mooring (internal turret, external turret, submerged buoy turret, single anchor leg, catenary anchor legs, etc.), spread mooring system and dynamic positioning systems. In this study, a literature review of recent designs of buoy-based single point mooring (SPM) systems or disconnectable buoy mooring system is performed. Table 2.4 summarizes the available data based on the literature reviews reported in this subsection.

Table 2.4 Mooring and Anchoring Systems for Existing Buoys

Platform Type	*Water Depth (ft)*	*Mooring Systems*	*Anchoring Systems*
Buoy	295	8 wire-chain	n/a
	4593	3×3 chain-polyester-chain	6 19.7in×59.1ft 3 19.7in×52.8ft suction piles
	8250	6 line spread mooring	n/a

Kaalstad and Hovde (2004) presented the technology of the first Submerged Turret Loading (STL) Buoy used as an offshore LNG receiving terminal located in the GoM where the water depth is approximately 90 m. The STL Buoy is designed with sufficient buoyancy to float at a submerged depth of about 27-30 m from the water surface to the top of the buoy, while supporting the mooring, riser and umbilical system. The mooring system is connected to the STL Buoy which is disconnectable from the LNG regasification vessel. The mooring system consists of 8 evenly distributed mooring lines comprising studless chain segments and spiral strand wire rope segments. Connection to the anchor is by the chain through an anchor shackle, while the connection to the STL Buoy is by the wire rope through an open socket bolted to the connecting link of the turret.

Jean, et al. (2005) summarized the methodology of assessing the bending induced fatigue damage in the chain of the Girassol loading buoy, which was installed in the Girassol field offshore Angola where the water depth is about 1,350 m. The buoy is anchored to the seabed by 3 groups of 3 anchor legs. Following the unexpected rupture of chains in the chain hawse of the Girassol buoy after only half a year of service, a new bending fatigue mechanism of failure was identified for mooring systems with high pretensions. The premature rupture was caused by bending fatigue of the first free chain link inside the chain hawse. Before the incident, the anchor legs were composed of segments of 81 mm studded chains and 130 mm polyester ropes. Within one group, the legs are spread 5° apart, while each group is spread 120° apart. The chain segments are situated at the upper and lower ends of the anchor legs, connecting to the buoy and the anchor piles, respectively.

Green (2010) described how new developments in mooring connector design and polyester ropes would provide operators with dedicated deepwater mooring systems. The paper reviewed the elements of deepwater mooring with a particular focus on the integrity of deepwater mooring connectors and the excessive complexity of mooring line interconnectivity.

Masson, et al. (2011) presented the unique benefits and challenges associated with using hybrid riser tower technology in combination with a disconnectable turret-moored FPSO in the GoM. Located at the site where the water depth is 8,200 ft, the Cascade & Chinook subsea risers were among the deepest production risers. The disconnectable turret buoy is designed to support the weight of the mooring lines, risers and umbilicals, when it is disconnected from the hull.

Latimer, et al. (2011) provided an overview of the key issues involved in designing, building and integrating the Disconnectable Transfer System (DTS) for the Helix Producer I (HP1) floating production installation in the Phoenix field in the GoM. A buoy supporting all risers, umbilicals, mooring lines and clump weight is parked in the moonpool at the connected state. When the buoy is disconnected, it is maintained at a submerged depth via a clump weight attached to the buoy to minimize the impact of environmental conditions or external causes.

2.1.2.5 Anchoring Systems for Floating Offshore Structures

This subsection summarizes the results of a literature review of anchoring systems for floating offshore structures.

Sparrevik (1998) discussed design and installation of suction anchors. The paper also presented applications of suction anchors in major permanent mooring systems deployed during the period between 1995 and 1998. The use of suction anchor foundations is considered a proven technology, which has been demonstrated by the increasing number of major offshore project applications worldwide. The principles of the suction anchor concept are simple, but require understanding the geotechnical behavior of the foundation soils during the anchor installation and loading. The main advantage of using suction anchors for mooring applications is the installation position accuracy, which is very important in a congested subsea field development. In addition, using reliable design methods for capacity predictions may also reduce load testing or pre-tensioning requirements and, therefore, is ideal for anchor systems subjected to large mooring loads.

Tjelta (2001) reviewed suction pile technology and commented on its applications and challenges. Suction anchors were introduced to the offshore industry in 1980 and used in the Gorm field for a loading buoy. Because of somewhat negative experience of their early applications, it took more than 10 years before interest in suction anchors revived. In the 1990's, concrete suction foundations were used to anchor the Snorre TLP and Heidrum TLP. Since 1995, suction anchors become the preferred solution for a number of mooring applications where reliable high capacity foundations for catenary and taut legged moorings were required. The author concluded that there existed no major limitations to the application of suction anchors in deep water projects.

Ruinen and Degenkamp (2001) focused on the selection of anchors for shallow and deep water environments. In shallow water (1,000 m or less), the most common mooring line arrangement is the catenary mooring using predominantly chain and wire rope. An important feature of such a mooring is that part of the mooring line lay on the seabed during all loading situations. This requires an anchor that can withstand large horizontal loads but small vertical loads. For these applications a wide selection of drag embedment anchors is available. In a deep water mooring system (1,000 m and deeper), on the other hand, the weight of a catenary mooring system using chain and wire rope becomes significant. To alleviate the impact of heavy mooring system on the design of floating structures, one solution would be to lighten the weight by including synthetic rope inserts, but a more common solution for deep water mooring systems is to use a taut leg mooring, where the mooring lines enter the seabed at a large angle (up to 45°) and the anchor must resist both horizontal and vertical loads. For such an application a new type of drag embedment anchor, the Vertically Loaded Anchor (VLA), was developed. The authors examined the performance of the VLA based on the project experience.

Colliat (2002) summarized trends for application of anchors in deep to ultra-deep water (between 1,500 m and 3,000 m). The author indicated that conventional anchor piles (hammer limitation to 2,000 m), drag anchor (limited uplift angle) and catenary moorings had their limitations in deep to ultra-deep waters. Taut leg mooring systems using fiber ropes and anchors with a vertical loading capability were considered more favorable for both temporary mooring of drilling units and permanent mooring of production floaters in deepwater to ultra-deepwater. In soft, normally consolidated clays that are commonly found at deepwater sites, suction piles and VLAs appeared to be the two preferred anchoring solutions. The availability of recognized design methods would facilitate further applications of suction piles and VLAs in deepwater to ultra-deep water moorings. The freefalling torpedo anchor was also identified as a promising anchor concept, in particular for use in temporary moorings beyond 3,000 m water depth.

Dendani and Colliat (2002) wrote about the design, analysis and installation of the suction anchors for the Girassol production facility, which includes an FPSO, an offloading export buoy, riser towers and subsea manifolds, located at the water depth of 1,400 m in offshore West Africa. This paper summarized the main assumptions in the geotechnical design analysis, as well as key features of installation process. The holding capacity of the suction anchors was calculated by both limit equilibrium and finite element methods using an elasto-plastic soil model. Based on installation results, a revised method for the penetration analysis was proposed.

Eltaher, et al. (2003) summarized the current industry practice for the geotechnical design of anchoring systems of deepwater production installations (TLPs, Spars, FPSOs, Semi-submersibles, etc.), with emphasis on in-place design conditions. The authors discussed the importance of site-specific geological and geotechnical characterization as well as the geo-hazards that may affect a project’s risk and reliability evaluations. Other issues addressed in this paper include short and long-term reverse end bearing for suction piles; holding capacity of VLAs; effects of cyclic and long-term environmental loading (e.g., Loop currents) that could lead to soil cyclic degradation and creep; and time-dependent soil set-up.

Audibert, et al. (2003) reported on the geotechnical monitoring results of the installation of the nine suction piles for anchoring the Horn Mountain Spar. The geotechnical monitoring involved self-weight penetration, suction penetration, and the pile’s verticality and orientation throughout the installation. In addition, the suction pile designs were compared and updated based on the geotechnical monitoring data collected during the installation. The authors indicated that the measured data fell between the predicted upper and lower bounds, which confirmed the reliability of the suction pile design method.

Ehlers, et al. (2004) discussed the applications of four popular anchor concepts: suction piles, VLAs, Suction Embedded Plate Anchors (SEPLAs), and Torpedo/Deep Penetrating Anchors (DPAs). The authors indicated that each anchor type considered in this paper was at a different level of technology maturity. Suction piles were considered preferred anchors for taut-leg mooring systems for permanent facilities and represented the most mature technology in terms of installation experience and prediction of holding capacity. The main issue with suction piles was believed to be high costs associated with fabrication and installation due to large sizes of suction piles. VLAs were considered second in the overall level of maturity in terms of the holding capacity prediction and installation confidence, while there were drawbacks associated with the installation and costs of marine vessels required to drag the anchors to the design penetration, to key the anchors, and to proof load the anchors. The author concluded that SEPLAs and

Torpedo/DPAs trailed in the level of maturity and required the most technological development in the future.

Araujo, et al. (2004) discussed the first long-term application of one of the torpedo pile designs (i.e. T-98 design) to the Petrobras FPSO P-50. The authors presented the design, fabrication, installation and field testing of the two T-98 torpedoes piles, each of which is a steel pile with the appropriate weight and shape that can be launched in a free fall and used as fixed anchoring point by any type of floating structures.

Doyle, et al. (2004) described the centrifuge model test of anchor piles and showed how the results were used as part of the foundation design considerations for Ursa TLP. Four centrifuge model tests were conducted to study the lateral response of large-diameter piles in clay subjected to large lateral displacements. The objectives were to quantify the cyclic response for the lateral loading of two closely-spaced piles loaded in line, and to establish the nature and the extent of any gap that may form between the piles and the soil as a result of static or cyclic loading.

Tang, et al. (2005) presented a study on pile driving fatigue damage during pile installation. A parametric study using the Magnolia TLP, which has eight 96-inch driven piles with a penetration of 313 ft, was performed to assess the effect of soil resistance to driving and hammer efficiency on the driving fatigue damage. The results provided a database and guidelines for the field engineer to control the pile driving fatigue damage by adjusting hammer efficiency when the field pile-driving blow counts were different from those predicted.

Rigzone (2006) reported the world's first permanent SEPLA-based mooring system for the Gomez floating production unit in the GoM. The application in the Gulf was also among the world's first to use polyester ropes, which reportedly provided lower cost and better performance than conventional steel catenary systems.

Colliat (2006) discussed the empirical evaluation and installation of suction piles and plate anchors, which currently were considered as the two main anchor solutions for soft deepwater clays. The author listed some applications of suction piles and plate anchors.

Audibert, et al. (2006) reported a multi-phase research program on torpedo piles. The results of the Deep-Ocean Model Penetrators tests performed during the 1980's were well documented and provided a unique opportunity to calibrate an embedment prediction model. The results of this successful calibration effort and the preliminary results of model torpedo pile were presented in the paper. The authors also described the proposed next phase of the research program, which would involve offshore field tests using a 0.3-m-diameter, 6-m-long torpedo test pile.

Schroeder, et al. (2006) described the laboratory testing and detailed geotechnical design of the anchors for the Mad Dog Spar, which is moored by a taut leg mooring system. The design procedures were explained in this paper, with emphasis on how the undrained shear strength was selected. The governing load cases together with results from holding capacity calculations using an efficient 3 dimensional finite element program were presented. The suction anchor design was performed using load and soil resistance factors in accordance with API RP2SK.

Ozmutlu (2009) described the model testing of drag embedment anchors under laboratory and offshore conditions. The model testing involved both fluke (e.g. Stevpris – Stevshark series) and plate (e.g. Stevmanta VLA series) anchors. Drag embedment fluke anchors are commonly used in catenary mooring systems, while drag embedment plate anchors (i.e. VLAs) are commonly chosen for semi-taut or taut-leg mooring systems. Both anchor types are installed by first lowering the anchor to the seabed and then applying a pull load using a surface installation vessel.

Young, et al. (2009) described a proposed site assessment risk matrix that can be used with existing geophysical and geotechnical data to help evaluate the risk that anchoring problems may occur within the proposed area of a mooring spread. An approach was described for the evaluation of these risks using integrated geoscience data. The site condition assessment matrix can also be updated as the mooring design evolves and as new data become available.

Zimmerman, et al. (2009) wrote about the development and advantage of a new gravity-installed mooring foundation, the OMNI-Max. The author indicated that the anchor could be released from about 50 m above the seafloor, penetrated into the seabed, and was then ready for use. The installation method and relatively small size of the anchor was reported to allow for rapid deployment from a wide range of installation platforms. The omni-directional loading capability were considered as an added benefit beyond installation tolerance, since the foundation can withstand loading from nearly any direction which potentially allows for damaged mooring systems to survive longer during an extreme event.

Lieng, et al. (2010) reported installation of two prototype Deep Penetrating Anchors (DPAs) at the Gjøa Field in the North Sea. The installation of two full-sized 80 ton DPAs in August 2009 marked the end of a technological qualification process for this free-fall anchor concept for mooring offshore floating structures. These anchors are 13 m in length with 4 m wide fins. Maximum pullout capacity is approximately 700 tons. The anchors were used by a mobile drilling unit for drilling and completion of wells at the Gjøa Field. The anchors were installed with less than two degrees tilt and the anchor tip penetrations achieved 24 m and 31 m after being dropped from 50 m and 75 m above the sea floor, respectively.

Gaudin, et al. (2010) presented an experimental investigation into the influence of a keying flap on the keying behavior of plate anchors. After plate anchors are installed under the seafloor, they must be rotated or "keyed" in order to mobilize full anchor capacity. A keying flap attached to the top of the anchor is commonly used to reduce the vertical translation component of the installation path during keying. To quantify the performance of this keying flap and to understand its mechanism, centrifuge tests were performed on an anchor model. Particle Image Velocimetry was employed to monitor the trajectory of the anchor and the behavior of the keying flap through examination of the soil failure mechanism. Results indicated that the keying flap did not affect the anchor trajectory, except for introducing an offset to the loading.

Wong, et al. (2012) presented a series of centrifuge tests undertaken to investigate the performance of a model SEPLA in the typical West African soil condition and under monotonic and various levels of sustained and cyclic loading. The testing process mimicked the operation of the anchor and studied the keying of the anchor and the associated loss of embedment, the combined effect of consolidation and strain softening during sustained loading and the associated loss or gain in capacity, and the cyclic degradation under various levels of cyclic loading. The test results and subsequent analysis demonstrated that SEPLAs could be used for permanent mooring, provided that sustained and peak cyclic loads remain lower than 80% of the ultimate monotonic capacity.

2.2 Design Codes and Standards

2.2.1 Overview

An extensive survey of design codes and standards relevant to FOWT stationkeeping systems is carried out in this study. The reviewed documents are categorized into five subject groups:

- Design codes and standards for FOWTs
- Design codes and standards for stationkeeping systems for floating offshore structures
- Design codes and standards for mooring hardware
- Guidelines for global performance analyses
- Other design codes and standards relevant to stationkeeping systems

2.2.2 Design Codes and Standards for FOWTs

There are only a few of existing codes and standards that specifically address the design of FOWT floating hull structures and stationkeeping systems. A state-of-the-art review of FOWT design concepts and design and analysis methods was reported in the BSEE TA&R Project 669 final report (Yu and Chen, 2012), which also presented case studies, an evaluation of the critical design considerations, and a proposed FOWT design guideline. This subsection summarizes the existing design codes and standards directly applicable to or relevant to the design of FOWT stationkeeping systems.

2.2.2.1 Codes and Standards for FOWTs

- ABS "Guide for Building and Classing Floating Offshore Wind Turbine Installations" (ABS FOWTI Guide) (ABS, 2013)
- Germanischer Lloyd (GL) "Guideline for the Certification of Offshore Wind Turbines" (GL, 2012)
- Lloyds Register "Guidance on Offshore Wind Farm Certification" (LR, 2012)

ABS FOWTI Guide (ABS, 2013) provides criteria for the design, construction, installation and survey of permanently sited FOWTs. It addresses three principal areas: the floating support structure; the stationkeeping system; and onboard machinery, i.e. equipment and systems that are not part of the Rotor-Nacelle Assembly (RNA). The design environmental conditions and design load cases specified in the Guide are developed on the basis of IEC 61400-3 standards in conjunction with a number of revisions and refinements to address the uniqueness of FOWTs. In addition to the design load cases, a set of survival load cases are defined for a further check of the robustness of FOWT stationkeeping systems. The guide also provides the design criteria for the mooring lines and tendons of FOWT stationkeeping systems, as well as the design criteria for the anchoring system and mooring components.

Germanischer Lloyd (GL) “Guideline for the Certification of Offshore Wind Turbines” (GL, 2012) applies to the design, assessment and certification of offshore wind turbines and offshore wind farms. The guideline’s latest edition expands its scope to address FOWTs. Design criteria for FOWT stationkeeping systems are mostly obtained by referencing to the design codes or standards used in the offshore oil and gas industry.

Lloyds Register (LR) “Guidance on Offshore Wind Farm Certification” (LR, 2012) provides LR’s certification criteria for offshore wind farms. Design requirements for FOWT stationkeeping systems are obtained by referencing to the design codes or standards used in the offshore oil and gas industry.

2.2.2.2 Other Codes and Standards Relevant to FOWTs

A list of other codes and standards, which are either directly referenced by FOWT codes and standards reviewed in Section 2.2.2.1, or highly relevant to FOWTs, is given as follows:

- IEC 61400-3 “Wind turbines – Part 3: Design Requirements for Offshore Wind Turbines” (IEC, 2009)
- ABS “Guide for Building and Classing Bottom-Founded Offshore Wind Turbine Installations” (ABS, 2013)
- DNV-OS-J101 “Design of Offshore Wind Turbine Structures” (DNV, 2012)
- IEC 61400-1 “Wind Turbines – Part 1: Design Requirements” (IEC, 2005)
- Germanischer Lloyd “Guideline for the Certification of Wind Turbines” (GL, 2010)
- BSEE TA&R Project 670 Final Report “Design Standards for Offshore Wind Farms” (Yu, et al., 2011)

2.2.3 Codes and Standards for Design of Stationkeeping Systems for Floating Offshore Structures

The following design codes and standards for the design of stationkeeping systems for floating offshore structures are reviewed:

- API RP 2SK (API, 2008)
- ISO 19901-7 (ISO, 2005)
- ABS "Rules for Building and Classing Single Point Moorings" (ABS SPM Rules) (ABS, 1996)

API RP 2SK (API, 2008) addresses the design, analysis and operation of station-keeping systems for floating structures. Different design requirements for mobile and permanent moorings are provided. The document also provides a rational design and analysis method which, when combined with site-specific environmental conditions and the characteristics of the floating structure to be moored, can be used to determine the adequacy and safety of the mooring system.

ISO 19901-7 (ISO, 2005) specifies methodologies and requirements for the design, analysis and evaluation of stationkeeping systems for floating structures and site-specific applications of mobile offshore units. It addresses various types of stationkeeping systems including the spread moorings (catenary, taut-line and semi-taut-line moorings), single point moorings, dynamic positioning systems, and thruster-assisted moorings. Descriptions of the characteristics and typical components of these systems are also provided.

ABS SPM Rules (ABS, 1996) provide the requirements of design, construction and survey of single point moorings. A single point mooring is a system which permits a vessel to weathervane while the vessel is moored to a fixed or floating structure that is anchored to the seabed by a rigid or an articulated structural system or by catenary spread mooring. Examples of such system are CALM (Catenary Anchor Leg Mooring), SALM (Single Anchor Leg Mooring), tower mooring, etc.

2.2.4 Codes and Standards for Mooring Hardware

The following design codes and standards for the mooring hardware of the stationkeeping systems are reviewed in this study:

- API Specification 2F (API, 1997)

- API RP 2SM (API, 2007)
- API RP 2I (API, 2008)
- API RP 9B (API, 2011)
- API Specification 9A (API, 2011)
- ABS "Guide for the Certification of Offshore Mooring Chain" (ABS Offshore Mooring Chain Guide) (ABS, 2009)
- ABS "Guidance Notes on the Application of Fiber Rope for Offshore Mooring" (ABS Fiber Rope Guidance Notes) (ABS, 2011)

API Specification 2F (API, 1997) covers specifications of flash-welded chain and forged kenter connecting links used for mooring offshore floating vessels, such as drilling vessels, pipe lay barges, derrick barges, and storage tankers.

API RP 2SM (API, 2007) provides guidelines on the use of synthetic fiber ropes for offshore mooring applications. It also highlights the differences between synthetic rope and traditional steel mooring systems, and provides practical guidance on how to handle these differences during mooring system design and installation. This document applies to synthetic fiber ropes used in the form of taut leg or catenary moorings for either permanent or temporary offshore installations.

API RP 2I (API, 2008) provides guidelines on inspections of mooring components of mobile offshore drilling units (MODUs) and permanent floating installations. Part of the guidelines may also be applicable to mooring systems of other floating vessels such as pipe-laying barges and construction vessels and to secondary or emergency moorings such as moorings for jack-up units, shuttle tanker moorings, and dynamic positioning (DP) vessel harbor mooring.

API RP 9B (API, 2011) addresses typical wire rope applications in the offshore oil and gas industry. API Specification 9A (API, 2011) specifies the minimum requirements and acceptance criteria for the manufacture and testing of steel wire ropes not exceeding rope grade 2160 and for the application to the petroleum and natural gas industry.

ABS Offshore Mooring Chain Guide (ABS, 2009) provides the criteria for material, design, manufacture, and testing of offshore mooring chain and accessories intended to be used for temporary and permanent applications, such as: mooring of mobile offshore units, mooring of floating production units, mooring of offshore loading systems, and mooring of gravity based structures during fabrication.

ABS Fiber Rope Guidance Notes (ABS, 2011) provides the criteria for design, material, testing, manufacturing, installation and subsequent survey of fiber ropes to be used as mooring components in permanent and temporary offshore mooring systems. In view of the influence of rope properties on mooring system performance, the document describes how rope testing, mooring analysis and installation should be integrated to provide a consistent mooring system design methodology.

2.2.5 Guidelines for Global Performance Analyses

The following guidelines for global performance analyses of floating offshore structures are reviewed:

- Deepstar Report 5401-2 (Deepster, 2003)
- Deepstar Report 6401-5 (Deepstar, 2004)
- API RP 2SK (API, 2008)

Deepstar Report 5401-2 (Deepster, 2003) is a product of a multi-year research project to assess the industry's capability to simulate deepwater (beyond 3,000ft water depth) and ultra-deepwater (beyond 6,000 ft water depth) floating structures through model testing and numerical analyses. The guideline provides guidance on coupled analyses of deepwater floating structures and riser/mooring systems, taking into account the current limitations of model tests in verifying these systems. The guideline represents the first attempt in deriving an industry consensus on analysis methods and model test verification for deepwater floating systems, and hence the document should be considered as a draft only and used with caution.

Deepstar Report 6401-5 (Deepstar, 2004) aimed at improving the understanding of critical issues identified by the analysis and model testing studies in previous DeepStar and related studies. It was also intended to support the development of the DeepStar Global Performance Guidelines, which were eventually adapted to become a part of API RP 2SK (API, 2008). The study included a survey and evaluation of current industry practice as well as a parametric investigation of the effects of slender bodies and other important parameters on floating vessel responses.

API RP 2SK (API, 2008) contains “Global Analysis Guidelines for Deepwater Floating Systems” in Appendix I, which is based on the outcome of DeepStar Phase VI research. The global analysis guidelines provided in Appendix I were derived from the DeepStar studies and other industry experience, and have gone through a lengthy process of consensus building. The objective of this Appendix is to provide general design and analysis principles. It is not the purpose of this Appendix to dictate a specific approach for global analysis. Various approaches have been used in the past and this trend is expected to continue. More importantly, this Appendix points out the critical parameters as well as the advantages and limitations of various approaches for global analysis. It also recommends the needs of future technology development.

2.2.6 Other Relevant Codes and Standards

The following design codes and standards are relevant to the design of floating offshore structures:

- API RP 2FPS (API, 2011)
- API RP 2T (API, 2010)
- ISO 19900 (ISO, 2002)
- ISO 19904-1 (ISO, 2006)

The following documents address the metocean design criteria for floating offshore structures:

- ISO 19901-1:2005 (ISO, 2005)
- API Bulletin 2INT-MET (API, 2007)
- API RP 2A-WSD (API, 2007)

The following documents address geotechnical design for floating offshore structures:

- API RP 2GEO (API, 2011)
- API RP 2T (API, 2010)

Guidance on the specific subjects that are relevant to the design of FOWTs can also be founded in appropriate classification society criteria.

2.3 Design and Analysis Software

A state-of-the-art review of the simulation software for FOWTs was reported in the BSEE TA&R Project 669 final report (Yu and Chen, 2012). The review covered FAST, CHARM3D + FAST, SIMO/RIFLEX + HAWC2, Flex 5, GH Bladed, TimeFloat + FAST, and a few other FOWT simulation software and modeling methods. As a supplement to the previous review, this subsection summarizes the results of a literature survey of other recently published papers relevant to FOWT simulation tools.

Masciola, et al., (2011) investigated the accuracy and stability of the FAST-OrcaFlex software package. Developed and maintained by the National Renewable Energy Laboratory (NREL), FAST is a collection of computer programs for modeling land-based and offshore wind turbines. The original FAST program implemented the quasi-static continuous cable theory to model the FOWT mooring lines. The authors concluded that improved modeling fidelity was achieved through the program interface that links FAST with OrcaFlex, which is commercial software for modeling mooring line dynamics using the finite element method. In the combined FAST-OrcaFlex program, FAST is responsible for calculating aerodynamic loads, the effect of the turbine control system, platform global motions, and elasticity of the wind turbine and the tower, while OrcaFlex models the mooring lines and hydrodynamic effects. The stability, usability, and functionality of the interface program, FASTlink, were assessed.

Ormberg, et al. (2011) described the upgrades of SIMO/RIFLEX computer program to include the capability of modeling aerodynamic forces on elastic structural members. SIMO is a computer code for the simulation of marine structures and operations. RIFLEX is a nonlinear time-domain hydrodynamics analysis program for slender marine structures. The combined SIMO/RIFLEX program has the capability of performing a fully coupled analysis, where one or more rigid-body floating structures are integrated with a dynamic model of the mooring and riser systems. The expanded version of SIMO/RIFLEX incorporates Blade Element Momentum (BEM) theory and the capability of simulating the turbine control systems for blade pitch and generator torque. The FOWT global responses are calculated by the nonlinear time-domain analysis, which is able to achieve dynamic equilibrium at each incremental analysis time step and provide a means of modeling dynamic interactions among the blade dynamics, the mooring dynamics and the tower motions.

Utsunomiya, et al. (2012) introduced a dynamic analysis program for FOWTs. The program consists of a multi-body dynamics solver (MSC.Adams), an aerodynamic force evaluation library (NREL/AeroDyn), a hydrodynamic force evaluation library (In-house program named SparDyn), and a mooring force evaluation library (In-house program named Moorsys). Simulation results were in general found to agree well with the experimental data, where the wind, current and wave were applied simultaneously. When the vortex induced motions occurred, the current loads and cross flow responses (sway and roll) appeared to be underestimated in the simulation, where the effect of the vortex induced motions was not considered.

Yan, et al. (2012) carried out coupled hydro-aero dynamic response analyses of an FOWT. A numerical code, known as COUPLE, was linked to FAST to model the dynamic interactions. Two analysis approaches, i.e. the fully coupled method and limited coupled method, were evaluated. In the fully coupled method, the two codes were linked at each time step to solve the overall floating system. The limited coupled method assumes wind loads are from a turbine installed on top of a fixed base. The comparison between the predicted global motions using the coupled method and those obtained using the limited coupled method exemplified the importance and advantages of using the coupled analysis in the FOWT design.

Simulation software for global performance analyses and mooring system designs for offshore oil & gas platforms are relatively mature. Deepstar Report 6401-5 (Deepstar, 2004) provided a comprehensive review and evaluation of well-known global performance analysis programs including WAMIT, MIMOSA, MULTISIM, WINPOST, REFLEX-C, AQWA, ARIANE, CABLE3D, DYNFLOAT, SEASOFT, COSMOS, RAMS, and DEEPCAT. The evaluation was carried out to assess the performance of these programs in un-coupled, semi-coupled and fully coupled analyses in both the frequency domain and the time domain. The definition of each type of global performance analysis methods can be found in Section 5.6.8. Although these programs may not be directly applicable, they could be used to calculate certain hydrodynamic coefficients required as the input to FOWT global performance analyses and could also be used as the bases to develop FOWT simulation programs.

2.4 Global Performance Analysis Procedures and Methodologies for FOWTs

A state-of-the-art review of design procedures and analysis methodologies for FOWTs is performed in this subsection. The review also covered those topics, including wind farm wake models, aeroelastic stability and aerodynamic damping, and model testing, that are considered critical to the simulation of FOWT global responses and the design of FOWT stationkeeping systems.

2.4.1 Analysis Procedures and Methodologies

Suzuki and Sato (2007) investigated the effect of motion of a floating platform on the strength of turbine blades, a key issue in designing FOWTs. The effect of platform motions on the bending moment in the blade was investigated using the numerical codes. Inertial load on the turbine blade induced by the platform motions and turbine rotation was calculated and verified by an experiment that used a rotating rod on an oscillating tower. It was concluded that the increase in the maximum load on the blade due to platform motions was relatively small, while the increase in the fatigue load could be significant. The authors indicated that the amplitude of the platform's pitching motion should be small in order to allow land-based wind turbines (i.e. RNAs) to be installed on the floating platform without major modifications.

Suzuki, et al. (2009) studied progressive drifting of FOWTs and the associated risk to the offshore wind farm. The authors indicated that the mooring system failure of an FOWT could result in excessive drift of that FOWT, which could in turn collide with neighboring FOWTs in an offshore wind farm, and might cause progressive drifting of other FOWTs. Quantitative risk of various wind farm arrangements and the effect of safety factor used in the mooring design were estimated. An improved risk assessment model was reported in Suzuki, et al. (2011). Deterioration and increase in variance of mooring line strength during the service life was modeled. Effect of pullout and drag of anchors and failure of mooring lines were also investigated.

Lijima, et al. (2010) presented a numerical procedure for the fully coupled aerodynamic and hydroelastic time-domain analysis of an FOWT concept, where two wind turbines were installed on the floating support structure. Hydroelastic response analyses were performed with consideration of combined wave and wind loads. The results were compared with those considering waves only and those with winds only to investigate the coupling effects on stresses and global motions.

Berthelsen (2011), and Fylling and Berthelsen (2011) introduced an integrated design tool WINDOPT for optimization of floating support structure and mooring system for a given wind turbine size and given design requirements. A Spar was used as an example for the optimization design.

Karimirad and Moan (2011) discussed the control-induced negative damping issue for a Tension Leg Spar (TLS) similar to the SWAY concept. The coupling effect was believed to be inevitable in such type of floating structures as the aerodynamic and hydrodynamic damping and excitation forces are strongly affected by each other through the relative motions. It was found that pitch resonant response was sensitive to the negative damping generated by the collective effect of the blade pitch controller operating in the over-rated wind speed region. The author concluded that, by tuning the controller gains, the negative damping could be eliminated.

Kvittem, et al. (2011) studied fatigue damage at the base of the tower of a semi-submersible wind turbine using coupled time-domain analyses. The software employed was SIMO/RIFLEX along with TDHmill, which modeled the wind thrust force and gyro moment on the wind turbine as point loads at the tower top. Short-term environmental conditions were chosen from a joint wind and wave distribution for a site in the Northern North Sea. Simulations showed that turbulent wind dominated the responses at low wind speeds and that the response spectral density functions appeared to be very wide-banded. For wave dominated responses, the response spectra have lower bandwidth,

Luxcey, et al. (2011) presented the results of a benchmark study of upgraded SIMO/RIFLEX computer program capable of taking into account aerodynamic forces on elastic structural members. The first part of this paper focused on the consequences of including the blades and tower elasticity and the dynamics of the mooring lines. The second part of the paper presented a benchmark study as a part of the Offshore Code Comparison Collaboration (OC3). The authors concluded that quasi-static catenary equations combined with the damping matrix were sufficient to capture the global motions of the FOWT subjected to the environmental conditions similar to those used to determine the linear damping, although more sophisticated finite element models could yield more accurate predictions of the mooring line tensions. The authors also concluded that it was crucial to correctly model the tower elasticity in a simulation intended to calculate the tower loads. However, when FOWT global motions or the performance of power generation is the matter of concern, using a rigid tower model appeared to be acceptable.

Philippe, et al. (2011) presented a comparison of the time- and frequency-domain analysis for an FOWT. A user defined module for the FAST program was developed to calculate hydrodynamic and mooring loads on the structure. Both time- and frequency-domain models were based on diffraction/radiation hydrodynamic theory. Mooring loads on the system were modeled with a mooring stiffness matrix. Hydrostatic forces were taken into account with a hydrostatic stiffness matrix. The wind turbine influence on the platform was modeled by equivalent inertia, damping and stiffness matrices. The authors studied the effect of quadratic roll damping on the global motions. As expected, quadratic damping reduces the value of roll and pitch motions around natural frequency. It also reduces yaw motions, because natural modes were coupled in roll and yaw.

Sultania and Manuel (2011) focused on the prediction of 50-year response values for a 5-MW spar buoy-supported FOWT. Long-term loads were estimated using inverse reliability procedures. For all the 116 candidate sea states, 25 ten-minute simulations were carried out and ten-minute extremes of the fore-aft tower base bending moment, the out-of-plane blade root bending moment, and the platform surge motion were computed. Fractiles of the response that was consistent with the desired return period of 50 years were estimated for the sea states. 50-year response levels of tower loads, blade loads, and platform surge motions were estimated and associated critical sea states were identified.

Perdrizet and Averbuch (2011) presented a methodology to assess the short-term and long-term failure probabilities of the extreme response of an FOWT subjected to wind and wave induced loads. This method was applied to the OC3-Hywind model used in Phase IV of the OC3 study.

Brommundt, et al. (2012) studied cost minimization of catenary mooring systems for a semi-submersible FOWT. Frequency-domain analyses were performed, where environmental loads due to wind, waves and current were considered separately. The optimization tool was able to determine the optimum mooring line orientations and lengths, constrained by ultimate load conditions, limits on platform movement and seabed conditions.

Matha, et al. (2012) explored analysis of the aerodynamic inflow conditions on a representative catenary moored FOWT. The authors indicated that, due to platform motions, large (5 MW class) and very large offshore (6-10 MW class) wind turbines installed on floating structures could have different offshore atmospheric boundary layer, higher average wind speeds, lower turbulence levels and increased blade roughness (sea salt, erosion, etc.) that could result in distinctive flow conditions not seen for onshore turbines.

Mostafa, et al. (2012) investigated the effect of the gyro moment on FOWT motions using a 1/360 scale model tests in various regular waves. One set of tests were performed to study the interaction between the rotary motion of the wind turbine blade and the dynamic motion of a Spar-type FOWT at small angle of inclination in the regular waves. Another set of tests were carried out to evaluate the interaction between the change of blade inertia and the FOWT motions. The experimental results agreed well with the result of numerical simulations. It was found that yaw response was reduced with the increase of moment of inertia of the rotating blades. It was also found that the inclination appeared to only affect (reduce) the yaw motion.

Philippe, et al. (2012) presented an aero-hydro-elastic model approach for a semisubmersible FOWT, Dutch Tri-Floater. The study aimed at evaluating the effect of different hydrodynamic modeling options on the results of aero-hydro-elastic simulations of a semi-submersible FOWT, with special attention placed on the effect of viscous drag, nonlinear Froude-Krylov loads (calculated on instantaneous wetted surface), and wave directionality.

Obhrai, et al. (2012) performed a review of current guidelines and research on wind modeling for designing offshore wind turbines. Offshore wind data from a met tower in the North Sea were used to demonstrate the importance of including stability (i.e. unstable, stable and neutral wind conditions) and thermal effects in the offshore wind modeling. The data were also used to demonstrate importance of non-logarithmic wind profiles.

Krause and Muskulus (2012) presented a model describing the mean tower shadow effect of an upwind turbine mounted on top of a full-height truss tower. A potential flow solution was assumed for a number of two-dimensional cross-sections of cylinders at different heights of the tower. The numerical results were compared with the flow field obtained by simple superposition of the potential solution for each circular member, showing the inadequacy of the latter. Equivalent models were developed, in which the multi-member tower was approximated by a single cylinder. By choosing the diameter of this cylinder appropriately, the flow field was determined in the blade passing area upstream of the tower. Existing wind turbine simulation software could therefore be used for load calculations of the wind turbine supported by full-height truss towers.

Song, et al. (2012) reported a preliminary study on the dynamic behavior of a 5-MW barge-type FOWT. Numerical simulations were carried out to calculate the motion and load responses of the FOWT with variations of mooring type and line extensional stiffness. The motion responses of substructure with catenary mooring were almost not affected by line extensional stiffness while the taut mooring was shown to affect surge and pitch motions at some frequencies. The shape of the dynamic loads of the catenary mooring in the frequency domain were similar to a Gauss function, while the dynamic loads of the taut mooring in the frequency domain were decreased exponentially. The influence of the magnitude of line extensional stiffness on the mooring dynamic loads varied with the types of mooring system.

Go, et al. (2012) presented time-domain analysis of the Spar-type floating offshore platform. Motion responses of the platform were investigated with changes of depth-diameter ratio and water plane area. The base model used was adapted from the OC3 Hywind Spar hull geometry. A new model for reducing motion responses was suggested. Effects of mooring connection points on motion responses were investigated.

Jiang, et al. (2012) calculated the steady state responses of a parked 5-MW Spar-type FOWT with pitch fault using the HAWC2 code. Nonlinear mooring line forces were fed to HAWC2 at each incremental analysis time step through the dynamic link library. Aerodynamic loads were calculated based on the steady-state airfoil data of lift and drag coefficient. Hydrodynamic forces were calculated based on Morison equation considering the instantaneous position of the platform as well as heave excitation based on linear potential theory.

Kvittem and Moan (2012) analyzed a semi-submersible FOWT with three different mooring line configurations using the linearized mooring line model and the more advanced finite element mooring line model. The analyses were carried out using a numerical tool which comprises the hydrodynamic analysis module, SIMO/RIFLEX, and the aerodynamic analysis module, AeroDyn. Significant differences were identified in the standard deviations for sway and yaw motions and the tower sideway bending moment calculated using the two different mooring line models.

Ormberg and Bachynski (2012) described the SIMO/RIFLEX computer program extension to incorporate Blade Element/Momentum (BEM) theory and the effect of control systems for blade pitch and electrical torque. The developed code was denoted as RIFLEX-BEM. The fixed tower case study was carried out to compare the responses of identical structural models and control systems in conjunction with different aerodynamic codes.

Jagdale and Ma (2012) examined the importance of nonlinear wave forces for a TLP-type FOWT. Non-linear equations of motions and forces were formulated and solved to demonstrate the significance of the nonlinear wave force components. A limited comparison with experimental data was also presented to show the acceptable accuracy. The wind loads on the turbine was calculated using BEM theory; the wave forces were determined using Rainey's slender body theory combined with drag force calculation procedure based on Morison's equation. It was shown that the magnitudes of all nonlinear wave forces are strongly dependent on wave conditions and cannot be neglected in general.

Bae, et al. (2012) presented a study on the effects of tower elasticity and aero-loading using an aero-elastic-control-floater-mooring coupled dynamic analysis program, CHARM3D-FAST. A monocolumn TLP-type FOWT with a 5-MW turbine was selected as an example. It was shown that the interaction between an elastic tower and platform motion was very important in view of the shift of natural frequencies as well as the aero-dynamic excitations and damping.

Shadman and Akbarpour (2012) investigated the response of an FOWT with a barge-type support structure in which a V-Shaped tuned liquid column damper was installed. A modified version of the FAST program was employed to perform the global response analyses.

Ramos (2012) proposed a state feedback aerodynamic controller for the stabilization and reduction of platform/tower pitch vibrations of a Spar-type FOWT. The controller was synthesized from a linearized rigid body model developed for the NREL 5-MW offshore wind turbine operating at the above rated condition. Wind turbulence and wave induced loads were obtained from BEM theory and Morison's equation, respectively. The simulation results showed that the proposed nonlinear control system yielded significant vibration reduction in comparison to a proportional-integral controller.

Bae, et al. (2012) presented a coupled analysis method for FOWTs in maximum operational and survival conditions. The conceptual design of Hywind Spar with 5-MW turbine was studied as an example using the coupled FOWT dynamic analysis program, CHARM3D-FAST. The maximum operational condition considered in the study was the maximum operational condition defined by the cut-out wind speed (25m/s) at hub height and the associated wave and current conditions. The survival condition represented the parked wind turbine in the extreme environmental conditions. The author concluded that there were different critical design environments for different structural components of the FOWT. In the case of Hywind Spar, it was found that the platform motions, tower-top accelerations, tower-base shear forces and moments in the survival condition were greater than those in the maximum operational condition. On the other hand, some local structural responses such as the blade-root shear forces and bending moments were found much larger in the maximum operational condition than in the survival conditions.

Karimirad and Moan (2012) compared the dynamic responses and performance of two Spar-type FOWTs, DeepSpar and ShortSpar, in deep and intermediate water depths. SIMO/RIFLEX and TDHMILL3D was used to perform the coupled wave- and wind-induced analyses. The total mass (the structural mass plus the ballast) of the ShortSpar was about 35% less than that of the DeepSpar, while the statistical characteristics of the power generated were found almost the same.

Kim and Manuel (2012) presented a framework aimed at estimating the potential damage to an offshore wind farm from hurricanes. The authors indicated that synthetic storm tracks should be simulated using available tropical storm data and a hurricane intensity evolution model should be developed for each of the tracks as they pass regions close to the wind farm site of interest. Based on the realized intensity levels, wind fields and associated wave kinematics should be simulated as the storm evolves and used to estimate wind speed probability distributions and wind turbine loads analyses.

Nihei, et al. (2012) discussed the effects of elasticity of the tower and the blades on global responses to a TLP-type FOWT supporting a 5-MW wind turbine. The authors performed experiments using the scaled model that was built to maintain the similarity in elasticity. The motions of the TLP, loads in tension legs and the bending stresses in tower and blades from waves and wind were measured. The author also evaluated the effects of the tower elasticity to the loads in the tension legs using a simplified beam theory.

Bachynski and Moan (2012) proposed a parametric study method for optimization of FOWTs. Three main steps were included in the proposed method: identifying four feasible points in the design space using a simple spreadsheet-based parametric design tool; performing coupled hydro-aero-servo-elastic time-domain analyses for the selected four designs; and comparing analysis results with the estimation obtained using a frequency-domain predictive tool. A single-column

TLP-type FOWT with three or four spokes, intended to support the NREL 5-MW wind turbine, was employed to demonstrate the proposed optimization method.

Bracchi and Krogstad (2012) presented measured and calculated yaw moments of a wind turbine with yaw errors. A three-bladed horizontal axis wind turbine model was tested in a wind tunnel. The yaw moments at fixed yaw angles were measured for the same model with the rotor in both upwind and downwind configurations. The yaw effects were also simulated using the FAST program. Special attention was given to the differences in the yaw behavior of the turbine in the upwind and downwind configurations and the ability of available simulation tools to predict the yaw moments.

2.4.2 Wind Farm Wake Models

Renkema (2007) presented a thesis to validate the wake models included in WindPRO (a simulation tool for wake effects) and other wake models using measurements at operating wind farms and wind tunnel experiments. Wind turbine wakes are generally divided into the near wake, where the influence of the separate rotor blades can be distinguished, and the far wake. Typical models describing the near wake are the asymptotic acceleration potential method, vortex wake models and generalized actuator disc models. Far wake models include kinematic wake models (also called explicit models) and field models (or implicit models).

Barthelmie, et al. (2011) studied flow and wakes in large wind farms. The authors performed a comprehensive model evaluation using the measurements from the Horns Rev and Nysted offshore wind farms. A number of existing models were assessed and some were further improved. The main observations from both wind farms showed that wake losses in the center of large offshore wind farms were greater than those predicted using the standard wind farm models, which could be corrected using measured data sets to improve their accuracy. Analyses of the wind farm data also showed that, although wind speeds governed the wake development, turbulence and atmospheric stability could also play an important role in determining the magnitude of wake losses in an offshore wind farm.

2.4.3 Aeroelastic Stability and Aerodynamic Damping

Kühn (2001) studied the method for estimating aerodynamic damping in his thesis work.

The first method is a closed-form linearization approach. The closed-form estimation reflects two main influences on the damping: firstly the slope of the lift coefficient versus angle of attack, and secondly the eigen-frequency and modal mass of the support structure. The slope of the lift coefficient versus the angle of attack can vary from approximately 2π for an attached flow to zero or even negative values for a separated flow. For illustration, the author evaluated a wind speed just below the rated wind speed using the DUWECS simulation code. The angle of attack at the inner four blade sections was large enough such that partial flow separation and reduction of the slope of the lift coefficient occurred and, as a result, the estimated aerodynamic damping was reduced.

The second method is based on numerical linearization. A numerical linearization is capable to model more comprehensive rotor aerodynamics, unsteady effects, a larger number of degrees of freedom and the dynamics of the control system. In general such an option is not implemented in standard wind turbine design tools used for dynamic load calculations. Special aero-elastic codes or extended design tools may be needed.

The third method is based on nonlinear time-domain simulations. A number of methods are available based on evaluating the steady state response under harmonic excitation, analyzing the transient decay of free vibrations, or using response spectral analyses.

Hansen, et al. (2006) presented a comprehensive review of wind turbine aeroelasticity analysis methods ranging from the relatively simple BEM method to sophisticated CFD simulation. The methods with intermediate complexity, such as vortex and panel methods, were also reviewed. Discussions and examples about the coupling between the aerodynamic and structural modeling were demonstrated in the context of possible instabilities.

Van Der Tempel (2006) focused on the design of the support structure. In this thesis a frequency-domain method was developed for the wind turbine fatigue assessment. A key issue in the accuracy of the method was the effect of the turbine's aerodynamic damping on the support structure dynamics. Several calculation methods for this damping were tested and showed to give reasonable results.

Bir and Jonkman (2007) presented results of stability analyses for both onshore and offshore configurations over a range of operating conditions following a brief review of the stability concept and the stability analysis approach. Aeroelastic instabilities are distinct from resonances and vibrations and are potentially more destructive. The authors indicated that future turbine designs would likely be stability-driven in contrast to the current loads-driven designs, because of the application of more flexible designs, especially the torsionally-flexible rotor blades, material and geometric couplings associated with smart structures, and hydrodynamic. The author studied the aeroelastic stability of a three-bladed 5-MW conceptual wind turbine mounted atop a floating barge with catenary moorings. The analysis results showed that the instability involving side-to-side motion of the tower, edgewise motion of the rotor blades, and yawing of the platform could occur when the turbine in the parked (idling) condition.

Staino, et al. (2012) proposed an actuator control of edgewise vibrations in wind turbine blades. Edgewise vibrations with low aerodynamic damping are of particular concern in modern multi-megawatt wind turbines, as large amplitude cyclic oscillations may significantly shorten the life-time of wind turbine components, and even lead to structural damage or failures. In this paper, a new blade design with active controllers was proposed for controlling edgewise vibrations. Numerical simulations were carried out using a 5-MW three-bladed horizontal-axis wind turbine in order to study the effectiveness of the proposed active controlled blade in reducing edgewise vibrations.

Damgaard, et al. (2012) reported experimental investigations of the first natural bending frequency and damping ratio of an offshore wind turbine located in the North Sea. Simple Fourier transformation and least square fitting to the vibration decay of ten rotor stop tests were employed to evaluate the dynamic properties of the wind turbine structure. The total system damping ratio was expressed as a linear combination of steel hysteretic damping ratio, damping ratio from the tower oscillation damper, aerodynamic damping ratio from the tower, wave making radiation and viscous hydrodynamic damping ratio due to the presence of water, and soil damping ratio. The author concluded that, in general, significant research that could lead to better understanding of the dynamic properties of offshore wind turbine structures was required.

2.5 FOWT Model Testing

Seebai, et al. (2009) conducted a model test study on a Spar platform designed to support a 5-MW wind turbine considering a water depth of 300 m. The 1:100 scale model tests of two Spar configurations, SPARD and SPAR1.5D, were conducted in a wave basin. For SPARD, the counterweight ballast tank at the bottom has the same diameter as the Spar hull; whereas for the SPAR1.5D configuration, the diameter of the counterweight ballast tank is 1.5 times the Spar hull diameter. The two Spar models were moored by four mooring lines. It was found that the over-sized counterweight disc at the bottom of SPAR1.5D would result in increased added mass, damping and wave forces, especially in the heave mode. The effect of the increased diameter did not change the surge motion significantly, even up to about 25 s. Hence, it seems beneficial to adopt the over-sized counterweight ballast tank at the bottom.

Chujo, et al. (2011) performed experiments in a wind tunnel and a wave basin for a Spar-type FOWT. The forced pitching experiments were carried out in a wind tunnel to evaluate the performance of upwind and downwind wind turbines. The wave basin tests were performed to identify the relationship between the location of the mooring line attachment point and the Spar motions in waves and to study the influence of turbine blade pitching angle on the SPAR motions in waves. A mechanism was installed on the scale model of the wind turbine to control the pitch angle of the blades. Through the blade pitch angle control tests, the negative damping effect was observed. By modifying the blade pitch angle control algorithm, the fluctuation of the Spar's pitch motion and rotor speed fluctuation were reduced.

Nihei and Fujioka (2010) developed a TLP-type FOWT concept to support a 5-MW wind turbine and performed experimental tests using a 1/100 scale model. The tests were carried out for the turbine in power production at the rated and cut-out wind speeds with associated waves and the parked turbine in the storm conditions. The TLP hull consisted of a cylindrical column and three extended pontoons. The mooring system comprised 6 tendons. The rotor blade assumed the NACA 4412 design. Based on the experimental results, the authors concluded that: 1) in the case of coexisting wave and wind conditions, the aerodynamic effect stabilized the TLP pitch motion; 2) the aerodynamic effect reduced vibrations of the mooring lines and the springing (second or third order force) when the FOWT was subjected to coexisting wave and wind conditions; 3) the estimated amount of reduced electricity generation was up to about 6% due to hull heeling.

Nihei, et al. (2011) developed two TLP-type FOWT prototypes (Model 350 and Model 550), where the mooring system consisted of 6 tendons made of steel pipes. Tank tests using 1/100 scale models were conducted under combined wind and wave conditions. The tests were carried out for the turbine in power production at the rated and cut-out wind speeds with associated waves and the parked turbine in the storm conditions. The motion characteristics, the rotor rotation speed, and the tendon tensions were measured. It was observed that in the case of Model 550, the tendons were able to maintain sufficient tension, while slacking and capsizing of Model 350 occurred at some wind speeds. It was found that the TLP heel motion and blade rotation caused a global yaw moment on the TLP. In the case of Model 350, the TLP yaw motion reached about 30 degrees; together with heeling moment from wind, the lee-ward tendon became slack and the TLP lost stability and capsized.

Kokubun, et al. (2012) presented model test of a Spar-type FOWT prototype, which comprised a steel-concrete hybrid hull structure and a spread mooring system consisting of three catenary chains. Four fins were attached around the hull to suppress yaw motions. In order to confirm the safety of the FOWT in storm condition, experiments using a 1/34.5 scale model were carried out. The paper reported the results of the experiments under three directional combinations of wind, wave and current in a 50-year return storm. Wave and current directions were assumed collinear, 90-degree misaligned, and 180-degree misaligned to the given wind direction which was always transverse to the rotor to give the maximum wind force. Since the water depth of the basin was not sufficient to model the water depth at full scale, mooring chains were instead modeled by springs and wires to capture the horizontal characteristics of the mooring system. Blades were modeled as flat plates and were fixed to the hub under feathering condition. A one-mooring-line-broken case was also tested by cutting one line on the weather side during the experiment with collinear wind, wave and current condition.

Jain, et al. (2012) investigated scaling laws that were adopted for the DeepCwind project for testing three different 1/50 scale FOWT models subjected to combined wind and wave loading. The 1/50 scaling was performed based on the Froude scaling laws, which are commonly used for offshore structures. The scaling approach was verified through numerical analyses using the FAST program and by comparing the consistency of simulation results between the scaled model and the full scale FOWT. Since the Froude scaling approach does not maintain proper Reynolds number scaling, the implications of this issue were discussed in the paper. The authors concluded that the scaling laws adopted by the DeepCwind project were an appropriate approach for performing scaled model tests even if there were issues with the Reynolds number.

Stewart, et al. (2012) compared the simulations using the FAST program to the model test results of DeepCwind TLP. A 1/50th-scale TLP-type FOWT was designed based on Froude scaling. The scaled FOWT model was extensively tested in a wave basin to provide data to calibrate and validate a full-scale simulation model. The data gathered include measurements from static load tests and free-decay tests, as well as a suite of tests with wind and wave forcing. A numerical analysis model of the full-scale FOWT was created for the global performance analysis using the FAST program. The numerical analysis results were compared with the test results scaled up to the full scale.

Martin, et al. (2012) presented a unified methodology for using Froude scaling in model tests of FOWTs subjected to combined wind and wave loading. An overview of the scaling relationships employed for the environment, floater and wind turbine were presented. The authors also explored the methods for creating a high-quality, low turbulence Froude scale wind environment in a wave basin to facilitate simultaneous application of wind and waves to the scaled FOWT model. The difficulties in scaling the highly Reynolds number dependent wind turbine aerodynamics was studied. Methods for tailoring the turbine and wind characteristics were developed to best emulate the full scale condition. The proposed scaling methodology was demonstrated using the results from a 1:50 scale FOWT model testing.

Gueydon and Weller (2012) reported a numerical study of a semi-submersible-type FOWT and compared the numerical analysis results with the 1:50 scale model test measurements. The numerical model was calibrated using the model test results for static loading and decay tests. Two wave-only conditions, including a white noise sea state and an operational sea state without wind, were applied in the tests. A steady wind and a combined wind and wave condition were also tested. The numerical model was able to simulate the surge drift behavior of the FOWT model in the operational sea state with a steady wind. However the time traces of the simulated pitch rotation did not match the measurements, possibly due to the omission of the rotor dynamic effects.

Koo, et al. (2012) described FOWT model tests based on 1:50 Froude scaling. The wind turbine tested was a scale model of the NREL 5-MW horizontal axis wind turbine supported by three floating platforms: a Spar, a Semi-submersible and a TLP. The paper provided details of the scale model wind turbine and floating platforms, the set-up configurations, and the instrumentation to measure motions, accelerations and loads as well as wind turbine rpm, torque and thrust for the three FOWTs. Hammer test results showed that the tower structural natural frequencies were significantly influenced by the supporting floater. The free decay test results showed that the steady wind substantially increased pitch damping of the Spar and the Semi-submersible. White noise test results also showed that the steady wind increased the surge and pitch damping for all three floating support structures. On the other hand, the wind load caused increases in the Spar wave frequency motion.

Goupee, et al. (2012a and 2012b) presented the results of a comprehensive data analysis of the 1:50 scale FOWT model tests. The wind turbine tested was a scaled model of the NREL 5-MW horizontal axis wind turbine supported by a Spar, a Semi-submersible and a TLP, respectively. The relative performance of the three models was evaluated in terms of their global motions, flexible tower dynamics and mooring system responses. The results also demonstrated the distinctive features of each of the three FOWT models which employed different types of floating support structure.

The test models consisted of the scaled platforms, towers and turbine mass properties. Froude scaling of both wind and waves was applied and the fundamental tower bending mode was also scaled. A low turbulence, low swirl wind generation system was installed in the wave basin. The model instrumentation allowed for measuring global motions, accelerations and loads as well as wind turbine rpm, torque and thrust. The test matrix indicated that system identification tests were performed, in addition to the tests representing various combinations of regular/irregular seas, steady/turbulent winds, and operational/extreme conditions.

The test results of the wave-only cases indicated that the Spar FOWT model had the smallest surge response in irregular seas, while the TLP FOWT model exhibited the smallest pitch response. The surge and pitch responses of the Semi-submersible FOWT model were within the respective ranges set by the TLP and Spar FOWTs' responses in the wave energy frequency domain. It was also found that the Semi-submersible FOWT model showed the greatest second-order, difference-frequency-associated motion responses.

The test results indicated that feathering the rotor blades was an effective means of minimizing the impact of wind loads on FOWTs. When the turbine RNA was in power production and in the environmental condition with moderate winds, the FOWT global motion responses could be significantly affected by the aerodynamic loads exerted on the turbine. For the TLP FOWT model, the wind loading significantly increased the global pitch response, although the pitch response energy as a whole remained small. For the Spar and Semi-submersible FOWT models, the operating wind turbine significantly damped the second-order difference-frequency pitch responses. The operating wind turbine also damped the second-order surge response of the Semi-submersible FOWT model.

The nacelle surge acceleration of the TLP FOWT model at low energy sea states showed significant response near the coupled platform pitch and tower bending frequency. For intermediate sea states, the unique motion characteristics of the Semi-submersible FOWT mode yielded a near net zero motion at the hub height, minimizing nacelle motion and the accompanying inertial loads. The tower base bending moment for all the three models at low sea states was characterized by significant response at the platform pitch frequencies. This occurred above the wave energy frequency for the TLP FOWT model and below the wave energy frequency for the Spar and Semi-submersible FOWT models. For severe sea state conditions, the tower base bending moment of all the three models was found to be dominated by wave, not the platform pitch, frequencies.

The test results showed that the mooring load of the TLP FOWT model in the frequency domain was approximately an order of magnitude larger than the mooring load of the Spar and Semi-submersible FOWT models. In addition, the frequency-domain mooring loads of the Spar and Semi-submersible FOWT models were primarily located near the global surge natural frequencies; whereas, the TLP mooring load was substantial in the wind energy, wave energy and coupled platform pitch and tower bending natural frequencies.

3 Case Studies Using Conceptual Designs

3.1 Overview

Characteristic responses of FOWTs and various global performance analysis procedures are evaluated through extensive case studies, which are the continuation of the case studies carried out in the BSEE TA&R project 669 (Yu and Chen, 2012) with the addition of more refined models, new site conditions, and more targeted assessment of FOWT stationkeeping systems and global performance analysis methods.

This section presented the models, methodologies and results of the case studies using three representative FOWT conceptual designs available in the public domain:

- The Spar-type and TLP-type FOWT concepts based on the BSEE TA&R project 669 (Yu and Chen, 2012)
- The Semi-submersible-type FOWT adapted from the OC4-DeepCwind conceptual design (Gueydon and Weller, 2012, Thiagarajan and Dagher, 2012). For the purpose of this study, the tower and the mooring system of the OC4-DeepCwind Semi-submersible FOWT are modified to accommodate the site conditions considered in the present study.

State-of-the-art global performance analysis techniques are implemented to study the characteristic responses of each FOWT modeled by an integrated system comprising the turbine RNA, turbine control system, floating support structure and stationkeeping system. The load cases evaluated in the study are based on those defined in the BSEE TA&R project 669 (Yu and Chen, 2012). To investigate the governing load cases, a full range of load cases including power production, power production with occurrence of fault, start-up, normal shutdown, emergency shutdown, and parked with and without fault conditions are studied for the Semisubmersible and TLP FOWTs in the Gulf of Mexico. Selected load cases are performed for the Spar FOWT off the US West Coast (Offshore Oregon), the Semisubmersible FOWT off the Northeast Coast (Gulf of Maine) and the US West Coast (Offshore Oregon), and the TLP FOWT off the US West Coast (Offshore Oregon). For the turbines in operational conditions, global performance analyses are conducted for power production, start-up and emergency shutdown. For the parked turbine conditions, global performance analyses are carried out for 1-year, 50-year and 500-year return storm conditions. The effects of the blade fault, nacelle yaw fault, loss of grid as well as the directionality of wind and wave conditions are assessed. Selected fatigue load cases are also analyzed for mooring line fatigue assessments.

Although efforts have been made to choose representative conceptual designs and environmental conditions as well as the latest simulation techniques, it should be noted that the applicability of the observations and conclusions obtained from the case studies may be limited due to the extent of the models, assumptions and software tools used in the study.

3.2 Problem Definition

The objectives of the case studies carried out in this project are

- to gain further insights into the dynamic interactions among the turbine RNA, turbine control system, floating support structure and stationkeeping system;
- to study critical design parameters and modeling strategies for stationkeeping systems; and
- to evaluate the relative importance of environmental loading due to wind, wave and current under various turbine design conditions.

Global responses of FOWTs under various load conditions are calculated with the consideration of the dynamic interactions among the turbine RNA, turbine control system, floating support structure and stationkeeping system. The design parameters and technical areas considered in the studies are listed as follows:

- Turbine operating conditions
- Configuration of the floating support structure
- Site variation
- Wind-wave directionality and misalignment
- Intact and damaged conditions of the stationkeeping system
- Governing load cases for floating support structure and stationkeeping system designs
- Simulation length for numerical simulations
- Applicability of different analysis methods

The three FOWT conceptual designs selected for the case studies are adapted from the existing designs available in the public domain, namely the OC3-Hywind Spar, the MIT/NREL mono-column TLP and the OC4-DeepCwind Semi-submersible FOWT concepts. Since the original conceptual designs were intended for less demanding metocean conditions, modifications are made in order to meet the design requirements for global motions and mooring line tensions under the 50-year return hurricane conditions in the GoM Central Region. Efforts have been made to keep these conceptual designs as realistic as possible. It is not, however, the focus of the case studies to produce optimized designs.

The NREL 5-MW baseline offshore wind turbine is assumed to be installed on each conceptual design of a floating support structure considered in the case studies. A generic turbine control scheme developed by NREL for the OC3-Hywind Spar concept is applied. The water depth is assumed to be 320 m, which is the same as that used in the study of the OC3-Hywind Spar. The tower base is 24.6 m above MSL (Mean Sea Level). The hub height is 95 m above MSL. The diameter and wall thickness of the tower are taken as the same as those of the OC3-Hywind Spar, while the total height of the tower is reduced from 77.6 m to 68 m.

Three representative coastal regions on the US OCS are considered in the case studies. Regional metocean conditions for the GoM Central Region (GOM) are determined based on API Bulletin 2INT-MET (2007). For the US West Coast, site-specific metocean data are derived from the records of a NOAA buoy and a NOAA water level station located offshore Oregon (OR). For the US Northeast coast, site-specific metocean data are derived using the records of a NOAA buoy and a NOAA water level station in the Gulf of Maine (ME).

The combinations of the selected FOWT design concepts and the site locations are listed in Table 3.1. In comparison to the case studies carried out in BSEE TA&R project 669 (Yu and Chen, 2012), these combinations are defined in such a way that the current study focuses more on a newly added site, i.e. Offshore Oregon, and a new generic Semi-submersible FOWT conceptual design. Reference is made to the BSEE TA&R project 669 final report for the results and conclusions of the previous case studies that remain valid for the purpose of this project.

A general description of the design load cases (DLC) considered in the case studies is provided in Table 3.1. Further details of the analysis load cases for each conceptual design are listed in Section 3.5.1 for the Spar FOWT, Section 3.6.1 for the Semi-submersible FOWT and Section 3.7.1 for the TLP FOWT.

Table 3.1 General Load Case Descriptions for the Case Studies

FOWT	*Site*	*Design Condition*	*DLC*	*Wind and wave directionality*	*Yaw Control/Event*	*Safety Factor*
		1) Power production	1.3	Collinear	Yaw misalignment φ=0°	Normal
Spar	OR	3) Start-up	3.2	Collinear	Yaw misalignment φ=0°	Normal
		5) Emergency shutdown	5.1	Collinear	Yaw misalignment φ=0°	Normal
		6) Parked (standing still or idling)	6.1	Collinear ±30° cross waves ±90° cross waves	Yaw misalignment φ=0°, ±8°	Normal
Semisubmersible	OR ME		6.2	Collinear ±30° cross waves ±90° cross waves	Yaw misalignment -180°≤φ≤+180°	Abnormal
			6.3	Collinear	Yaw misalignment φ=0°, ±20°	Normal
TLP	OR	7) Parked and fault conditions	7.1	Collinear	Yaw misalignment φ=0°, ±8°, Seized Blade	Abnormal
				Collinear	Yaw misalignment -180°≤φ≤+180°	Abnormal
		Survival condition	NA	Collinear	Yaw misalignment -180°≤φ≤+180°	Survival

Table 3.1 General Load Case Descriptions for the Case Studies (Continued)

FOWT	*Site*	*Design Condition*	*DLC*	*Wind and wave directionality*	*Yaw Control/Event*	*Safety Factor*
Semisubmersible & TLP	GOM	1) Power production	1.3	Collinear	Yaw misalignment φ=0°	Normal
			1.4	Misaligned, wind direction change	Yaw misalignment φ=0°	Normal
			1.5	Collinear	Yaw misalignment φ=0°	Normal
			1.6	Collinear	Yaw misalignment φ=0°	Normal
		2) Power production plus occurrence of fault	2.1	Collinear	Yaw misalignment φ=0° Blade Pitch Runaway	Normal
				Collinear	Yaw Runaway	Normal
			2.3	Collinear	Yaw misalignment φ=0° Loss of Load	Abnormal
		3) Start-up	3.2	Collinear	Yaw misalignment φ=0°	Normal
			3.3	Misaligned, wind direction change	Yaw misalignment φ=0°	Normal
		4) Normal shutdown	4.2	Collinear	Yaw misalignment φ=0°	Normal
		5) Emergency shutdown	5.1	Collinear	Yaw misalignment φ=0°	Normal
		6) Parked (standing still or idling)	6.1	Collinear ±30° cross waves ±90° cross waves	Yaw misalignment φ=0°, ±8°	Normal
			6.2	Collinear ±30° cross waves ±90° cross waves	Yaw misalignment -180°≤φ≤+180°	Abnormal
			6.3	Collinear	Yaw misalignment φ=0°, ±20°	Normal
		7) Parked and fault conditions	7.1	Collinear	Yaw misalignment φ=0°, ±8°, Seized Blade	Abnormal
				Collinear	Yaw misalignment -180°≤φ≤+180°	Abnormal
		Survival condition	NA	Collinear	Yaw misalignment -180°≤φ≤+180°	Survival

3.3 Modeling and Analysis Procedures

3.3.1 Overall Approach and Analysis Tools

Global performance analyses are carried out using a time-domain aero-hydro-servo-elastic analysis program, CHARM3D-FAST, developed at Texas A&M University by integrating the CHARM3D program from Texas A&M University and the FAST program from NREL.

CHARM3D is a static/dynamic global performance analysis program for coupled floating hull-mooring-riser systems. In CHARM3D, a floating hull structure is modeled as a rigid body undergoing motions induced by wave, wind, and current actions, while mooring lines are modeled using a higher order finite element formulation. The mooring/riser dynamics and hull motions are solved simultaneously in a combined matrix at each time step. Various nonlinearities, including drag forces on mooring lines and hull structures, large translational hull motions, the free surface effect, and geometric nonlinearity of the mooring system, are taken into account in the time-domain motion analysis. Current loads and viscous forces on the floating hull structure are modeled by drag elements following Morison's equation. Except for the hull drag forces and mooring line loads, all the wave forces on the floating hull are calculated using WAMIT, which serves as a pre-processor for CHARM3D.

The FAST program suite (v7.00.01a-bjj) incorporates the servo-elastic analysis program modules as well as the aerodynamic load analysis program, AeroDyn (v13.0). A data interface with turbulent wind field simulator, TurbSim (v1.50), is also included in the FAST program. Both the FAST and TurbSim programs are developed and maintained by NREL. An enhancement to the original TurbSim (v1.50) program was implemented by ABS to include the wind shear and the turbulent wind model recommended in API RP 2A-WSD (2007). The deterministic wind events specified by IEC 61400-1 (2005) are generated using the IECWind (v5.01.01) program developed by NREL.

In the integrated CHARM3D-FAST program (2011 version, see Bae, et al., 2011a, 2011b), FAST calculates all the dynamic responses of the turbine components, tower and floating hull structure, while CHARM3D determines the hydrodynamic wave forces (first-order wave-frequency and second-order sum-/difference-frequency forces), viscous forces on Morison members, radiation damping forces in the form of convolution integral, and mooring restoring forces. FAST uses the forces calculated by CHARM3D as part of the input to solve the equations of motion for the dynamics of turbine, tower and floating hull structure. The resultant displacements, velocities, and accelerations of the hull structure are passed to CHARM3D for the next step calculation of hydrodynamic forces and mooring forces.

The hydrostatic and hydrodynamic properties, including the hydrostatic restoring coefficients, added-mass coefficients, damping coefficients, linear transfer functions (LTF) of wave forces (1st-order wave forces), quadratic transfer functions (QTF) of sum- and difference-frequency wave forces (2nd-order wave forces), and Response Amplitude Operators (RAOs) of 6-DOF of hull motions are calculated using WAMIT, which is a frequency-domain hydrodynamic analysis program based on the radiation/diffraction theory and the boundary element method. The second-order difference-frequency wave forces are derived based on Newman's approximation for the Spar and Semi-submersible conceptual design. For the TLP concept, however, the full QTF of second-order sum- and difference-frequency wave forces are used in the analysis.

The 3-D turbulent wind field is generated by the TurbSim program and used in FAST simulations. For the turbine in operation, the Kaimal wind model and the exponential coherence function recommended by IEC 61400-1 (2005) are applied to generate the turbulent wind field. For the parked turbine subjected to the 1-year, 50-year and 500-year return extreme wind conditions, the wind spectrum and spatial coherence model recommended by API RP 2A-WSD (2007) are applied to all the site locations. The API wind model is commonly used in the design of offshore oil and gas platforms when the wind load induced dynamic responses need to be considered. The turbulent wind is represented by the NPD wind spectrum (also known as the Frøya wind model) and the two-point coherence function in conjunction with the logarithmic wind shear law.

The quasi-static wind loads on the floating hull structure above still water level (SWL) are modeled as wind drag loads and used as an input of global static forces in CHARM3D-FAST simulations. The wind shear law recommended in API RP 2A-WSD (2007) is applied in the calculation of the wind drag loads on the hull. The quasi-static wind loads on the nacelle and tower are typically much smaller than the aerodynamic loads and, therefore, not included in the tower base load calculation in CHARM3D-FAST simulations. In the post-processing of analysis results, such quasi-static wind loads are modeled as wind drag loads and superimposed onto the maximum tower base loads obtained from CHARM3D-FAST simulations.

The tower 1st and 2nd fore-aft and side-to-side bending mode shapes are derived for an elastic tower model supported on a floating foundation. The mass properties of the turbine RNA and the moving foundation of the floating hull structure are included in modal analyses using the BModes program, which is a finite-element code developed by NREL for calculating mode shapes and natural frequencies of a tower or a single turbine blade (Bir and Jonkman, 2008).

Global responses, including 6-DOF motions and accelerations of the floating support structure, tensions in the mooring lines or tendons, bending moments and shear forces at the tower-hull interface, and the tower top accelerations, are determined through the global performance analyses using the integrated CHARM3D-FAST program.

3.3.2 Site Conditions

The regional metocean data for the GoM Central Region and the site-specific metocean data for the two offshore sites on the US West Coast (Offshore Oregon) and Northeast Coast (Gulf of Maine), respectively, are assessed and applied in the case studies. The water depth for the three locations is taken to be 320 m.

For the GoM, metocean data for the GoM Central Region (see Figure 3.1) as defined in API Bulletin 2INT MET (2007) are employed in the case studies. The peak wind and peak wave conditions in the GoM Central Region with return periods of 50 years are derived for a water depth of 320 m. The 500-year return hurricane conditions in the GoM Central Region, including both the peak wind and the peak wave scenarios, are derived based on API Bulletin 2INT-MET (2007), with the assumption that the extreme values of wave height, wind speed, current speed and storm surge follow the Weibull distribution. Only the 500-year return peak wind conditions are used in the robustness check for the Semi-submersible and TLP FOWTs. The 1-year return environmental conditions for design load case 7.1 are based on the 1-year winter storm condition in the GoM Central Region, as defined in Table C.21,Annex C of ISO 19901-1 (2005). For the turbine operating conditions with wind speeds lower than 1-year return values, theoretical correlations between wind speed and wave height and period recommended in Appendix 4.J of GL Guideline for the Certification of Offshore Wind Turbines (GL, 2005) are used to derive the associated waves.

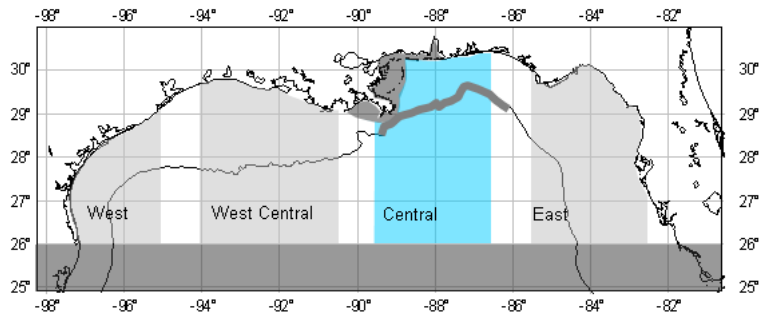


Figure 3.1 GoM Central Region

The site-specific metocean condition assessment on the US West Coast (Offshore Oregon) and Northeast Coast (Gulf of Maine) is based on historical data analyses using the measurements of selected NOAA buoys and water level stations. The site assessment is not meant to be a rigorous exercise of metocean condition assessment, which normally involves hindcast data analysis and is not within the scope of this project.

For the Offshore Oregon, the site metocean data are derived based on the historical data analysis using the measurements from the NOAA NDBC buoy (Station 46050) and NOAA NOS water level station (Station 9432780) located off the coast of central Oregon as shown in Figure 3.2. Wind and wave data analyses based on the measurements from Station 46050 are further verified by the historical data analysis using the measurements of the nearby NOAA NDBC Station 46015.

The extreme wind speed and significant wave height at the site are derived using the buoy measurements (Station 46050) between 1991 and 2011. The annual maxima of 8-minute wind speeds at 5 m above the water surface and the significant wave heights are extracted from the measurements. Gumbel curve fitting is used to determine the 1-year, 50-year and 500-year return wind speeds and wave heights as shown in Figure 3.3 and Figure 3.4. Figure 3.5 depicts the correlation between wave spectrum peak period (T_p) and significant wave height (H_s) derived using the binned buoy data. The correlation between the significant wave height (H_s) and the wind speed (W_s, 8-minute wind speed at 5 m elevation) is derived using the buoy data as shown in Figure 3.6. The extreme water levels (storm surge and tide) at the site are derived using the water level station measurements (Station 9432780) between 1982 and 2011. Gumbel curve fitting is used to determine the 1-year, 50-year and 500-year return water levels as shown in Figure 3.7. The current speed and profile with return periods of 1, 50, and 500 years are derived based on ISO 19901-1.

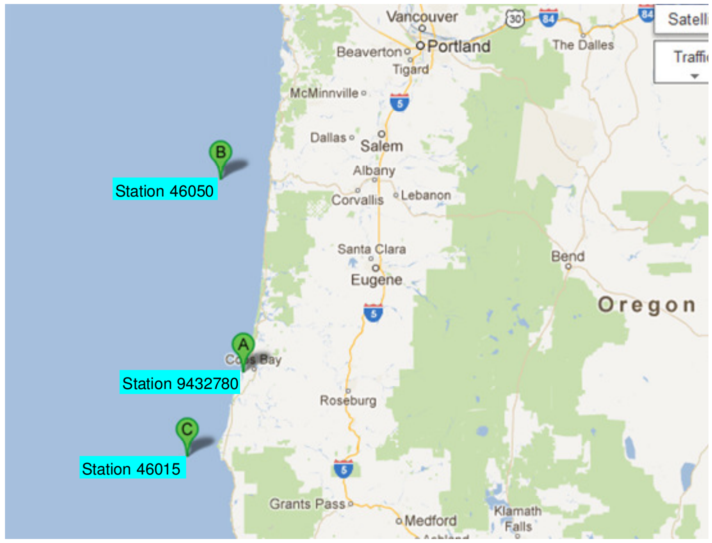


Figure 3.2 Locations of the NOAA Stations Selected for the US West Coast Case Study

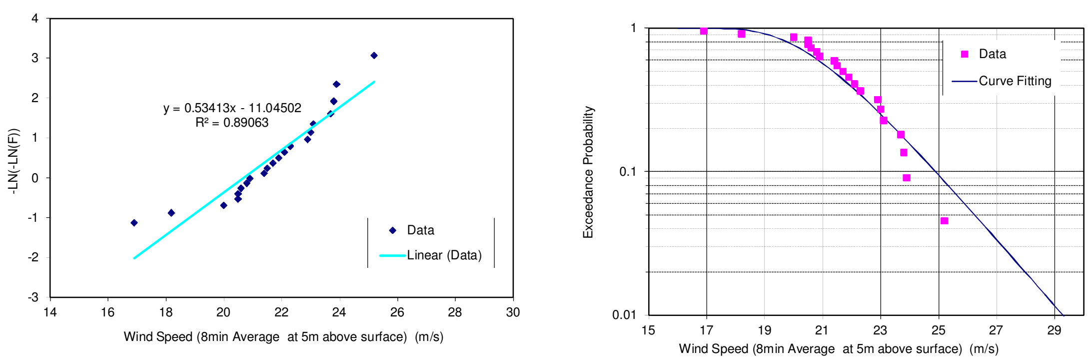


Figure 3.3 Gumbel Curve Fitting for the Buoy Wind Data (Station 46050)

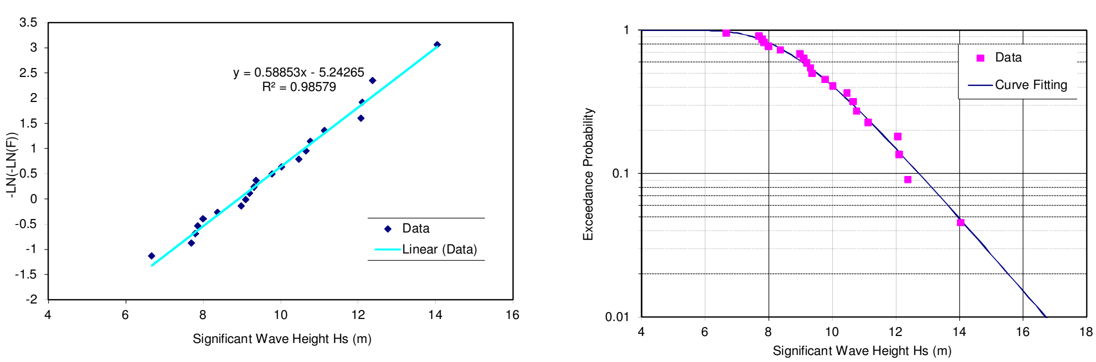


Figure 3.4 Gumbel Curve Fitting for the Buoy Wave Data (Station 46050)

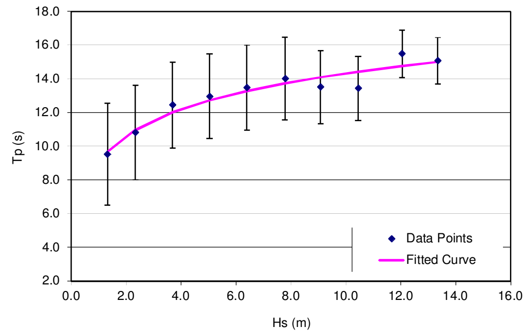


Figure 3.5 Correlation of T_p and H_s Using the Binned Buoy Data (Station 46050)

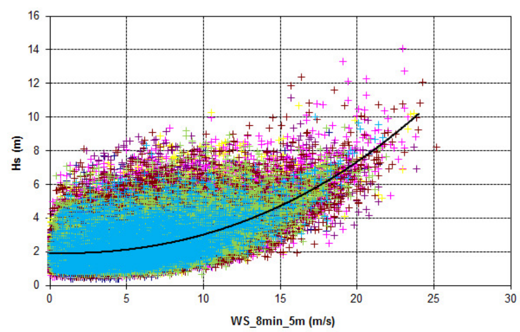


Figure 3.6 Correlation of H_s and W_s (Station 46050)

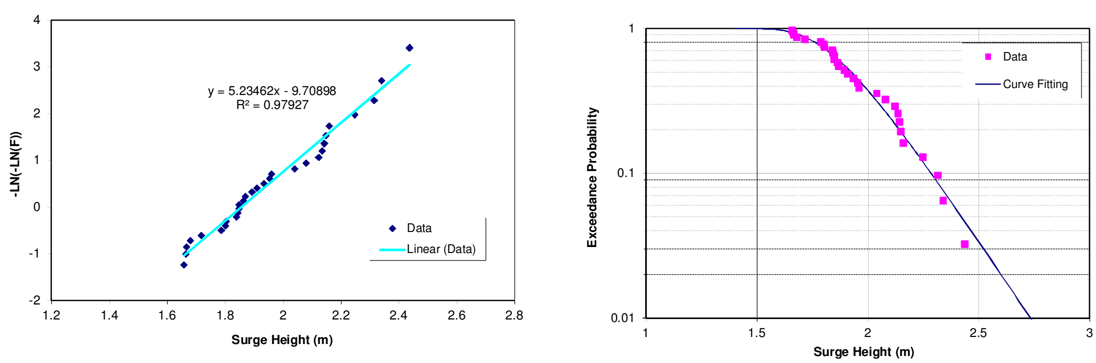


Figure 3.7 Gumbel Curve Fitting for the Water Level Data (Station 9432780)

For the US Northeast Coast (Gulf of Maine), the site metocean data are derived based on the historical data analysis using the measurements from NOAA NDBC buoy (Station 44005) and NOAA NOS water level station (Station 8418150) located off the coast of Maine, as depicted in Figure 3.8. Wind and wave data analysis based on the measurements from Station 44005 are further verified by the historical data analysis using the measurements of the nearby NOAA NDBC Station 44007.

The extreme wind speed and significant wave height at the site are derived using the buoy measurements (Station 44005) between 1979 and 2010. The annual maxima of 8-minute wind speeds at 5 m above the water surface and the significant wave heights are extracted from the measurements. Gumbel curve fitting is used to determine the 1-year, 50-year and 500-year return wind speeds and wave heights as shown in Figure 3.7 and Figure 3.10. The correlation between wave spectrum peak period (T_p) and significant wave height (H_s) is derived using the binned buoy data as shown in Figure 3.11. Figure 3.12 depicts the correlation between the significant wave height and the wind speed (W_s, 8-minute wind speed at 5 m elevation) derived using the buoy data. The extreme water levels (storm surge and tide) at the site are derived using the water level station measurements (Station 8418150) between 1960 and 2010. Gumbel curve fitting is used to determine the 1-year, 50-year and 500-year return water levels as shown in Figure 3.13. The current speed and profile with return periods of 1, 50, and 500 years are derived based on API RP 2A-WSD (2007).

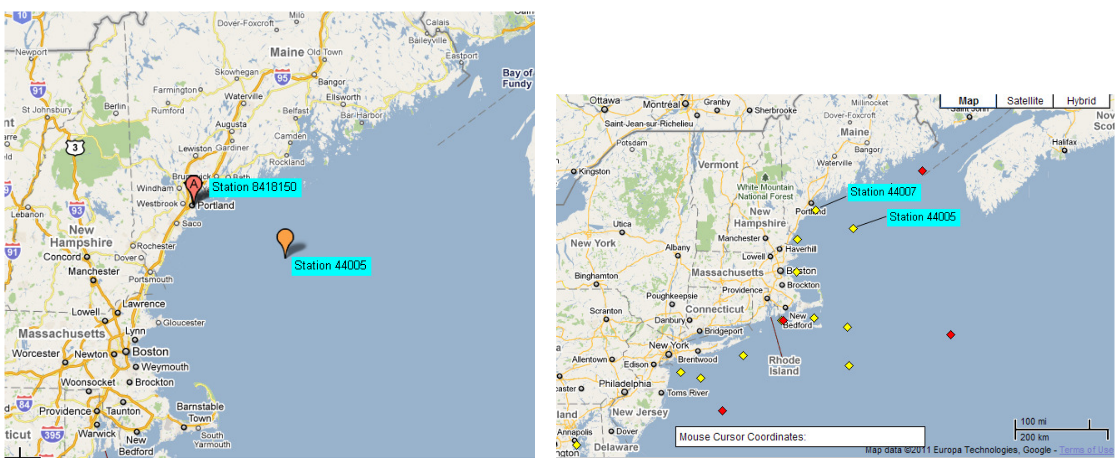


Figure 3.8 Locations of the NOAA Stations Selected for the US Northeast Coast Case Study

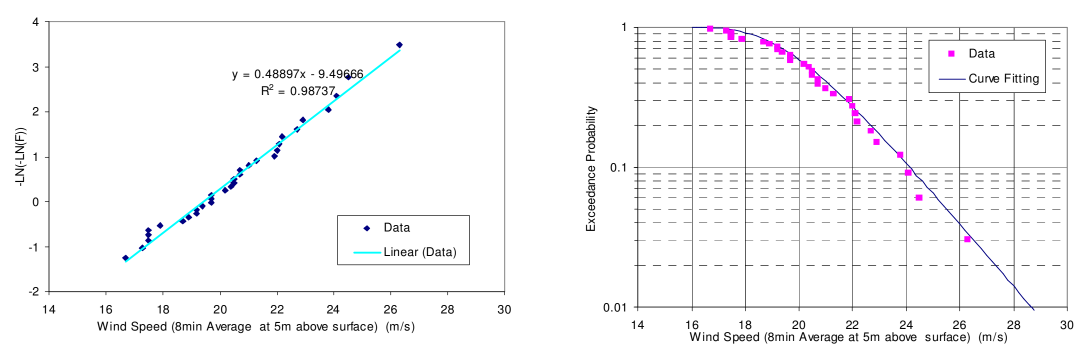


Figure 3.9 Gumbel Curve Fitting for the Buoy Wind Data (Station 44005)

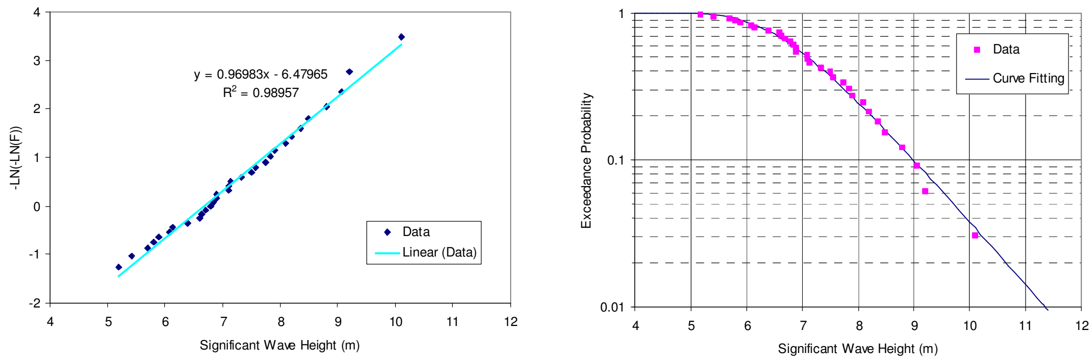


Figure 3.10 Gumbel Curve Fitting for the Buoy Wave Data (Station 44005)

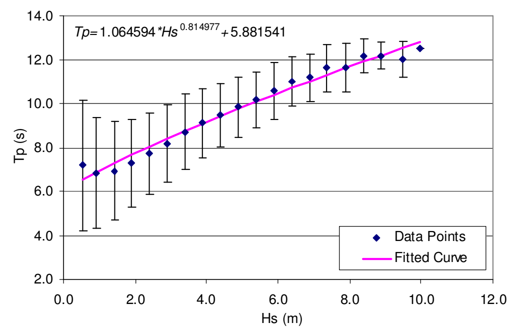


Figure 3.11 Correlation of T_p and H_s Using the Binned Buoy Data (Station 44005)

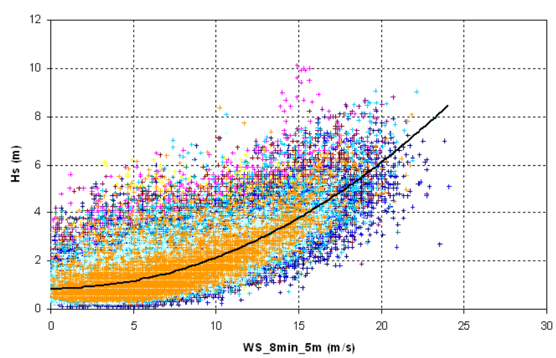


Figure 3.12 Correlation of H_s and W_s (Station 44005)

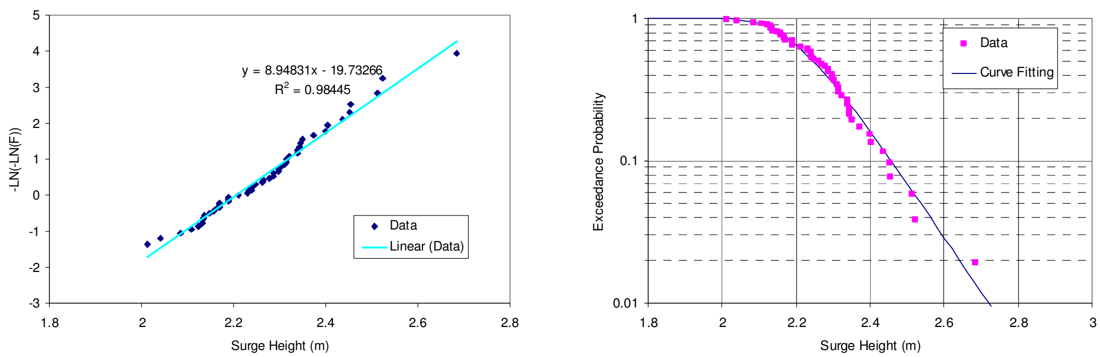


Figure 3.13 Gumbel Curve Fitting for the Water Level Data (Station 8418150)

The current speed and profile associated with the wind and wave conditions for the turbine in the operation mode are determined using different data sources. For the GoM Central Region and the US West Coast (Offshore Oregon), the current speed and profile are derived based on the 1-year winter storm generated current as defined in ISO 19901-1. For the US Northeast Coast (Gulf of Maine), the surface current speed and the current profile are assumed to follow the guidance in API RP 2A-WSD (2007). These current profiles are used with the normal current model (NCM) in the case studies.

3.3.3 Extreme Value Prediction and Data Post-Processing

The statistics of each simulation are calculated using the Crunch (v3.00.00) program developed by NREL. For all load cases, the statistics of the following parameters are obtained from the simulations:

- Wind speed
- Wave elevation
- Platform motions (Surge, Sway, Heave, Roll, Pitch, Yaw, Offset, Heel)
- Tower base loads (Shear Forces F_x and F_y, Vertical Force F_z, Bending Moments M_x and M_y , Torsion M_z, Horizontal Shear Force, and Overturning Bending Moment)
- Tower top deflection (Fore-Aft Deflection, Side-to-Side Deflection)
- Tower acceleration at four different elevations including tower top
- Fairlead (top) line tensions
- Tower top loads (Yaw bearing loads) (Shear Forces F_x and F_y, Vertical Force F_z, Bending Moments M_x and M_y , Torsion M_z)
- Blade root bending moments (Out-of-Plane and In-Plane)

- Blade tip deflection (Out-of-Plane and In-Plane)
- Blade pitch
- Low speed shaft bending moments (M_y and M_z)
- Rotor thrust
- Rotor torque
- Rotor speed

For DLCs 1.x (Power Production), 2.x (Power Production plus Occurrence of Fault), 3.x (Start-up), 4.2 (Normal Shutdown) and 5.1 (Emergency Shutdown), the statistics of the following generator and rotor responses are also calculated in addition to those parameters listed above.

- Generator power
- Generator torque
- Generator speed

In the data post-processing analysis, the statistics of the four global responses, including the tower base shear, tower base overturning moment, hull offset and hull heel, are calculated by the Crunch program based on the time series output from CHARM3D-FAST. The horizontal tower base shear is the combined shear force calculated by $(F_x^2+F_y^2)^{1/2}$. The tower base overturning moment is the combined moment calculated by $(M_x^2+M_y^2)^{1/2}$. The hull offset is the combined hull surge and sway motion calculated by $(Surge^2+Sway^2)^{1/2}$, and the hull heel is the combined hull roll and pitch calculated by $(Roll^2+Pitch^2)^{1/2}$. All the platform motions are given at the origin of the coordinate system.

For DLCs 1.x (Power Production), 2.x (Power Production plus Occurrence of Fault), 3.x (Start-up), 4.2 (Normal Shutdown) and 5.1 (Emergency Shutdown), twenty 10-mintue simulations are performed for the operational wind speeds. The mean wind, wave and current conditions associated with the turbine in operation are used in the simulation. The wind models used for the wind are the IEC wind models. Wave conditions are modeled by irregular waves based on P-M wave spectra with a different random seed for each simulation. A 200 s ramp time is applied in the analysis, and the total simulation time is 800 s for one simulation. Statistics are obtained based on time series from 200 s to 800 s. The mean value is the average of the mean values of all 10-minute simulations. The maximum value is the maximum of all 10-minute simulations. The minimum value is the minimum of all 10-minute simulations. The standard deviation is the average of the standard deviations of all 10-minute simulations.

For DLC 1.3, the turbulence model used for the wind is the IEC Extreme Turbulence Model (ETM). For DLCs 1.6, 2.1 and 5.1, the turbulence model used for the wind is the IEC Normal Turbulence Model (NTM). For DLCs 1.4, 1.5, 2.3, 3.2, 3.3 and 4.2, the IEC deterministic wind models are applied. A different starting time of the wind event is assigned for each simulation.

In the start-up load cases (DLC 3.2 and DLC 3.3), the turbine is first at parked (idling) condition. The turbine is started up by pitching the blade from the feathered position at a pitch rate of 2° per second. When the generator speed reaches the cut-in rotor speed, the generator is switched on and the turbine assumes the normal power production condition. In the simulation, the blade starts to pitch from the feathered position at 305s. Three wind speeds including cut-in (V_{in}), rated (V_r) and cut-out (V_{out}) wind speeds are considered for start-up. Statistics are obtained based on time series from 305 s to 800 s.

In the normal shutdown load case (DLC 4.2), the turbine is shut down by pitching the blade to feathered position at a pitch rate of 2° per second. When the generator speed is below the cut-in generator speed, the generator is switched off. Rotor speed is finally reduced to the idling condition. In the simulation, the blade starts to pitch to feather at 305 s. Both the rated (V_r) and cut-out (V_{out}) wind speeds are considered for normal shutdown. Statistics are obtained based on time series from 305 s to 800 s.

In the emergency shutdown (DLC 5.1), the generator is first switched off and then the turbine is shut down by pitching the blade to feathered position at a pitch rate of 8° per second. Rotor speed is finally reduced to the idling condition. In the simulation, the generator is switched off at 360 s. The blade starts to pitch to feather at 360.2 s. Both the rated (V_r) and cut-out (V_{out}) wind speeds are considered for emergency shutdown. Statistics are obtained based on time series from 360 s to 800 s.

For DLC 2.x, three types of faults are considered in the analysis: pitch runaway, yaw runaway and grid loss. The pitch runaway and yaw runaway (control system fault) with normal turbulent wind conditions are considered as normal conditions (DLC 2.1). The grid loss conditions with extreme operating gust (EOG) are considered as abnormal conditions (DLC 2.3).

For DLC 2.1 with the pitch runaway, one of the blade runs away from the operational position to 0° blade pitch position at a pitch rate of 8° per second, then the blade is seized at the that position. The turbine then initiates a shutdown by feathering the other two blades. In the simulation, the turbine is initially at normal power production conditions. One of the blades starts to run away at 305 s, the turbine then shuts down at 305.2 s. Statistics are obtained based on time series from 305 s to 800 s.

For DLC 2.1 with the yaw runaway, the RNA runs away from the 0° yaw potion (facing to the wind direction) to the 90° yaw position (perpendicular to the wind direction) at 8° per second yaw rate, then the RNA is seized at that position. When the RNA reaches 90° yaw error, the turbine shuts down. In the simulation, the turbine is initially at normal power production conditions. The RNA starts to run away at 305 s and reaches 90° yaw error at 316.25 s, then the generator is switched off and the turbine shuts down by feathering the blades. In the simulation during yaw runaway, it is assumed there is relatively lower yaw bearing stiffness and higher yaw bearing damping. After the yaw error reaches 90° and is seized at that positions, the stiffness and damping values are not suitable for a seized position in the numerical simulations. Thus the data after transient effects die out are discarded from the post processing. Statistics are obtained based on time series from 305 s to 400 s.

For DLC 2.3 with loss of grid connection, the turbine initiates a shutdown by feathering the blades after grid loss. In the simulation, the turbine is initially at normal power production conditions. The generator is switched off at 305 s and the turbine shuts down at 305.2 s. Statistics are obtained based on time series from 305 s to 800 s.

For the turbine in the parked (idling) conditions with or without fault, six 1-hour simulations are performed for each load case. Significant wave height (H_s) is factored by 1.09 in the simulation, as recommended in IEC 61400-3 (2009). The API (NPD) recommended turbulence model is applied. Each simulation is 4000 s with a 400 s ramp. Statistics are obtained based on time series from 400 s to 4000 s. Design statistics (maximum, mean, minimum and standard deviation) are averages of corresponding statistics of the six simulations.

3.4 Case Study Models

3.4.1 Site Conditions

Section 3.3.2 describes the technical background and methods used in the determination of the metocean data at three representative locations on the US OCS. The GoM Central Region is shown in Figure 3.1. The site location on the US West Coast (Offshore Oregon) represented by NOAA NDBC Station 46050 is shown in Figure 3.2, while the site location on the US Northeast Coast (Gulf of Maine) represented by NOAA NDBC Station 44005 is shown in Figure 3.8.

Both the peak wind and the peak wave conditions for a water depth of 320 m in the GoM Central Region are derived. The peak wind conditions with associated wave, storm surge and current are summarized in Table 3.2. The peak wave conditions with associated wind, storm surge and current are given in Table 3.3. The 1-year, 50-year and 500-year return storm conditions for the US West Coast (Offshore Oregon) and Northeast Coast (Gulf of Maine) are listed in Table 3.4 and Table 3.5, respectively. JONSWAP wave spectrum with peak parameter (γ) of 2.4 is used for all the 50-year and 500-year wave conditions. JONSWAP wave spectrum with peak parameter (γ) of 1.0 (i.e. P-M spectrum) is used for all the 1-year wave conditions.

Table 3.2 Environmental Conditions in the GoM Central Region (GOM) – Peak Wind

Return Period (Years)		1 1)	50 2)	500 2)
Wind (10m Elevation)	1-hour Mean Wind Speed (m/s)	16.4	44.4	55.9
	10-min Mean Wind Speed (m/s)	17.6	50.1	64.3
	1-min Mean Wind Speed (m/s)	19.2	57.4	75.1
	3-sec Gust (m/s)	22.1	66.9	89.1
Wave	Significant Wave Height (m)	4.9	13.87	17.21
	Maximum Wave Height (m)	9.4	24.51	30.38
	Peak Spectral Period (s)	10.3	14.62	16.17
	Period of Maximum Wave (s)	9.4	13.16	14.55
Current Profile	Current Speed (m/s)	0.4 at 0.0 m	1.67 at 0.0 m	2.10 at 0.0 m
	Current Speed (m/s)	0.4 at 70.0 m	1.25 at 34.95 m	1.57 at 43.7 m
	Current Speed (m/s)	0.1 at 90.0 m	0.0 at 69.90 m	0.0 at 87.4 m
Water Level	Storm Surge (m)	0.08	0.47	0.72
	Tidal Amplitude (m)	0.42	0.42	0.42
	Surge and Tide (m)	0.50	0.89	1.14

Note: 1) Winter Storm
2) Hurricane

Table 3.3 Environmental Conditions in the GoM Central Region (GOM) – Peak Wave

Return Period (Years)		1 [1)]	50 [2)]	500 [2)]
Wind (10m Elevation)	1-hour Mean Wind Speed (m/s)	16.4	42.2	53.1
	10-min Mean Wind Speed (m/s)	17.6	47.4	60.8
	1-min Mean Wind Speed (m/s)	19.2	54.1	70.7
	3-sec Gust (m/s)	22.1	62.9	83.5
Wave	Significant Wave Height (m)	4.9	14.60	18.11
	Maximum Wave Height (m)	9.4	25.80	31.98
	Peak Spectral Period (s)	10.3	15.00	16.59
	Period of Maximum Wave (s)	9.4	13.50	14.92
Current Profile	Current Speed (m/s)	0.4 at 0.0 m	1.67 at 0.0 m	2.10 at 0.0 m
	Current Speed (m/s)	0.4 at 70.0 m	1.25 at 34.95 m	1.57 at 43.7 m
	Current Speed (m/s)	0.1 at 90.0 m	0.0 at 69.90 m	0.0 at 87.4 m
Water Level	Storm Surge (m)	0.08	0.47	0.72
	Tidal Amplitude (m)	0.42	0.42	0.42
	Surge and Tide (m)	0.50	0.89	1.14

Note: 1) Winter Storm
2) Hurricane

Table 3.4 Environmental Conditions in US West Coast (Offshore Oregon - OR)

Return Period (Years)		1	50	500
Wind (10m Elevation)	1-hour Mean Wind Speed (m/s)	20.28	27.33	31.44
	10-min Mean Wind Speed (m/s)	21.95	29.95	34.70
	1-min Mean Wind Speed (m/s)	24.10	33.32	38.89
	3-sec Gust (m/s)	26.90	37.70	44.34
Wave	Significant Wave Height (m)	8.91	15.56	19.47
	Maximum Wave Height (m)	16.57	28.93	36.21
	Peak Spectral Period (s)	14.06	15.36	15.89
	Period of Maximum Wave (s)	12.77	13.95	14.43
Current Profile	Current Speed (m/s) at 0.0 m	0.60	0.80	0.90
	Current Speed (m/s) at 90.0 m	0.50	0.70	0.80
	Current Speed (m/s) at 319.0 m	0.50	0.70	0.80
Water Level	Storm Surge (m)	0.09	0.84	1.28
	Tidal Amplitude (m)	1.77	1.77	1.77
	Surge and Tide (m)	1.85	2.60	3.04

Table 3.5 Environmental Conditions in US Northeast Coast (Gulf of Maine - ME)

Return Period (Years)		1	50	500
Wind (10m Elevation)	1-hour Mean Wind Speed (m/s)	19.41	26.70	30.94
	10-min Mean Wind Speed (m/s)	20.98	29.23	34.12
	1-min Mean Wind Speed (m/s)	23.00	32.48	38.20
	3-sec Gust (m/s)	25.62	36.70	43.52
Wave	Significant Wave Height (m)	6.73	10.66	12.97
	Maximum Wave Height (m)	12.51	19.83	24.13
	Peak Spectral Period (s)	10.92	13.21	14.48
	Period of Maximum Wave (s)	9.91	11.99	13.15
Current Profile	Current Speed (m/s) at 0.0 m	0.49	0.57	0.61
	Current Speed (m/s) at 61.0 m	0.49	0.57	0.61
	Current Speed (m/s) at 91.0 m	0.10	0.10	0.10
	Current Speed (m/s) at 319.0 m	0.10	0.10	0.10
Water Level	Storm Surge (m)	0.14	0.58	0.84
	Tidal Amplitude (m)	2.06	2.06	2.06
	Surge and Tide (m)	2.21	2.64	2.90

The operational wave conditions in association with the cut-in, rated and cut-out wind speeds and the wind speeds in between are provided in Table 3.6 through Table 3.8. Table 3.9 lists the current speed and profiles associated with the operational wind/wave conditions. JONSWAP wave spectrum with peak parameter (γ) of 1.0 (i.e. P-M spectrum) is used for all the operational wave conditions.

Table 3.6 Operational Wind-Wave Conditions – GoM Central Region (GOM)

10-minitue Wind Speed (95m Elevation) (m/s)	*1-hour Wind Speed (10m Elevation) (m/s)*	*Significant Wave Height (Hs) (m)*	*Peak Period (Tp) (s)*
3.00 (cut-in speed)	2.53	0.13	1.61
4.00	3.35	0.23	2.14
7.00	5.76	0.67	3.67
8.00	6.55	0.87	4.17
9.40	7.64	1.19	4.87
11.40 (rated speed)	9.17	1.71	5.84
13.40	10.68	2.32	6.80
17.00	13.33	3.61	8.50
18.00	14.06	4.02	8.96
21.00	16.21	5.34	10.33
24.00	18.32	6.82	11.68
25.00 (cut-out speed)	19.02	7.35	12.12

Table 3.7 Operational Wind-Wave Conditions – US West Coast (Offshore Oregon - OR)

10-minitue Wind Speed (95m Elevation) (m/s)	*1-hour Wind Speed (10m Elevation) (m/s)*	*Significant Wave Height (Hs) (m)*	*Peak Period (Tp) (s)*
3.00 (cut-in speed)	2.53	1.95	10.56
4.00	3.35	1.99	10.61
8.00	6.55	2.33	10.97
9.40	7.64	2.52	11.14
11.40 (rated speed)	9.17	2.84	11.42
13.40	10.68	3.23	11.72
18.00	14.06	4.42	12.43
24.00	18.32	6.55	13.34
25.00 (cut-out speed)	19.02	6.97	13.49

Table 3.8 Operational Wind-Wave Conditions – US Northeast Coast (Gulf of Maine - ME)

10-minitue Wind Speed (95m Elevation) (m/s)	*1-hour Wind Speed (10m Elevation) (m/s)*	*Significant Wave Height (Hs) (m)*	*Peak Period (Tp) (s)*
3.00 (cut-in speed)	2.53	0.95	6.90
4.00	3.35	1.01	6.95
8.00	6.55	1.43	7.30
9.40	7.64	1.63	7.47
11.40 (rated speed)	9.17	1.98	7.74
13.40	10.68	2.38	8.04
18.00	14.06	3.52	8.85
24.00	18.32	5.42	10.11
25.00 (cut-out speed)	19.02	5.79	10.33

Table 3.9 Operational Current Conditions

GoM Central Region (GOM)		*US West Coast (Offshore Oregon - OR)*		*US Northeast Coast (Gulf of Maine - ME)*	
Depth (m)	*Speed(m/s)*	*Depth (m)*	*Speed(m/s)*	*Depth (m)*	*Speed(m/s)*
0.0	0.4	0.0	0.60	0.0	0.50
70.0	0.4	90.0	0.50	61.0	0.50
90.0	0.1	319.0	0.50	91.0	0.10
319.0	0.1	-	-	319.0	0.10

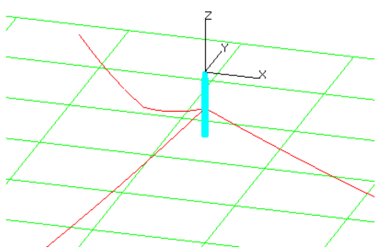
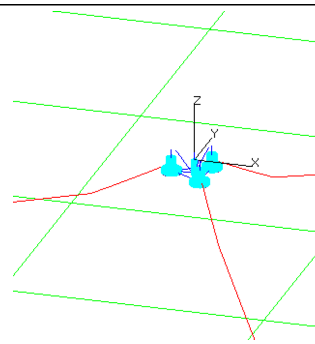
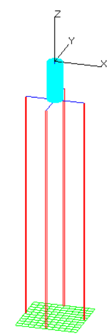
3.4.2 Floating Support Structure and Stationkeeping System Configurations

The three conceptual designs of floating support structures are adapted from the OC3-Hywind Spar, the MIT/NREL mono-column TLP and the OC4-DeepCwind Semi-submersible concepts. The configuration and the general arrangement of these concepts are collected from various publications in the public domain. Modifications to the original designs are made to satisfy the case study requirements for the 50-year return storm conditions in the GoM Central Region. The main modifications are summarized below. More descriptions of the modified floating support structures can be found in Section 3.4.2.1 through Section 3.4.2.3.

- In all the three cases, the tower base is raised to 24.6 m above the still water level to provide sufficient air gap. The height of the tower is changed to 68 m, which leads to a hub height of 95 m.
- The modified OC3-Hywind Spar for the GoM Central Region used in the case studies of BSEE TA&R project 669 (Yu and Chen, 2012), are employed in the present case studies for the site Offshore Oregon due to the severe wave conditions.
- For the OC4-DeepCwind Semi-submersible, the original mooring system consisted of 3 uniform lines for a 200 m water depth. In this case study, the mooring system is modified for the 320 m water depth. The modified mooring system consists of 3 lines, each of which comprises segments of wire rope, clump weight, polyester rope and wire rope arranged from top to bottom. Pretensions are also increased to prevent contact of the polyester rope with the sea floor.
- It is found that the tendons used in the original MIT/NREL TLP could become slack under the hurricane conditions in the GoM Central Region. The slack-line issue is resolved by increasing the tendon fairlead radius and tendon pretensions. Material properties for a typical 163 mm diameter spiral strand wire rope are used in the analysis. Due to increased pretensions, the weight of the concrete ballast of the original concept was reduced.

The main particulars of the modified conceptual designs of the floating support structure are summarized in Table 3.10. The CHARM3D models of the coupled hull and mooring system are also shown in the table.

Table 3.10 Main Particulars of the Floating Support Structures and the Stationkeeping Systems

	Spar	*Semi-Submersible*	*TLP*
Draft	120 m	20 m	47.89 m
Displacement	10279 ton	14265 ton	12485 ton
Column Diameter	6.5 m – 10.6 m (tapered)	12 m	18 m
Center of Gravity below SWL	89.56 m	13.46 m	38.154 m
Mooring or Tendon System	3 lines 1000 m length each line 88.7 kg/m dry weight per unit length 3000 kN Pretensions 45 ton clump weight on each line	3 lines 100 m 163 mm spiral wire rope 60 ton clump weight 1100 m 180mm polyester rope 350 m 163 mm spiral wire rope 2350 kN Pretension	8 lines 163 mm spiral wire rope 35 m tendon fairlead radius 6000 kN Pretension
Global Model and Coordinates			

3.4.2.1 Spar Hull and Mooring System

The OC3 Hywind Spar concept is configured to support the NREL 5-MW baseline offshore wind turbine. It consists of a deep draft cylinder with tapered cross sections below the water line. The Spar is moored by a spread mooring system with three catenary mooring lines. Each mooring line includes multiple segments and a clump weight. To provide yaw stiffness to the platform, the mooring lines are connected to the Spar hull structure via a so-called "crowfoot" (delta connection).

A modified OC3 Hywind Spar for the GoM Central Region for the case studies of BSEE TA&R project 669 is used in the present case studies. The mooring line size and pretension have been increased from those of the original OC3 Hywind Spar to provide sufficient yaw stiffness for both static and dynamic yaw stability. The diameter of the lower part of the Spar is also increased in order to provide sufficient buoyancy to compensate for the increased pretensions and to maintain the lower center of gravity (CG) of the Spar. The tower base is raised to 24.6 m above the still water level and a 68 m high tower is mounted at the top of the Spar hull structure. The weight of Spar hull is increased due to the increase in the hull size as well as the higher tower base elevation and hub height.

The coordinate system and mooring line numbering for the Spar is depicted in Figure 3.14. The origin is at the crossing of the still water level and the tower center line with z-axis pointing upwards.

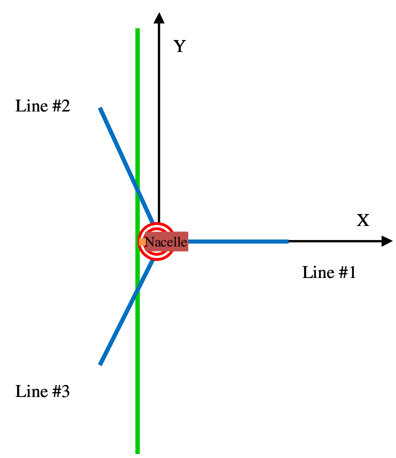


Figure 3.14 Coordinate System and Numbering of Mooring Lines – Spar FOWT

3.4.2.2 Semi-submersible Hull and Mooring System

The OC4-DeepCwind Semi-submersible is configured to support the NREL 5-MW baseline offshore wind turbine. It consists of a column-stabilized hull fitted with water-entrapment plates (heave plates) and moored by a spread mooring system with 3 mooring lines. The original mooring system is configured for 200 m water depth offshore Maine. For the present case studies, the tower base of the OC4-DeepCwind design is raised to 24.6 m above the still water level. Except for the tower base elevation, other dimensions of the Semi-submersible hull remain the same as the original design. The weight of Semi-submersible hull is slightly decreased due to the combined effects of the shortened tower and increased mooring pretensions. A 68 m high tower is mounted at the top of the center column. The mooring system is modified for 320 m water depth. The modified mooring system consists of 3 mooring lines. Each mooring line has a three-segment wire-polyester rope-wire configuration. A clump weight is attached between the upper wire segment and the polyester rope segment.

The coordinate system and mooring line numbering for the Semi-submersible is depicted in Figure 3.15. The origin is at the crossing of the still water level and the tower center line with z-axis pointing upwards.

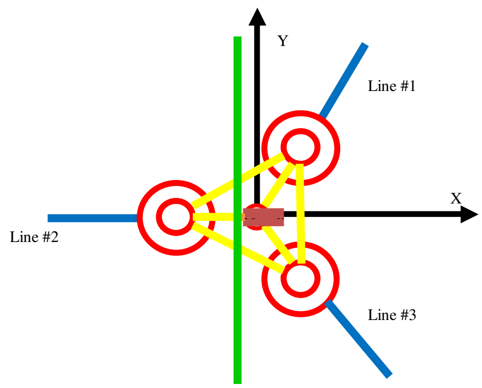


Figure 3.15 Coordinate System and Numbering of Mooring Lines – Semi-Submersible FOWT

3.4.2.3 TLP Hull and Mooring System

The MIT/NREL TLP supporting the NREL 5-MW baseline offshore wind turbine is a mono-column TLP. The hull of the TLP is a concrete ballasted cylinder. At the bottom of the cylinder, there are four spokes extended from the hull. Each spoke tip connects to two tendons. The spokes are assumed mass-less in the global performance model. In the original MIT/NREL TLP design, the length from the center of the cylinder to the spoke tip (tendon fairlead radius) is 27 m. The tower base is at the still water level.

For the present case study, the TLP hull diameter and draft remain the same as the original design, while the tower base is raised to 24.6 m above the still water level. A 68 m high tower is mounted atop of the center column (i.e. the TLP hull). In order to avoid negative tendon tensions, the fairlead radius is increased to 35 m and the pretension of the tendon is increased to 6000 kN. The steel weight of the TLP hull is also increased as a result of the elevated freeboard of the TLP column. The concrete ballast is reduced to compensate for the increased tendon pretensions. In order to meet the strength requirements for the TLP tendon, the tendon size is increased. Each tendon is assumed to be made of a generic spiral strand wire rope with diameter of 163 mm.

The coordinate system and tendon numbering for the TLP is shown in Figure 3.16. The origin is at the crossing of the still water level and the tower center line with z-axis pointing upwards. The distance between two tendons at each spoke tip is 2 m.

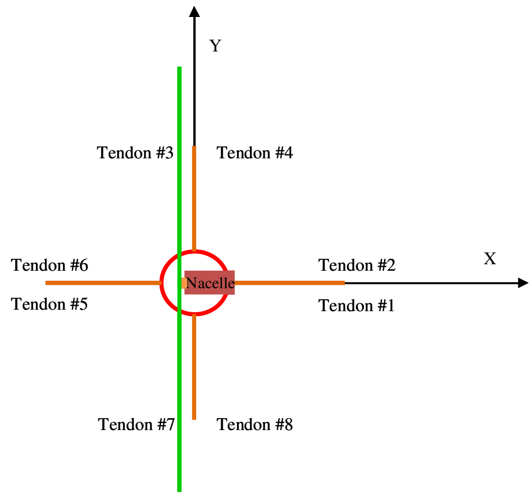


Figure 3.16 Coordinate System and Numbering of Tendons – TLP FOWT

3.4.3 Tower Specifications and Mode Shapes

The tower of the three conceptual designs is adapted from the OC3 Hywind Spar conceptual design. The original OC3 Hywind tower length is 77.6 m and the tower base elevation is 10 m above the still water level. In order to provide a sufficient air gap, the elevation of the tower base is increased from 10 m to 24.6 m. The tower height is therefore reduced from 77.6 m to 68 m, and the tower top elevation becomes 92.6 m and the hub height becomes 95 m above the still water level. The main dimensions and mass properties of the modified tower are provided in Table 3.11.

Table 3.11 Main Particulars for the Modified OC3 Hywind Tower

Elevation to Tower Base (Platform Top) Above SWL	24.6 m
Elevation to Tower Top (Yaw Bearing) Above SWL	92.6 m
Overall Tower Length (from Tower Base to Tower Top)	68.0 m
Tower Base Diameter	6.5 m
Tower Top Diameter	3.87 m
Tower Base Thickness	0.027 m
Tower Top Thickness	0.019 m
Overall (Integrated) Tower Mass	218,825 kg
Center of Gravity Above SWL Along Tower Centerline	53.87 m
Tower Structural-Damping Ratio (All Modes)	1%

The tower's first and second fore-aft and side-to-side bending mode shapes are calculated by assuming that the tower is supported by a floating foundation. The RNA mass is taken into account in the tower modal analysis. A 1% structural damping ratio is applied for all modes of the tower. The mode shapes are shown in Figure 3.17, Figure 3.18 and Figure 3.19 for the Spar, Semi-submersible and TLP FOWTs, respectively. The natural frequencies for the four modes are listed in Table 3.12, Table 3.13 and Table 3.14.

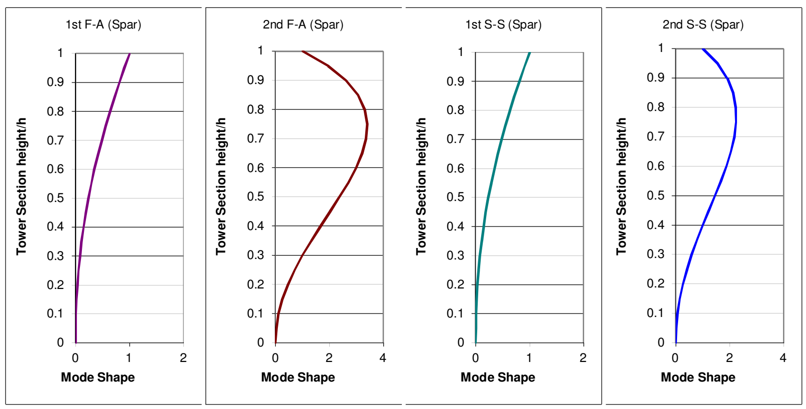


Figure 3.17 Tower 1st & 2nd Fore-Aft and Side-to-Side Bending Mode Shapes – Spar FOWT

Table 3.12 Tower Modal Frequency – Spar FOWT

Mode	*Frequency (Hz)*	*Radial Frequency (rad/s)*	*Period (s)*
1st Fore-Aft	0.569	3.578	1.756
2nd Fore-Aft	2.888	18.145	0.346
1st Side-to-Side	0.556	3.493	1.799
2nd Side-to-Side	2.287	14.367	0.437

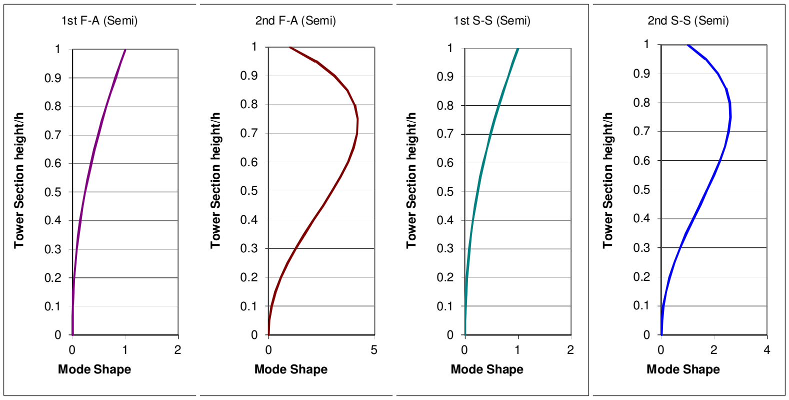


Figure 3.18 Tower 1st & 2nd Fore-Aft and Side-to-Side Bending Mode Shapes – Semisubmersible FOWT

Table 3.13 Tower Modal Frequency – Semisubmersible FOWT

Mode	*Frequency (Hz)*	*Radial Frequency (rad/s)*	*Period (s)*
1st Fore-Aft	0.532	3.345	1.878
2nd Fore-Aft	2.853	17.927	0.350
1st Side-to-Side	0.522	3.278	1.917
2nd Side-to-Side	2.253	14.155	0.444

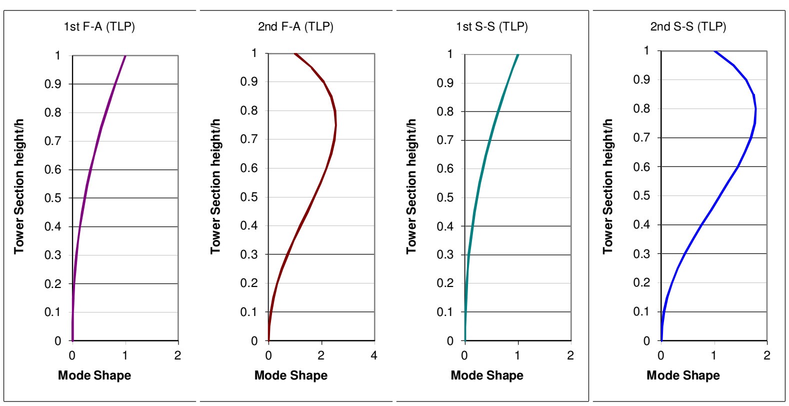


Figure 3.19 Tower 1st & 2nd Fore-Aft and Side-to-Side Bending Mode Shapes – TLP FOWT

Table 3.14 Tower Modal Frequency – TLP FOWT

Mode	*Frequency (Hz)*	*Radial Frequency (rad/s)*	*Period (s)*
1st Fore-Aft	0.842	5.292	1.187
2nd Fore-Aft	2.969	18.654	0.337
1st Side-to-Side	0.816	5.128	1.225
2nd Side-to-Side	2.373	14.908	0.421

3.4.4 Wind Turbine RNA Specifications

The wind turbine RNA selected for the case studies is the NREL 5-MW baseline offshore wind turbine (Jonkman et al., 2009), which is a three-blade, pitch regulated and variable speed horizontal axis wind turbine. Figure 3.20 illustrates the main dimensions (in meters) of the turbine RNA. The main properties of the turbine RNA and blades are listed in Table 3.15 and Table 3.16.

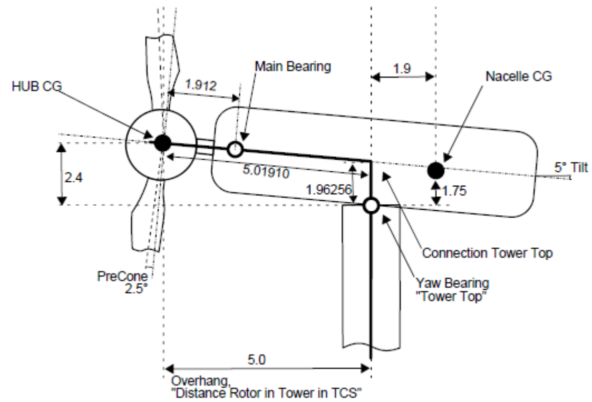


Figure 3.20 RNA of the NREL 5-MW Baseline Offshore Wind Turbine (Jonkman et al., 2009)

Table 3.15 Properties of the RNA of the NREL 5-MW Baseline Offshore Wind Turbine

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drive train	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126 m, 3 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s (10-minute average, at hub height)
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Rotor Mass	110000 kg
Nacelle Mass	240000 kg

Table 3.16 Undistributed Blade Properties

Length	61.5 m
Mass	17740 kg
Second Mass Moment of Inertia (with Respect to the Root)	11776047 kg-m2
First Mass Moment of Inertia (with Respect to the Root)	363231 kg-m
CM Location (with Respect to the Root along Precone Axis)	20.475 m
Structural Damping Ratio (All Modes)	2.5 %

3.4.5 Control System Properties

The RNA control scheme for OC3 Hywind Spar (Jonkman, et al., 2010) is implemented for the case studies in this project. The OC3 Hywind control scheme was developed based on the conventional variable-speed, variable blade-pitch-to-feather control system of the NREL 5-MW baseline offshore wind turbine.

For a conventional pitch-to-feather-controlled wind turbine, when the wind speed runs above turbine's rated wind speed, the rotor speed is regulated by changing the blade pitch angle and the steady-state rotor thrust is reduced with increasing relative wind speed. As pointed out by Nielsen, et al. (2006), this control strategy may introduce the negative aerodynamic damping that could lead to large resonant global motions of an FOWT.

Jonkman, et al. (2010) modified the conventional control scheme by reducing the gains in the blade-pitch-to-feather control system. The generator-torque control strategy was also changed from maintaining constant generator power output to constant generator torque for the RNA operating above the rated wind speed. For a conventional land based turbine, the proportional and integral gains (Kp, KI) were determined using the controller response natural frequency of 0.6 rad/s and damping ratio of 0.7. For the OC3 Hywind control system, however, the controller response natural frequency was reduced to 0.2 rad/s, which was lower than the platform pitch natural frequency and the wave-excitation frequency of most sea states.

The control system properties for the OC3 Hywind applied in this project, together with those of the conventional control system (land-based) are listed in Table 3.17. These control system properties are applied through a dynamic link library (DLL) in CHARM3D-FAST simulations.

Table 3.17 Control System Properties for the NREL 5-MW Baseline Offshore Wind Turbine

	For the Land Based Turbine	*For the OC3 Hywind*
Controller natural frequency	0.6 rad/s	0.2 rad/s
Damping Ratio	0.7	0.7
Proportional Gain, Kp	0.01882681 s	0.006275604 s
Integral Gain, KI	0.00806863	0.0008965149
Generator-torque control	Constant Power	Constant Torque

3.4.6 Wind Field Models and Simulations

Wind field data are generated by IECWind for deterministic wind conditions and by TurbSim for turbulent wind conditions. For 1-year, 50-year and 500-year return storm wind conditions, the API (NPD) wind spectrum is applied to all the load cases where the extreme wind conditions need to be considered. For operational wind conditions, the IEC (Kaimal) wind spectrum is used to generate turbulent wind field data.

A grid size of 51×7 for a 139.98 m (height) by 300.00 m (width) domain centered at hub height is used in the simulation for both the API (NPD) and IEC (Kaimal) wind spectra.

For each extreme wind condition, six 1-hour turbulent wind field data are simulated using TurbSim with different random seeds. Additional 400 s of wind data are used for the ramp time in CHARM3D-FAST simulations. For each operational wind condition, twenty 10-minute turbulent wind field data are simulated using TurbSim with different random seeds. Additional 200 s of wind data are included for the ramp time in CHARM3D-FAST simulations.

For DLC 1.3 (Power Production), twenty 10-mintue wind field data are simulated for operational wind speeds between the cut-in (V_{in}) and cut-out (V_{out}) wind speeds. The turbulence model used for the wind is the IEC Extreme Turbulence Model (ETM).

For DLCs 1.6, 2.1 and 5.1 (Emergency Shut Down), twenty 10-mintue wind field data are simulated for operational wind speeds between the cut-in (V_{in}) and cut-out (V_{out}) wind speeds. The turbulence model used for the wind is the IEC Normal Turbulence Model (NTM).

For DLCs 1.4, 1.5, 2.3, 3.2, 3.3 and 4.2, IEC deterministic wind models are applied. The wind field data are generated by IECWind at wind speeds between the cut-in (V_{in}) and cut-out (V_{out}). Each simulation lasts 800 s, in which the first 200 s is used as ramp time in CHARM3D-FAST simulations. Different starting time of the wind event is assigned for each simulation.

3.5 Spar FOWT

3.5.1 Summary of Model Parameters

The Spar hull and mooring system are defined in Section 3.4.2.1. The site conditions are summarized in Section 3.4.1. The tower and the turbine RNA related parameters are given in Section 3.4.3 and 3.4.4, respectively. The OC3 Hywind turbine control scheme, as described in Section 3.4.5, is applied when the turbine is in the power production mode. The turbulent and deterministic wind field data for the aerodynamic analysis in FAST are generated according to Section 3.4.6.

A total of 21 load cases are defined to evaluate the global responses of the Spar FOWT sited offshore Oregon (OR) considering the return period of environmental conditions, turbine operating modes (power production, start-up, emergency shut down and parked), and wind and wave directionality and misalignment. These load cases are summarized in Table 3.18, which correlates to the general description of the design load cases (DLCs) provided in Table 3.1.

For the Spar FOWT with the parked turbine subjected to the 50-year return storm conditions, both aligned (collinear) and misaligned (cross wave) wind and wave directions are incorporated into the load case definitions. The aligned cases include the wind, wave and current headings of 0 degree, 30 degrees and 90 degrees. The misaligned cases assume that the wind heading is always 0 degree, while the wave and current heading is taken as 30 degrees and 90 degrees, respectively. The definitions of the headings are depicted in Figure 3.21.

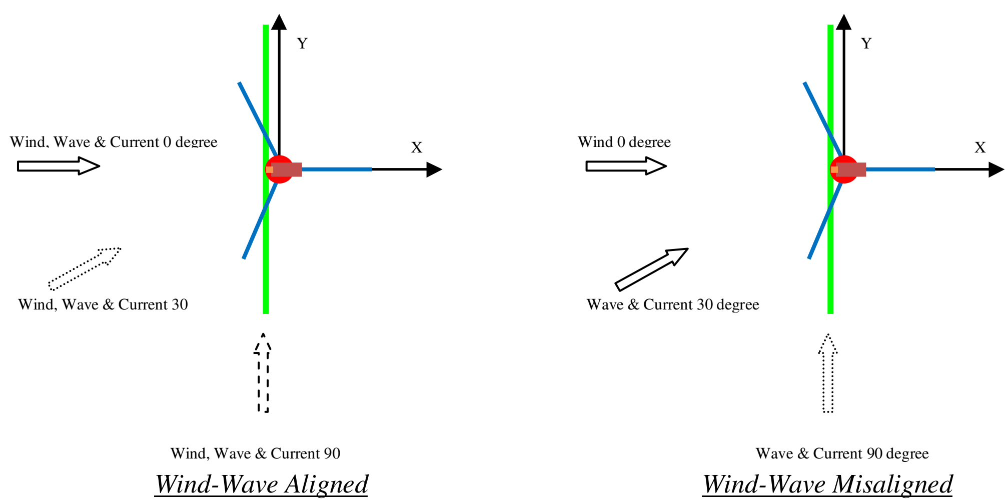


Figure 3.21 Definition of Wind, Wave and Current Directionality – Spar FOWT

The hydrostatic and hydrodynamic properties, including the hydrostatic restoring coefficients, added-mass coefficients, damping coefficients, linear transfer functions (LTF) of wave forces (1st-order wave forces), mean wave drift forces (2nd-order wave forces), and Response Amplitude Operators (RAOs) of 6-DOF Spar hull motions are calculated using WAMIT. The second-order difference-frequency wave forces are determined using Newman's approximation.

The panel model for the Spar hull, consisting of 1094×4 panels (1094 panels on one quarter of the hull, considering x- and y-symmetry), is created for the hydrodynamic analysis using WAMIT (see Figure 3.22).

Figure 3.22 Hydrodynamic Panel Model of the Spar Floating Support Structure

The integrated hull-mooring model for the CHARM3D-FAST time-domain analysis is shown in Figure 3.23 (wind turbine not shown). Each mooring line is modeled by 20 high-order cable elements.

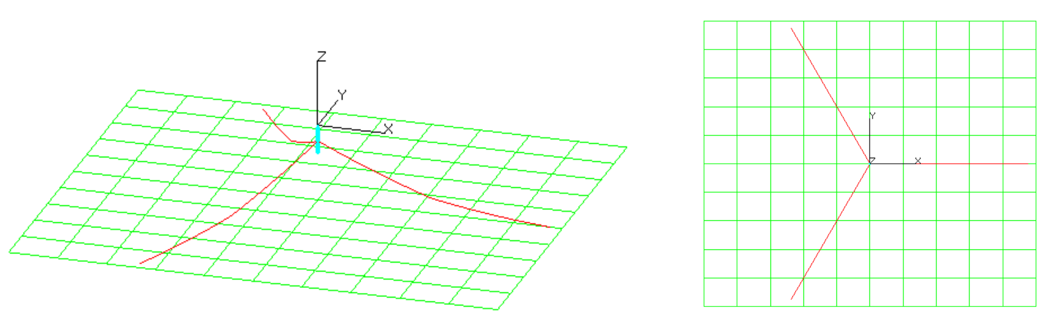


Figure 3.23 Integrated Spar-Mooring Model

In addition to the radiation damping, the viscous damping is applied in the time-domain analysis using the Morison elements. The drag coefficient for the Spar hull is taken as 0.6. The added-mass and drag coefficients for the mooring lines are assumed to be 1.0 and 1.0, respectively.

Two different time marching steps are used in the CHARM3D-FAST simulations, with 0.05s in CHARM3D for calculating the global hull and mooring responses and the tower-hull interface loads and 0.005s in FAST for calculating the aero-servo-elastic responses of the integrated RNA-tower-hull model. The output time step is 0.05s.

Since the FAST program does not account for the quasi-static wind drag load and CHARM3D is not able to read the wind field data generated by TurbSim or IECWind, quasi-static wind loads on the nacelle, tower and Spar hull above the still water level are approximately taken into account following the approach described in Section 3.3.1.

Table 3.18 Summary of Load Cases for the Spar FOWT Case Studies

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions*			*Wave & Wind Misalignment*	*Yaw Error/ Fault Conditions*	*Wind Speed (1-hour) at Ref. 10 m*	*Wind Speed (10-min) at Hub Height*	*Wave Condition*		*Current*	*Water Level*
					Wind	*Wave*	*Current*					*Hs*	*Tp*		
					(deg)	(deg)	(deg)	(deg)	(deg)	(m/s)	(m)	(m)	(s)	(m/s)	
Power Production	1.3	Spar	OR	ETM, V_r	0	0	0	0	0	9.17	11.40	2.84	11.42	0.60	MSL
		Spar	OR	ETM, V_{out}	0	0	0	0	0	19.02	25.00	6.97	13.49	0.60	MSL
Start-up	3.2	Spar	OR	EOG, V_r	0	0	0	0	0	9.17	11.40	2.84	11.42	0.60	MSL
		Spar	OR	EOG, V_{out}	0	0	0	0	0	19.02	25.00	6.97	13.49	0.60	MSL
Emergency shut down	5.1	Spar	OR	NTM, V_r	0	0	0	0	0	9.17	11.40	2.84	11.42	0.60	MSL
		Spar	OR	NTM, V_{out}	0	0	0	0	0	19.02	25.00	6.97	13.49	0.60	MSL
Parked (Idling)	6.1	Spar	OR	50yr storm	0	0	0	0	8	27.33	37.35	15.56	15.36	0.80	MSL
		Spar	OR	50yr storm	30	30	30	0	8	27.33	37.35	15.56	15.36	0.80	MSL
		Spar	OR	50yr storm	90	90	90	0	8	27.33	37.35	15.56	15.36	0.80	MSL
		Spar	OR	50yr storm	0	30	30	30	8	27.33	37.35	15.56	15.36	0.80	MSL
		Spar	OR	50yr storm	0	90	90	90	8	27.33	37.35	15.56	15.36	0.80	MSL
	6.2	Spar	OR	50yr storm	0	0	0	0	30	27.33	37.35	15.56	15.36	0.80	MSL
		Spar	OR	50yr storm	30	30	30	0	30	27.33	37.35	15.56	15.36	0.80	MSL
		Spar	OR	50yr storm	90	90	90	0	30	27.33	37.35	15.56	15.36	0.80	MSL
		Spar	OR	50yr storm	0	30	30	30	30	27.33	37.35	15.56	15.36	0.80	MSL
		Spar	OR	50yr storm	0	90	30	90	30	27.33	37.35	15.56	15.36	0.80	MSL
	6.3	Spar	OR	1yr storm	0	0	0	0	20	20.28	26.82	8.91	14.06	0.60	MSL

Table 3.18 Summary of Load Cases for the Spar FOWT Case Studies (Continued)

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions*			*Wave & Wind Misalignment*	*Yaw Error/ Fault Conditions*	*Wind Speed (1-hour) at Ref. 10 m*	*Wind Speed (10-min) at Hub Height*	*Wave Condition*		*Current*	*Water Level*
					Wind	*Wave*	*Current*					*Hs*	*Tp*		
					(deg)	(deg)	(deg)	(deg)	(deg)	(m/s)	(m)	(m)	(s)	(m/s)	
Parked and fault conditions	7.1	Spar	OR	1yr storm	0	0	0	0	Yaw=8; 1 seized blade	20.28	26.82	8.91	14.06	0.60	MSL
		Spar	OR	1yr storm	0	0	0	0	30	20.28	26.82	8.91	14.06	0.60	MSL
Survival Condition	-	Spar	OR	500yr storm	0	0	0	0	8	31.44	43.74	19.47	15.89	0.90	MSL
		Spar	OR	500yr storm	0	0	0	0	30	31.44	43.74	19.47	15.89	0.90	MSL

Notes:

1. API wind models are used for the 1-year, 50-year and 500-year condition for turbine parked.
2. IEC wind models are used for power production, start-up and emergency shutdown.
3. OR: Offshore Oregon (US West Coast)
4. ETM: Extreme Turbulence Model
5. EOG: Extreme Operating Gust
6. NTM: Normal Turbulence Model
7. V_r is the rated wind speed at hub height.
8. V_{out} is the cut-out wind speed at hub height.
9. H_s and T_p are the significant wave height and the peak period of wave spectrum
10. Current Speed are given at water surface
11. MSL: Mean Sea Level (Mean Still Water Level)

3.5.2 Natural Periods and Motion RAOs

To derive the natural periods of the 6-DOF motions of the Spar FOWT, numerical free decay analyses are performed using CHARM3D-FAST in the time domain. The natural periods for 6-DOF motions are listed in Table 3.19. The hull motion RAOs calculated by WAMIT for 0, 30 and 90 degree wave headings are shown in Figure 3.24 for the Spar FOWT.

Table 3.19 Natural Periods of the Spar Hull Motions

Mode of Motion	*Natural Periods (seconds)*
Surge	62.6
Sway	62.2
Heave	34.4
Roll	27.4
Pitch	27.4
Yaw	4.3

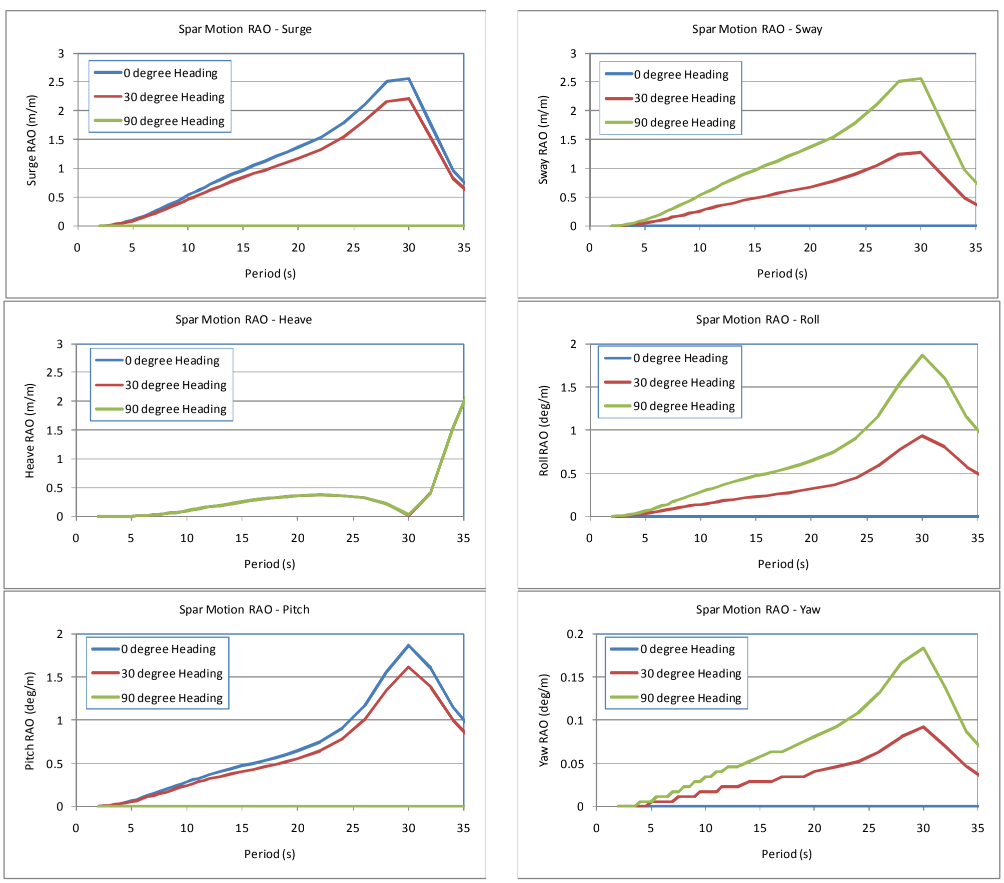


Figure 3.24 Motion RAOs for the Spar Floating Support Structure

3.5.3 Spar FOWT Case Study Results

Selected load cases are analyzed for the Spar FOWT assumed to be deployed on the US West Coast offshore Oregon (OR). Responses are evaluated in this Section in the following aspects:

- Power production and parked conditions - responses for normal power production and normal parked conditions
- Effects of environment directionality and misalignment - responses of the parked turbine in the 50-year return condition with different directionality and misalignment of wind, wave and current conditions
- Effects of return periods for parked turbines - responses for parked turbines in the 1-year, 50-year and 500-year return conditions

3.5.3.1 Power Production and Parked Conditions

Responses of the following normal power production and normal parked conditions are compared in Figure 3.25:

- Turbine in power production (DLC 1.3) with the rated and cut-out wind speeds
- Turbine parked with a nacelle yaw error of 20 degrees in the 1-year storm condition (DLC 6.3)
- Turbine parked with a nacelle yaw error of 8 degrees in the 50-year storm condition (DLC 6.1)

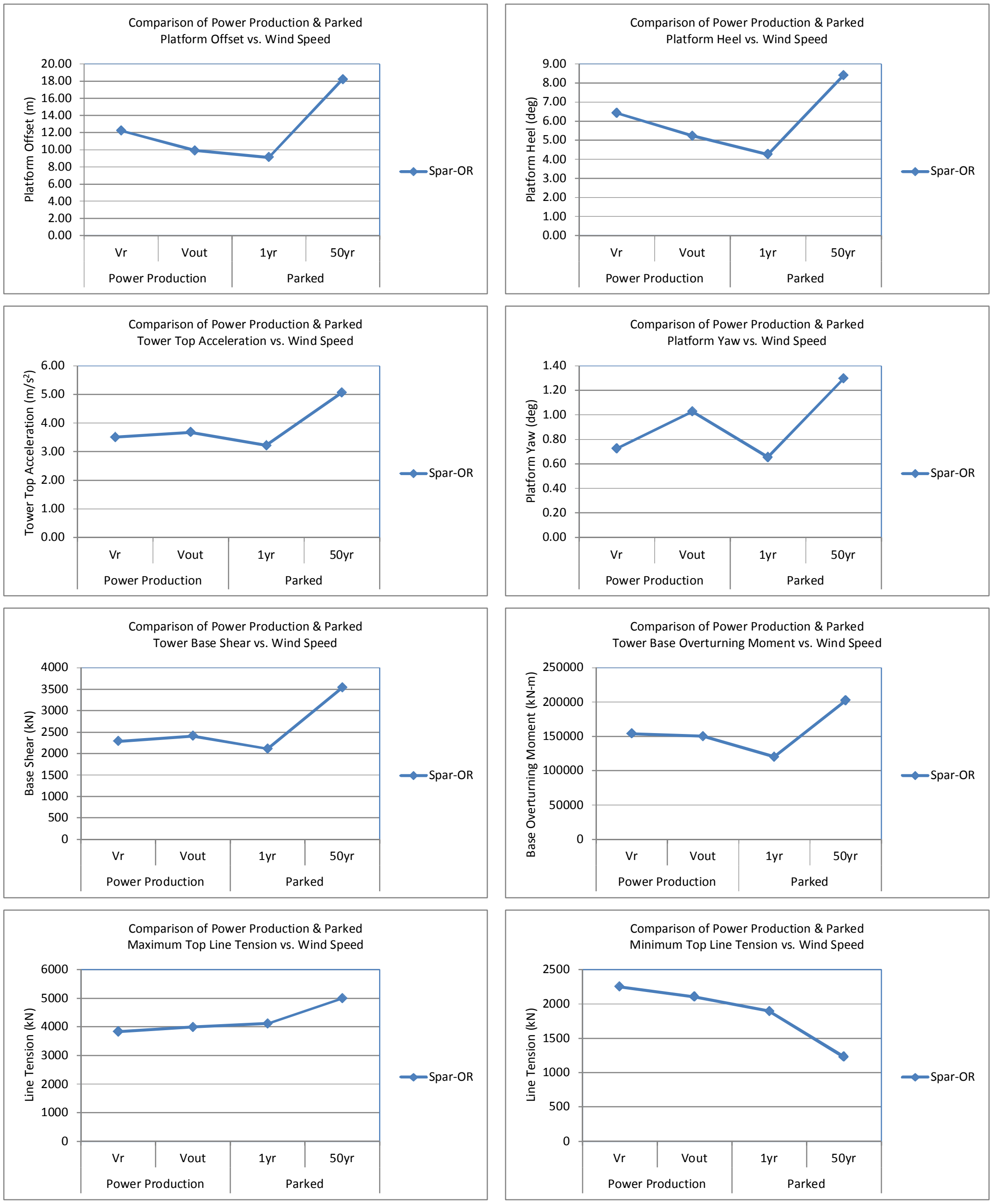


Figure 3.25 Comparisons between Power Production and Parked Conditions – Support Structure and Mooring Responses of the Spar FOWT in OR

3.5.3.2 Effects of Environment Directionality and Misalignment

Responses of the parked turbine in the 50-year storm conditions with different environmental headings and wind/wave misalignment with a nacelle yaw error of 8 and 30 degrees (DLC 6.1 & 6.2), respectively, are compared in Figure 3.26.

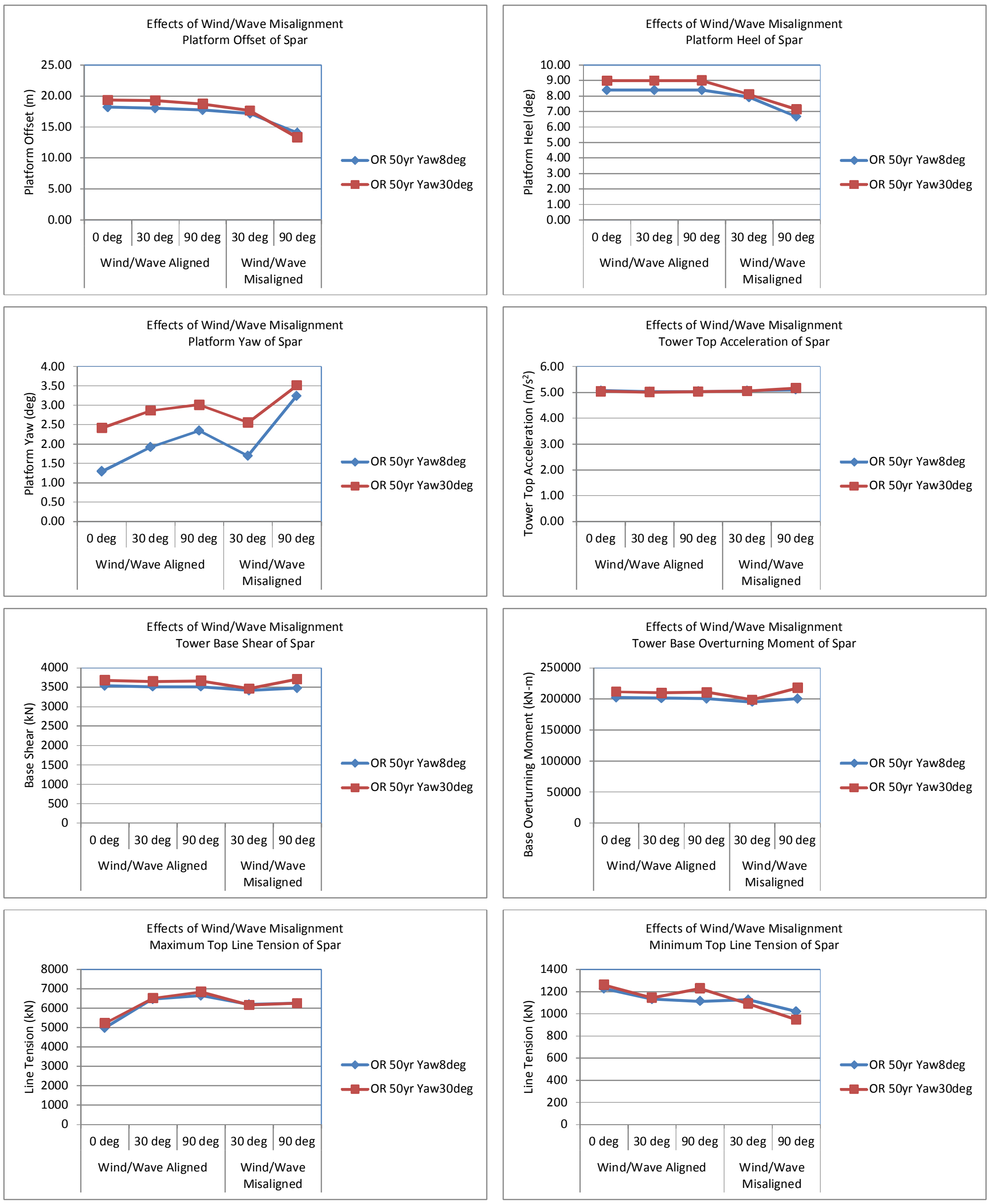


Figure 3.26 Effects of Environment Directionality and Misalignment – Support Structure and Mooring Responses of the Spar FOWT in OR

3.5.3.3 Effects of Return Periods for Parked Turbines

Responses of the following parked conditions with or without fault of the Spar FOWT, as well as semisubmersible and TLP FOWTs, in OR are compared in Figure 3.27:

- Parked condition with a nacelle yaw error of 20 degrees in the 1-year storm condition (DLC 6.3)
- Parked condition with a nacelle yaw error of 30 degrees or 1 sized blade with a nacelle yaw error of 8 degrees in the 1-year storm condition (DLC 7.1)
- Parked condition with a nacelle yaw error of 8 degrees in the 50-year storm condition (DLC 6.1)
- Parked condition with a nacelle yaw error of 30 degrees in the 50-year storm condition (DLC 6.2)
- Parked condition with a nacelle yaw error of 8 degrees in the 500-year storm condition (Survival)
- Parked condition with a nacelle yaw error of 30 degrees in the 500-year storm condition (Survival)

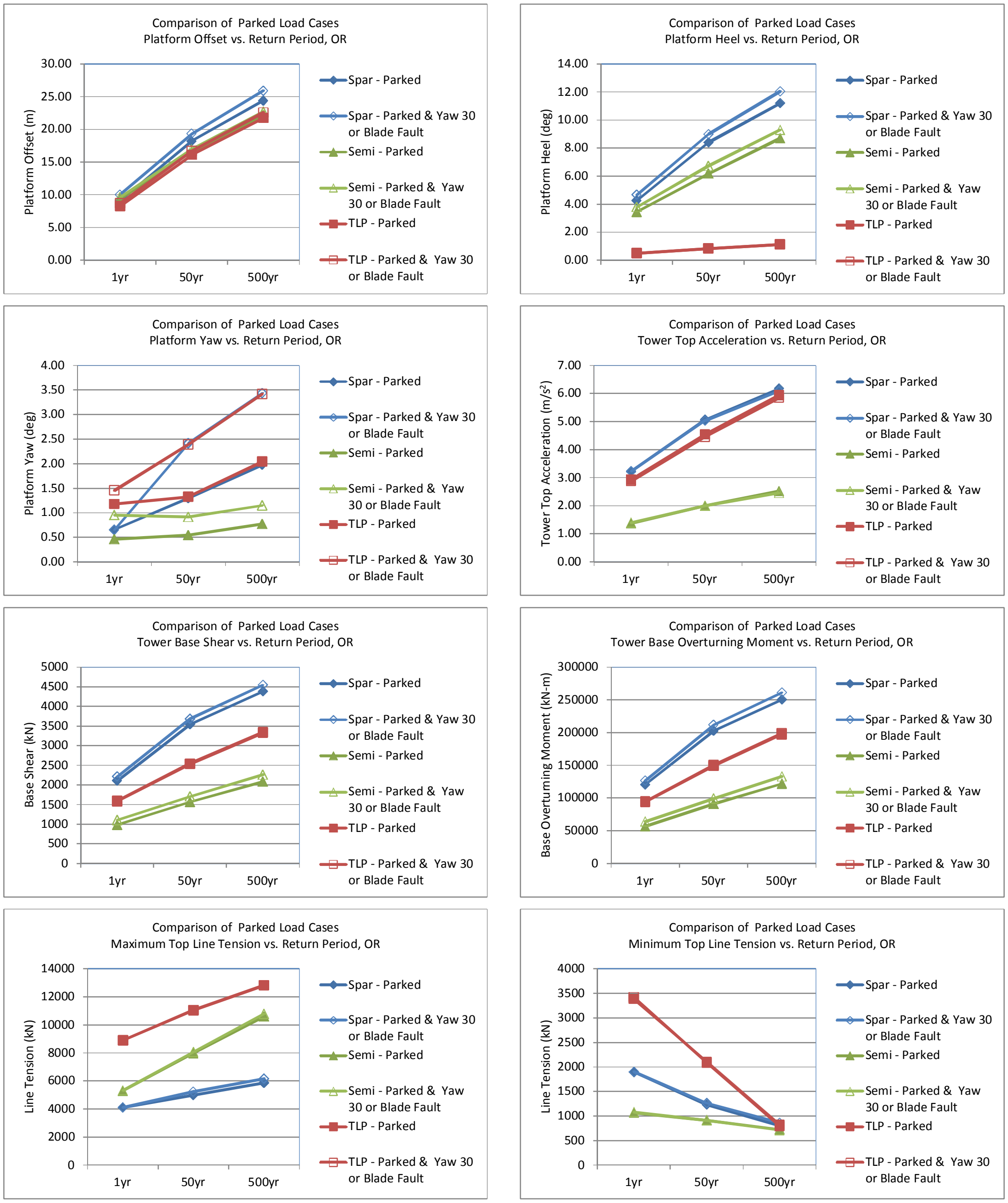


Figure 3.27 Comparisons of Responses for the Parked RNA Conditions – Support Structure and Mooring Responses of the Spar, Semisubmersible and TLP FOWTs in OR

Ratios of the maximum responses of the Spar FOWT subjected to the 500-year storm condition (survival load cases) to those subjected to 50-year storm conditions (DLC 6.1 and DLC 6.2) and with the yaw error of 8 and 30 degrees are compared in Figure 3.28.

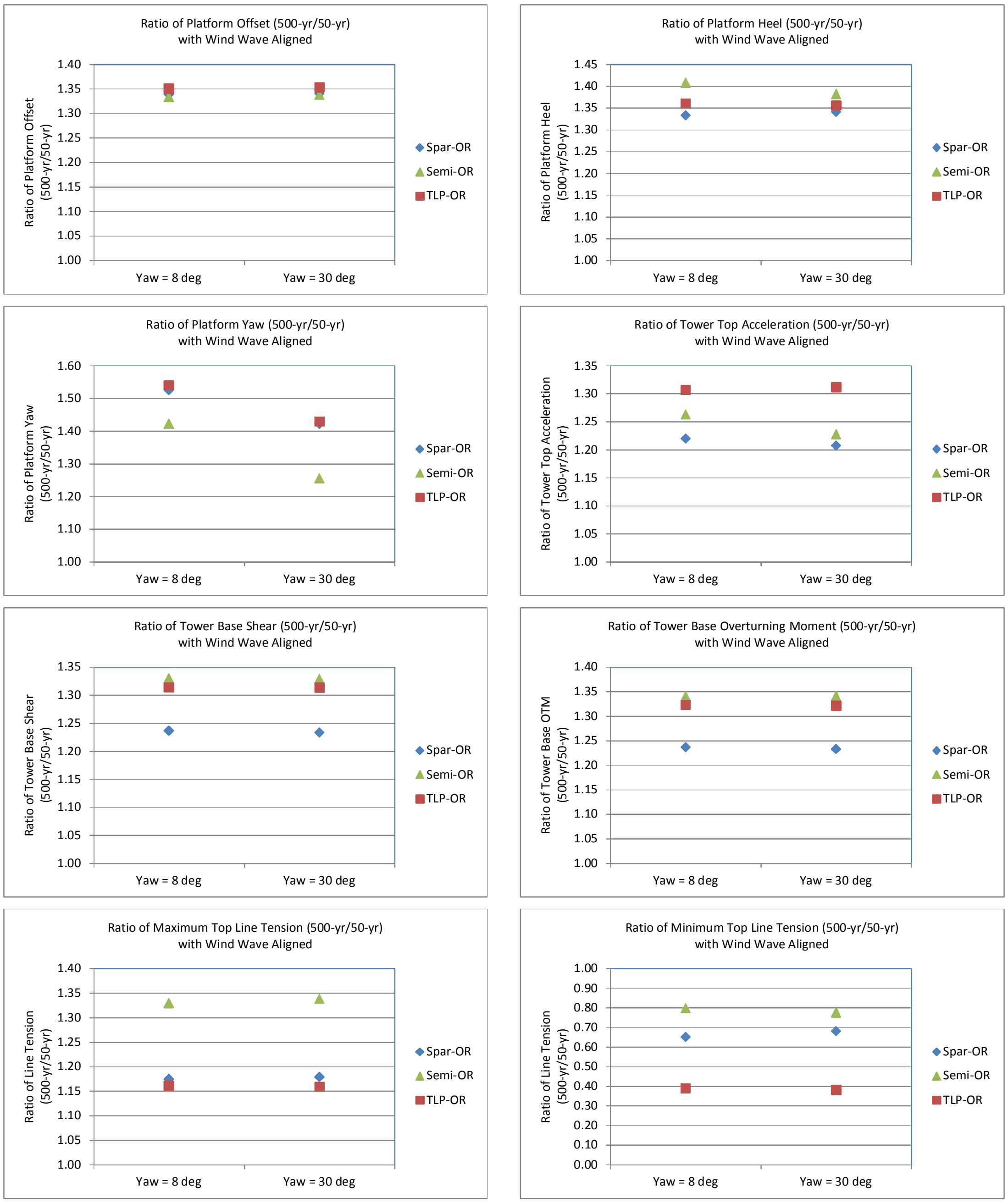


Figure 3.28 Ratios of 500yr to 50yr Responses for the Parked RNA Conditions – Support Structure and Mooring Responses of the Spar, Semisubmersible and TLP FOWTs in OR

3.5.3.4 Conclusions

Based on the results of global performance analyses for the load cases as presented in Table 3.18 for the Spar FOWT in OR, the following conclusions are made:

- Turbine components loads (blade root bending and shaft bending moments) are governed by DLC 1.3 (power production) in combination with the extreme turbulent wind model.
- Tower base loads and mooring loads are governed by DLC 6.1 & 6.2 with the parked turbine.
- Collinear wind and wave in general result in larger maximum mooring loads and larger platform offsets.
- Misalignment of wind and wave may result in a smaller minimum line tension.
- Misalignment of wind and wave may result in a larger maximum platform yaw motion.
- Misalignment of wind and wave may result in larger maximum tower base loads. However, the effects appear to be marginal.
- Platform yaw motions are more sensitive to effects of yaw errors and blade faults (blade fault in DLC 7.1; yaw error in DLC 6.2 and DLC 7.1; and the survival load cases) with comparison to the hull global motions of other degrees-of-freedom and line tensions.
- Yaw error and blade fault conditions (blade fault in DLC 7.1; nacelle yaw error in DLC 6.2 and DLC 7.1; and the survival load cases) are more critical for the design of wind turbine components than the Spar hull structure and the stationkeeping system.
- Ratios of the Spar FOWT responses to the 500-year return site conditions to those to the 50-year return site conditions show that the ratios of the maximum line tension range between 1.17 and 1.18; the ratios of the maximum tower base loads range between 1.23 and 1.24.

3.6 Semi-submersible FOWT

3.6.1 Summary of Model Parameters

The Semi-submersible hull and mooring system are defined in Section 3.4.2.2. The site conditions are summarized in Section 3.4.1. The tower and the turbine RNA related parameters are given in Section 3.4.3 and 3.4.4, respectively. The OC3 Hywind turbine control scheme, as described in Section 3.4.5, is applied when the turbine is in the power production mode. The turbulent and deterministic wind field data for the aerodynamic analysis in FAST are generated according to Section 3.4.6.

A total of 89 load cases are defined to evaluate the global responses of the Semi-submersible FOWT considering the return period of environmental conditions, turbine operating modes (power production, start-up, shutdown and parked), wind and wave misalignment and site condition variations. These load cases are summarized in Table 3.20, which correlates to the general description of the design load cases (DLCs) provided in Table 3.1. All the load cases presented in this section are using the lower bound stiffness for the polyester ropes.

For the Semi-submersible FOWT with the parked turbine subjected to the 50-year return storm conditions, both aligned (collinear) and misaligned (cross wave) wind and wave directions are incorporated into the load case definitions. The aligned cases include the wind, wave and current headings of 0 degree, 30 degrees and 90 degrees. The misaligned cases assume that the wind heading is always 0 degree, while the wave and current heading is taken as 30 degrees and 90 degrees, respectively. The definitions of the headings are depicted in Figure 3.29.

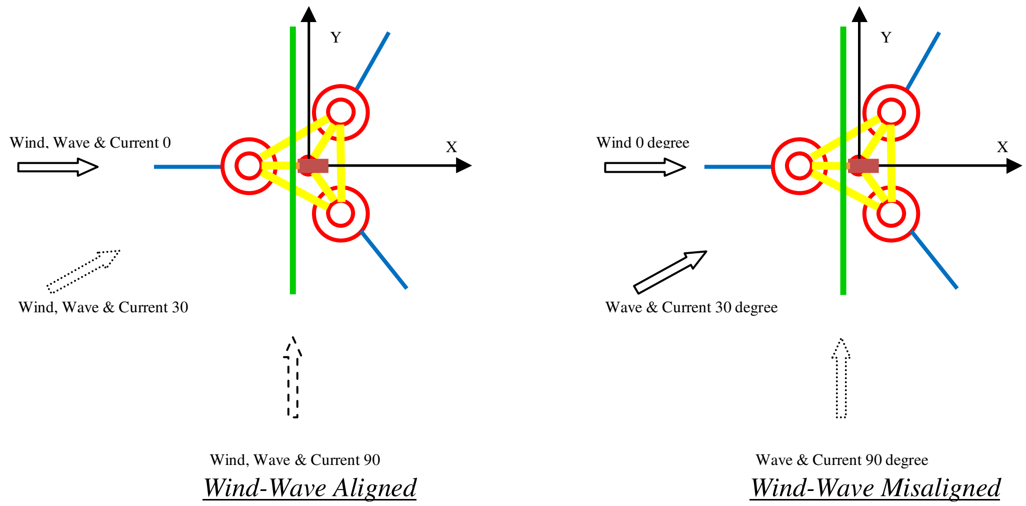


Figure 3.29 Definition of Wind, Wave and Current Directionality – Semi-submersible FOWT

The hydrostatic and hydrodynamic properties, including the hydrostatic restoring coefficients, added-mass coefficients, damping coefficients, linear transfer functions (LTF) of wave forces (1st-order wave forces), mean wave drift forces (2nd-order wave forces), and 6-DOF Semi-submersible hull motions RAOs are calculated using WAMIT. The second-order difference-frequency wave forces are determined using Newman's approximation.

The panel model for the Semi-submersible hull, consisting of 3129×2 panels (with 3129 panels on half of the hull and considering the y-symmetry with respect to the x-z plane) as plotted in Figure 3.30, is created for the hydrodynamic analysis using WAMIT.

The integrated hull-mooring model for the CHARM3D-FAST time-domain analysis is shown in Figure 3.31 (wind turbine not shown). Each mooring line is modeled by 20 high-order cable elements.

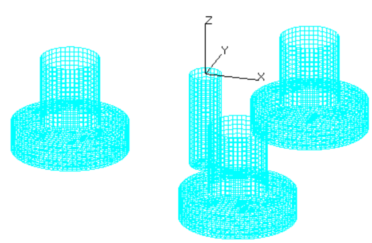


Figure 3.30 Hydrodynamic Panel Model of the Semi-submersible Floating Support Structure

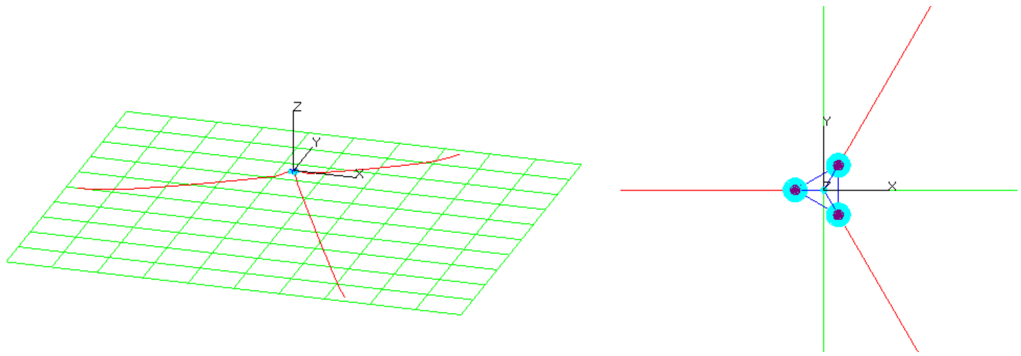


Figure 3.31 Integrated Semi-submersible-Mooring Model

In addition to the radiation damping, the viscous damping is applied in the time-domain analysis using the Morison elements. The drag coefficient for the Semi-submersible columns is chosen as 0.61. The drag coefficient for the heave plate is assumed to be 4.8. The added-mass and drag coefficients of the truss members are taken as 0.59 and 0.63, respectively.

Two different time marching steps are used in the CHARM3D-FAST simulations, with 0.025s in CHARM3D for calculating the global hull and mooring responses and the tower-hull interface loads and 0.005s in FAST for calculating the aero-servo-elastic responses of the integrated RNA-tower-hull model. The output time step is 0.05s.

Quasi-static wind loads on the nacelle, tower and Semi-submersible hull above the still water level are approximately taken into account following the approach described in Section 3.3.1.

Table 3.20 Summary of Load Cases for the Semi-submersible FOWT Case Studies

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions*			*Wave & Wind Misalignment*	*Yaw Error/ Fault Conditions*	*Wind Speed (1-hour) at Ref. 10 m*	*Wind Speed (10-min) at Hub Height*	*Wave Condition*		*Current*	*Water Level*
					Wind	*Wave*	*Current*					*Hs*	*Tp*		
					(deg)	(deg)	(deg)	(deg)	(deg)	(m/s)	(m)	(m)	(s)	(m/s)	
Power Production	1.3	Semi	GOM	ETM, V_{in}	0	0	0	0	0	2.53	3.00	0.13	1.61	0.40	MSL
		Semi	GOM	ETM, V_{in}+4 *m/s*	0	0	0	0	0	5.76	7.00	0.67	3.67	0.40	MSL
		Semi	GOM	ETM, V_r-2 *m/s*	0	0	0	0	0	7.64	9.40	1.19	4.87	0.40	MSL
		Semi	GOM	ETM, V_r	0	0	0	0	0	9.17	11.40	1.71	5.84	0.40	MSL
		Semi	GOM	ETM, V_r+2 *m/s*	0	0	0	0	0	10.68	13.40	2.32	6.80	0.40	MSL
		Semi	GOM	ETM, V_{out}-8 *m/s*	0	0	0	0	0	13.33	17.00	3.61	8.50	0.40	MSL
		Semi	GOM	ETM, V_{out}-4 *m/s*	0	0	0	0	0	16.21	21.00	5.34	10.33	0.40	MSL
		Semi	GOM	ETM, V_{out}	0	0	0	0	0	19.02	25.00	7.35	12.12	0.40	MSL
	1.4	Semi	GOM	ECD, V_r-2 *m/s*	0	0	0	MIS	0	7.64	9.40	1.19	4.87	0.40	MSL
		Semi	GOM	ECD, V_r	0	0	0	MIS	0	9.17	11.40	1.71	5.84	0.40	MSL
		Semi	GOM	ECD, V_r+2 *m/s*	0	0	0	MIS	0	10.68	13.40	2.32	6.80	0.40	MSL
	1.5	Semi	GOM	EWS, V_r	0	0	0	0	0	9.17	11.40	1.71	5.84	0.40	MSL
		Semi	GOM	EWS, V_{out}	0	0	0	0	0	19.02	25.00	7.35	12.12	0.40	MSL
	1.6	Semi	GOM	NTM, V_r-2 *m/s*	0	0	0	0	0	7.64	9.40	13.87	14.62	1.67	MSL
		Semi	GOM	NTM, V_r	0	0	0	0	0	9.17	11.40	13.87	14.62	1.67	MSL
		Semi	GOM	NTM, V_r+2 *m/s*	0	0	0	0	0	10.68	13.40	13.87	14.62	1.67	MSL
		Semi	GOM	NTM, V_{out}	0	0	0	0	0	19.02	25.00	13.87	14.62	1.67	MSL

Table 3.20 Summary of Load Cases for the Semi-submersible FOWT Case Studies (Continued)

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions*			*Wave & Wind Misalignment*	*Yaw Error/ Fault Conditions*	*Wind Speed (1-hour) at Ref. 10 m*	*Wind Speed (10-min) at Hub Height*	*Wave Condition*		*Current*	*Water Level*
					Wind	*Wave*	*Current*					*Hs*	*Tp*		
					(deg)	(deg)	(deg)	(deg)	(deg)	(m/s)	(m)	(m)	(s)	(m/s)	
Power production plus occurrence of fault	2.1	Semi	GOM	NTM, V_r	0	0	0	0	blade pitch runaway	9.17	11.40	1.71	5.84	0.40	MSL
		Semi	GOM	NTM, V_{out}	0	0	0	0	blade pitch runaway	19.02	25.00	7.35	12.12	0.40	MSL
		Semi	GOM	NTM, V_r	0	0	0	0	yaw runaway	9.17	11.40	1.71	5.84	0.40	MSL
		Semi	GOM	NTM, V_{out}	0	0	0	0	yaw runaway	19.02	25.00	7.35	12.12	0.40	MSL
	2.3	Semi	GOM	EOG, V_r	0	0	0	0	grid loss	9.17	11.40	1.71	5.84	0.40	MSL
		Semi	GOM	EOG, V_{out}	0	0	0	0	grid loss	19.02	25.00	7.35	12.12	0.40	MSL
Start-up	3.2	Semi	GOM	EOG, V_r	0	0	0	0	0	9.17	11.40	1.71	5.84	0.40	MSL
		Semi	GOM	EOG, V_{out}	0	0	0	0	0	19.02	25.00	7.35	12.12	0.40	MSL
	3.3	Semi	GOM	EDC, V_r	0	0	0	MIS	0	9.17	11.40	1.71	5.84	0.40	MSL
		Semi	GOM	EDC, V_{out}	0	0	0	MIS	0	19.02	25.00	7.35	12.12	0.40	MSL
Normal shutdown	4.2	Semi	GOM	EOG, V_r	0	0	0	0	0	9.17	11.40	1.71	5.84	0.40	MSL
		Semi	GOM	EOG, V_{out}	0	0	0	0	0	19.02	25.00	7.35	12.12	0.40	MSL
Emergency shutdown	5.1	Semi	GOM	NTM, V_r	0	0	0	0	0	9.17	11.40	1.71	5.84	0.40	MSL
		Semi	GOM	NTM, V_{out}	0	0	0	0	0	19.02	25.00	7.35	12.12	0.40	MSL

Table 3.20 Summary of Load Cases for the Semi-submersible FOWT Case Studies (Continued)

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions*			*Wave & Wind Misalignment*	*Yaw Error/ Fault Conditions*	*Wind Speed (1-hour) at Ref. 10 m*	*Wind Speed (10-min) at Hub Height*	*Wave Condition*		*Current*	*Water Level*
					Wind	*Wave*	*Current*					*Hs*	*Tp*		
					(deg)	(deg)	(deg)	(deg)	(deg)	(m/s)	(m)	(m)	(s)	(m/s)	
Parked (Idling)	6.1	Semi	GOM	50yr peak wind	0	0	0	0	8	44.40	64.96	13.87	14.62	1.67	MSL
		Semi	GOM	50yr peak wind	30	30	30	0	8	44.40	64.96	13.87	14.62	1.67	MSL
		Semi	GOM	50yr peak wind	90	90	90	0	8	44.40	64.96	13.87	14.62	1.67	MSL
		Semi	GOM	50yr peak wind	0	30	30	30	8	44.40	64.96	13.87	14.62	1.67	MSL
		Semi	GOM	50yr peak wind	0	90	90	90	8	44.40	64.96	13.87	14.62	1.67	MSL
	6.2	Semi	GOM	50yr peak wind	0	0	0	0	30	44.40	64.96	13.87	14.62	1.67	MSL
		Semi	GOM	50yr peak wind	30	30	30	0	30	44.40	64.96	13.87	14.62	1.67	MSL
		Semi	GOM	50yr peak wind	90	90	90	0	30	44.40	64.96	13.87	14.62	1.67	MSL
		Semi	GOM	50yr peak wind	0	30	30	30	30	44.40	64.96	13.87	14.62	1.67	MSL
		Semi	GOM	50yr peak wind	0	90	90	90	30	44.40	64.96	13.87	14.62	1.67	MSL
	6.3	Semi	GOM	1yr storm	0	0	0	0	8	16.40	21.27	4.90	10.30	0.40	MSL
		Semi	GOM	1yr storm	0	0	0	0	20	16.40	21.27	4.90	10.30	0.40	MSL
Parked and fault conditions	7.1	Semi	GOM	1yr storm	0	0	0	0	Yaw=8; 1 seized blade	16.40	21.27	4.90	10.30	0.40	MSL
		Semi	GOM	1yr storm	0	0	0	0	30	16.40	21.27	4.90	10.30	0.40	MSL
Survival Condition	-	Semi	GOM	500yr peak wind	0	0	0	0	8	55.92	85.16	17.21	16.17	2.10	MSL
		Semi	GOM	500yr peak wind	0	0	0	0	30	55.92	85.16	17.21	16.17	2.10	MSL

Table 3.20 Summary of Load Cases for the Semi-submersible FOWT Case Studies (Continued)

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions*			*Wave & Wind Misalignment*	*Yaw Error/ Fault Conditions*	*Wind Speed (1-hour) at Ref. 10 m*	*Wind Speed (10-min) at Hub Height*	*Wave Condition*		*Current*	*Water Level*
					Wind	*Wave*	*Current*					*Hs*	*Tp*		
					(deg)	(deg)	(deg)	(deg)	(deg)	(m/s)	(m)	(m)	(s)	(m/s)	
Power Production	1.3	Semi	ME	ETM, V_r	0	0	0	0	0	9.17	11.40	1.98	7.74	0.50	MSL
		Semi	ME	ETM, V_{out}	0	0	0	0	0	19.02	25.00	5.79	10.33	0.50	MSL
Start-up	3.2	Semi	ME	EOG, V_r	0	0	0	0	0	9.17	11.40	1.98	7.74	0.50	MSL
		Semi	ME	EOG, V_{out}	0	0	0	0	0	19.02	25.00	5.79	10.33	0.50	MSL
Emergency shut down	5.1	Semi	ME	NTM, V_r	0	0	0	0	0	9.17	11.40	1.98	7.74	0.50	MSL
		Semi	ME	NTM, V_{out}	0	0	0	0	0	19.02	25.00	5.79	10.33	0.50	MSL
Parked (Idling)	6.1	Semi	ME	50yr storm	0	0	0	0	8	26.70	36.39	10.66	13.21	0.57	MSL
		Semi	ME	50yr storm	30	30	30	0	8	26.70	36.39	10.66	13.21	0.57	MSL
		Semi	ME	50yr storm	90	90	90	0	8	26.70	36.39	10.66	13.21	0.57	MSL
		Semi	ME	50yr storm	0	30	30	30	8	26.70	36.39	10.66	13.21	0.57	MSL
		Semi	ME	50yr storm	0	90	90	90	8	26.70	36.39	10.66	13.21	0.57	MSL
	6.2	Semi	ME	50yr storm	0	0	0	0	30	26.70	36.39	10.66	13.21	0.57	MSL
		Semi	ME	50yr storm	30	30	30	0	30	26.70	36.39	10.66	13.21	0.57	MSL
		Semi	ME	50yr storm	90	90	90	0	30	26.70	36.39	10.66	13.21	0.57	MSL
		Semi	ME	50yr storm	0	30	30	30	30	26.70	36.39	10.66	13.21	0.57	MSL
		Semi	ME	50yr storm	0	90	90	90	30	26.70	36.39	10.66	13.21	0.57	MSL
	6.3	Semi	ME	1yr storm	0	0	0	0	20	19.41	25.56	6.73	10.92	0.49	MSL
Parked and fault conditions	7.1	Semi	ME	1yr storm	0	0	0	0	Yaw=8; 1 seized blade	19.41	25.56	6.73	10.92	0.49	MSL
		Semi	ME	1yr storm	0	0	0	0	30	19.41	25.56	6.73	10.92	0.49	MSL
Survival Condition	-	Semi	ME	500yr storm	0	0	0	0	8	30.94	42.95	12.97	14.48	0.61	MSL
		Semi	ME	500yr storm	0	0	0	0	30	30.94	42.95	12.97	14.48	0.61	MSL

Table 3.20 Summary of Load Cases for the Semi-submersible FOWT Case Studies (Continued)

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions* Wind (deg)	*Environment Directions* Wave (deg)	*Environment Directions* Current (deg)	*Wave & Wind Misalignment* (deg)	*Yaw Error/ Fault Conditions* (deg)	*Wind Speed (1-hour) at Ref. 10 m* (m/s)	*Wind Speed (10-min) at Hub Height* (m)	*Wave Condition* Hs (m)	*Wave Condition* Tp (s)	*Current* (m/s)	*Water Level*
Power Production	1.3	Semi	OR	ETM, V_r	0	0	0	0	0	9.17	11.40	2.84	11.42	0.60	MSL
		Semi	OR	ETM, V_{out}	0	0	0	0	0	19.02	25.00	6.97	13.49	0.60	MSL
Start-up	3.2	Semi	OR	EOG, V_r	0	0	0	0	0	9.17	11.40	2.84	11.42	0.60	MSL
		Semi	OR	EOG, V_{out}	0	0	0	0	0	19.02	25.00	6.97	13.49	0.60	MSL
Emergency shut down	5.1	Semi	OR	NTM, V_r	0	0	0	0	0	9.17	11.40	2.84	11.42	0.60	MSL
		Semi	OR	NTM, V_{out}	0	0	0	0	0	19.02	25.00	6.97	13.49	0.60	MSL
Parked (Idling)	6.1	Semi	OR	50yr storm	0	0	0	0	8	27.33	37.35	15.56	15.36	0.80	MSL
		Semi	OR	50yr storm	30	30	30	0	8	27.33	37.35	15.56	15.36	0.80	MSL
		Semi	OR	50yr storm	90	90	90	0	8	27.33	37.35	15.56	15.36	0.80	MSL
		Semi	OR	50yr storm	0	30	30	30	8	27.33	37.35	15.56	15.36	0.80	MSL
		Semi	OR	50yr storm	0	90	90	90	8	27.33	37.35	15.56	15.36	0.80	MSL
	6.2	Semi	OR	50yr storm	0	0	0	0	30	27.33	37.35	15.56	15.36	0.80	MSL
		Semi	OR	50yr storm	30	30	30	0	30	27.33	37.35	15.56	15.36	0.80	MSL
		Semi	OR	50yr storm	90	90	90	0	30	27.33	37.35	15.56	15.36	0.80	MSL
		Semi	OR	50yr storm	0	30	30	30	30	27.33	37.35	15.56	15.36	0.80	MSL
		Semi	OR	50yr storm	0	90	90	90	30	27.33	37.35	15.56	15.36	0.80	MSL
	6.3	Semi	OR	1yr storm	0	0	0	0	20	20.28	26.82	8.91	14.06	0.60	MSL

Table 3.20 Summary of Load Cases for the Semi-submersible FOWT Case Studies (Continued)

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions*			*Wave & Wind Misalignment*	*Yaw Error/ Fault Conditions*	*Wind Speed (1-hour) at Ref. 10 m*	*Wind Speed (10-min) at Hub Height*	*Wave Condition*		*Current*	*Water Level*
					Wind	*Wave*	*Current*					*Hs*	*Tp*		
					(deg)	(deg)	(deg)	(deg)	(deg)	(m/s)	(m)	(m)	(s)	(m/s)	
Parked and fault conditions	7.1	Semi	OR	1yr storm	0	0	0	0	Yaw=8; 1 seized blade	20.28	26.82	8.91	14.06	0.60	MSL
		Semi	OR	1yr storm	0	0	0	0	30	20.28	26.82	8.91	14.06	0.60	MSL
Survival Condition	-	Semi	OR	500yr storm	0	0	0	0	8	31.44	43.74	19.47	15.89	0.90	MSL
		Semi	OR	500yr storm	0	0	0	0	30	31.44	43.74	19.47	15.89	0.90	MSL

Notes:

1. API wind models are used for the 1-year, 50-year and 500-year condition for turbine parked.
2. IEC wind models are used for power production, start-up, normal shut down and emergency shutdown.
3. GOM: GoM Central Region
4. OR: Offshore Oregon (US West Coast)
5. ME: Gulf of Maine (US Northeast Coast)
6. ETM: Extreme Turbulence Model
7. ECD: extreme coherent gust with direction change
8. EDC: extreme direction change
9. EWS: extreme wind shear
10. MIS: misaligned wind and wave directions
11. EOG: Extreme Operating Gust
12. NTM: Normal Turbulence Model
13. V_{in} is the cut-in wind speed at hub height.
14. V_r is the rated wind speed at hub height.
15. V_{out} is the cut-out wind speed at hub height.
16. H_s and T_p are the significant wave height and the peak period of wave spectrum
17. Current Speed are given at water surface
18. MSL: Mean Sea Level (Mean Still Water Level)
19. HSWL: Highest Still Water Level
20. LSWL: Lowest Still Water Level

3.6.2 Natural Periods and Motion RAOs

To derive the natural periods of the 6-DOF motions of the Semi-submersible FOWT, numerical free decay analyses are performed using CHARM3D-FAST in the time domain. The natural periods for 6-DOF motions of Semi-submersible are listed in Table 3.21.The hull motion RAOs calculated by WAMIT for 0, 30 and 90 degree wave headings are shown in Figure 3.32.

Table 3.21 Natural Periods of the Semi-submersible Hull Motions

Mode of Motion	*Natural Periods (seconds)*
Surge	67.88
Sway	68.00
Heave	17.44
Roll	25.65
Pitch	25.67
Yaw	52.92

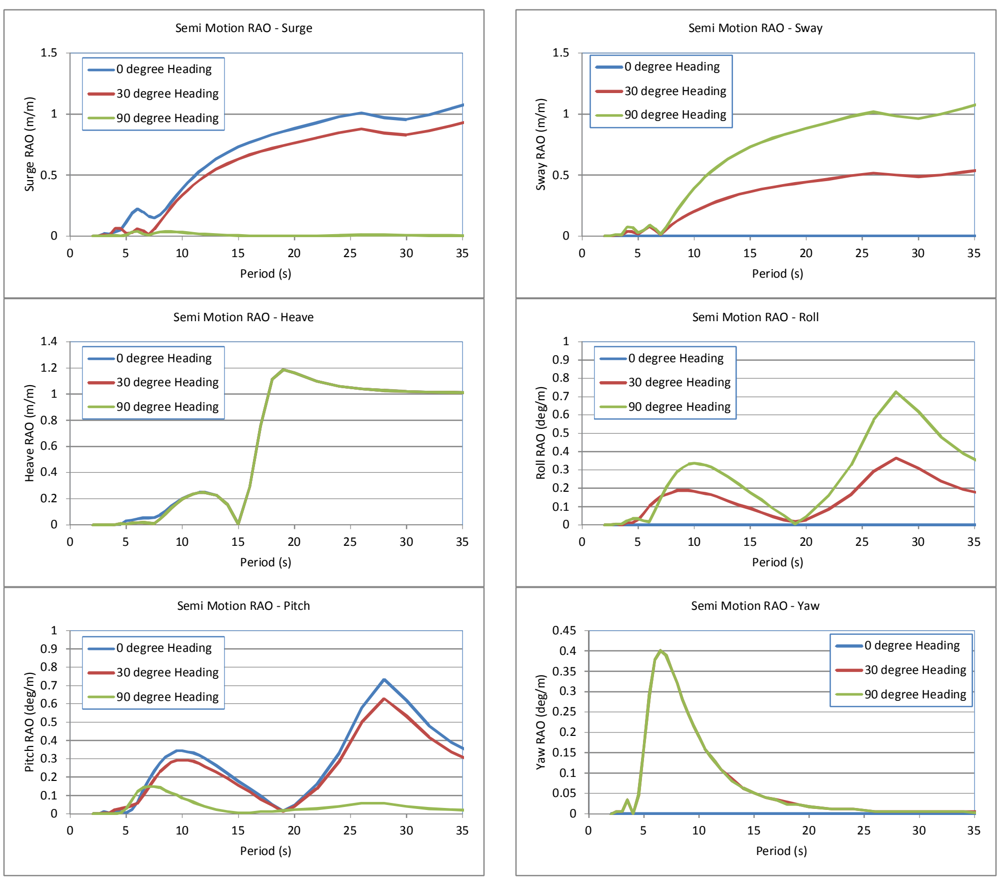


Figure 3.32 Motion RAOs for the Semi-submersible Floating Support Structure

3.6.3 Semi-submersible FOWT Case Study Results

In the case studies for the load case DLC 2.x, three independent fault conditions - pitch runaway, yaw runaway and loss of grid (loss of load) - are considered.

- In the pitch runaway case, one of the blade pitch control fails and the pitch angle runs away from operational pitch to 0 degree pitch position and consequently the turbine is shut down by feathering the other two blades (denoted as “DLC2.1B”).
- In the yaw runaway case, the nacelle yaw angle runs away from 0 degree to 90 degrees fixed mean yaw position and consequently the turbine is shut down by feathering the three blades (denoted as “DLC2.1Y”).
- In the loss of grid case, the generator torque is lost and the turbine is shut down by feathering the three blades (denoted as “DLC2.3”).

Responses are compared in this section for the following aspects:

- Governing load cases
- Power production and parked conditions - responses for normal power production and normal parked conditions
- Effects of environment directionality and misalignment - responses of the parked turbines in the 50-year return condition with different directionality and misalignment of wind, wave and current conditions
- Effects of return periods for parked turbines - responses for the parked turbines in the 1-year, 50-year and 500-year return conditions

3.6.3.1 Governing Load Cases

In order to identify governing load cases for the Semi-submersible FOWT design, the results of all the load cases with collinear wave, wind and current conditions performed for the semi-submersible FOWT in the GoM Central Region (GOM) are compared in Figure 3.33 and Figure 3.34. Results of DLC 1.3 and DLC 1.6 for the wind turbines in power production are compared in Figure 3.35.

From these results, it can be concluded that:

- DLC 1.3 in general is more critical for the wind turbine components and tower design than DLC 1.6, which appears more critical for the design of the hull structure and the stationkeeping system.
- DLC 1.4, 1.5, 3.x, 4.x and 5.x with transient effects may result in extreme values slightly higher than DLC 1.3. However, the effects appear to be marginally higher.
- DLC 2.1 (power production with fault) governs the blade and shaft loads. However, the fault conditions considered in the load cases have no significant effect on the support structure and mooring responses.
- Governing load cases are found as below
    - Platform offset – Survival, DLC 6.2
    - Platform heave – Survival, DLC 6.1
    - Platform heel – Survival, DLC 6.2
    - Platform yaw – DLC 1.3, DLC 2.1Y
    - Tower top acceleration – DLC 1.3
    - Maximum line tension – DLC 6.2
    - Tower base loads – Survival, DLC 6.2 (abnormal), DLC 6.1 (normal)
    - Blade root loads – Survival, DLC 2.1
    - Shaft loads – DLC 2.1

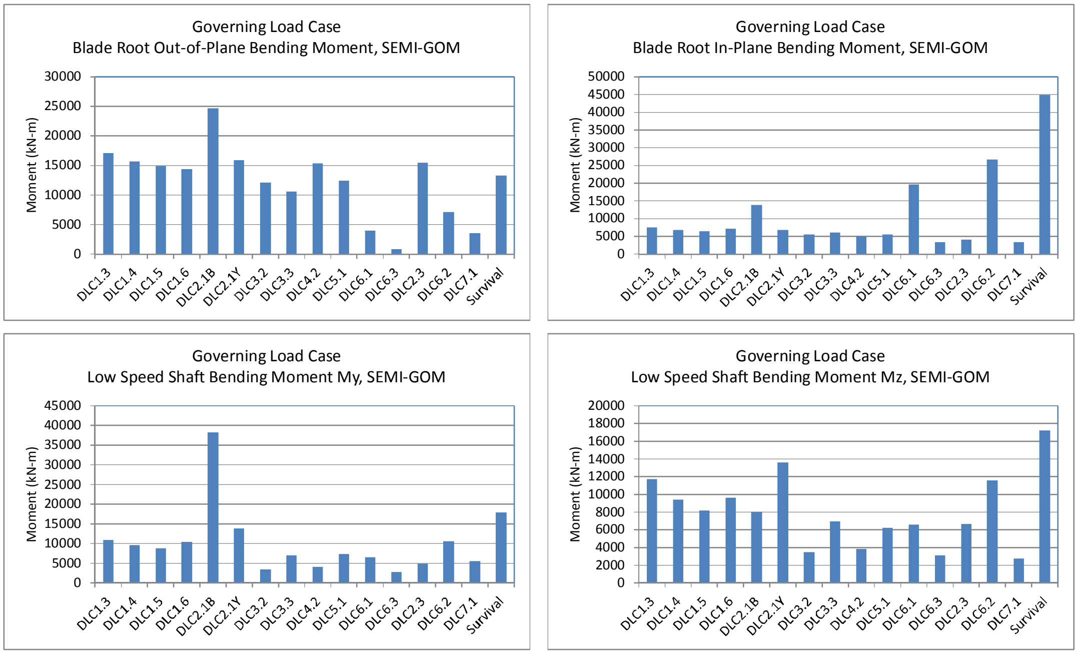


Figure 3.33 Governing Load Cases – RNA Responses of the Semi-submersible FOWT in GOM

Figure 3.34 Governing Load Cases – Support Structure and Mooring Responses of the Semi-submersible FOWT in GOM

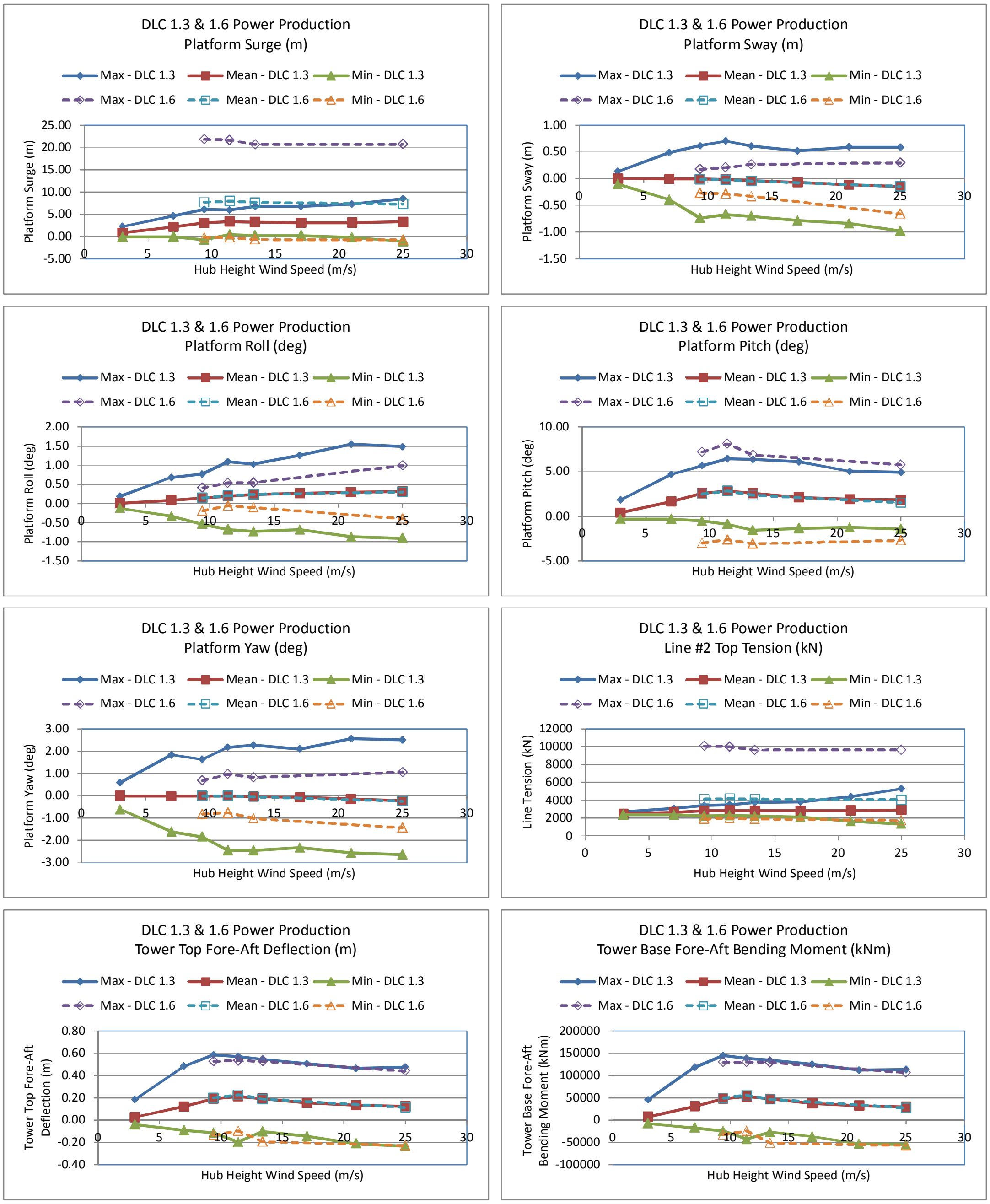


Figure 3.35 Comparison of DLC 1.3 and DLC 1.6 - Support Structure and Mooring Responses of the Semi-submersible FOWT in GOM

3.6.3.2 Power Production and Parked Conditions

Responses of the following normal power production and normal parked conditions are compared in Figure 3.36 for the Semi-submersible FOWT in GOM, ME and OR:

- Turbine in power production (DLC 1.3) with the rated and cut-out wind speeds
- Turbine parked with a nacelle yaw error of 20 degrees in the 1-year storm condition (DLC 6.3)
- Turbine parked with a nacelle yaw error of 8 degrees in the 50-year storm condition (DLC 6.1)

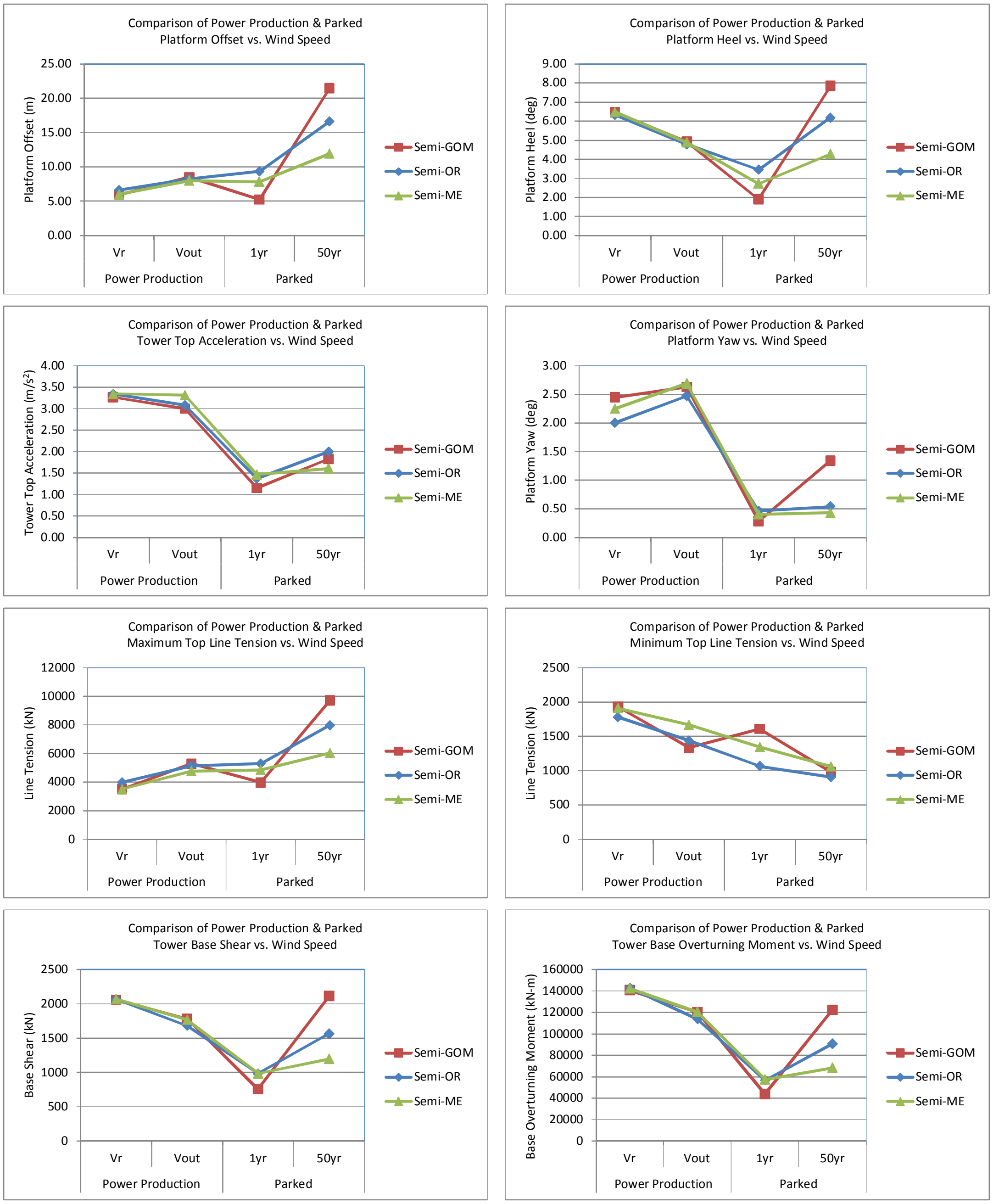


Figure 3.36 Comparison of Power Production and Parked Conditions - Support Structure and Mooring Responses of the Semi-submersible FOWT in GOM, OR and ME

3.6.3.3 Effects of Environment Directionality and Misalignment

Responses of the Semi-submersible FOWT with the parked turbine subjected to the 50-year storm conditions with different environmental headings and wind/wave misalignment and with the nacelle yaw error of 8 and 30 degrees (DLC 6.1 & 6.2) are compared in Figure 3.37.

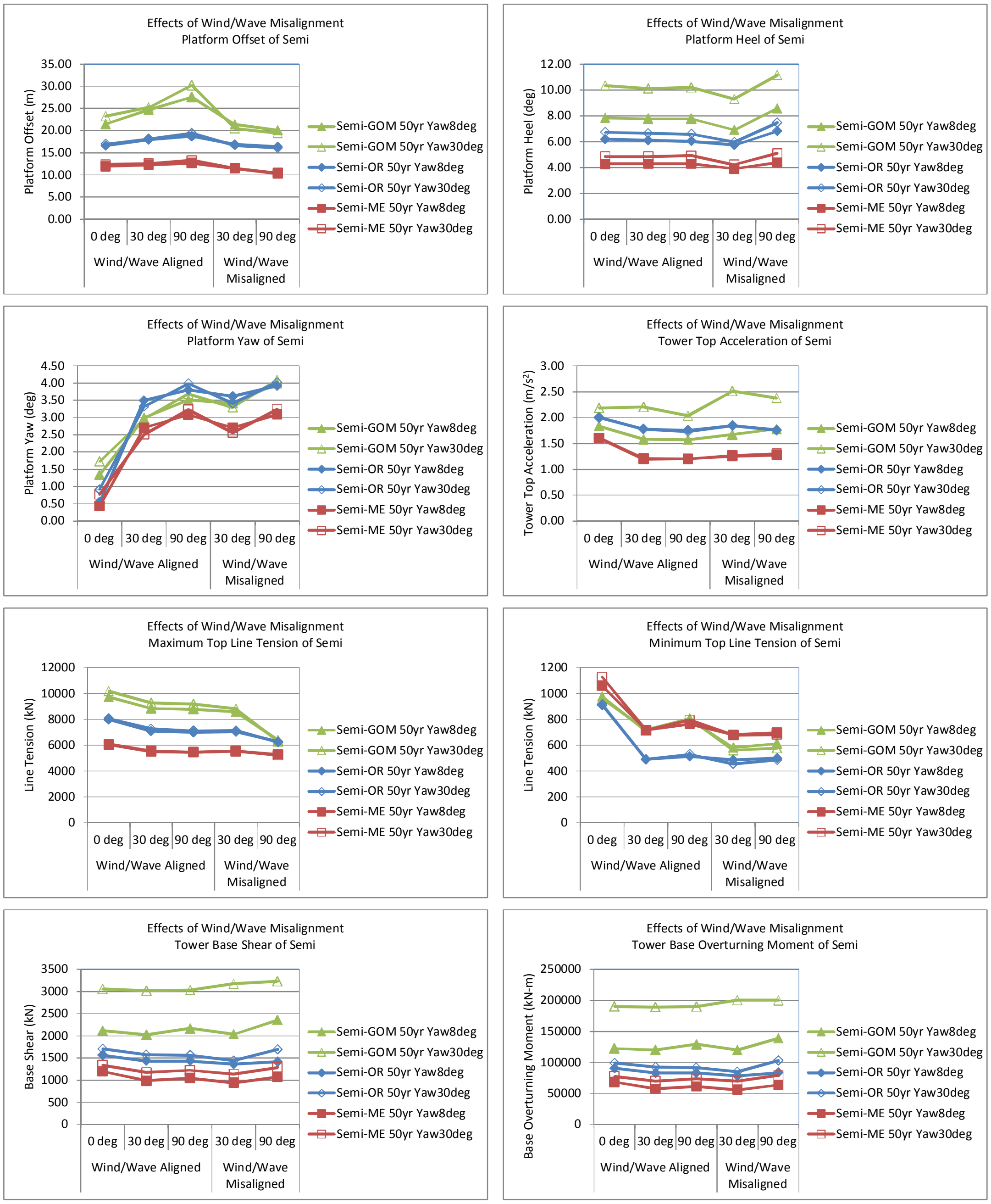


Figure 3.37 Effects of Environment Directionality and Misalignment – Support Structure and Mooring Responses of the Semi-submersible FOWT in GOM, ME and OR

3.6.3.4 Effects of Return Periods for Parked Turbines

Responses of the following parked conditions with/without fault of the Semisubmersible FOWT in GOM, ME and OR are compared in Figure 3.38:

- Parked condition with a nacelle yaw error of 20 degrees in the 1-year storm condition (DLC 6.3)
- Parked condition with a nacelle yaw error of 30 degrees or 1 sized blade with a yaw error of 8 degrees in the 1-year storm condition (DLC 7.1)
- Parked condition with a nacelle yaw error of 8 degrees in the 50-year storm condition (DLC 6.1)
- Parked condition with a nacelle yaw error of 30 degrees in the 50-year storm condition (DLC 6.2)
- Parked condition with a nacelle yaw error of 8 degrees in the 500-year storm condition (Survival)
- Parked condition with a nacelle yaw error of 30 degrees in the 500-year storm condition (Survival)

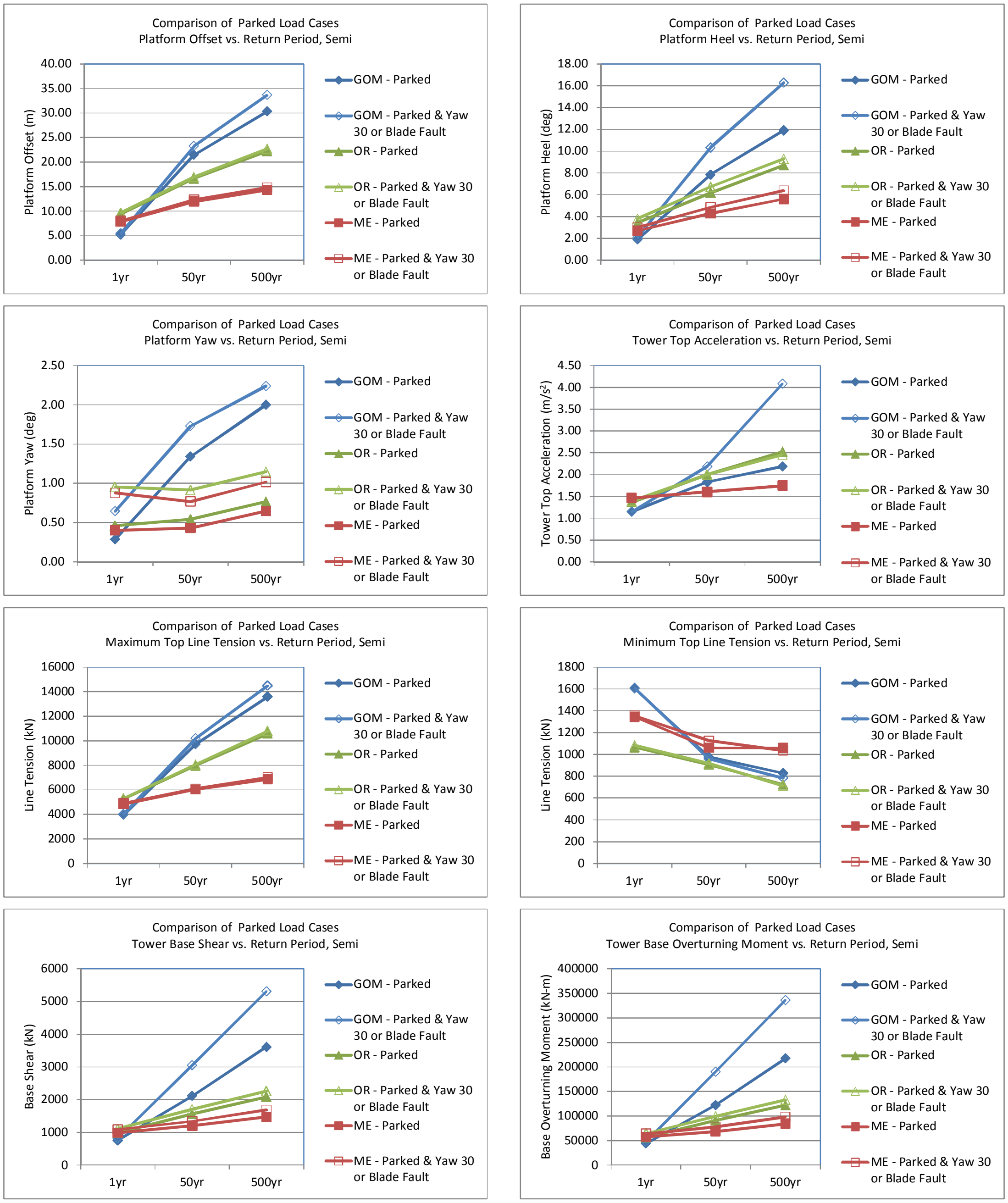


Figure 3.38 Comparisons of Responses for the Parked RNA Conditions – Support Structure and Mooring Responses of the Semisubmersible FOWT in GOM, ME and OR

Ratios of the maximum responses of the Semi-submersible FOWT subjected to the 500-year storm condition (survival load cases) to those subjected to 50-year storm conditions (DLC 6.1 and DLC 6.2) are depicted in Figure 3.39, where the results for the cases with both 8 and 30 degree nacelle yaw errors are included.

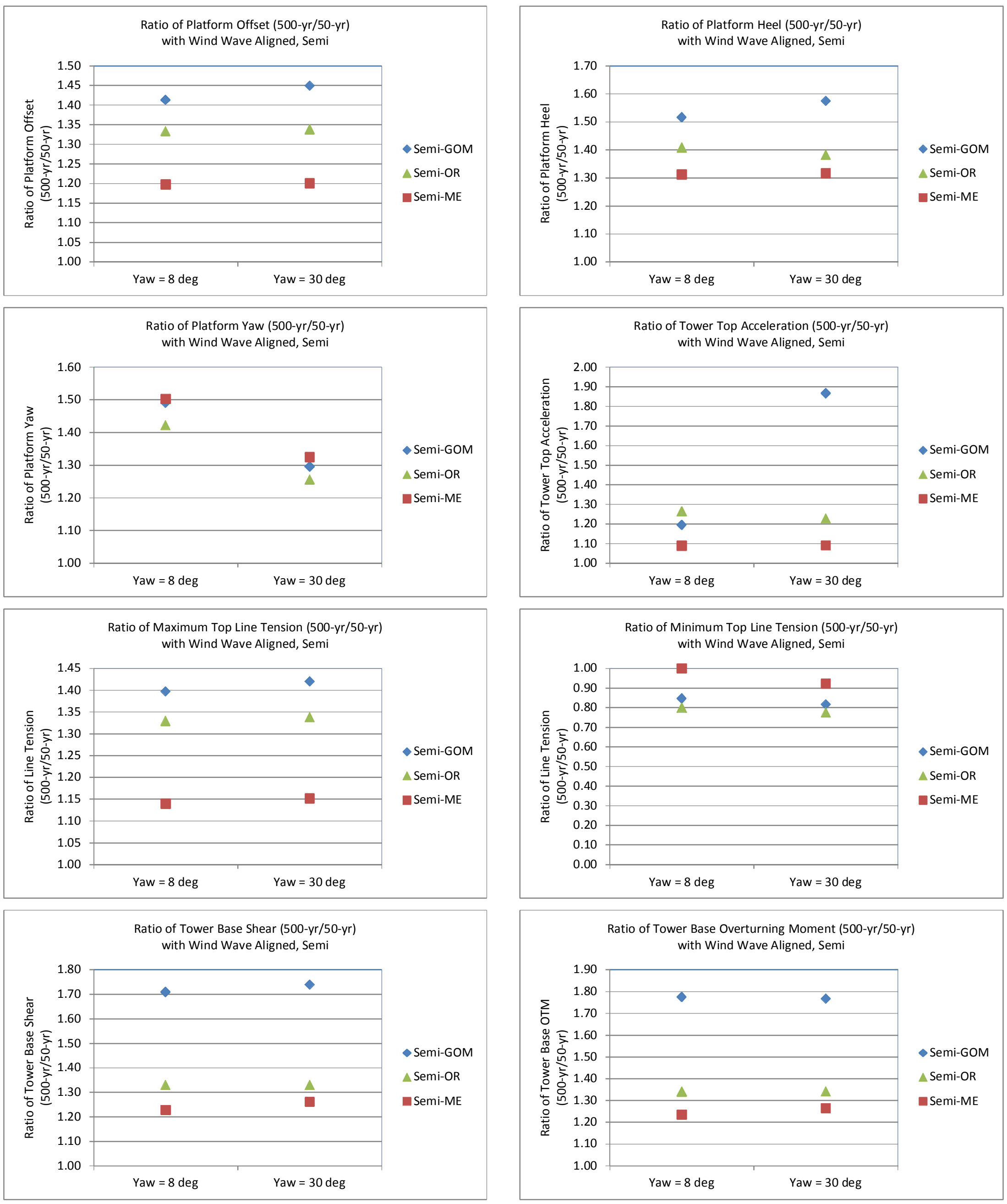


Figure 3.39 Ratios of 500yr to 50yr Responses for the Parked RNA Conditions – Support Structure and Mooring Responses of the Semisubmersible FOWT in GOM, ME and OR

3.6.3.5 Conclusions

Based on the results of global performance analyses for the load cases defined in Section 3.6.1 for the Semisubmersible FOWT in GOM (i.e. the GoM Central Region as defined in API 2INT MET, 2007), ME and OR, the following conclusions are made:

- Yaw error and fault conditions (blade pitch runaway and nacelle yaw runaway in DLC 2.1; blade fault in DLC 7.1; nacelle yaw error in DLC 6.2 and DLC 7.1; and the survival load cases) are critical for the design of wind turbine components. However, fault conditions are in general not critical for the design of the Semi-submersible support structure and the stationkeeping system.
- For normal conditions without occurrence of faults (DLC 1.x, DLC 3.x, DLC 4.2, DLC 5.1, DLC 6.1, and DLC 6.3) turbine components loads (blade root bending and shaft bending moments) are in general governed by DLC 1.3 (power production) in combination with the extreme turbulent wind model in ME and OR.
- Turbine blade loads (blade root bending and shaft bending moments) are governed by DLC 6.1 and the survival load cases with the parked turbine in GOM.
- Hull motions and mooring loads are in general governed by DLC 6.1 & 6.2 and the survival load cases with the parked turbine for all the three sites.
- Tower base loads are governed by DLCs 6.1 & 6.2 and survival load cases with the parked turbine in GOM as well as DLC 1.3 with the operating turbine in ME and OR.
- DLCs 1.4, 1.5, 3.x, 4.x and 5.x with transient effects may result in larger maximum responses than DLC 1.3. However, the effects appear to be marginal.
- Collinear wind and wave conditions in general result in larger maximum mooring loads and larger platform offsets.
- Misalignment of wind and wave may result in larger maximum platform yaw motion and larger maximum tower base loads. However, the effects appear to be marginal.
- For the Semi-submersible FOWT with the parked turbine, the ratios of 500-year return to 50-year return global responses are:
    - maximum line tension: 1.40 to 1.42 (GOM), 1.33 to 1.34 (OR) and 1.14 to 1.15 (ME);
    - tower base load: 1.71 to 1.77 (GOM), 1.33 to 1.34 (OR), 1.23 to 1.25 (ME)

3.7 TLP FOWT

3.7.1 Summary of Model Parameters

The TLP hull and mooring system are defined in Section 3.4.2.3. The site conditions are summarized in Section 3.4.1. The tower and the turbine RNA related parameters are given in Section 3.4.3 and 3.4.4, respectively. The OC3 Hywind turbine control scheme, as described in Section 3.4.5, is applied when the turbine is in the power production mode. The turbulent and deterministic wind field data for the aerodynamic analysis in FAST are generated according to Section 3.4.6.

A total of 68 load cases are defined to evaluate the global responses of the TLP FOWT considering the return period of environmental conditions, turbine operating modes (power production, start-up, emergency shut down and parked), wind and wave misalignment and site condition variations. These load cases are summarized in Table 3.22, which correlates to the general description of the design load cases (DLCs) provided in Table 3.1.

For the TLP FOWT with the parked turbine subjected to the 50-year return storm conditions, both aligned (collinear) and misaligned (cross wave) wind and wave directions are incorporated into the load case definitions. The aligned cases include the wind, wave and current headings of 0 degree and 30 degrees. The misaligned cases assume that the wind heading is always 0 degree, while the wave and current heading is taken as 30 degrees and 90 degrees, respectively. The definitions of the headings are depicted in Figure 3.40.

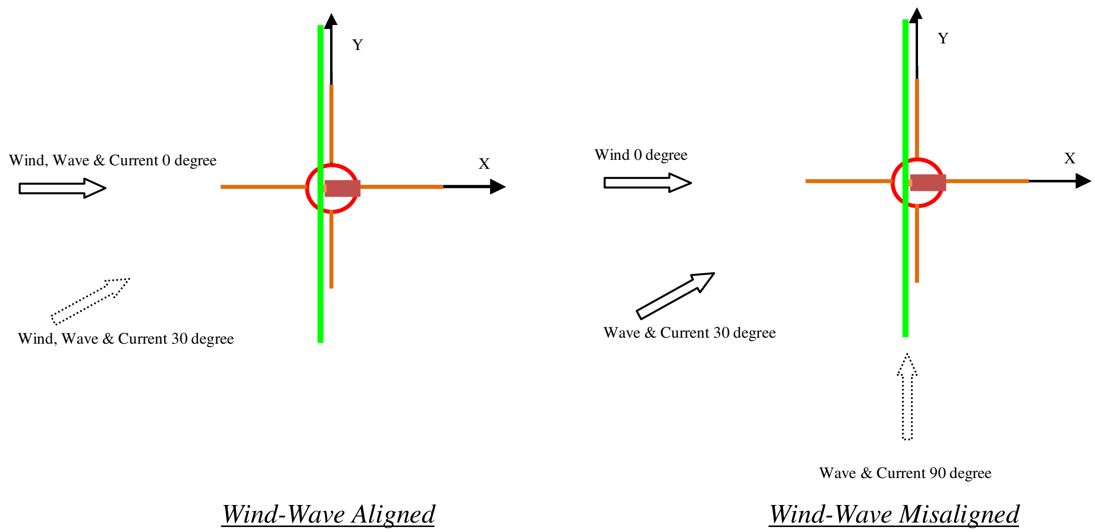


Figure 3.40 Definition of Wind, Wave and Current Directionality – TLP FOWT

The hydrostatic and hydrodynamic properties, including the hydrostatic restoring coefficients, added-mass coefficients, damping coefficients, linear transfer functions (LTF) of wave forces (1st-order wave forces), quadratic transfer functions (QTF) of sum-frequency and difference-frequency wave forces (2^{nd}-order wave forces), and 6-DOF TLP hull motions RAOs are calculated using WAMIT. The second-order wave forces are determined using full QTF.

The panel model for the TLP hull and free surface is plotted in Figure 3.41. A total of 795×4 panels (with 795 panels on quarter of the hull and considering the x- and y-/symmetry) for the hull and 900×4 panels for the free surface are created for the hydrodynamic analysis in WAMIT. The radius of the free surface is chosen as 90 m. The integrated hull-mooring model for the CHARM3D-FAST time-domain analysis is shown in Figure 3.42 (wind turbine not shown). Each tendon is modeled by 20 high-order cable elements.

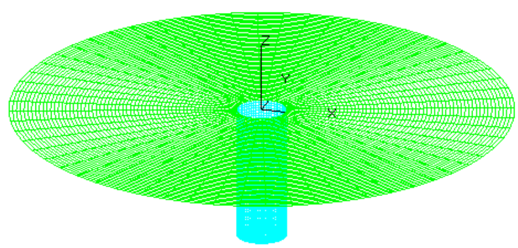


Figure 3.41 Hydrodynamic Panel Model of the TLP Floating Support Structure

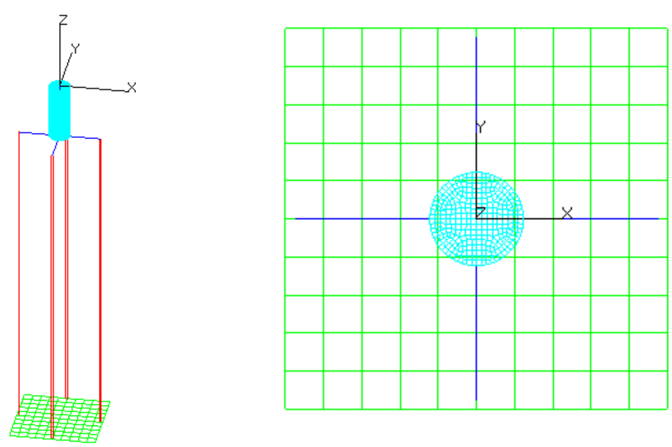


Figure 3.42 Integrated TLP-Tendon Model

In addition to the radiation damping, the viscous damping is applied in the time-domain analysis using the Morison elements. The drag coefficient for the TLP column is chosen as 0.6. The added-mass and drag coefficients of the truss members are taken as 1.0 and 1.2, respectively.

Two different time marching steps are used in the CHARM3D-FAST simulations, with 0.01s in CHARM3D for calculating the global hull and mooring responses and the tower-hull interface loads and 0.005s in FAST for calculating the aero-servo-elastic responses of the integrated RNA-tower-hull model. The output time step is 0.05s.

Quasi-static wind loads on the nacelle, tower and TLP hull above the still water level are approximately taken into account following the approach described in Section 3.3.1.

Table 3.22 Summary of Load Cases for the TLP FOWT Case Studies

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions*			*Wave & Wind Misalignment*	*Yaw Error/ Fault Conditions*	*Wind Speed (1-hour) at Ref. 10 m*	*Wind Speed (10-min) at Hub Height*	*Wave Condition*		*Current*	*Water Level*
					Wind	*Wave*	*Current*					*Hs*	*Tp*		
					(deg)	(deg)	(deg)	(deg)	(deg)	(m/s)	(m)	(m)	(s)	(m/s)	
Power Production	1.3	TLP	GOM	ETM, V_r-2 m/s	0	0	0	0	0	7.64	9.40	1.19	4.87	0.40	MSL
		TLP	GOM	ETM, V_r	0	0	0	0	0	9.17	11.40	1.71	5.84	0.40	MSL
		TLP	GOM	ETM, V_r+2 m/s	0	0	0	0	0	10.68	13.40	2.32	6.80	0.40	MSL
		TLP	GOM	ETM, V_{out}	0	0	0	0	0	19.02	25.00	7.35	12.12	0.40	MSL
	1.4	TLP	GOM	ECD, V_r-2 m/s	0	0	0	MIS	0	7.64	9.40	1.19	4.87	0.40	MSL
		TLP	GOM	ECD, V_r	0	0	0	MIS	0	9.17	11.40	1.71	5.84	0.40	MSL
		TLP	GOM	ECD, V_r+2 m/s	0	0	0	MIS	0	10.68	13.40	2.32	6.80	0.40	MSL
	1.5	TLP	GOM	EWS, V_r	0	0	0	0	0	9.17	11.40	1.71	5.84	0.40	MSL
		TLP	GOM	EWS, V_{out}	0	0	0	0	0	19.02	25.00	7.35	12.12	0.40	MSL
	1.6	TLP	GOM	NTM, V_r-2 m/s	0	0	0	0	0	7.64	9.40	13.87	14.62	1.67	MSL
		TLP	GOM	NTM, V_r	0	0	0	0	0	9.17	11.40	13.87	14.62	1.67	MSL
		TLP	GOM	NTM, V_r+2 m/s	0	0	0	0	0	10.68	13.40	13.87	14.62	1.67	MSL
		TLP	GOM	NTM, V_{out}	0	0	0	0	0	19.02	25.00	13.87	14.62	1.67	MSL

Table 3.22 Summary of Load Cases for the TLP FOWT Case Studies (Continued)

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions*			*Wave & Wind Misalignment*	*Yaw Error/ Fault Conditions*	*Wind Speed (1-hour) at Ref. 10 m*	*Wind Speed (10-min) at Hub Height*	*Wave Condition*		*Current*	*Water Level*
					Wind	*Wave*	*Current*					*Hs*	*Tp*		
					(deg)	(deg)	(deg)	(deg)	(deg)	(m/s)	(m)	(m)	(s)	(m/s)	
Power production plus occurrence of fault	2.1	TLP	GOM	NTM, V_r	0	0	0	0	blade pitch runaway	9.17	11.40	1.71	5.84	0.40	MSL
		TLP	GOM	NTM, V_{out}	0	0	0	0	blade pitch runaway	19.02	25.00	7.35	12.12	0.40	MSL
		TLP	GOM	NTM, V_r	0	0	0	0	yaw runaway	9.17	11.40	1.71	5.84	0.40	MSL
		TLP	GOM	NTM, V_{out}	0	0	0	0	yaw runaway	19.02	25.00	7.35	12.12	0.40	MSL
	2.3	TLP	GOM	EOG, V_r	0	0	0	0	grid loss	9.17	11.40	1.71	5.84	0.40	MSL
		TLP	GOM	EOG, V_{out}	0	0	0	0	grid loss	19.02	25.00	7.35	12.12	0.40	MSL
Start-up	3.2	TLP	GOM	EOG, V_r	0	0	0	0	0	9.17	11.40	1.71	5.84	0.40	MSL
		TLP	GOM	EOG, V_{out}	0	0	0	0	0	19.02	25.00	7.35	12.12	0.40	MSL
	3.3	TLP	GOM	EDC, V_r	0	0	0	MIS	0	9.17	11.40	1.71	5.84	0.40	MSL
		TLP	GOM	EDC, V_{out}	0	0	0	MIS	0	19.02	25.00	7.35	12.12	0.40	MSL
Normal shutdown	4.2	TLP	GOM	EOG, V_r	0	0	0	0	0	9.17	11.40	1.71	5.84	0.40	MSL
		TLP	GOM	EOG, V_{out}	0	0	0	0	0	19.02	25.00	7.35	12.12	0.40	MSL
Emergency shutdown	5.1	TLP	GOM	NTM, V_r	0	0	0	0	0	9.17	11.40	1.71	5.84	0.40	MSL
		TLP	GOM	NTM, V_{out}	0	0	0	0	0	19.02	25.00	7.35	12.12	0.40	MSL

Table 3.22 Summary of Load Cases for the TLP FOWT Case Studies (Continued)

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions*			*Wave & Wind Misalignment*	*Yaw Error/ Fault Conditions*	*Wind Speed (1-hour) at Ref. 10 m*	*Wind Speed (10-min) at Hub Height*	*Wave Condition*		*Current*	*Water Level*
					Wind	*Wave*	*Current*					*Hs*	*Tp*		
					(deg)	(deg)	(deg)	(deg)	(deg)	(m/s)	(m)	(m)	(s)	(m/s)	
Parked (Idling)	6.1	TLP	GOM	50yr peak wind	0	0	0	0	8	44.40	64.96	13.87	14.62	1.67	MSL
		TLP	GOM	50yr peak wind	30	30	30	0	8	44.40	64.96	13.87	14.62	1.67	MSL
		TLP	GOM	50yr peak wind	0	30	30	30	8	44.40	64.96	13.87	14.62	1.67	MSL
		TLP	GOM	50yr peak wind	0	90	90	90	8	44.40	64.96	13.87	14.62	1.67	MSL
	6.2	TLP	GOM	50yr peak wind	0	0	0	0	30	44.40	64.96	13.87	14.62	1.67	MSL
		TLP	GOM	50yr peak wind	0	0	0	0	30	44.40	64.96	13.87	14.62	1.67	HSWL
		TLP	GOM	50yr peak wind	0	0	0	0	30	44.40	64.96	13.87	14.62	1.67	LSWL
		TLP	GOM	50yr peak wind	30	30	30	0	30	44.40	64.96	13.87	14.62	1.67	MSL
		TLP	GOM	50yr peak wind	0	30	30	30	30	44.40	64.96	13.87	14.62	1.67	MSL
		TLP	GOM	50yr peak wind	0	90	90	90	30	44.40	64.96	13.87	14.62	1.67	MSL
	6.3	TLP	GOM	1yr storm	0	0	0	0	8	16.40	21.27	4.90	10.30	0.40	MSL
		TLP	GOM	1yr storm	0	0	0	0	20	16.40	21.27	4.90	10.30	0.40	MSL
Parked and fault conditions	7.1	TLP	GOM	1yr storm	0	0	0	0	Yaw=8; 1 seized blade	16.40	21.27	4.90	10.30	0.40	MSL
		TLP	GOM	1yr storm	0	0	0	0	30	16.40	21.27	4.90	10.30	0.40	MSL
Survival Condition	-	TLP	GOM	500yr peak wind	0	0	0	0	8	55.92	85.16	17.21	16.17	2.10	MSL
		TLP	GOM	500yr peak wind	0	0	0	0	30	55.92	85.16	17.21	16.17	2.10	MSL
		TLP	GOM	500yr peak wind	0	0	0	0	30	55.92	85.16	17.21	16.17	2.10	HSWL
		TLP	GOM	500yr peak wind	0	0	0	0	30	55.92	85.16	17.21	16.17	2.10	LSWL

Table 3.22 Summary of Load Cases for the TLP FOWT Case Studies (Continued)

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions*			*Wave & Wind Misalignment*	*Yaw Error/ Fault Conditions*	*Wind Speed (1-hour) at Ref. 10 m*	*Wind Speed (10-min) at Hub Height*	*Wave Condition*		*Current*	*Water Level*
					Wind	*Wave*	*Current*					*Hs*	*Tp*		
					(deg)	(deg)	(deg)	(deg)	(deg)	(m/s)	(m)	(m)	(s)	(m/s)	
Power Production	1.3	TLP	OR	ETM, V_r	0	0	0	0	0	9.17	11.40	2.84	11.42	0.60	MSL
		TLP	OR	ETM, V_{out}	0	0	0	0	0	19.02	25.00	6.97	13.49	0.60	MSL
Start-up	3.2	TLP	OR	EOG, V_r	0	0	0	0	0	9.17	11.40	2.84	11.42	0.60	MSL
		TLP	OR	EOG, V_{out}	0	0	0	0	0	19.02	25.00	6.97	13.49	0.60	MSL
Emergency shut down	5.1	TLP	OR	NTM, V_r	0	0	0	0	0	9.17	11.40	2.84	11.42	0.60	MSL
		TLP	OR	NTM, V_{out}	0	0	0	0	0	19.02	25.00	6.97	13.49	0.60	MSL
Parked (Idling)	6.1	TLP	OR	50yr storm	0	0	0	0	8	27.33	37.35	15.56	15.36	0.80	MSL
		TLP	OR	50yr storm	30	30	30	0	8	27.33	37.35	15.56	15.36	0.80	MSL
		TLP	OR	50yr storm	0	30	30	30	8	27.33	37.35	15.56	15.36	0.80	MSL
		TLP	OR	50yr storm	0	90	90	90	8	27.33	37.35	15.56	15.36	0.80	MSL
	6.2	TLP	OR	50yr storm	0	0	0	0	30	27.33	37.35	15.56	15.36	0.80	MSL
		TLP	OR	50yr storm	0	0	0	0	30	27.33	37.35	15.56	15.36	0.80	HSWL
		TLP	OR	50yr storm	0	0	0	0	30	27.33	37.35	15.56	15.36	0.80	LSWL
		TLP	OR	50yr storm	30	30	30	0	30	27.33	37.35	15.56	15.36	0.80	MSL
		TLP	OR	50yr storm	0	30	30	30	30	27.33	37.35	15.56	15.36	0.80	MSL
		TLP	OR	50yr storm	0	90	90	90	30	27.33	37.35	15.56	15.36	0.80	MSL
	6.3	TLP	OR	1yr storm	0	0	0	0	20	20.28	26.82	8.91	14.06	0.60	MSL

Table 3.22 Summary of Load Cases for the TLP FOWT Case Studies (Continued)

Turbine Operational Mode	*DLC*	*Floater Type*	*Location*	*Wind Condition*	*Environment Directions*			*Wave & Wind Misalignment*	*Yaw Error/ Fault Conditions*	*Wind Speed (1-hour) at Ref. 10 m*	*Wind Speed (10-min) at Hub Height*	*Wave Condition*		*Current*	*Water Level*
					Wind	*Wave*	*Current*					*Hs*	*Tp*		
					(deg)	(deg)	(deg)	(deg)	(deg)	(m/s)	(m)	(m)	(s)	(m/s)	
Parked and fault conditions	7.1	TLP	OR	1yr storm	0	0	0	0	Yaw=8; 1 seized blade	20.28	26.82	8.91	14.06	0.60	MSL
		TLP	OR	1yr storm	0	0	0	0	30	20.28	26.82	8.91	14.06	0.60	MSL
Survival Condition	-	TLP	OR	500yr storm	0	0	0	0	8	31.44	43.74	19.47	15.89	0.90	MSL
		TLP	OR	500yr storm	0	0	0	0	30	31.44	43.74	19.47	15.89	0.90	MSL
		TLP	OR	500yr storm	0	0	0	0	30	31.44	43.74	19.47	15.89	0.90	HSWL
		TLP	OR	500yr storm	0	0	0	0	30	31.44	43.74	19.47	15.89	0.90	LSWL

Notes:

1. API wind models are used for the 1-year, 50-year and 500-year condition for turbine parked.
2. IEC wind models are used for power production, start-up, normal shut down and emergency shutdown.
3. GOM: GoM Central Region
4. OR: Offshore Oregon (US West Coast)
5. ETM: Extreme Turbulence Model
6. ECD: extreme coherent gust with direction change
7. EDC: extreme direction change
8. EWS: extreme wind shear
9. MIS: misaligned wind and wave directions
10. EOG: Extreme Operating Gust
11. NTM: Normal Turbulence Model
12. V_r is the rated wind speed at hub height.
13. V_{out} is the cut-out wind speed at hub height.
14. H_s and T_p are the significant wave height and the peak period of wave spectrum
15. Current Speed are given at water surface
16. MSL: Mean Sea Level (Mean Still Water Level)
17. HSWL: Highest Still Water Level
18. LSWL: Lowest Still Water Level

3.7.2 Natural Periods and Motion RAOs

The natural periods for 6-DOF motions, as listed in Table 3.23, are obtained from free decay time-domain simulations using CHARM3D-FAST. The hull motion RAOs calculated by WAMIT for 0, 30 and 90 degree wave headings are shown in Figure 3.43.

Table 3.23 Natural Periods the TLP Hull Motions

Mode of Motion	*Natural Periods (seconds)*
Surge	65.5
Sway	65.5
Heave	2.25
Roll	3.02
Pitch	3.02
Yaw	9.73

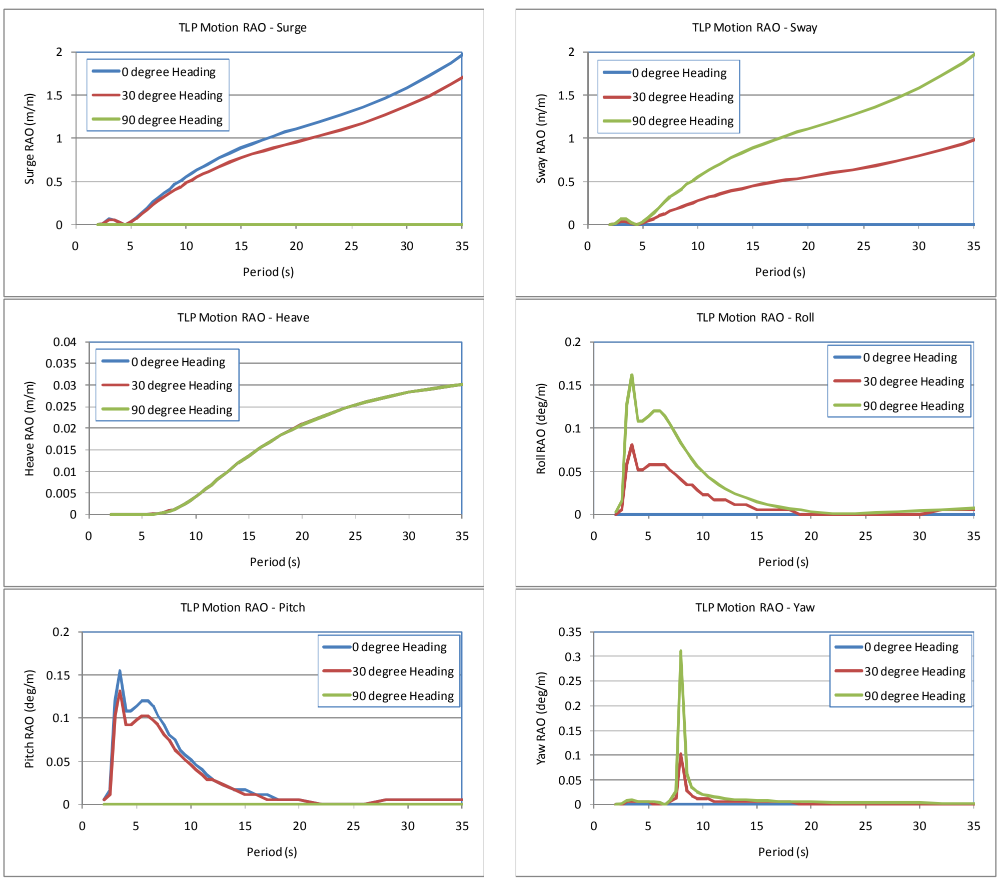


Figure 3.43 Motion RAOs for the TLP Floating Support Structure

3.7.3 TLP FOWT Case Study Results

In the case studies for the load case DLC 2.x, three independent fault conditions - pitch runaway, yaw runaway and loss of grid (loss of load) - are considered.

- In the pitch runaway case, one of the blade pitch control fails and the pitch angle runs away from operational pitch to 0 degree pitch position and consequently the turbine is shut down by feathering the other two blades (denoted as “DLC2.1B”).
- In the yaw runaway case, the nacelle yaw angle runs away from 0 degree to 90 degrees fixed mean yaw position and consequently the turbine is shut down by feathering the three blades (denoted as “DLC2.1Y”).
- In the loss of grid case, the generator torque is lost and the turbine is shut down by feathering the three blades (denoted as “DLC2.3”).

Responses are compared in this section for the following aspects:

- Governing load cases
- Power production and parked conditions - responses for normal power production and normal parked conditions
- Effects of environment directionality and misalignment - responses of the parked turbines in the 50-year return condition with different directionality and misalignment of wind, wave and current conditions
- Effects of return periods for parked turbines - responses for the parked turbines in the 1-year, 50-year and 500-year return conditions

3.7.3.1 Governing Load Cases

In order to identify governing load cases for the TLP FOWT design, the results of all the load cases with collinear wind, wave and current conditions performed for the TLP FOWT in the GoM Central Region (GOM) are compared in Figure 3.44 and Figure 3.45. Results of DLC 1.3 and DLC 1.6 for wind turbines in power production are compared in Figure 3.46.

From these results, it can be concluded that:

- DLC 1.3 in general is more critical for wind turbine components design than DLC 1.6, which is critical for the design of support structure and stationkeeping system.
- DLCs 1.4, 1.5, 3.x, 4.x and 5.x with transient effects may result in higher maximum responses than DLC 1.3. However, the effects appear to be marginal.
- DLC 2.1 (power production with fault) governs the blade and shaft loads. However, the fault conditions considered in the load cases have less significant effects on the TLP support structure and mooring responses.
- Governing load cases are found as below
  - Platform offset – Survival, DLC 6.2
  - Platform heel – Survival, DLC 6.2
  - Platform yaw – Survival, DLC 6.2
  - Tower top acceleration – Survival, DLC 6.1
  - Maximum line tension – DLC 6.2
  - Minimum line tension – Survival
  - Tower base loads – Survival, DLC 6.2 (abnormal), DLC 6.1 (normal)
  - Blade root loads – Survival, DLC 2.1
  - Shaft loads – DLC 2.1

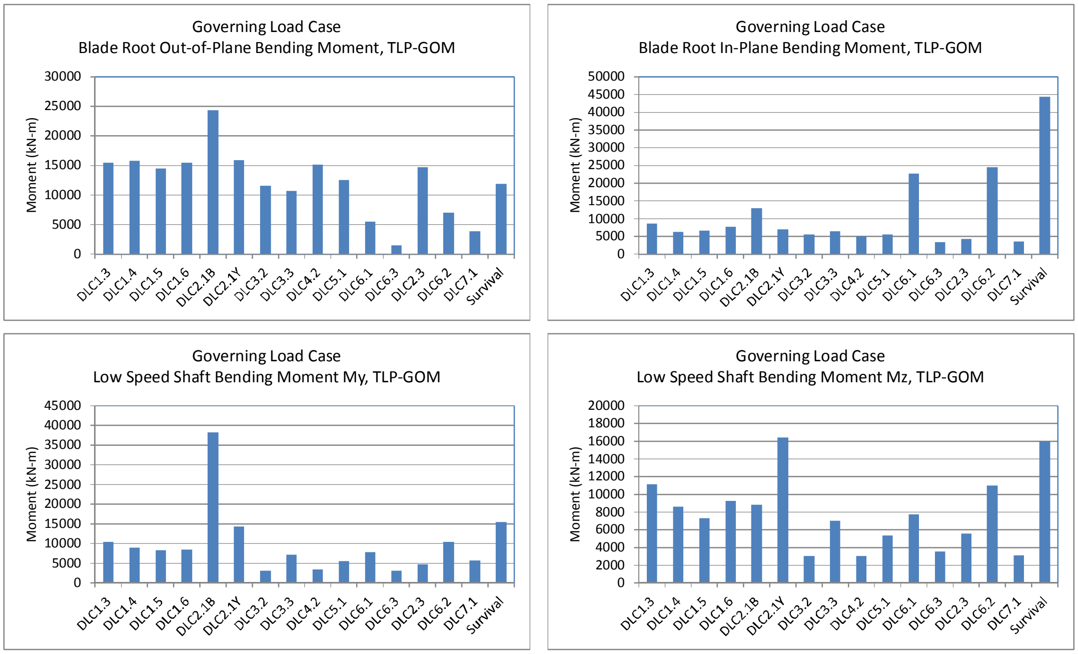


Figure 3.44 Governing Load Cases – RNA Responses of the TLP FOWT in GOM

Figure 3.45 Governing Load Cases – Support Structure and Mooring Responses of the TLP FOWT in GOM

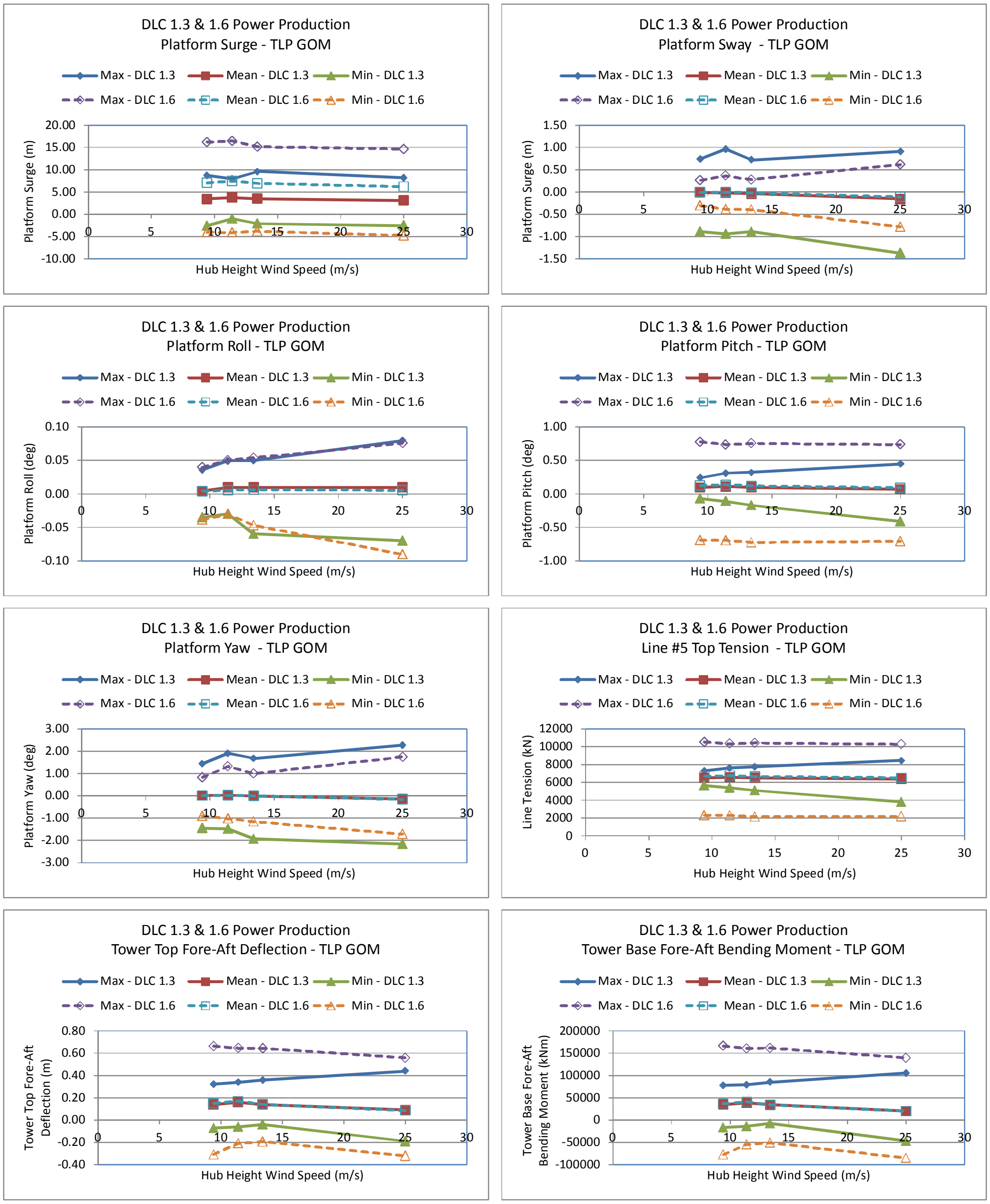


Figure 3.46 Comparison of DLC 1.3 and DLC 1.6 - Support Structure and Mooring Responses of the TLP FOWT in GOM

3.7.3.2 Power Production and Parked Conditions

Responses of the following normal power production and normal parked conditions are compared in Figure 3.47 for the TLP FOWT in GOM and OR:

- Turbine in power production (DLC 1.3) with the rated and cut-out wind speeds
- Turbine parked with a nacelle yaw error of 20 degrees in the 1-year storm condition (DLC 6.3)
- Turbine parked with a nacelle yaw error of 8 degrees in the 50-year storm condition (DLC 6.1)

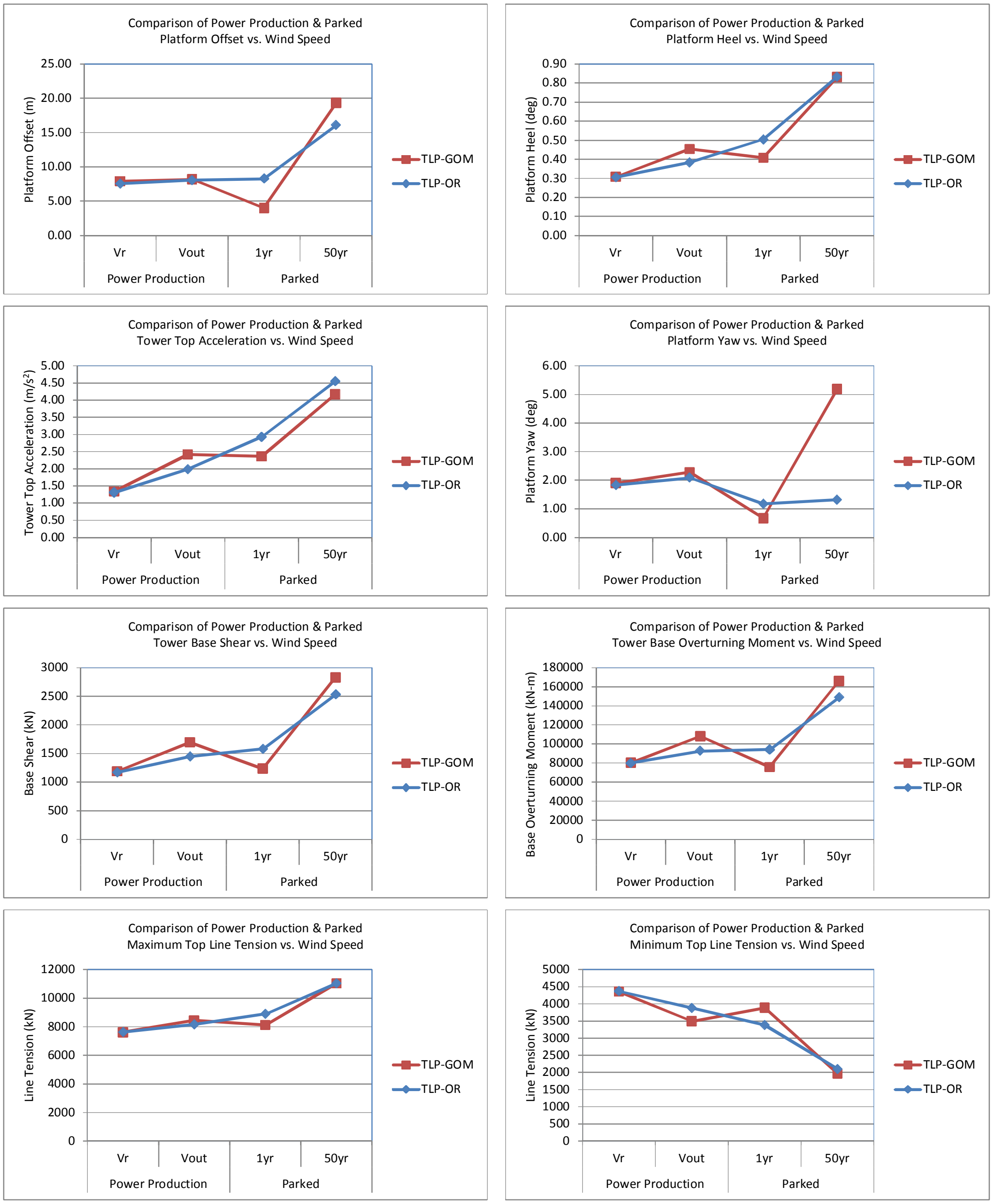


Figure 3.47 Comparison of Power Production and Parked Conditions - Support Structure and Mooring Responses of the TLP FOWT in GOM and OR

3.7.3.3 Effects of Environment Directionality and Misalignment

Responses of the TLP FOWT with the parked turbine subjected to the 50-year storm conditions with different environmental headings and wind/wave misalignment and with the nacelle yaw error of 8 and 30 degrees (DLC 6.1 & 6.2) are compared in Figure 3.48.

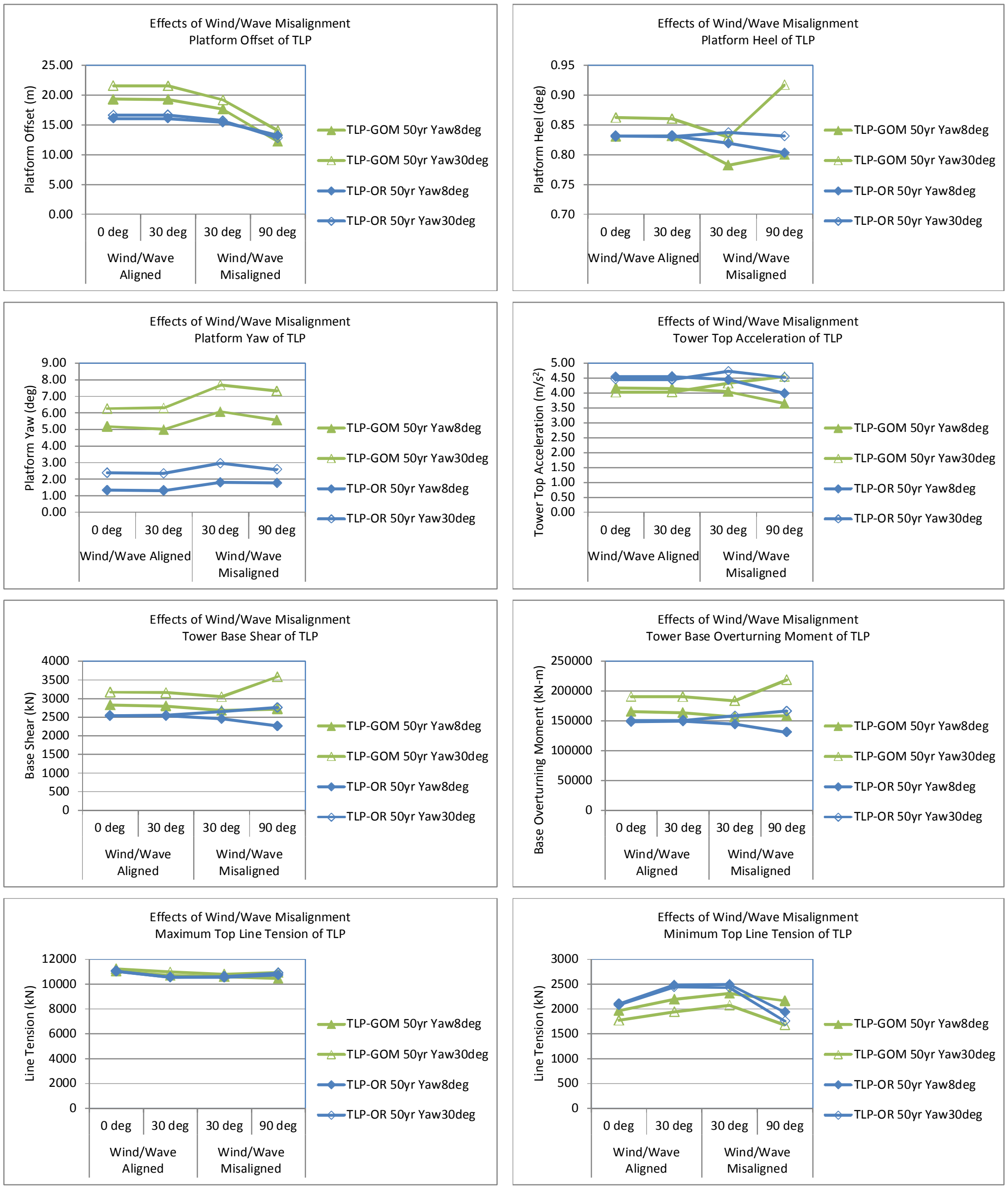


Figure 3.48 Effects of Environment Directionality and Misalignment – Support Structure and Mooring Responses of the TLP FOWT in GOM and OR

3.7.3.4 Effects of Return Periods for Parked Turbines

Responses of the following parked conditions with/without fault of the TLP FOWT in GOM and OR are compared in Figure 3.49:

- Parked condition with a nacelle yaw error of 20 degrees in the 1-year storm condition (DLC 6.3)
- Parked condition with a nacelle yaw error of 30 degrees or 1 sized blade with a yaw error of 8 degrees in the 1-year storm condition (DLC 7.1)
- Parked condition with a nacelle yaw error of 8 degrees in the 50-year storm condition (DLC 6.1)
- Parked condition with a nacelle yaw error of 30 degrees in the 50-year storm condition (DLC 6.2)
- Parked condition with a nacelle yaw error of 8 degrees in the 500-year storm condition (Survival)
- Parked condition with a nacelle yaw error of 30 degrees in the 500-year storm condition (Survival)

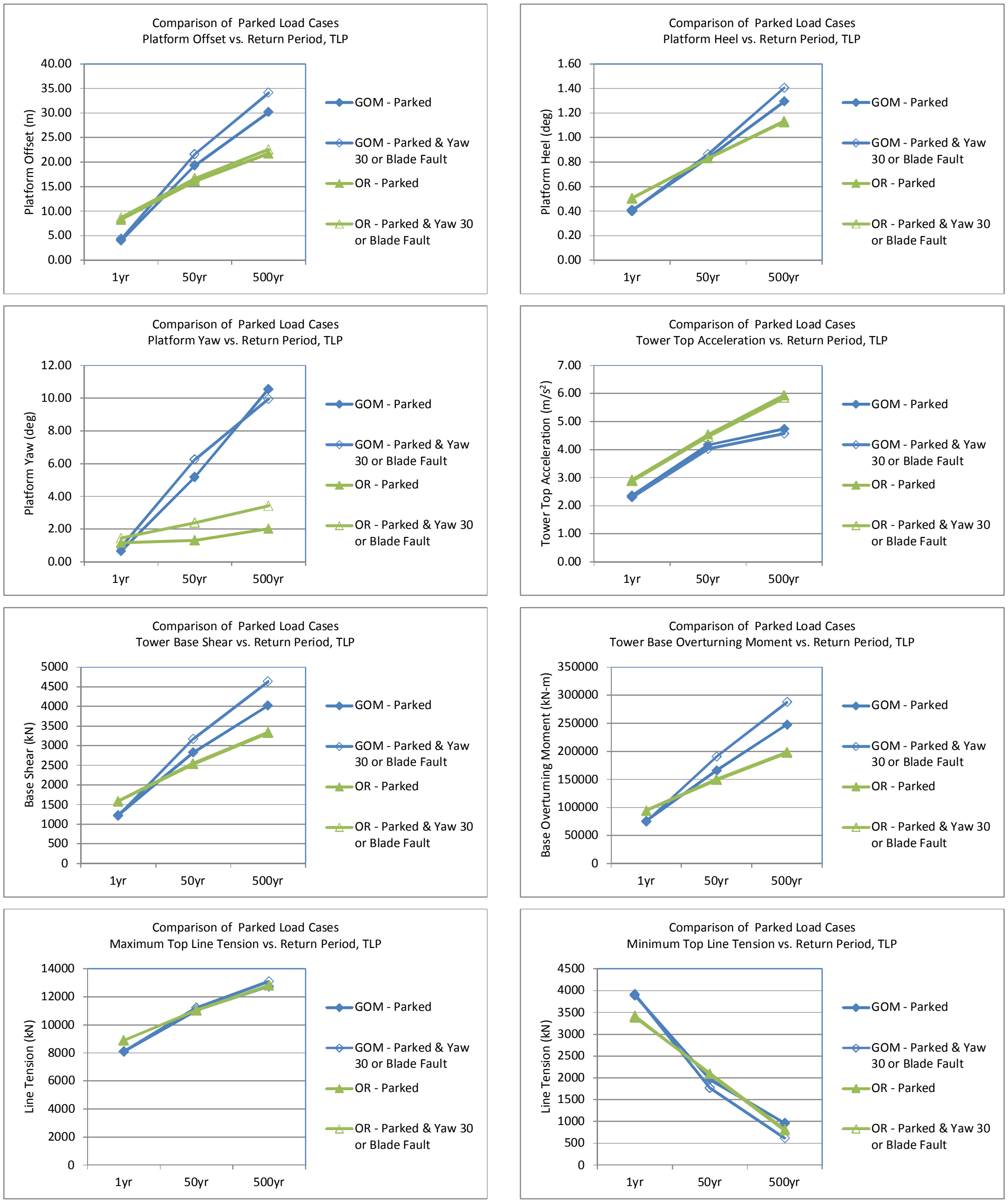


Figure 3.49 Comparisons of Responses for the Parked RNA Conditions – Support Structure and Mooring Responses, TLP FOWT in GOM and OR

Ratios of the maximum responses of the TLP FOWT subjected to the 500-year storm condition (survival load cases) to those subjected to 50-year storm conditions (DLC 6.1 and DLC 6.2) and with the nacelle yaw error of 8 and 30 degrees are compared in Figure 3.50.

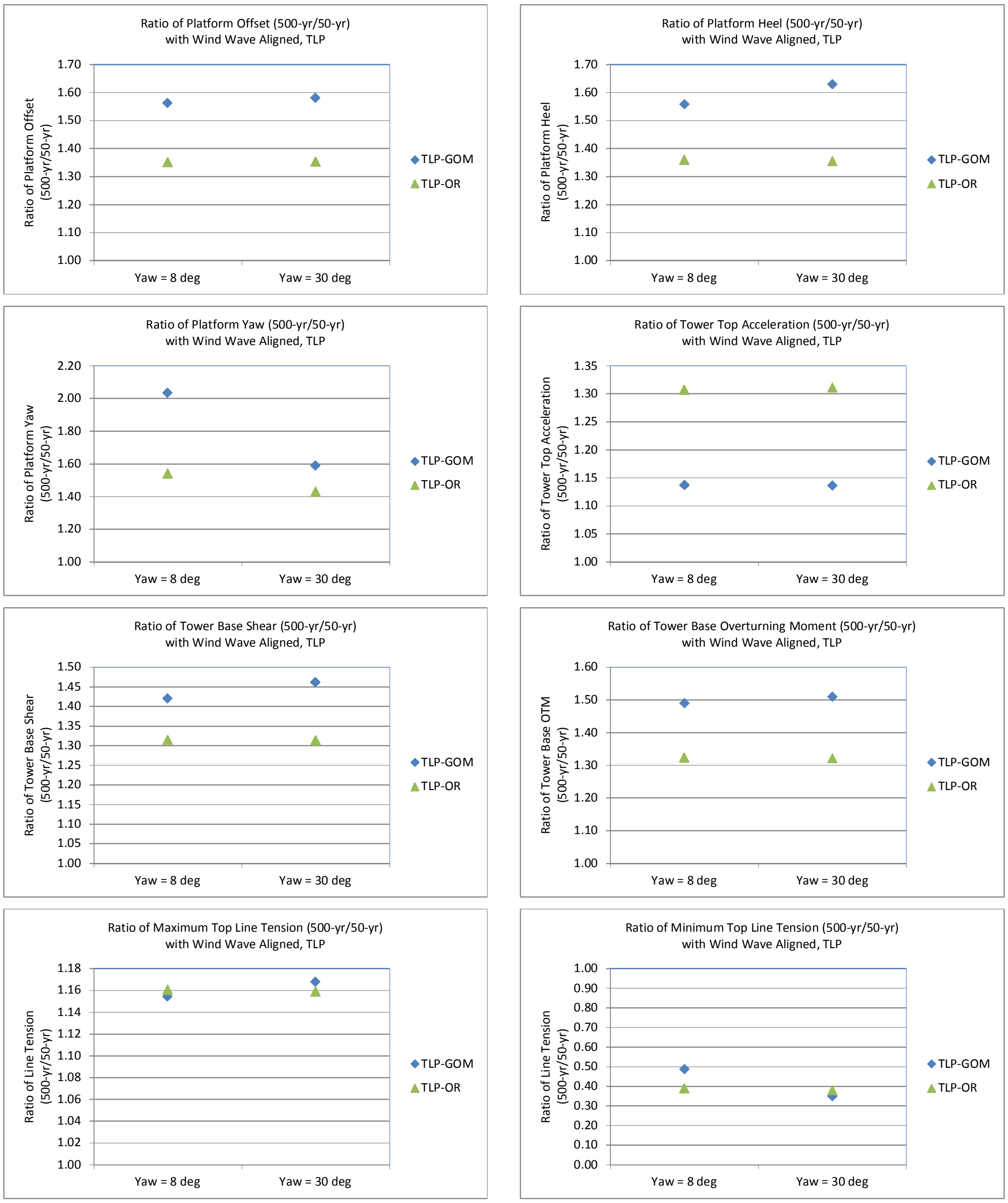


Figure 3.50 Ratios of 500yr to 50yr Responses for the Parked RNA Conditions – Support Structure and Mooring Responses of the TLP FOWT in GOM and OR

3.7.3.5 Conclusions

Based on the results of global performance analyses for the load cases as defined in Section 3.7.1 for the TLP FOWT in GOM and OR, the following conclusions are made:

- Yaw error and fault conditions (blade pitch runaway and nacelle yaw runaway in DLC 2.1; blade fault in DLC 7.1; nacelle yaw error in DLC 6.2 and DLC 7.1; and the survival load cases) are more critical for the design of wind turbine components than for the design of the TLP support structure and the stationkeeping (tendon) system.
- Platform yaw motions are more sensitive to the effects of yaw error and blade faults (blade pitch runaway and nacelle yaw runaway in DLC 2.1; blade fault in DLC 7.1; nacelle yaw error in DLC 6.2 and DLC 7.1; and the survival load cases) compared to other degrees-of-freedom of hull global motions and tendon tensions.
- For the normal conditions without occurrence of faults (DLC 1.x, DLC 3.x, DLC 4.2, DLC 5.1, DLC 6.1, and DLC 6.3), turbine components loads (blade root bending and shaft bending moments) are in general governed by DLC 1.3 (power production) in combination with the extreme turbulent wind model in OR.
- Turbine blade loads (blade root bending) are governed by DLC 6.1 and the survival load cases with the parked turbine in GOM.
- Hull motions and tendon loads are in general governed by DLC 6.1 & 6.2 and the survival load cases with the parked turbine for both OR and GOM sites.
- Tower base loads are governed by DLC 6.1 & 6.2 and the survival load cases with the parked turbine for both OR and GOM sites.
- DLC 1.4, 1.5, 3.x, 4.x and 5.x with transient effects may result in higher maximum responses than DLC 1.3. However, the effects appear to be marginal.
- Collinear wind and wave in general result in larger maximum tendon tensions and larger maximum platform offsets.
- Misalignment of wind and wave may result in smaller minimum tendon tensions.
- Misalignment of wind and wave may result in larger maximum tower base loads. However, the effects appear to be marginal.

- For the TLP FOWT with the parked turbine, the ratios of 500-year return to 50-year return global responses are:
  - maximum line tension: 1.15 to 1.17 (GOM), and 1.16 (OR)
  - tower base loads: 1.42 to 1.51 (GOM), and 1.31 to 1.32 (OR)

3.8 Sensitivity Study on Modeling Parameters and Methodologies

In the BSEE TA&R project 669 (Yu and Chen, 2012), sensitivity studies were carried out to evaluate the significance of the following modeling parameters that affect FOWT global performance analyses.

- Storm wind models and grid sizes of wind field domain
- Duration of the extreme operating gust
- Control schemes for the blade pitch angle
- Polyester rope stiffness (for the semi-submersible concept).

The present study further expands the scope of sensitivity analyses, with the primary focus on the global performance of FOWTs and their stationkeeping systems, to evaluate the significance of various modeling parameters and methodologies, which include:

- Simulation time duration for extreme value prediction
- Relative importance of wind, wave and current loads
- Effects of turbine availability and transient events on the mooring fatigue
- Tower flexibility
- Mooring line damage
- Applicability of the un-coupled analysis method
- Applicability of the quasi-static analysis method

3.8.1 Platform Motion Effects on Power Production

Influence of platform motions on power production is studied using the design load case DLC 1.3 (see Section 3.2), which is one of the governing load cases for wind turbine components strength design (blade, drive train and yaw bearing). The results of the TLP and Semi-submersible FOWTs at the site in the GoM Central Region (GOM) are compared to a land based wind turbine subjected to the same wind conditions. Comparisons of responses of the Semi-submersible and TLP FOWTs to the relevant responses of the land-based wind turbine are presented in Figure 3.51 through Figure 3.53. Based on the comparisons, it can be concluded that:

- Turbine components (blade, drive train and yaw bearing) loads of the Semi-submersible and TLP FOWTs are close to those of the land-based wind turbine.
- Tower base loads of the Semi-submersible FOWT are higher than those of the land-based turbine.
- Tower base loads of the TLP FOWT are close to those of the land-based turbine.

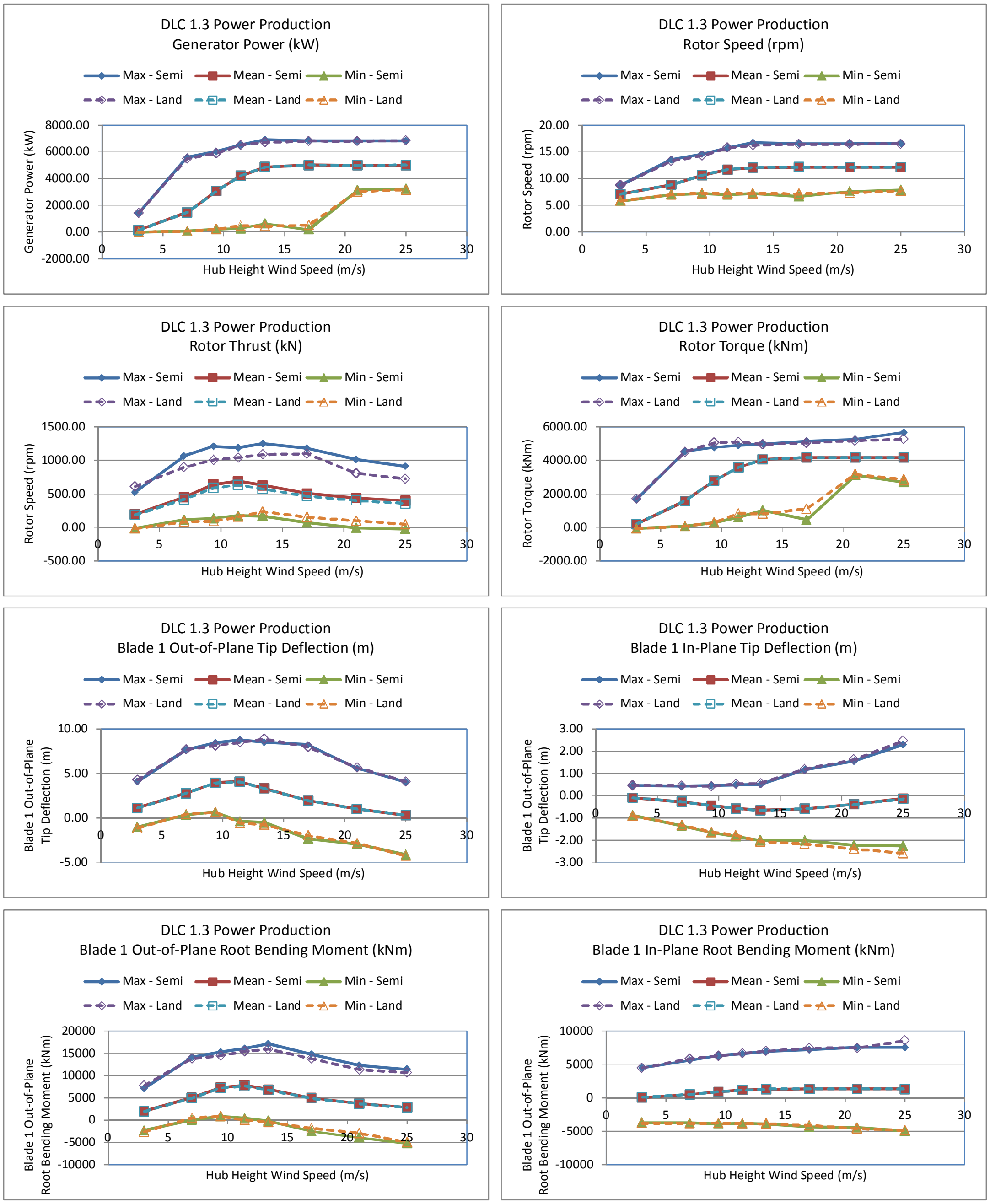


Figure 3.51 Comparison of DLC 1.3 – Semi-submersible FOWT vs. Land-based Turbine

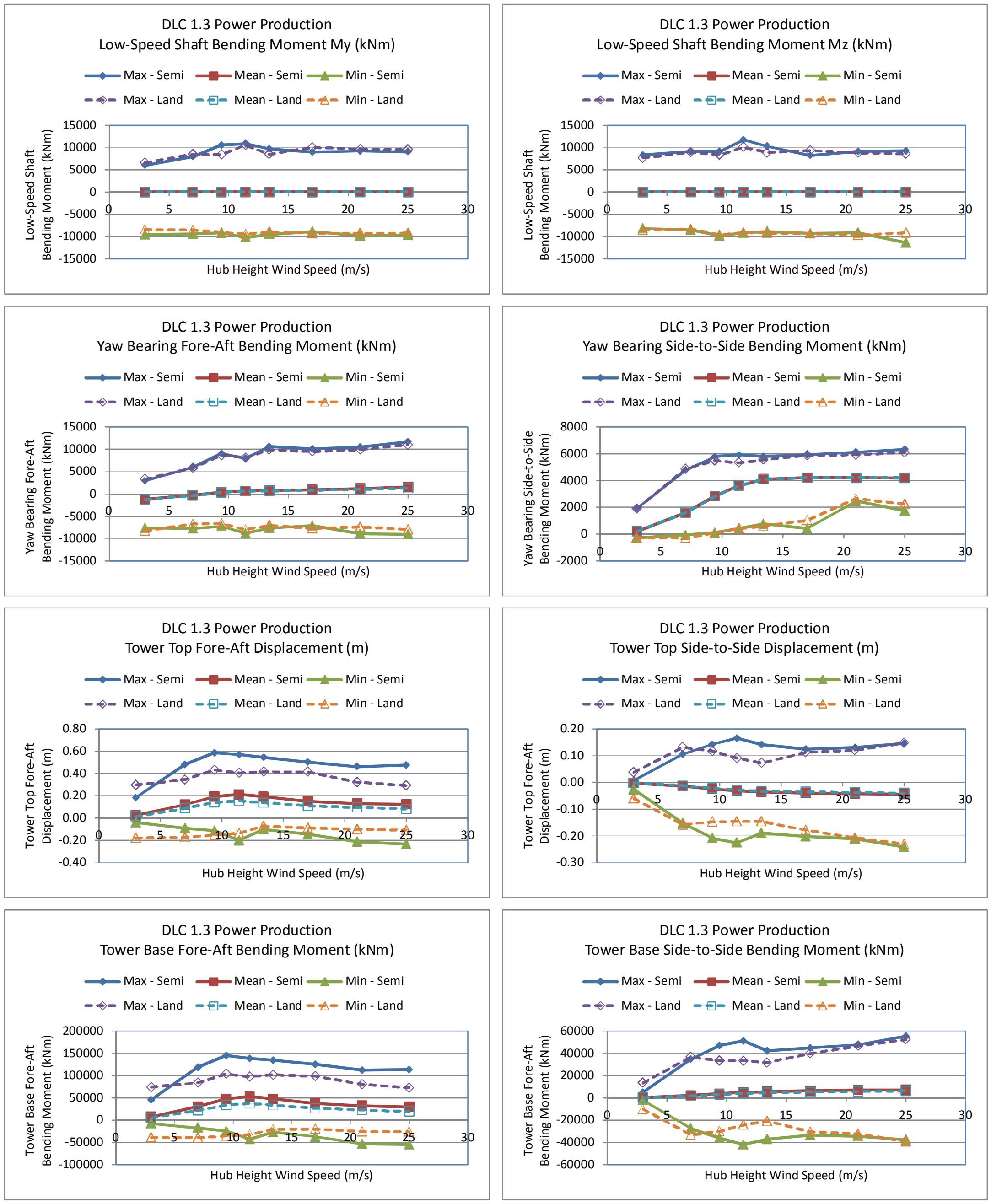


Figure 3.52 Comparison of DLC 1.3 – Semi-submersible FOWT vs. Land-based Turbine (Continued)

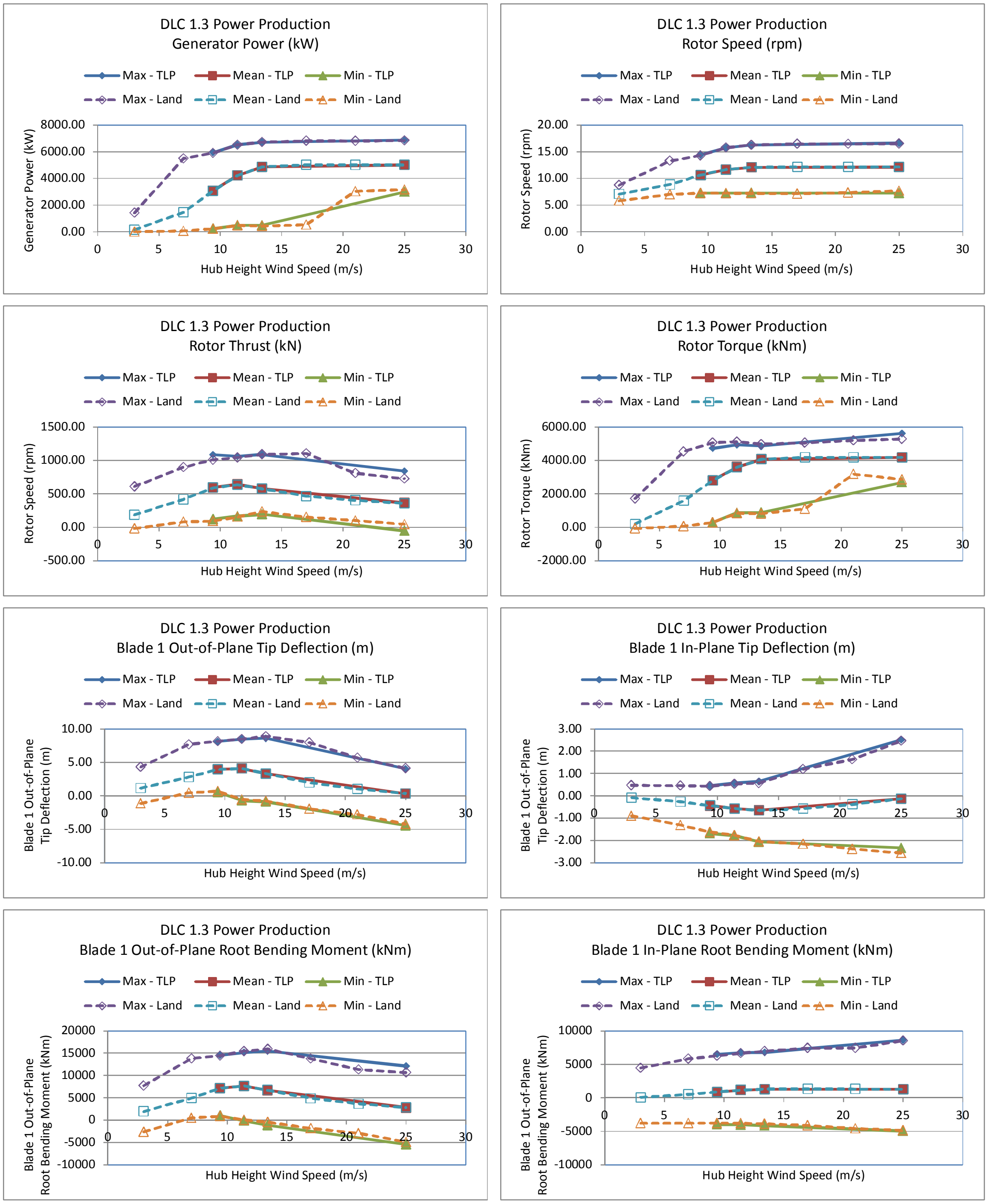


Figure 3.53 Comparison of DLC 1.3 – TLP FOWT vs. Land-based Turbine

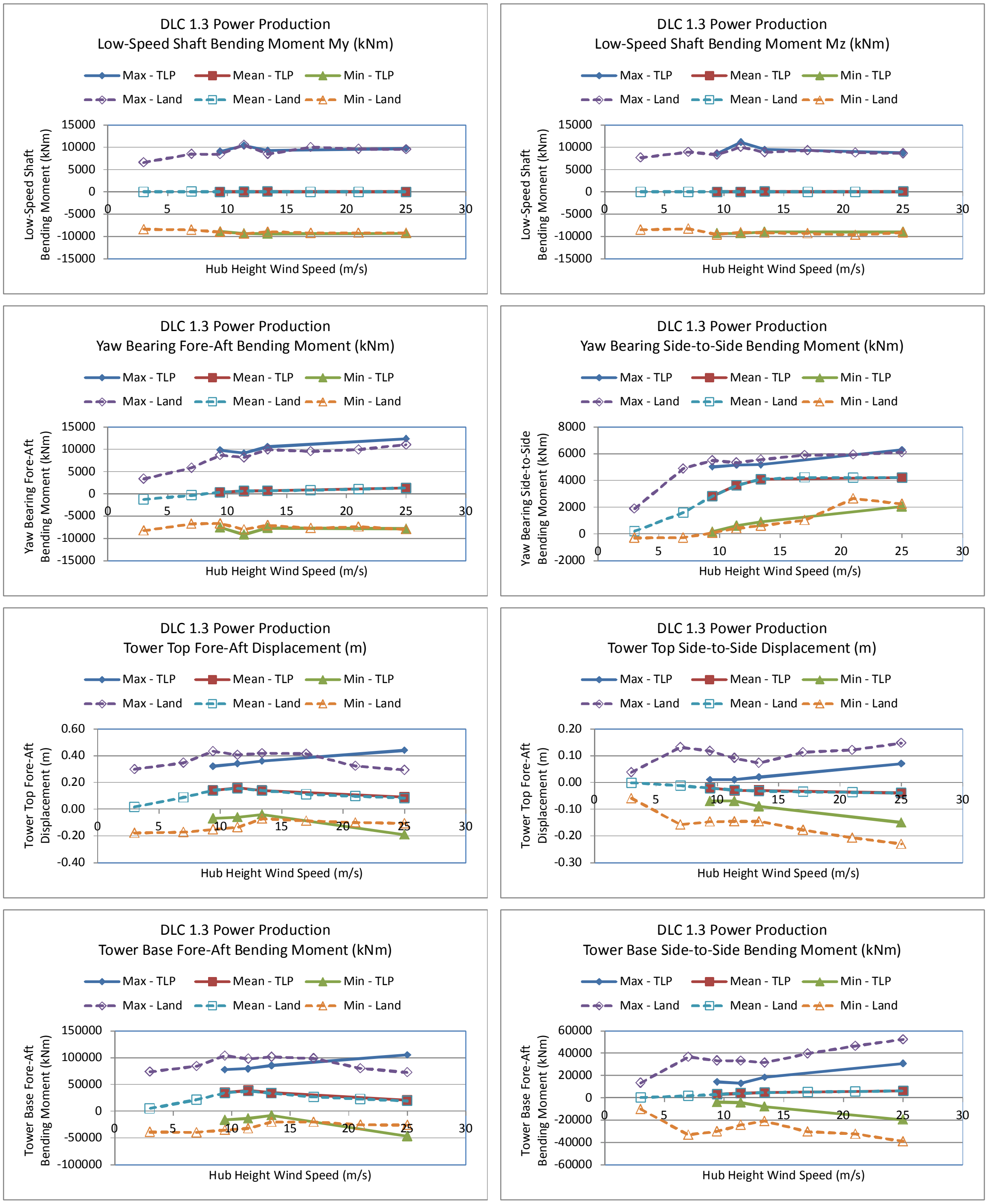


Figure 3.54 Comparison of DLC 1.3 – TLP FOWT vs. Land-based Turbine (Continued)

3.8.2 Simulation Time Duration for Extreme Value Prediction

The following load cases that cover the power production condition and the extreme environmental condition are simulated to study the effects of simulation time duration on the extreme value prediction.

Table 3.24 Load Cases – Sensitivity of Simulation Time Duration

FOWT	*Site*	*Design Condition*	*DLC*	*Wind and wave directionality*	*Yaw Control*	*Safety Factor*
Semisubmersible	GOM	1) Power production	1.3	Collinear	Yaw misalignment $\phi=0^0$	Normal
		6) Parked (standing still or idling)	6.1	Collinear	Yaw misalignment $\phi=0^0$	Normal

For DLC 1.3, 18×10-minute simulations and 6×1-hour simulations are performed. The 18×10-minute simulations are equivalent to a 3-hour simulation. For the 1-hour simulations, both wave and wind conditions are adjusted based on IEC 61004-3, thus a 1-hour simulation is equivalent to a 3-hour simulation in terms of extreme responses. For the 18×10-minute simulations, the maximum value of a response is taken as the maximum among the responses of all the 18 simulations. For the 6×1 hour simulations, the maximum value of a response is taken as the average of that response's maximum values of the 6 simulations. The wind and wave conditions for the 18×10-minute simulations and the adjusted wind and wave conditions for the 6×1-hour simulations for DLC 1.3 are presented in Table 3.25.

For DLC 6.1, 6×1 hour simulations and 6×3 hour simulations are performed. Wave conditions are adjusted for each 1-hour simulation based on IEC 61004-3. For wind conditions, both 1-hour simulation and 3-hour simulation are based on 1-hour mean wind speed and API (NPD) spectrum. For 6×1 hour simulations and 6×3 hour simulations, the maximum value of a response is taken as the average of that response's maximum value of the 6 simulations. The adjusted wind and wave conditions for DLC 1.3 are presented in Table 3.26.

Table 3.25 Wind and Wave Conditions – Sensitivity of Simulation Time Duration, DLC 1.3

DLC 1.3	*Parameters*	*10 –minute Simulation*	*1-hour Simulation*
	Number of Simulations	18	6
	Extreme Value	Maximum of maximum	Average of maximum
	Wind Spectrum	IEC Kaimal	IEC Kaimal
	Wave Spectrum	Jonswap	Jonswap
V_{hub} = 11.4 m/s	Mean Wind Speed (m/s)	11.4	10.835
	Turbulence Intensity	26.966%	30.226%
	Hs (m)	1.71	1.86
	Tp (s)	5.84	5.84
V_{hub} = 25 m/s	Mean wind speed (m/s)	25	23.750
	Turbulence Intensity	16.684%	18.397%
	Hs (m)	7.35	8.02
	Tp (s)	12.12	12.12

Table 3.26 Wind and Wave Conditions – Sensitivity of Simulation Time Duration, DLC 6.1

DLC 6.1	*Parameters*	*1-hour Simulation*	*3-hour Simulation*
	Number of Simulations	6	6
	Extreme Value	Maximum of maximum	Average of maximum
	Wind Spectrum	API (NPD)	API (NPD)
	Wave Spectrum	Jonswap	Jonswap
$V_{hub} = V_{50\text{-}yr}$	Mean Wind Speed (m/s)	60.3	60.3
	Turbulence Intensity	10.37%	10.37%
	Hs (m)	15.12	14.60
	Tp (s)	14.62	14.62

Comparisons of the mean and maximum responses for DLC 1.3 based on 18×10-minute simulations and 6×1-hour simulations are presented in Table 3.27 for the rated wind speed (V_r) and Table 3.28 for the cut-out wind speed (V_{out}).

Comparisons of the mean and maximum responses for DLC 6.1 based on 6×1 hour simulations and 6×3 hour simulations are presented in Table 3.29.

From these results, it is concluded that:

- There are differences in extreme values based on different simulation time durations, but the extreme values are reasonably close.
- In general, wind conditions are more critical than wave conditions for wind turbine component loads, while both wind and wave conditions are important for the floating support structure and mooring system responses.
- Simulation time duration is important for the hull offset and the mooring line tension due to low frequency motions induced by wave drift forces and low frequency wind loads.
- For DLC 1.3, 10-minute simulations appear to give reasonable results. Wind conditions are more important than wave conditions for this load case. In general using maximum of 18 10-minute simulations results in slightly conservative extreme responses. However, combined with the effects of control system, the effect of simulation time duration on wind loads and resultant load effects are difficult to evaluate.
- For both DLC 1.3 and DLC 6.1, a factor of 1.09 applied to the significant wave height (*Hs*) in the 1-hour simulations overestimates the 2nd-oder wave loads. When the 2nd-order wave loads are important, this gives slightly conservative predictions of global responses, especially for the hull offset and the mooring line tensions.
- For DLC 6.1, the 1-hour simulations, with comparison to the 3-hour simulations, lead to the slightly higher hull offset, heel and mooring line tensions, and the slightly lower hull sway, yaw, and turbine components loads. This is because the factor of 1.09, as recommended in IEC 61400-3 (IEC, 2009) applied to the significant wave height (*Hs*) in the 1-hour simulations overestimates the 2nd-oder wave loads. In the 3-hour simulations, where the wind average speed and turbulence intensity are not adjusted for an API (NPD) wind spectrum which is defined in terms of the wind speed with an averaging time duration of 1 hour, the wind loads are overestimated.
- For the operational load cases (for example DLC 1.3), when wind conditions are more important for the design, a 10-minute simulation time duration appears more reasonable.
- For DLC 1.6, both wind and wave conditions are important, 1-hour simulation time duration is recommended.

- For the turbine in the parked conditions and subjected to 1-year, 50-year and 500-year return storm conditions, a longer simulation length, for instance 3 hours, is recommended for the global performance analyses because the low frequency motions induced by both wind and wave loads could be significant.

Table 3.27 Responses of DLC 1.3 (*Vr*) – Sensitivity to Simulation Time Duration

Parameter	*Units*	*18×10-minute*		*6×1-hour*		*Difference Maximum*
		Mean	*Maximum*	*Mean*	*Maximum*	
		Vhub=11.4 m/s				
Wind Speed	(m/s)	11.41	23.91	10.76	22.25	7.47%
Wave Elevation	(m)	0.00	1.81	0.00	1.56	16.23%
Platform Surge	(m)	3.36	5.98	3.34	6.11	-2.09%
Platform Sway	(m)	-0.02	0.66	-0.01	0.66	0.87%
Platform Heave	(m)	-0.03	0.11	-0.03	0.10	8.88%
Platform Roll	(deg)	0.19	0.97	0.18	0.94	2.91%
Platform Pitch	(deg)	2.80	5.98	2.75	5.87	1.89%
Platform Yaw	(deg)	0.00	2.14	-0.01	1.93	10.49%
Offset	(m)	3.37	5.98	3.34	6.11	-2.11%
Heel	(deg)	2.83	5.98	2.77	5.87	1.80%
Fairlead Tension #1	(kN)	2181	2444	2182	2423	0.89%
Fairlead Tension #2	(kN)	2837	3466	2834	3457	0.26%
Fairlead Tension #3	(kN)	2181	2437	2183	2429	0.33%
Tower Top Acceleration	(m/s^2)	0.52	3.06	0.55	2.87	6.56%
Tower Base Shear	(kN)	816	2028	802	1999	1.44%
Tower Base Moment	(kN·m)	53322	133900	52262	132683	0.92%
Tower Top Fore-Aft Force	(kN)	720	1764	705	1786	-1.25%
Tower Top Side-to-Side Force	(kN)	-16	525	-14	562	-6.51%
Tower Top Fore-Aft Deflection	(m)	0.21	0.55	0.21	0.54	1.58%
Tower Top Side-to-Side Deflection	(m)	-0.03	0.20	-0.03	0.20	-1.97%
Blade Tip Out-of-Plane Deflection	(m)	4.06	8.87	4.06	8.66	2.36%
Blade Tip In-Plane Deflection	(m)	-0.57	1.80	-0.53	1.81	-0.64%
Blade Root In-Plane Moment	(kN·m)	1141	6356	1071	6518	-2.49%
Blade Root Out-of-Plane Moment	(kN·m)	7754	16630	7650	15992	3.99%
Rotor Torque	(kN·m)	3580	4802	3360	4847	-0.93%
Low Speed Shaft Moment My	(kN·m)	3	11140	5	10338	7.76%
Low Speed Shaft Moment Mz	(kN·m)	-5	10600	3	10387	2.05%

Table 3.28 Responses of DLC 1.3 (*Vout*) – Sensitivity to Simulation Time Duration

Parameter	*Units*	*18×10-minute*		*6×1-hour*		*Difference*
		Mean	*Maximum*	*Mean*	*Maximum*	*Maximum*
		Vhub=25 m/s				
Wind Speed	(m/s)	25.09	43.06	23.76	40.44	6.47%
Wave Elevation	(m)	0.00	7.00	0.00	7.12	-1.65%
Platform Surge	(m)	3.32	8.55	3.48	8.73	-2.14%
Platform Sway	(m)	-0.14	1.05	-0.13	0.87	20.72%
Platform Heave	(m)	0.02	1.85	0.02	2.05	-9.96%
Platform Roll	(deg)	0.31	1.31	0.31	1.32	-1.13%
Platform Pitch	(deg)	1.83	4.72	1.87	4.85	-2.71%
Platform Yaw	(deg)	-0.22	2.18	-0.20	1.98	10.02%
Offset	(m)	3.33	8.55	3.50	8.74	-2.17%
Heel	(deg)	1.90	4.73	1.93	4.86	-2.72%
Fairlead Tension #1	(kN)	2200	2921	2192	2880	1.42%
Fairlead Tension #2	(kN)	2915	5265	2957	5096	3.31%
Fairlead Tension #3	(kN)	2180	2914	2173	2853	2.13%
Tower Top Acceleration	(m/s^2)	0.62	2.66	0.64	2.63	1.47%
Tower Base Shear	(kN)	496	1838	508	1673	9.85%
Tower Base Moment	(kN·m)	33781	117400	34398	113567	3.38%
Tower Top Fore-Aft Force	(kN)	389	1576	398	1473	6.98%
Tower Top Side-to-Side Force	(kN)	-41	641	-39	625	2.48%
Tower Top Fore-Aft Deflection	(m)	0.12	0.47	0.13	0.46	2.01%
Tower Top Side-to-Side Deflection	(m)	-0.04	0.23	-0.04	0.23	3.10%
Blade Tip Out-of-Plane Deflection	(m)	0.30	4.75	0.50	4.71	0.83%
Blade Tip In-Plane Deflection	(m)	-0.12	2.64	-0.20	2.36	11.92%
Blade Root In-Plane Moment	(kN·m)	1290	7696	1299	7622	0.98%
Blade Root Out-of-Plane Moment	(kN·m)	2851	10540	3079	10675	-1.26%
Rotor Torque	(kN·m)	4180	5692	4180	5659	0.59%
Low Speed Shaft Moment My	(kN·m)	-4	10690	8	9788	9.22%
Low Speed Shaft Moment Mz	(kN·m)	8	10660	-5	9409	13.30%

Table 3.29 Responses of DLC 6.1 – Sensitivity to Simulation Time Duration

Parameter	*Units*	*6×1-hour*		*6×3-hour*		*Difference*
		Mean	*Maximum*	*Mean*	*Maximum*	*Maximum*
		Vhub=60.3 m/s				
Wind Speed	(m/s)	60.31	83.96	60.27	85.61	-1.93%
Wave Elevation	(m)	0.00	12.30	0.00	11.90	3.33%
Platform Surge	(m)	10.09	20.95	9.82	20.33	3.02%
Platform Sway	(m)	-0.11	1.75	-0.08	2.09	-16.51%
Platform Heave	(m)	0.15	5.86	0.14	5.85	0.22%
Platform Roll	(deg)	0.08	1.62	0.06	1.75	-7.73%
Platform Pitch	(deg)	2.89	7.35	2.89	7.20	2.06%
Platform Yaw	(deg)	0.13	0.71	0.13	0.85	-16.55%
Offset	(m)	10.11	20.95	9.84	20.35	2.98%
Heel	(deg)	2.94	7.36	2.93	7.20	2.24%
Fairlead Tension #1	(kN)	1904	2845	1910	2799	1.64%
Fairlead Tension #2	(kN)	4927	9643	4799	9431	2.25%
Fairlead Tension #3	(kN)	1890	2828	1899	2789	1.40%
Tower Top Acceleration	(m/s^2)	0.45	1.84	0.42	1.74	5.52%
Tower Base Shear	(kN)	449	1436	443	1424	0.83%
Tower Base Moment	(kN·m)	28355	87898	27993	88132	-0.26%
Tower Top Fore-Aft Force	(kN)	303	1042	303	1034	0.77%
Tower Top Side-to-Side Force	(kN)	-19	495	-14	525	-5.55%
Tower Top Fore-Aft Deflection	(m)	0.11	0.35	0.11	0.36	-0.91%
Tower Top Side-to-Side Deflection	(m)	-0.01	0.15	0.00	0.16	-5.66%
Blade Tip Out-of-Plane Deflection	(m)	-0.13	1.24	-0.13	1.28	-3.27%
Blade Tip In-Plane Deflection	(m)	-1.53	9.94	-1.44	9.92	0.20%
Blade Root In-Plane Moment	(kN·m)	403	15085	239	16027	-5.88%
Blade Root Out-of-Plane Moment	(kN·m)	248	2960	195	3276	-9.64%
Rotor Torque	(kN·m)	0	1232	0	1309	-5.88%
Low Speed Shaft Moment My	(kN·m)	158	4164	-114	4492	-7.29%
Low Speed Shaft Moment Mz	(kN·m)	-160	3682	-8	4174	-11.79%

3.8.3 Mooring Fatigue Analysis

Effects of turbine availability and transient events on mooring fatigue are studied using the selected load cases DLC 1.2, DLC 3.1, DLC 4.1 and DLC 6.4, as summarized in the Table 3.30, for the TLP FOWT in OR.

Table 3.30 Load Cases for Studying the Mooring Line Fatigue

FOWT	*Site*	*Design Condition*	*DLC*	*Wind and wave directionality*	*Yaw Control*	*Type of Analysis*
TLP	OR	1) Power production	1.2	Collinear, MUL	Yaw misalignment $\phi=0^0$	F
		3) Start-up	3.1	Collinear, UNI	Yaw misalignment $\phi=0°$	F
		4) Normal shutdown	4.1	Collinear, UNI	Yaw misalignment $\phi=0°$	F
		6) Parked (standing still or idling)	6.4	Collinear, MUL	Yaw misalignment $\phi=0^0$	F

Note: 1) MUL: multi-directional wind and wave
2) UNI: uni-directional wind and wave directions

The annualized directional wind scatter diagram in OR in Table 3.31 is derived based on the NOAA NDBC buoy data (Station 46050, see Section 3.3.2). Fatigue analyses are performed for selected wind bins of the scatter diagram in Table 3.31 along with the associated wave and current conditions defined in accordance with Section 3.4.1. For Wind BIN #1, the wind speed is below the cut-in (V_{in}) wind speed and thus the wind turbine is in the parked condition. Wind speeds for Wind BIN #2 through Wind BIN #10 are between the cut-in (V_{in}) and cut-out (V_{out}) wind speeds. The wind turbine is either in the operational conditions or the parked condition. For Wind BIN #11 and above, wind speeds are above the cut-out (V_{out}) wind speed and the wind turbine is always in the parked condition. It is noted that the possibility for wind speed above the cut-out wind speed is only 0.11%.

For the purpose of sensitivity analysis, Wind BIN #3, #5, #7 and #9 are selected for DLC 1.2 while the turbine is in power production. Wind BIN #3, #5, #7, #9 and #11 are selected for DLC 6.4 while the turbine is parked. It is assumed that all the wind for a specific bin is coming from the same direction. For the convenience of comparing the fatigue damages associated with different bins and turbine operating conditions, the fatigue life is calculated for each bin by assuming the probability of occurrence of the bin is 100%, meaning the total fatigue life associated with a wind bin is not factored by the occurrence probability of that wind bin.

For DLC 3.1 (start-up) and DLC 4.1 (normal shut-down), fatigue analyses are performed for the rated and cut-out wind speeds. It is assumed the number of start-up and shut-down are 50 times at the rated or cut-out wind speeds per year. The design life is assumed to be 20 years.

Results of fatigue analyses are given in Table 3.32 and Table 3.33. The fatigue analyses are based on rain flowing counting method using program Crunch. A TN curve of wire rope is used in the analysis.

Table 3.31 Wind Scatter Diagram Offshore Oregon

Wind BIN	*V8min @5m Range*		*V8min @5m*	*V1hr @10m*	*Vhub (10 min)*	*Probability of Occurrence (%)*								
						Wind Direction Defined by NDBC Buoy Data (degrees)								
#	*(m/s)*		*(m/s)*	*(m/s)*	*(m/s)*	0	45	90	135	180	225	270	315	Total
1	0	2	1.0	0.99	1.16	0.64	0.94	0.93	1.04	1.65	1.19	1.11	2.12	9.62
2	2	4	3.0	2.96	3.52	1.96	1.99	1.54	1.91	3.07	2.05	1.76	5.73	20.01
3	4	6	5.0	4.93	5.96	3.04	1.67	1.68	1.80	4.00	2.06	1.65	7.78	23.67
4	6	8	7.0	6.90	8.45	3.09	0.77	1.30	1.31	4.04	1.90	1.33	7.28	21.02
5	8	10	9.0	8.87	11.01	2.13	0.27	0.56	0.73	3.39	1.38	0.78	4.58	13.83
6	10	12	11.0	10.84	13.62	0.68	0.07	0.17	0.38	2.61	0.88	0.32	1.55	6.66
7	12	14	13.0	12.80	16.27	0.07	0.03	0.06	0.17	1.74	0.44	0.11	0.25	2.88
8	14	16	15.0	14.76	18.97	0.00	0.00	0.01	0.05	1.02	0.14	0.03	0.05	1.31
9	16	18	17.0	16.71	21.70	0.00	0.00	0.00	0.01	0.54	0.06	0.00	0.01	0.62
10	18	20	19.0	18.65	24.47	0.00	0.00	0.00	0.00	0.24	0.02	0.00	0.00	0.26
11	20	22	21.0	20.59	27.28	0.00	0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.09
12	22	24	23.0	22.53	30.13	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02
13	24	26	25.0	24.45	32.99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	26	28	27.0	26.37	35.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	28	30	29.0	28.28	38.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	30	32	31.0	30.19	41.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	32	34	33.0	32.09	44.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	34	36	35.0	33.98	47.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	36	38	37.0	35.86	50.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total						11.63	5.74	6.26	7.40	22.41	10.12	7.10	29.35	100.00

Table 3.32 Effect of Turbine Availability on the Mooring Line Fatigue

Load Case	*Wind BIN*	*Possibility*	*Fatigue Life (Years)*							
		(%)	*Line #1*	*Line #2*	*Line #3*	*Line #4*	*Line #5*	*Line #6*	*Line #7*	*Line #8*
DLC 1.2 Power Production	BIN3	100	1448	1449	3.22E+07	3.68E+07	1148	1148	2.99E+07	3.21E+07
	BIN5	100	622	621	4.06E+06	4.70E+06	378	378	4.15E+06	4.33E+06
	BIN7	100	198	198	3.33E+05	3.51E+05	139	138	3.23E+05	3.29E+05
	BIN9	100	67	66	2.80E+04	2.89E+04	47	47	2.55E+04	2.58E+04
DLC 6.4 Parked (Idling)	BIN3	100	1029	1029	8.82E+07	1.10E+08	972	972	8.66E+07	1.11E+08
	BIN5	100	390	390	1.12E+07	1.34E+07	362	362	1.12E+07	1.32E+07
	BIN7	100	117	117	8.47E+05	9.34E+05	104	104	8.40E+05	9.71E+05
	BIN9	100	42	42	7.01E+04	7.33E+04	37	37	6.48E+04	7.16E+04
	BIN11	100	22	22	6.55E+03	6.82E+03	19	19	6.16E+03	6.56E+03

Table 3.33 Effect of Transient Event on the Mooring Line Fatigue

Load Case	*Wind Condition*	*Number of Occurrence (20 Years)*	*Lifetime Damage (20 Years)*							
			Line #1	*Line #2*	*Line #3*	*Line #4*	*Line #5*	*Line #6*	*Line #7*	*Line #8*
DLC 3.1 Start-up	*Vr*	50×20	2.38E-05	2.38E-05	2.48E-09	2.08E-09	3.83E-05	3.83E-05	2.75E-09	2.33E-09
	Vout	50×20	1.70E-04	1.70E-04	5.59E-07	5.47E-07	2.24E-04	2.24E-04	5.89E-07	5.56E-07
DLC 4.1 Normal shutdown	*Vr*	50×20	2.33E-05	2.33E-05	1.40E-09	1.15E-09	2.72E-05	2.72E-05	1.31E-09	1.07E-09
	Vout	50×20	2.33E-04	2.33E-04	4.67E-07	4.37E-07	2.66E-04	2.66E-04	4.91E-07	4.66E-07

Based on the fatigue analysis results, the following conclusions are made:

- Under the same combination of wave, wind and current conditions, the parked turbine induces more fatigue damage in the mooring system than the turbine in power production. This indicates that the turbine in parked condition introduces lower aerodynamic damping and therefore lower total damping, which results in larger wave-induced motions of the floating hull and higher fatigue damage in the mooring system.
- In the power production conditions, the load case defined by the rated wind speed and its associated wave and current conditions causes less fatigue damage in the mooring system than the load case with a higher wind speed and the associated wave and current condition.

This indicates that, for the TLP FOWT under consideration, dynamic wave loads are more important than dynamic wind loads for the mooring fatigue damage.

- The accumulation of the mooring fatigue damage due to transient events appears to be insignificant.

3.8.4 Comparison of Wind, Wave and Current Loads

Wind, wave and current loads are compared for the Spar, Semi-submersible and TLP FOWTs, with the consideration of DLC 1.3 for the turbine in power production conditions and the load cases in which the turbine is parked and the 1-year, 50-year and 500-year return storm environmental conditions are applied. Only the horizontal loads in surge direction are compared, because they are the most important for FOWT offsets and mooring system loads. The wind loads are taken as the yaw bearing shear forces in the x-direction on top of the tower.

The loads are compared in Figure 3.55 through Figure 3.60 for:

- the Spar FOWT Offshore Oregon (OR);
- the Semi-submersible FOWT in the GoM Central Region (GOM), the Gulf of Maine (ME), and OR; and
- the TLP FOWT in GOM and ME.

Main conclusions from the load comparison are:

- For the Spar FOWT in OR, the mean wind loads are higher than the mean viscous drag loads and the mean wave drift loads in all the load cases considered. However, dynamically the wave loads are larger than the dynamic wind loads. The largest wind load occurs in DLC 1.3 with the turbine operating at the rated wind speed.
- For the Semi-submersible FOWT in GOM, the total mean loads (wind, wave and current) and the dynamic loads in the power production load case are smaller than those in the storm load cases subjected to the 50-year and 500-year return environmental conditions.
- For the Semi-submersible FOWT in ME, the mean wind loads are higher than the mean viscous drag loads and the mean wave drift loads in all the load cases under consideration.

However, the dynamic wave loads are larger than the dynamic wind loads. The largest wind load occurs in DLC 1.3 with the turbine operating at the rated wind speed.

- For the Semi-submersible FOWT in OR, the mean wind loads are higher than the mean viscous drag loads in the power production load case, while the mean viscous drag loads are higher than the mean wind loads in the storm load cases where the turbine is parked. The total mean loads (wind, wave and current) and the dynamic loads in the power production load case are smaller than those in the storm load cases subjected to the 50-year and 500-year return environmental conditions.
- For the TLP FOWT in GOM, both the mean loads (wind, wave and current) and the dynamic loads in the power production load case are smaller than those in the storm load cases subjected to the 50-year and 500-year return environmental conditions.
- For the TLP FOWT in OR, the mean wind loads are higher than the mean viscous drag loads and the mean wave drift loads in all the load cases under consideration. The total mean loads (wind, wave and current) and the dynamic loads in the power production load case are smaller than those in the storm load cases subjected to 50-year and 500-year return environmental conditions.

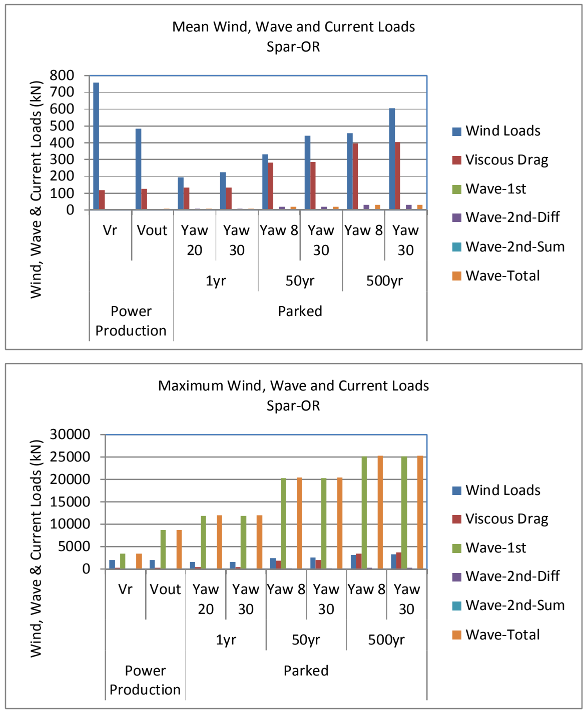


Figure 3.55 Environmental Loads – Spar FOWT (OR)

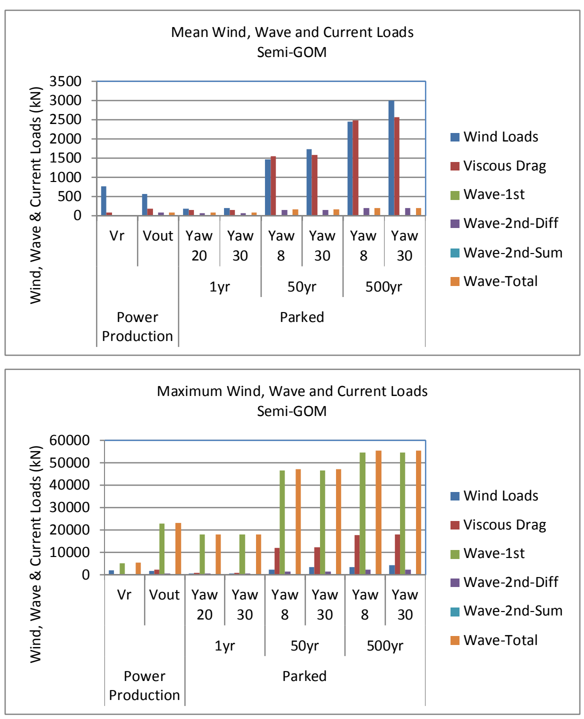


Figure 3.56 Environmental Loads – Semi-submersible FOWT (GOM)

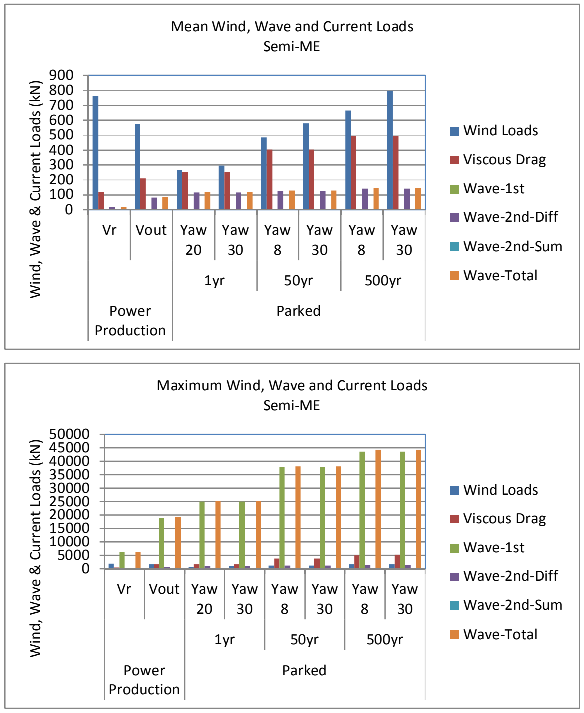


Figure 3.57 Environmental Loads – Semi-submersible FOWT (ME)

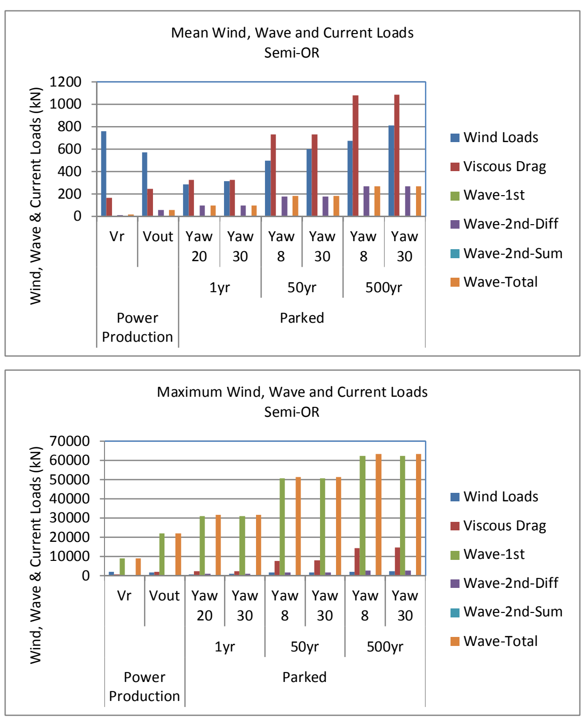


Figure 3.58 Environmental Loads – Semi-submersible FOWT (OR)

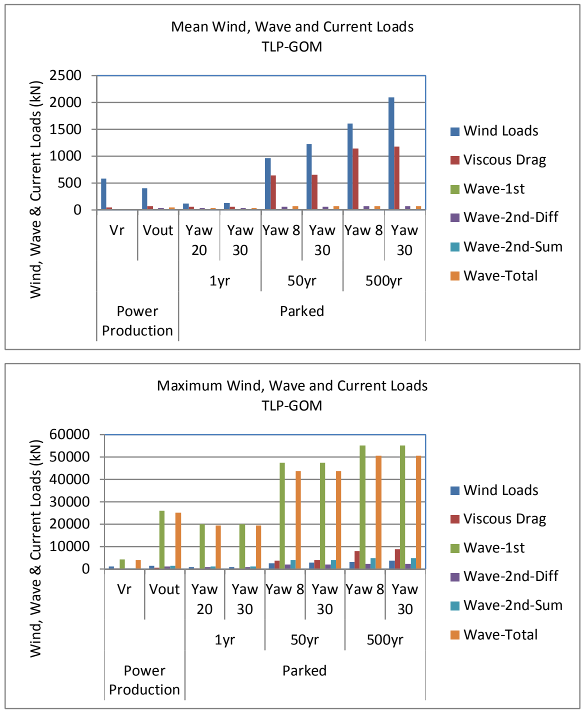


Figure 3.59 Environmental Loads – TLP FOWT (GOM)

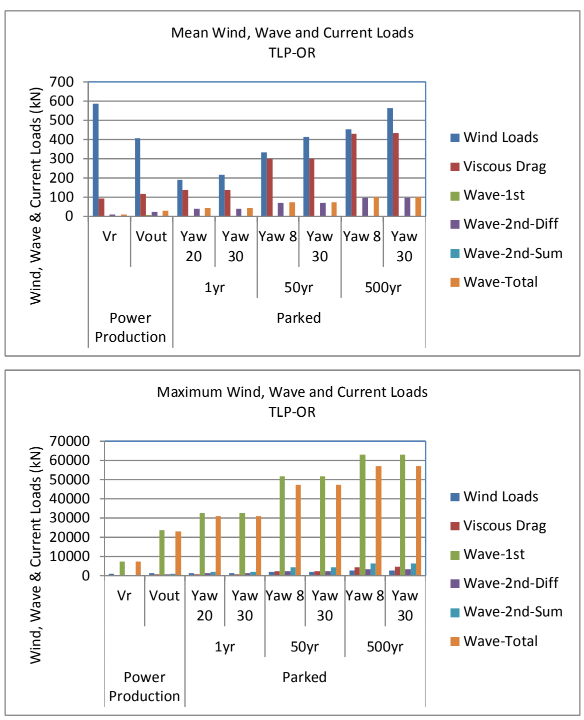


Figure 3.60 Environmental Loads – TLP FOWT (OR)

3.8.5 Effects of Tower Flexibility

The load cases in Table 3.34 are simulated to study the effects of tower flexibility on the global load predictions. To compare the effects of tower flexibility, the same load cases are simulated with two tower options: one assumes the tower is flexible, and another assumes the tower is rigid. Figure 3.61 depicts the effects of tower flexibility on the pitch natural period of the TLP FOWT observed in a numerical free decay test of the hull pitch motion.

Table 3.34 Load Cases to Study Sensitivity of Tower Flexibility

FOWT	*Site*	*Design Condition*	*DLC*	*Wind and wave directionality*	*Yaw Control*	*Safety Factor*
Semisubmersible & TLP	GOM	1) Power production	1.3	Collinear	Yaw misalignment $\phi=0^0$	Normal
		6) Parked (standing still or idling)	6.2	Collinear	Yaw misalignment $\phi=30^0$	Abnormal

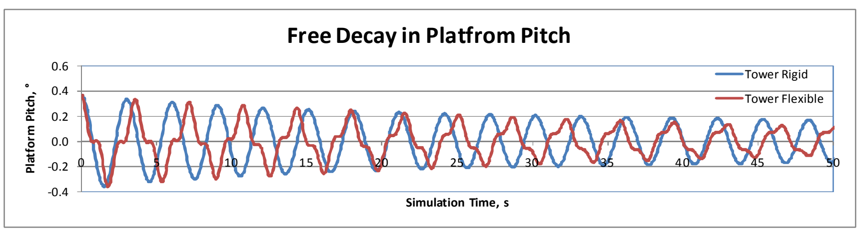


Figure 3.61 Effect of Tower Flexibility on Pitch Natural Period of the TLP FOWT

Global responses obtained with the assumption of two different tower models are compared in Figure 3.62 for the Semi-submersible FOWT in GOM, and in Figure 3.63 for the TLP FOWT in GOM.

Based on these comparisons, it can be concluded that:

- For the Semi-submersible FOWT, tower flexibility has almost no effect on the hull motions and line tensions. However, tower base loads of the flexible tower are much higher than those of the rigid tower.

- For the TLP FOWT, tower flexibility has noticeable effects on the hull motions and line tensions as well as tower base loads. This is mainly because that a flexible tower will change the natural periods of hull pitch and roll motions.

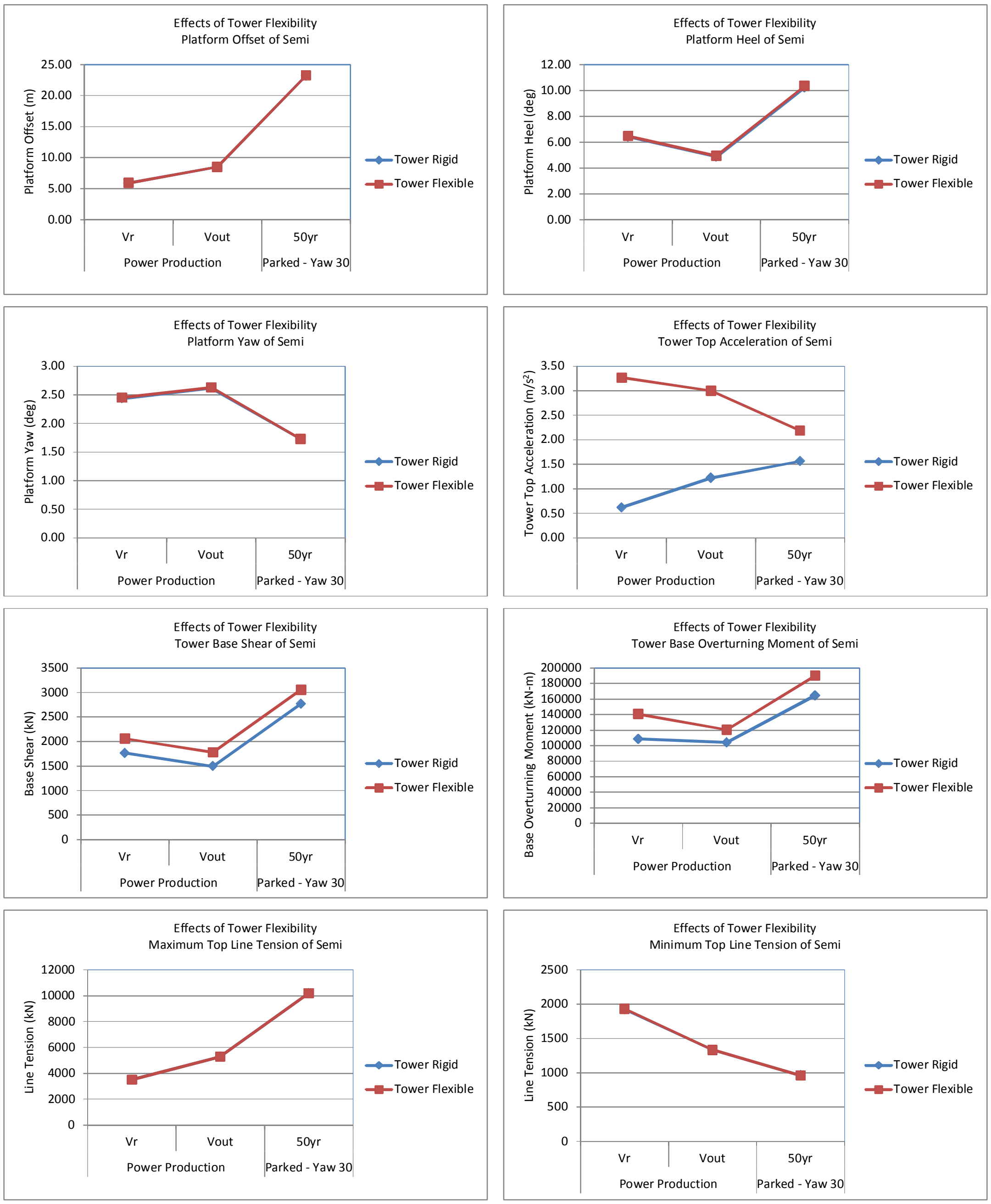


Figure 3.62 Effects of Tower Flexibility – Semi-submersible FOWT Support Structure and Mooring Responses for DLC 1.3 & 6.2

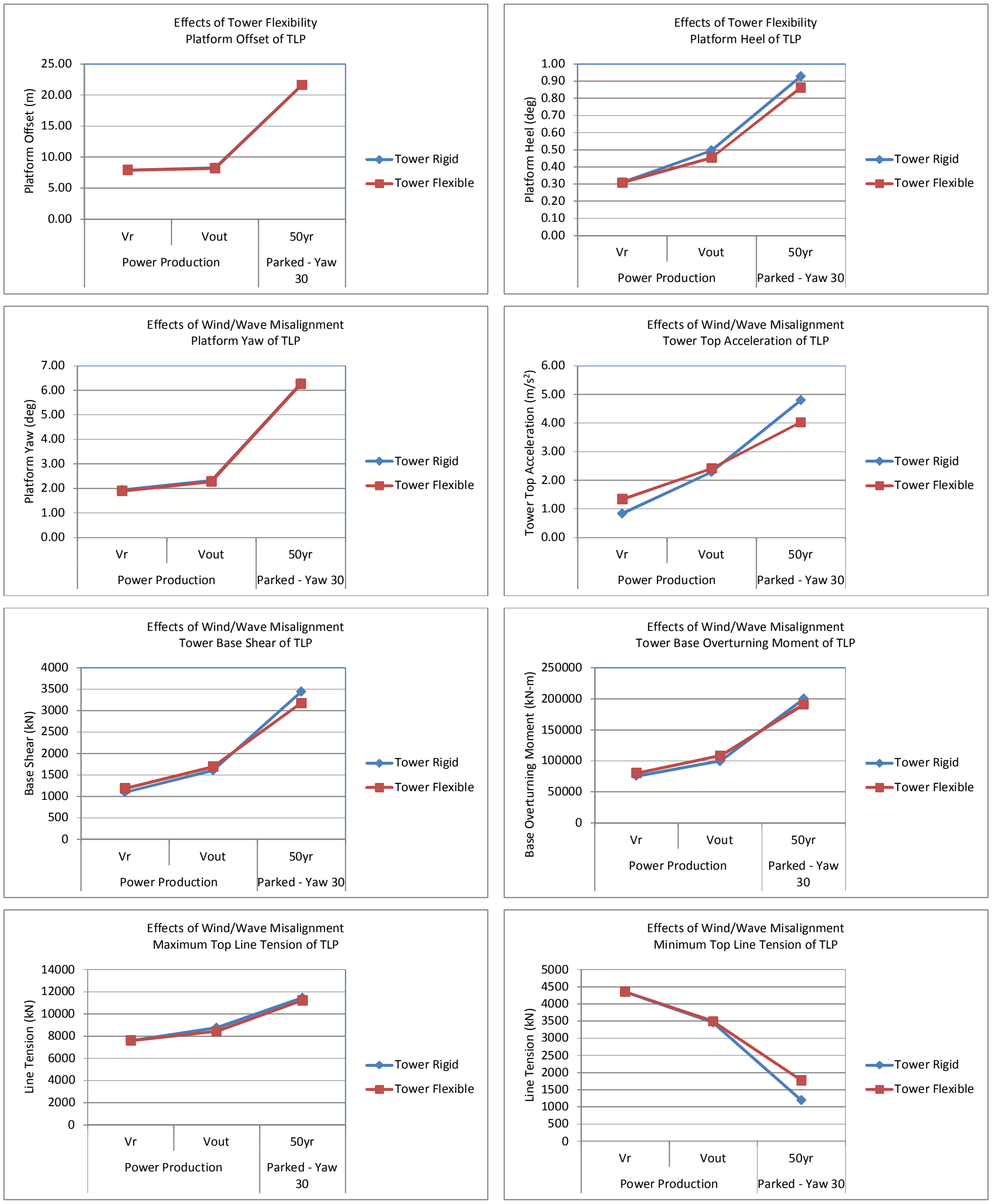


Figure 3.63 Effects of Tower Flexibility – TLP FOWT
Support Structure and Mooring Responses for DLC 1.3 & 6.2

3.8.6 Effects of Mooring/Tendon Line Damage

The effect of mooring/tendon line damage (i.e. one broken line) on FOWT global responses are studied using the TLP FOWT subjected to the 50-year return hurricane in the GOM as defined by the design load case DLC 6.1 in Table 3.35 and Table 3.36. Table 3.36 presents the comparison of the global responses of the TLP FOWT with the intact mooring lines and with one mooring line broken. It is shown that

- Mooring line damage does not appear to significantly affect the turbine component loads (i.e. the loads on the blade and shaft) while the RNA is in the parked condition.
- Heel motions of the hull and the tower base loads are higher in the case having one damaged line than in the case with intact lines.
- Maximum tendon tension is much higher in the case having one damaged line than in the case with intact lines. Slack lines in one of the four corners of tendons are also observed in the case with one damaged line.

Table 3.35 Load Cases – Effects of Line Damage

FOWT	*Site*	*Design Condition*	*DLC*	*Wind and wave directionality*	*Yaw Control*	*Safety Factor*
TLP	GOM	6) Parked (standing still or idling)	6.1	Collinear	Yaw misalignment $\phi=8^0$	Normal

Table 3.36 Maximum Responses – Effects of Line Damage, TLP FOWT, DLC 6.1

Maximum Responses	*Unit*	*Intact*	*One-line Damage*
Offset	m	19.32	19.82
Heel	degree	0.83	1.80
Yaw	degree	5.19	4.78
Maximum Line Tension	kN	11042	18083
Minimum Line Tension	kN	1967	-58
Tower Base Shear	kN	2830	3461
Tower Base Overturning Moment	kN-m	166096	207846
Blade Root Out-of-Plane Bending Moment	kN-m	5480	5479
Blade Root In-Plane Bending Moment	kN-m	22738	21657
Low Speed Shaft Bending Moment My	kN-m	7858	7644
Low Speed Shaft Bending Moment Mz	kN-m	7760	7456

3.8.7 Evaluation of Semi-coupled Analysis

The semi-coupled analysis method assumes that the tower and the turbine RNA are rigid bodies and can be modeled as part of the rigid floating hull. The wind loads are applied at the hub height in the form of $F_{wind}=f_w V_{hub}^2$, where f_w is the wind force coefficient; and V_{hub} is the hub height wind speed.

The design load cases DLC 1.3 and DLC 6.1 as defined in Table 3.37 for the Semi-submersible FOWT in the GOM are simulated to study the applicability of the semi-coupled analysis method. Each load case is simulated with two options: one uses the fully coupled (or integrated) analysis method, and another uses the semi-coupled analysis method. The wind force coefficients, f_w, are calculated using the NREL-FAST program for a fixed (land-based) wind turbine subjected to a series of uniform steady wind conditions with different mean wind speeds. The wind forces as shown in Figure 3.64 are applied as the horizontal shear forces at the tower top.

Table 3.37 Load Cases – Semi-coupled Analysis

FOWT	*Site*	*Design Condition*	*DLC*	*Wind and wave directionality*	*Yaw Control*	*Safety Factor*
Semisubmersible	GOM	1) Power production	1.3	Collinear	Yaw misalignment $\phi=0^0$	Normal
		6) Parked (standing still or idling)	6.1	Collinear	Yaw misalignment $\phi=0^0$	Normal

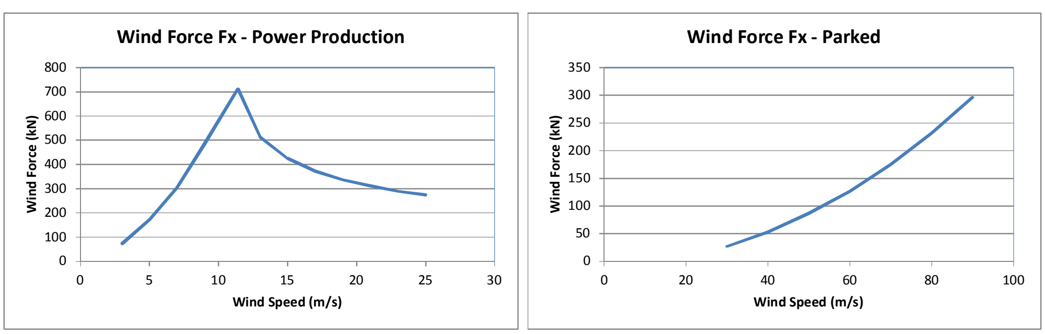


Figure 3.64 Wind Loads – Land-based Turbine in Uniform Steady Wind

Figure 3.65 plots the comparison of the semi-coupled analysis results with those calculated using the fully coupled (or integrated) method in for semisubmersible FOWT in GOM. It can be concluded that:

- Due to the effect of the turbine blade pitch control, the semi-coupled analysis using the wind force coefficients derived from the steady wind load analysis tends to over-predict the turbine wind loads when the turbine RNA is operating with the rated wind speed and subjected to a turbulent wind condition.
- For the power production condition, dynamic loads induced by turbine rotation (1P, 3P, etc.) as well as the hull sway and roll motions due to unsymmetrical loads are not captured in the semi-coupled analysis.
- For the parked turbine condition, the fully coupled (i.e. integrated) and the semi-coupled analysis yield fairly close results. This indicates that the semi-coupled analysis may be more appropriate for the turbine in the parked condition than for the turbine in the power production condition, provided wind loads are properly modeled in the analysis.

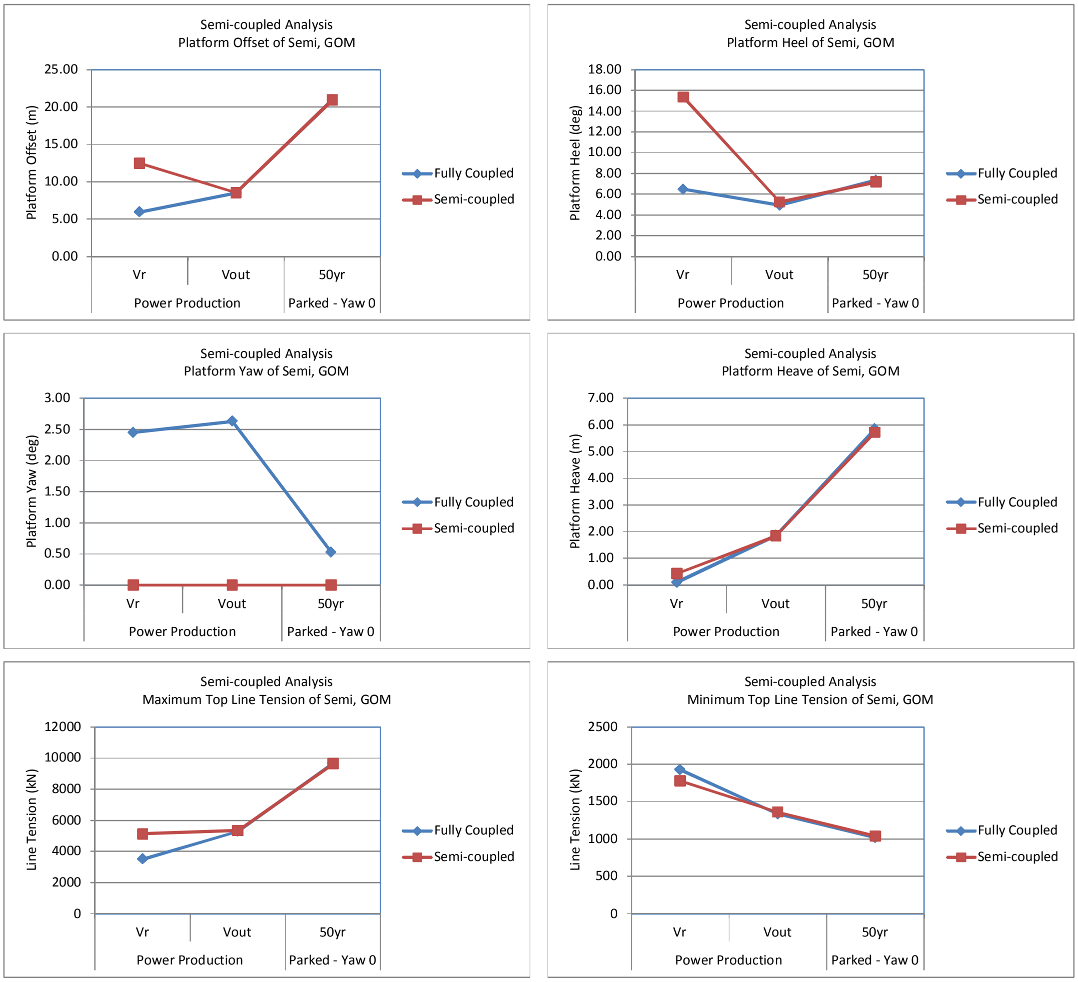


Figure 3.65 Effects of Semi-coupled Analysis – Semi-submersible FOWT Support Structure and Mooring Responses in DLC 1.3 & 6.1

3.8.8 Evaluation of Quasi-static Analysis

In a fully coupled (or integrated) analysis, the mooring system is modeled dynamically. In a quasi-static analysis, one the other hand, the mooring system is modeled statically and, therefore, the mooring induced damping and added-mass are neglected.

The design load cases DLC 1.3 and DLC 6.1 as presented in Table 3.38 for the Spar FOWT in OR and the Semi-submersible and the TLP FOWTs in GOM are simulated to study the applicability of the quasi-static analysis method. Each load case is simulated with two options:

one employs the fully coupled (or integrated) analysis method; and another uses the quasi-static analysis method.

Comparisons of FOWT global responses calculated using the fully coupled (or integrated) method and the quasi-static analysis method are plotted in Figure 3.66 and Figure 3.67 for the Spar FOWT, in Figure 3.68 and Figure 3.69 for the Semi-submersible FOWT, and in Figure 3.70 and Figure 3.71 for the TLP FOWT. Based on these comparisons, it can be concluded that:

- For the Spar FOWT, the quasi-static analysis method gives relatively higher platform offsets and the lower line tensions. The mooring dynamic effects on the mooring line tension can be important.
- For the Semi-submersible FOWT, the quasi-static analysis method yields relatively higher platform offsets. The mooring dynamic effects on the taut line made of polyester ropes appear to be insignificant when the turbine is in the parked condition.
- For the TLP FOWT, the quasi-static analysis method predicts relatively higher platform offsets. The mooring dynamic effects on the tendon loads appear to be insignificant.
- Mooring dynamics affect the platform yaw motions.
- For both the Spar and the Semi-submersible FOWTs, the mooring dynamic effects on the tower loads and the turbine component loads appear to be insignificant.
- For the TLP FOWT, due to the absence of mooring-induced damping, the quasi-static analysis method predicts the higher platform heel and yaw motions and the larger tower and turbine component loads, especially when the turbine is in the parked condition.

Table 3.38 Load Cases – Quasi-static Analysis

FOWT	*Site*	*Design Condition*	*DLC*	*Wind and wave directionality*	*Yaw Control*	*Safety Factor*
Spar Semisubmersible TLP	OR GOM GOM	1) Power production	1.3	Collinear	Yaw misalignment $\phi=0^0$	Normal
		6) Parked (standing still or idling)	6.1	Collinear	Yaw misalignment $\phi=8^0$	Normal

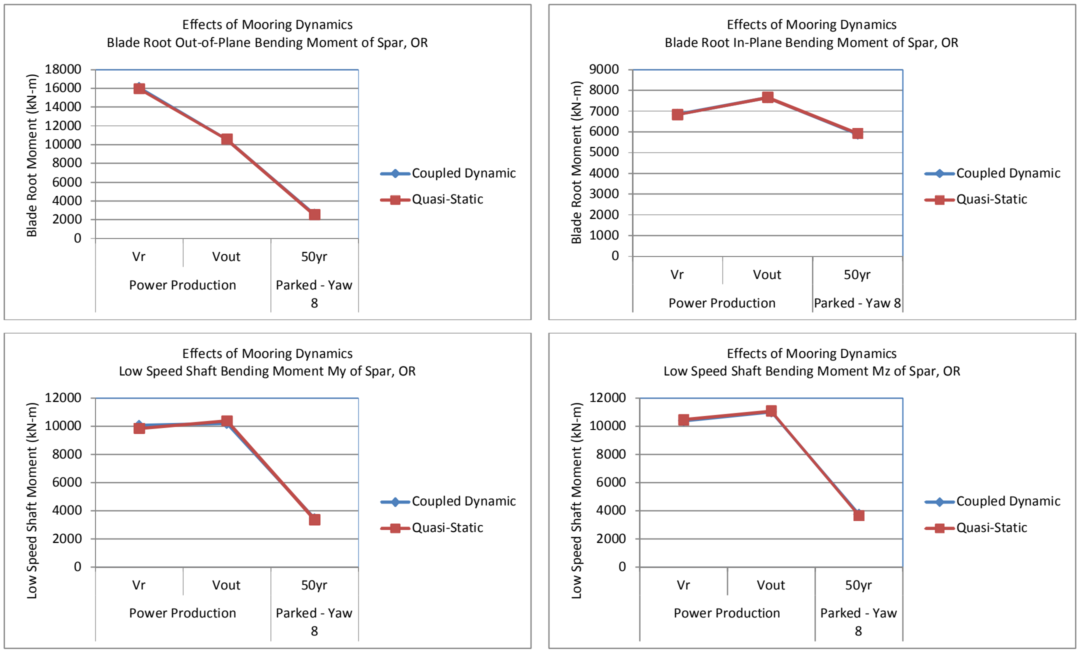


Figure 3.66 Effects of Mooring Dynamics – Spar FOWT in OR; RNA Responses for DLC 1.3 & 6.1

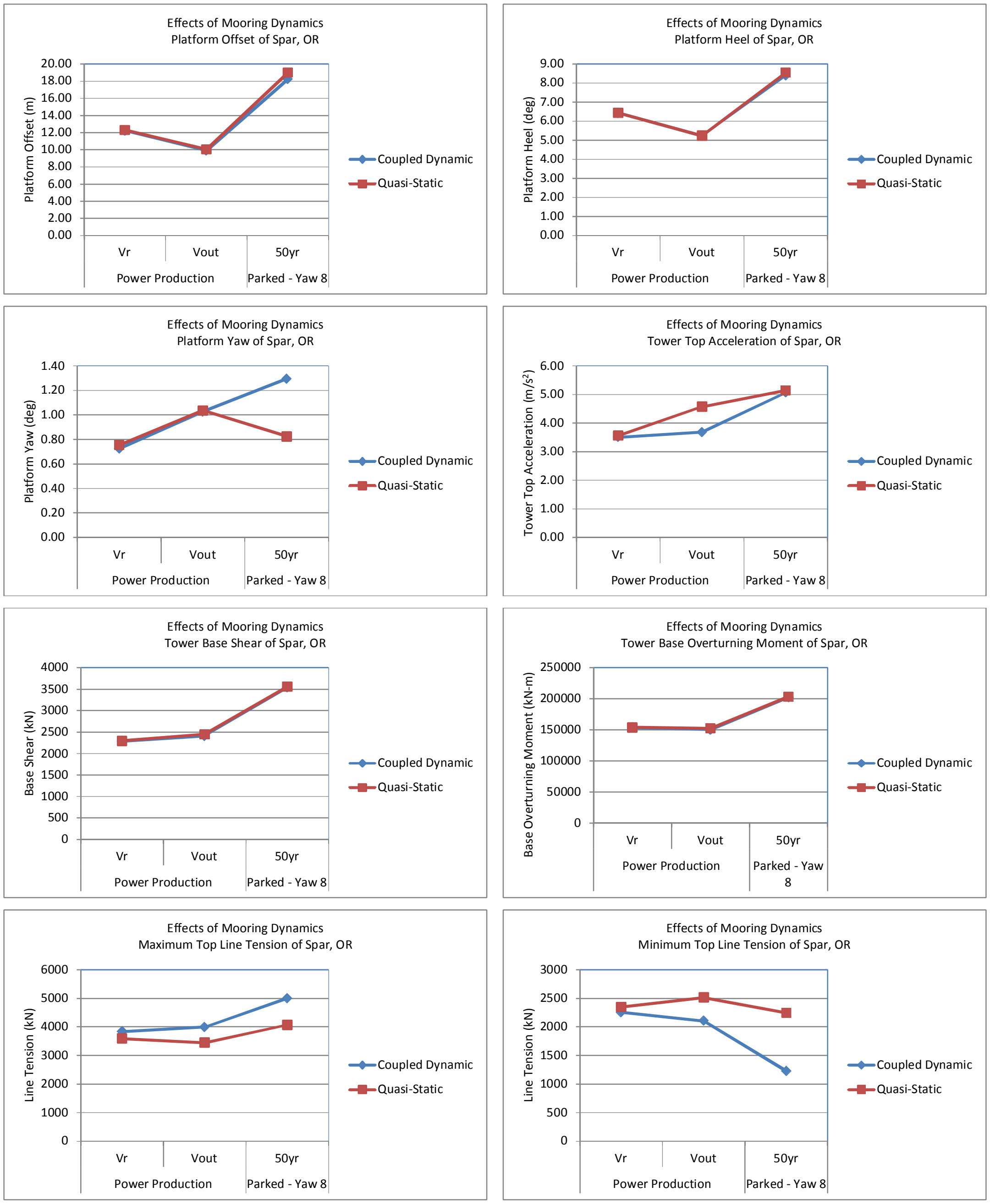


Figure 3.67 Effects of Mooring Dynamics – Spar FOWT in OR; Support Structure and Mooring Responses for DLC 1.3 & 6.1

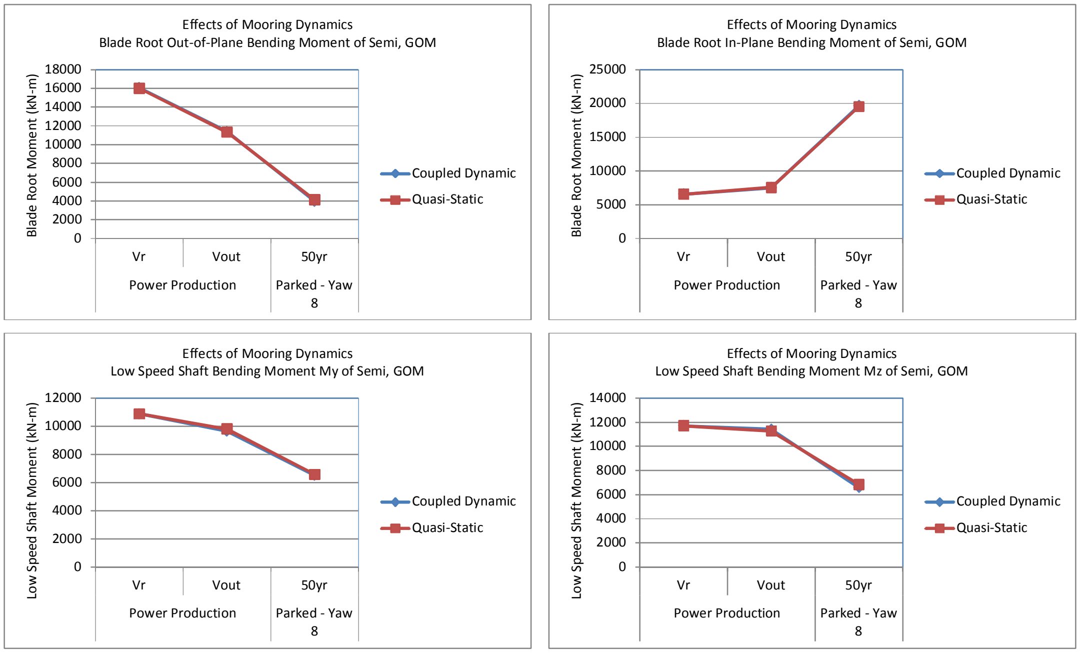


Figure 3.68 Effects of Mooring Dynamics – Semi-submersible FOWT in GOM; RNA Responses for DLC 1.3 & 6.1

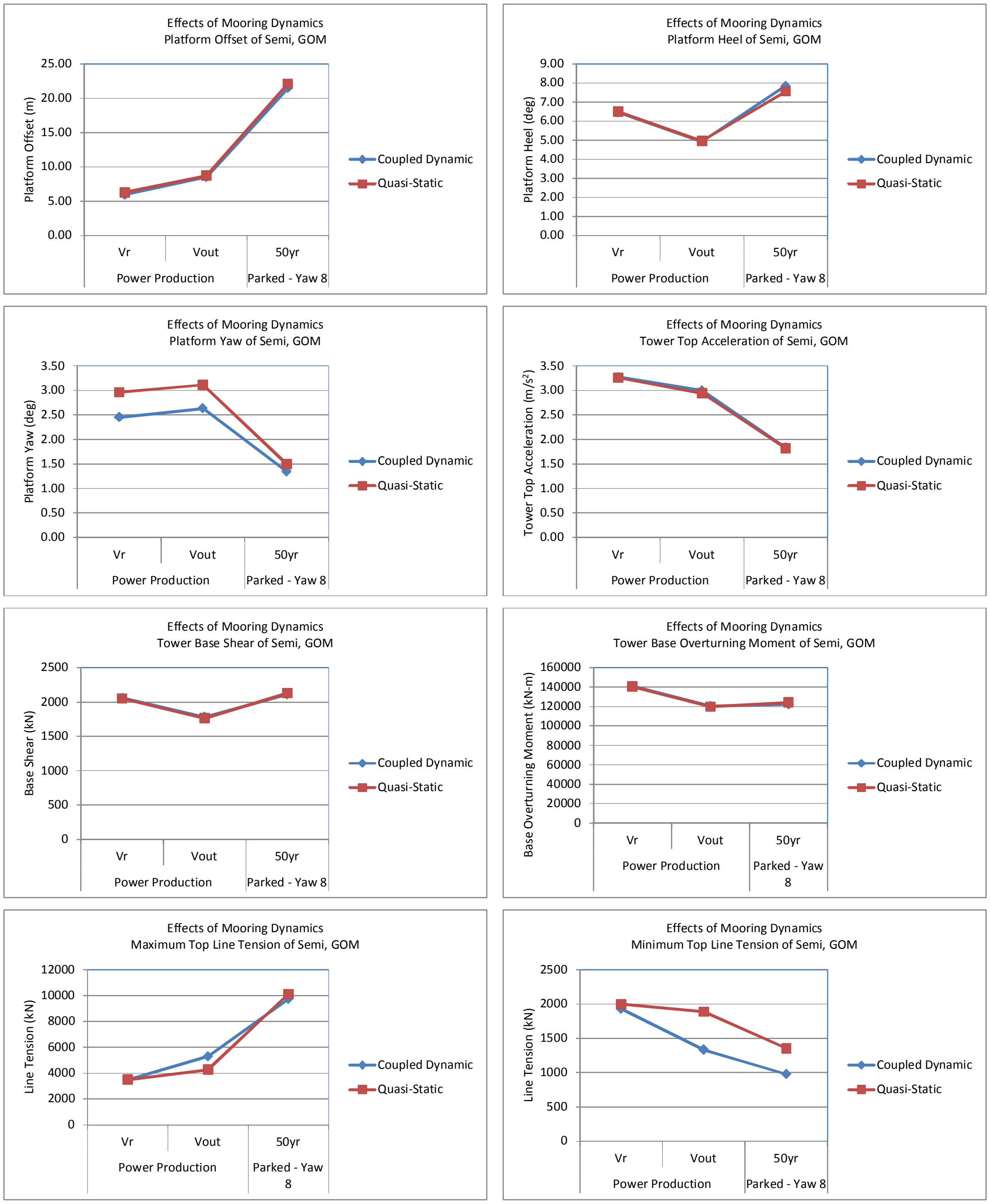


Figure 3.69 Effects of Mooring Dynamics – Semi-submersible FOWT in GOM; Support Structure and Mooring Responses for DLC 1.3 & 6.1

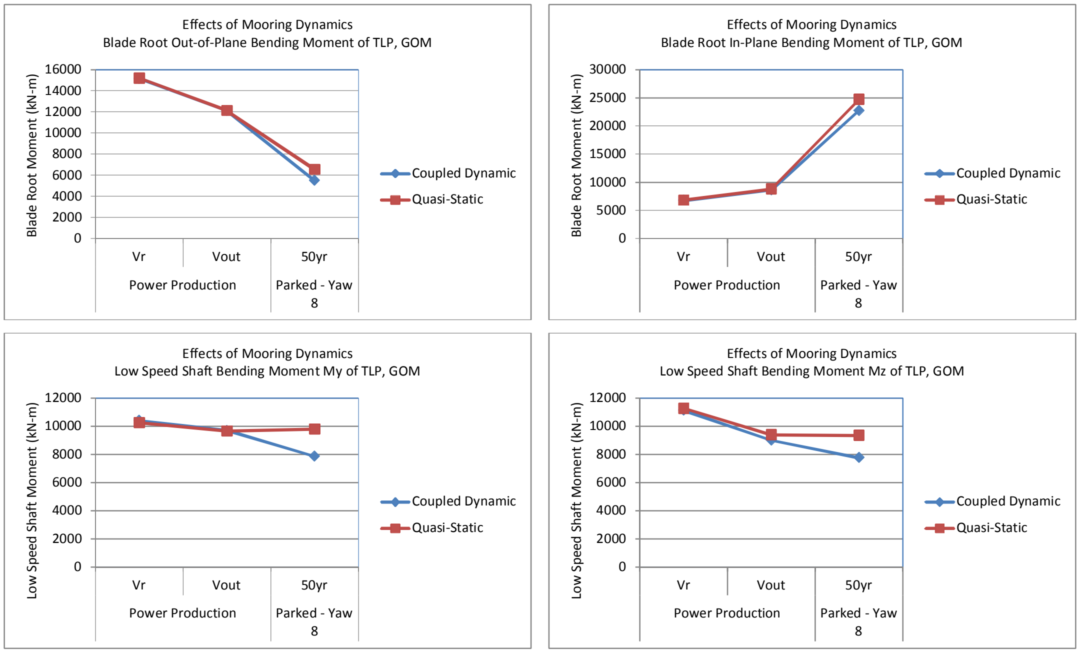


Figure 3.70 Effects of Mooring Dynamics – TLP FOWT in GOM; RNA Responses for DLC 1.3 & 6.1

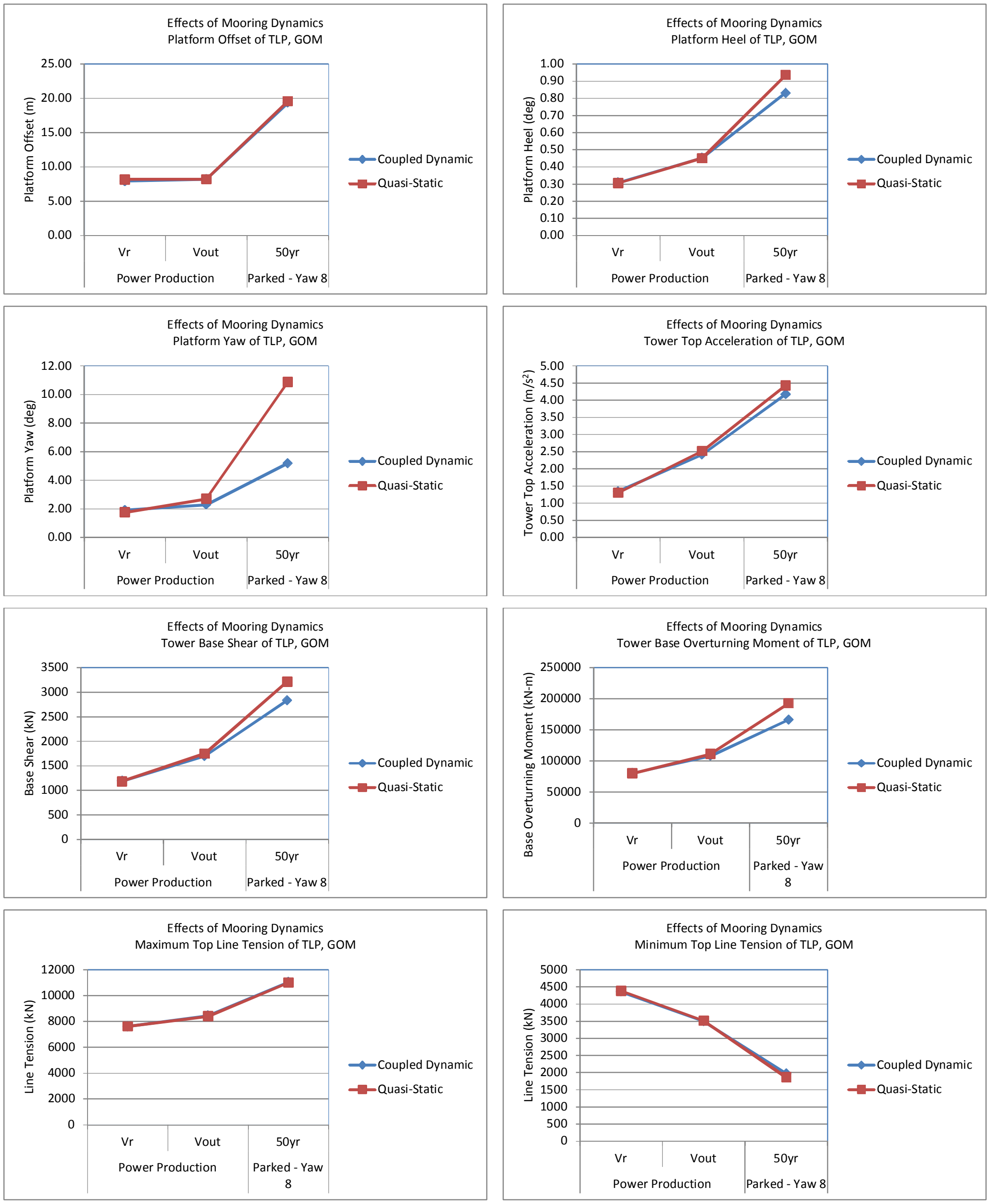


Figure 3.71 Effects of Mooring Dynamics – TLP FOWT in GOM; Support Structure and Mooring Responses for DLC 1.3 & 6.1

4 Critical Design Parameters and Technical Challenges in the Design of FOWT stationkeeping systems

This section identifies important design parameters and technical challenges in the design of FOWT stationkeeping systems. The state-of-the-art review and the case studies presented in Section 2 and Section 3, as well as experience in designing stationkeeping systems for floating oil and gas offshore installations, provide the technical basis of this section.

4.1 Important Design Parameters

The design parameters that should be appropriately considered in the design of FOWT stationkeeping systems include:

i.) Configuration and properties of the floating support structure

- Type of hull structure
- Tower configuration and flexibility
- Dimensions and mass properties
- Motion characteristics

ii.) Configuration and properties of the wind turbine RNA

- Size (rated power)
- Rotor thrust forces or thrust coefficients
- Hub height operating wind speed range (cut-in wind speed, rated wind speed, and cut-out wind speed)
- Operational modes (power production, start-up, shut-down, parked) and operating procedures
- Safety and control system behaviors
- Natural frequencies and damping

iii.) Environmental conditions

- Wind
- Wave
- Current
- Water level

- Water depth
- Seafloor and soil conditions
- Other environmental conditions (ice, earthquakes, etc.)

iv.) Electrical network conditions that affect the RNA operations

v.) Configuration and properties of the stationkeeping system

- Type of mooring (or tendon) system
- Pattern and number of mooring lines
- Material of mooring line (or tendon) components, especially elasticity of the mooring line
- Pretension
- Mooring line length
- Type, size and holding capacity of anchor (or foundation of the tendon system)
- Interface between the hull and the stationkeeping system
- Material, configuration, properties, capacities and fatigue resistance as applicable, of other mooring components and equipment (such as windlass, winches, fairleads, in-line buoys, clamp weights, chain stoppers, etc.)

Design parameters of the stationkeeping system may also include construction, installation, operation, inspection, maintenance and repair methods and procedures, electrical power cable layout, offshore wind farm configuration, etc.

Among the design parameters listed above, some parameters deserve special attention mainly because of unique load and response characteristics of FOWTs. Based on the outcome of the literature review and case studies, the critical design parameters for FOWT stationkeeping systems are summarized as follows:

- Water depth - Water depths at the installation site of FOWTs may be relatively shallow and may affect hydrodynamic loads applied on the hull. Water depth will also affect the restoring forces of the mooring (or tendon) system. Anchoring in shallow water could be difficult and expensive.

- Wind, wave and current loads - These are the most important environmental loads that determine the mooring line loads and global motions. These loads are mainly dependent on the configuration of the floating support structure and the wind turbine RNA.
- Aerodynamic load and damping - Aerodynamic responses are the major contributor to wind loads especially when the wind turbine RNA is in the power production mode. Aerodynamic damping is a major damping source for tower loads, global motions, and mooring line loads. The calculation of aerodynamic loads should at least include the aero-elastic responses of the RNA and the tower.
- Wind, wave and current directionality and misalignment - Wind, wave and current directionality, including misalignment and multiple directions, could significantly affect FOWT global responses and mooring line loads.
- Direction-dependent dynamic responses of the stationkeeping system and the FOWT - The global performance of the stationkeeping system is highly dependent on the direction of environmental actions. Thus a full range of directions with enough intervals should be considered in the design analysis to capture the critical headings for global motions and mooring lines loads.
- Water levels - Both the lowest and the highest water levels should be considered for the design of the TLP-type FOWTs. Water levels will affect the minimum and maximum tendon tensions and the air gap.
- Soil conditions - Soil conditions will affect the selection of anchor type and size as well as the anchor holding capacity.
- Properties of the mooring (or tendon) system - In addition to the pattern and number of the mooring lines, elasticity of the mooring line, pretension and line length will affect the mooring system restoring forces and mooring line loads. The properties of the mooring (or tendon) system, especially the restoring forces, will affect the natural frequencies of the floating support structure.
- Mooring (or tendon) system yaw stiffness - Yaw stability and yaw motions are important design considerations for FOWTs. Mooring (or tendon) system should provide sufficient yaw stiffness for the FOWT.

- Fiber rope stiffness model of the mooring system using synthetic fiber ropes – Appropriate modeling of fiber rope stiffness is important for achieving correct global responses and mooring line loads.
- Tower flexibility - Tower bending flexibility could change the natural periods of the roll and pitch motions of the TLP-type FOWTs.
- Turbine control system behavior - Negative damping due to unfavorable interactions between the turbine control system and the hull motions should be avoided.
- Coupling effects - Coupling effects of floating support structure, wind turbine RNA and its control system, mooring (or tendon), and electrical power cables could be significant and should be appropriately modeled in the design analysis.
- Turbine operational modes - Load cases associated with the turbine in power production could be more important than the load cases considering a parked (idling) turbine subjected to extreme storm wind and wave conditions.
- Operational procedures of the turbine - Due to transient effects and, to some extent, the effect of operational procedures, the start-up and shut-down load cases could potentially prevail over the power production load cases.
- Electrical network conditions - Number and duration of grid loss will affect the number of start-up and shut-down of the wind turbine and duration of parked conditions and, therefore, affect the mooring (or tendon) system fatigue damage accumulation.
- Natural frequencies and damping of the wind turbine – The turbine RNA properties, in particular natural frequencies, will influence the selection of the configurations of the floating support structure and the stationkeeping system. On the other hand, the configuration of the floating support structure and stationkeeping system could affect the natural frequencies and damping of the wind turbine RNA installed on the FOWT.
- High frequency vibrations of the RNA and the tower - Higher frequency vibrations induced by vibration modes of the RNA and the tower may be transmitted into taut-line mooring systems and tension leg systems.
- Offshore wind farm conditions - Design of the stationkeeping system with a small foot-print in a space-constrained offshore wind farm could be challenging. The consequences of platform drift due to mooring line failure can be high.

- Wind farm wake effects - Global yawing moment exerted on the floating support structure due to unbalanced rotor aerodynamic loads caused by the shade effect or the wake effect of neighboring FOWTs may be important for the stationkeeping system design. Other loads due to wake effects may also be important for the strength and fatigue designs of stationkeeping systems.

4.2 Technical Challenges

The existing knowledge of site-specific, permanent floating structures and stationkeeping systems is mostly developed by the offshore oil and gas industry. The major differences between FOWTs and oil and gas floating offshore structures reside in the following areas:

- Exposure level (for instance, manned vs. unmanned)
- Functional requirements
- The presence of the wind turbine and the tower
- Effect of electrical network conditions
- Offshore wind farm conditions, if applicable
- Construction, installation, operation, inspection, maintenance and repair procedures
- Economic considerations

FOWTs may well be designed with the following features due to economic considerations and functional requirements:

- Leaner designs
- Smaller water plane area to reduce wave loads
- Less or non-redundant stationkeeping system
- Small foot-print of the stationkeeping system in a space-constrained offshore wind farm
- Serial production and mass deployment in a wind farm

On the other hand, RNAs installed on top of floating foundations experience some unique loading conditions and operational requirements in contrast to those RNAs of land-based wind turbines and bottom-founded offshore wind turbines and should be suitably considered in the design.

- The effect of hull and tower motions on the RNAs needs to be considered. The turbine RNA installed on an FOWT may need to be designed to tolerate large deflections and accelerations which are typically not significant, or can be avoided by design changes, for land-based wind turbines or bottom-founded offshore wind turbines.
- Wind flow conditions surrounding the FOWT may be disturbed by large tower deflections and hull motions and, as a result, affect the aerodynamic load calculation. Current state-of-the-art simulation tools may not be capable of considering such complex flow conditions in the aerodynamic load calculations for FOWTs.
- Interactions of the control system of the wind turbine and motions of the floating support structures need to be considered. Control system of a load-based wind turbine or bottom-founded offshore wind turbine cannot be applied to FOWTs without modifications.
- Interactions of electrical power cables and motions of the floating support structures need to be considered.

In general, common practices of global performance analyses for oil and gas floating offshore structures, as summarized in API RP 2SK, API RP 2SM, ISO 19901-7, API RP 2T, and appropriate classification society criteria, can be adapted for the application to FOWTs, provided that the distinctive load and response characteristics of FOWTs are taken into account. Based on the results of the literature reviews and the case studies performed in the current project as well as the research of BSEE TAR Project 669 (Yu and Chen, 2012), the challenging technical issues that require special attentions in the design and global performance analyses of FOWT stationkeeping systems are identified and listed below:

- Governing design load cases for FOWT stationkeeping systems
- Aerodynamic loads and damping with consideration of aero-elastic coupling effects
- Coupling effects of floating support structure, wind turbine RNA and its control system, mooring (or tendon) systems, and electrical power cables
- Direction-dependent dynamic responses of the stationkeeping system and the floating support structure
- Influence of the stationkeeping system on the natural frequencies of a floating support structure

- Actions of turbine's safety and control systems
- Time scale difference between wind speeds (normally 10 minutes or 1 hour) and storm waves (normally 3 hours)
- Simulation time duration that is sufficient to capture statistics of responses
- Number of realizations (random seeds) that can achieve statistical convergence for FOWTs subjected to both turbulent wind and irregular wave loading
- Wind farm wake effects
- Mooring hardware, material, and connection to hull and anchorages.

A number of simulation programs that are capable of performing global performance analyses for FOWTs are currently available, although their modeling capabilities vary significantly (see Section 2.3). A common issue with all the existing simulation programs is the software validation. Significant efforts have been made by the offshore wind energy industry to perform "code-to-code" comparison campaigns, among which the most prominent study is organized through IEA Wind Task 30 (OC4). Further validation of the global performance analysis software against experimental test results or field measurements remains to be a challenging task, although increasing amount of model test data with various levels of details became available recently (see Section 2.5).

5 Design Guideline for Stationkeeping Systems of Floating Offshore Wind Turbines

5.1 Scope

Floating offshore wind turbine (FOWT) technology is rapidly evolving with innovative concepts for floating support structures and stationkeeping systems. This recommended design guideline is intended to provide guidance for the design of FOWT stationkeeping systems. It is developed on the basis of:

- the study carried out in this project, as reported in Section 2, 3 and 4;
- BSEE TA&R Project 669 final report;
- ABS Guide for Building and Classing Floating Offshore Wind Turbine Installations;
- industry experience with bottom-founded offshore wind turbines and, to a limited extent, FOWTs; and
- common practice of designing stationkeeping systems in the offshore oil and gas industry.

The stationkeeping system referred to in this design guideline comprises the mooring (or tendon) and anchoring systems. The stationkeeping system could be either a passively or an actively controlled system, or a combination of both. A passive stationkeeping system could be one of the following types:

- spread mooring (catenary, semi-taut-line and taut-line);
- catenary anchor leg mooring (CALM) consisting of a buoy and several catenary anchor legs;
- turret mooring;
- single anchor leg mooring (SALM), such as an articulated leg; and
- tension leg system.

An active system could be a mooring system with the ability of changing mooring line tensions or a system consisting actively controlled thrusters in the form of:

- dynamic positioning system; or
- thruster-assisted mooring.

An anchoring system could be one of the following types:

- drag anchor;

- vertically loaded anchor (VLA);
- pile anchor;
- suction anchor; and
- foundation system (for tendons).

A floating support structure could be one of a variety of hull types, such as:

- Spars;
- Column-Stabilized Platforms (Semi-submersibles);
- Tension Leg Platforms (TLPs); or
- Mono-hulls (ship-shaped structures or barges).

The type of wind turbine addressed in this guideline is the horizontal-axis wind turbine, whose rotor axis is substantially horizontal. For other types of wind turbines, such as vertical-axis wind turbines, the recommended design guideline should be used with caution. Due consideration should be given to potential changes in the characteristic dynamic interactions among the turbine, the floating support structure and the stationkeeping system. Such changes in expected dynamic interaction should be reflected in modifications to the design load cases.

The main contents of the design guideline are organized into the following seven subsections:

- Definitions (Section 5.2)
- Overall Design Considerations (Section 5.3)
- Environmental Conditions (Section 5.4)
- Design Load Conditions and Load Calculations (Section 5.5)
- Global Performance Analysis (Section 5.6)
- Strength and Fatigue Design Criteria of Mooring Lines and Tendons (Section 5.7)
- Stationkeeping System Hardware and Material Selection Criteria (Section 5.8).

5.2 Definitions

5.2.1 Types of Stationkeeping Systems

5.2.1.1 Spread moorings (catenary, taut-line and semi-taut-line)

Spread moorings are often used with Spars and Semi-submersibles, which are relatively insensitive to the directionality of metocean conditions. When the prevailing metocean conditions at a site come from one direction and floating structures can be oriented within a narrow range of heading, spread moorings may also be used with ship-shaped offshore structures whose responses could be greatly affected by the directionality of metocean conditions. Spread moorings may incorporate chain, wire rope, fiber rope, or a combination of the three. Drag anchors or anchor piles are typically used to terminate the mooring lines.

In addition to a catenary mooring, a spread mooring could take the form of a taut-line or a semi-taut-line mooring where the mooring lines are nearly straight between the anchor and the fairlead on the floating structure.

The main advantage of the spread mooring system is that it limits the orientation of the floating support structure, so that the wind direction relative to the rotor plane can be better controlled by the yaw control system of the wind turbine. On the other hand, a spread mooring system has a fairly large mooring spread (several times the water depth) that could complicate the layout of the offshore wind farm.

5.2.1.2 Single point moorings

Single point moorings, which allow the floating support structure to weathervane, may be used for ship-shaped or other types of floating support structures. They are more likely to be used with passive RNA yaw control systems, unless the effectiveness of the active systems is suitably addressed in the design. There is wide variety of single point mooring designs, but they all assume essentially the same function. A summary of typical single point mooring systems is given below.

5.2.1.2.1 Turret mooring

In this type of mooring system, catenary, taut or semi-taut mooring lines are attached to a turret, which is typically a part of the floating structure to be moored. The turret includes bearings to allow the floating structure to rotate (yaw) independently of the mooring system.

The turret can be mounted either inside the hull or externally from the floating structure's bow or stern. The chain table can be above or below the waterline.

5.2.1.2.2 Catenary anchor leg mooring (CALM)

A CALM system consists of a large buoy that supports a number of catenary mooring legs anchored to the sea floor. A hawser, typically a synthetic rope, may be used to connect the floating support structure to the buoy. Alternatively, rigid structural yokes with articulations may be used to tie the floating support structure to the top of the buoy. These rigid yoke articulations virtually eliminate horizontal motions between the buoy and the floating support structure. A number of variations of this basic arrangement have been proposed.

5.2.1.2.3 Single anchor leg mooring (SALM)

A SALM system employs a vertical articulated leg pre-tensioned by a floating support structure. The buoyancy acting on the top of the articulated leg tends to restore the articulated leg to a vertical position (inverted pendulum effect). The articulated leg is connected to the sea floor through a universal joint (U-joint).

Alternatively, a SALM system may use a vertical chain mooring leg that is pre-tensioned by a buoy. A floating support structure can be moored to the top of this buoy with a hawser or a rigid arm. The base of the chain is usually attached through a U-joint to a piled or deadweight concrete or a steel structure on the sea floor. In deeper water, the chain mooring leg may be replaced by tubular components.

5.2.1.3 Tendon system

A tendon system provides a vertical mooring system to the floating support structure by linking the hull to the foundation system.

Each tendon consists of a top section for attaching the tendon to the hull-mounted tendon porches, a tendon main body, and a bottom termination assembly for attaching the tendon to the foundation system. The tendon main body is commonly made up of steel tubulars. Any other form of tendons such as solid rods, bars or wire ropes and any other materials such as non-metallic materials and composites that meet the service requirements may also be specially considered.

The tendon main body may consist of a number of tendon components that are connected together to form one continuous tendon. Tendon connections could be mechanical couplings, welded joints or other forms of structural connection that meet the service requirements. The tendons may also have ancillary components such as corrosion protection system components, tendon load and performance monitoring devices and vortex-induced-vibration (VIV) suppression devices.

The term “tendon”, as used in this guideline, refers to the main body of the tendon system between the hull-mounted porch and the foundation system.

5.2.1.4 Dynamic positioning (DP) systems

A DP system automatically maintains the position of a floating support structure within a specified tolerance by controlling onboard thrusters to generate thrust vectors to counter wind, wave and current actions. DP systems have not yet been used in conceptual or existing FOWT designs, but could be an option in the future for the FOWT stationkeeping.

The DP systems referred to in this guideline are meant for the FOWT stationkeeping without moorings.

5.2.1.5 Thruster-assisted moorings

Floating support structures could be designed to operate with moorings assisted by thrusters and thruster control systems. The thrusters are used to control the structure's heading and reduce mooring loads under severe environmental conditions.

5.2.2 Terms and Definitions

5.2.2.1 Added Mass

Effective addition to system mass, which is proportional to the mass of displaced water

5.2.2.2 Air Gap

Clearance between the highest water surface that occurs during the extreme environmental conditions and the lowest exposed structures not designed to withstand wave impingement

5.2.2.3 Catenary Mooring

Mooring system where the restoring action is provided by the distributed weight of mooring lines

5.2.2.4 *Classification Society*

A company or organization with recognized and relevant competence and experience with floating structures, and with established rules and procedures for classification/certification of installations used in petroleum, natural gas or wind energy activities, located at a specific site for an extended period of time

5.2.2.5 *Cut-In Wind Speed (V_{in})*

The lowest 10-minute mean wind speed at Hub Height at which the wind turbine starts to produce power in the case of steady wind without turbulence

5.2.2.6 *Cut-Out Wind Speed (V_{out})*

The highest 10-minute mean wind speed at Hub Height at which the wind turbine is designed to produce power in the case of steady wind without turbulence

5.2.2.7 *Design Life*

Assumed period for which a structure, device, equipment or system is to be used for its intended purpose with anticipated maintenance, but without substantial repair being necessary

5.2.2.8 *Dip and Thrash Zone*

A chain or wire rope section above and close to the seafloor that may touch the seabed due to the motions of the Floating Support Structure

5.2.2.9 *Dynamic Positioning (DP)*

Stationkeeping technique primarily using a system of automatically controlled on-board thrusters to generate appropriate thrust vectors to counter the environmental actions and maintain an intended position within prescribed tolerances

5.2.2.10 *Emergency Shutdown*

Rapid shutdown of the wind turbine triggered by a protection function or by manual intervention

5.2.2.11 *Fabricator*

Any person or organization having the responsibility to perform any or all of the following: fabrication, assembly, erection, inspection, testing, load-out, transportation and installation

5.2.2.12 Floating Offshore Wind Turbine (FOWT)

Wind Turbine consisting of the Rotor-Nacelle Assembly (RNA), the Floating Support Structure and the Stationkeeping System

5.2.2.13 Floating Support Structure

The Floating Support Structure of offshore wind turbine is a site dependent offshore structure supported by buoyancy and maintained on location by its Stationkeeping System. The Floating Support Structure consists of the Tower and the Hull structure.

5.2.2.14 Foundation System (for Tendons)

Structural, mechanical and geotechnical components which are located on and beneath the sea floor and transfer the loads acting on the TLP Tendons into the sea bed

5.2.2.15 Gust

Brief rise and fall in wind speed lasting less than 1 minute

5.2.2.16 Hull

Combination of connected buoyant structural components such as columns, pontoons and intermediate structural braces; see also *Monohull*

5.2.2.17 Hub Height

Height of the center of the swept area of the wind turbine rotor above the Mean Sea Level

5.2.2.18 Idling

Condition of a wind turbine that is rotating slowly and not producing power

5.2.2.19 Load

External load applied to the structure (direct load) or an imposed deformation or acceleration (indirect load)

5.2.2.20 Load Effect

Effect of a single load or combination of loads on a structural component or system, e.g. internal force, stress, strain, motion etc.

5.2.2.21 Mean Sea Level or Mean Still Water Level (MSL)

Average level of the sea over a period long enough to remove variations due to waves, tides and storm surges [see also Fig. 5.1 in Section 5.4.7.4]

5.2.2.22 Mean Wind Speed

Statistical mean value of the instantaneous wind speed over a specified time interval

5.2.2.23 Maintenance

Set of activities performed during the operating life of a structure, device, equipment or system to ensure it is fit-for-purpose

5.2.2.24 Minimum Breaking Strength (MBS)

Certified strength of a chain, wire rope, fiber rope or accessories

5.2.2.25 Monohull

Floating structure consisting of a single, continuous, buoyant hull, and geometrically similar to an ocean-going ship or barge

5.2.2.26 Mooring Components

General class of components used in the Stationkeeping System

5.2.2.27 Normal Shutdown

Wind turbine shutdown operation in which all stages are under the control of the control system

5.2.2.28 Offshore Wind Farm

A group of wind turbines installed at an offshore site. An Offshore Wind Farm may also include the other installations such as transformer/converter platforms, meteorological measurement facilities, electrical cables, accommodation units, etc.

5.2.2.29 Omni-directional (Wind, Waves or Currents)

Acting in all directions

5.2.2.30 Owner

An owner is any person or organization who owns an offshore wind farm

5.2.2.31 Parked

Condition of a wind turbine that is either in the Standstill or Idling condition, depending on the design of the wind turbine

5.2.2.32 Pretension

Tension applied to a mooring line or tendon when the Floating Support Structure at its static equilibrium position in mean still water and still air

5.2.2.33 Rated Power

Quantity of power assigned, generally by a manufacturer, for a specified operating condition of a component, device, or equipment. For wind turbines, it is the maximum continuous electrical power output which a wind turbine is designed to achieve under normal operating and external conditions.

5.2.2.34 Rated Wind Speed (V_r)

Minimum 10-minute mean wind speed at Hub Height at which a wind turbine's Rated Power is achieved in the case of steady wind without turbulence

5.2.2.35 Return Period (Recurrence Period)

A return period is the average time duration between occurrences of an event or of a particular value being exceeded. A return period in years is equal to the reciprocal of the annual probability of exceedance of an event or of a particular value of a random parameter such as wind speed, wave height or sea elevation.

5.2.2.36 Rotor-Nacelle Assembly (RNA)

The Rotor-Nacelle Assembly (RNA) of a horizontal axis wind turbine, carried by the Floating Support Structure, consists of: *i*) The Rotor components, including blades, hub, shaft, and spinner; and *ii)* The Nacelle, a housing which contains the mainframe, generator frame, drive train components, electrical generator components, wind turbine control and protection components and other elements on top of the Tower.

5.2.2.37 Ringing

High frequency vertical vibration of the TLP spring-mass system excited by impulsive loading

5.2.2.38 Semi-submersible

Floating structure normally consisting of a deck structure connected to submerged pontoons through a number of widely spaced, large cross-section supporting columns

5.2.2.39 Serviceability

Ability of a structure, device, equipment or system to perform adequately for normal functional use

5.2.2.40 Set-down

Increase in the draft of a floating structure (for example, TLP) with the increase in the offset due to mooring or tendon system restraint

5.2.2.41 Single Point Mooring

Mooring system that allows the floating structure to which it is connected to vary its heading (weathervane)

5.2.2.42 Spar

Deep-draught, small water-plane area floating structure

5.2.2.43 Splash Zone

Part of the mooring lines or tendons of the Stationkeeping System above and below the Mean Sea Level and regularly subjected to wetting due to wave actions, motions of the Floating Support Structure and, if applicable, tide and draft variations. Areas which are only wetted during major storms are not included.

5.2.2.44 Spread Mooring

Mooring system consisting of multiple mooring lines terminated at different locations on a floating structure and extending outwards, providing an almost constant heading to the Floating Support Structure

5.2.2.45 Springing

High frequency vertical vibration of the TLP spring-mass system excited by cyclic loading at or near the TLP pitch or heave resonant periods

5.2.2.46 Standstill

Condition of a wind turbine that is not rotating

5.2.2.47 Stationkeeping System

System capable of: limiting the excursions of the Floating Support Structure within prescribed limits, maintaining the intended orientation, and helping to limit motions at the Tower top

5.2.2.48 Still Water Levels (SWL)

Abstract water levels used for the calculation of wave kinematics and wave crest elevation. See Fig. 5.1 in 5.4.7.4. Still Water Levels, which can be either above or below the Mean Sea Level, are calculated by adding to and subtracting from the effect of tide and surge on the Mean Sea Level.

5.2.2.49 Tendon

A system of components, which form a link between the Hull structure and the Foundation System for the purpose of restraining motion of the TLP-type Floating Support Structure within specified limits in response to environmental and other loading

5.2.2.50 Tendon Connector

Device used to connect a tendon to the TLP Hull (top connector) or to the foundation template (bottom connector)

5.2.2.51 Tension Leg

A collective group of tendons associated with one column of the platform

5.2.2.52 Tower

The structural component or assembly that connects the Hull Structure to the Rotor-Nacelle Assembly

5.2.2.53 Turbulence Intensity

Ratio of the wind speed standard deviation to the mean wind speed, determined from the same set of measured data samples of wind speed, and taken over a specified period of time

5.2.2.54 Taut-line Mooring

Mooring system where the restoring action is provided by elastic deformation of mooring lines

5.2.2.55 Thruster-assisted Mooring

Stationkeeping system consisting of mooring lines and thrusters

5.2.2.56 Tropical Cyclone (Hurricane, Typhoon)

A tropical storm with sustained wind speeds in excess of 33 m/s (64 knots or 74 mph). Such a storm is called a hurricane, typhoon, or cyclone based on the storm location. For example, tropical cyclones are typically referred to as hurricanes in the Gulf of Mexico and North Atlantic, while in the South China Sea and Northwest Pacific they are called typhoons. In the South Pacific and South Indian Ocean, however, they are commonly referred to as cyclones.

5.2.2.57 Uni-directional (Wind, Waves or Currents)

Acting in a single directions

5.2.2.58 Un-manned

An FOWT is considered un-manned when: *i)* visits to the FOWT are undertaken for specific planned inspection, maintenance or modification operations on the FOWT itself; *ii)* visits are not expected to last more than 24 hours during seasons when severe weather can be expected to occur; and *iii)* appropriate evacuation meanings are provided during visits.

5.2.2.59 Verification

Examination made to confirm that an activity, product, or service is in accordance with specified requirements

5.2.2.60 Water Depth

Vertical distance between the sea floor and the Still Water Level

5.2.2.61 Wind Profile (Wind Shear Law)

Mathematical expression for assumed wind speed variation with height above the Still Water Level

5.2.2.62 Weathervaning

Process by which a floating support structure passively varies its heading in response to time-varying environmental actions

5.2.2.63 Yawing

Rotation of the rotor axis about a vertical axis for horizontal axis wind turbines

5.2.2.64 Yaw Misalignment

Horizontal deviation of the wind turbine rotor axis from the wind direction

5.3 Overall Design Considerations

5.3.1 General

The stationkeeping system for a floating support structure can be either passive or active or a combination of both. Passive stationkeeping systems include single point mooring, spread mooring and tendon systems. Active systems include thrusters-based dynamic positioning systems or mooring systems with the ability of changing mooring line tensions. Typically passive stationkeeping systems are the most commonly used.

In general, an FOWT stationkeeping system should be designed to

- maintain the position of the FOWT within a specified limit from its reference position;
- control the directional heading of the FOWT if the orientation is important for safety or operational considerations; and
- assist in maintaining the acceleration and the tilting angle at tower top within a specified limit.

The design of the stationkeeping system should consider all conditions relevant to pre-service operations during installation and commissioning, in-service conditions including operations, maintenance and repair operations.

Section 5.3 provides general guidance on subjects that are considered important to the design of FOWT stationkeeping systems. Additional design criteria are given in Section 5.4 through Section 5.8.

5.3.2 Safety Level

The Floating support structures of an un-manned FOWT are typically designed to have a minimum safety level equivalent to the medium (L2) exposure level as defined in ISO 19904-1 for un-manned, medium consequence floating offshore structures used in the oil and gas industry. The safety level of FOWT stationkeeping systems should be equal to or higher than that of the floating support structure to which it is connected.

For an offshore wind farm having multiple FOWTs located in a close proximity, failure of an individual stationkeeping system could potentially cause extensive damage to many other structures and electrical cables in the offshore wind farm. A risk analysis may be used to establish an appropriate safety level of the stationkeeping system.

5.3.3 Design Life

The design life of FOWT stationkeeping systems should in general be at least 20 years. A shorter design life may be acceptable for an FOWT installed for the purpose of testing new design concepts or conducting pilot operations.

5.3.4 Environmental Conditions

The stationkeeping system should be designed to withstand specified operational and environmental conditions at the site while the RNA is under various operating conditions. Design environmental criteria for stationkeeping systems can be found in Section 5.4.

The stationkeeping system should also be designed for all pre-service operations. The environmental conditions for pre-service operations can be found in Section 5.4.3.

Additionally, survival environmental conditions should be specified for verifying the robustness of the stationkeeping system. Survival environmental conditions are those that produce responses having a very low probability of being exceeded during the design life and that the stationkeeping system can endure such responses without losing their intended functions and structural integrity. Survival environmental criteria for the FOWT stationkeeping systems can be found in Section 5.4.3.2.

5.3.5 Design Load Conditions and Load Calculations

Design Load Cases (DLCs) should be evaluated to verify the design adequacy of the stationkeeping system as part of the FOWT subjected to the combination of turbine operational conditions, site-specific environmental conditions, electrical network conditions and other applicable design conditions, such as specific transportation, assembly, maintenance or repair conditions.

Because the failure of an individual stationkeeping system could result in severe damage to the offshore wind farm, the adequacy of stationkeeping capacity should be verified by the robustness check, in which the FOWT is subjected to survival environmental conditions that are more severe than extreme design environmental conditions. The robustness check provides a direct indicator of the survivability of a specific design.

The recommended DLCs and Survival Load Cases (SLCs) for the stationkeeing system design are defined in Section 5.5.2.2 and Section 5.5.2.3.

Both loads directly applied on the stationkeeping system and the loads due to the motions of the FOWT subjected to wind, waves, currents, water level variations and other site conditions should be taken into account. Combinations of these loads as well as the turbine operating conditions that produce the most unfavorable local and global effects on the stationkeeping systems, as determined from the pre-service and in-service operations, should be applied.

5.3.6 Global Performance Analyses

Global performance analyses of the FOWT are used to determine the global effects of environmental loads and other loads on the main FOWT subsystems including the turbine RNA, the floating support structure, the stationkeeping system and the subsea electrical cable. Global response analyses should be performed for each of the critical design conditions during pre-service and in-service phases.

Global performance analyses for all the design load cases and survival load cases are required. It is recommended that the integrated (also known as "coupled") simulation models including the influential FOWT subsystems be used in global performance analyses. For those global loads and responses that are deemed as having weak coupling effects, global performance analyses may also be performed using a non-integrated model.

Either frequency-domain or time-domain methods, or a combination of both, may be used in global performance analyses. However, for those cases that have transient or highly nonlinear effects, time-domain analyses are normally required. Methods and models employed in analyses should account for the relevant nonlinear and dynamic coupling effects of FOWT subsystems.

Section 5.6 outlines specific requirements for FOWT global performance analyses.

5.3.7 Mooring Components and Hardware

A mooring system consists of a number of components such as chain, wire rope, fiber rope, connecting hardware, clump weight, buoy, winch, fairlead and anchor.

In general, mooring hardware used for floating oil and gas platforms can also be used in FOWT stationkeeping systems. However, some mooring hardware, such as chain jack, may not need to be permanent onboard equipment if no mooring adjustment is required during the design life of the FOWT.

Design guidelines for mooring components and hardware can be found in Section 5.7 and Section 5.8.

5.3.8 Method of Analysis

Dynamic analyses are required for the final design of a FOWT stationkeeping system. The strength and fatigue assessments of FOWT stationkeeping systems should be based on the dynamic analysis results.

5.3.9 FOWT Offset and Orientation

Offset and orientation limits of an FOWT should be established either by the Owner of the FOWT or by clearance requirements and limitations of equipment such as cables and the RNA. The layout of the offshore wind farm should be considered when determining the maximum allowable offset or orientation limits.

5.3.10 Tower Top Motion

The tower top motion limits should be established by the Owner with consideration of design requirements of the tower and the RNA.

The stationkeeping system of FOWT should be designed to comply with the prescribed tower top motion limits.

5.3.11 Air Gap and Wave Impact Loads

A minimum air gap requirement should satisfy Section 5.6.4. Where topside deck structural members, equipment support structures, tower transition piece and turbine tower are designed for passage of waves or if wave impact on these structures is anticipated, the wave impact loads should be appropriately considered in the stationkeeping system design.

5.3.12 FOWT Stability

The stationkeeping system should not impose detrimental effects on the static and dynamic floating stability of the FOWT.

An FOWT stationkeeping system should be designed to be able to provide sufficient yaw stiffness to mitigate the floating support structure yaw motions. Effects of the RNA yaw control on the floating support structure yaw motions should be taken into consideration in the stationkeeping system design.

For the TLP-type floating support structure in in-service conditions, the floating stability is provided by the pretension and stiffness of the tendons rather than the righting moments of the hull. Reference can be made to the ABS *FOWTI Guide* (2013) for the floating stability requirement of the TLP-type FOWTs and the associated design requirements for the tendon systems.

5.3.13 Mooring Line Length

If drag anchors are used, the outboard mooring line length should in general be sufficient to prevent anchor uplift under conditions as specified in Section 5.7. This requirement is especially important for anchors in sand and hard soil where anchor penetration may be shallow. Predicted uplift of a drag anchor may be permitted if it can be demonstrated that the anchor will have sufficient vertical load resistance for the soil condition under consideration. Guidelines for the use of drag anchor to resist vertical loads are provided in Section 5.8.3.2.

Shorter line lengths can be used for moorings with other anchoring systems such as pile anchors, suction anchors, or vertically loaded anchors that can resist substantial vertical loads.

For the fiber rope mooring systems, bottom and top chain/wire length should be sufficient for handling and to avoid marine growth and contact with the seabed.

5.3.14 Wear and Corrosion

Protection against chain corrosion and wear is normally provided by increasing chain diameters. Current industry practice is to increase the chain diameter by 0.2 mm to 0.4 mm per service year in the splash zone and in the dip or thrash zone on the hard seabed; a diameter increase of 0.1 mm to 0.2 mm per service year is typically applied to other areas of the chain.

In the strength analysis, the chain diameter for determination of required Minimum Breaking Strength (MBS) should not include corrosion and wear margins. In the fatigue analysis, the chain diameters associated with various service periods within the design life can be established if the corrosion rate can be predicted. The chain diameter for a given service period is the nominal diameter minus the expected corrosion and wear at the end of that period. It should be noted that the corrosion rate depends on the type of steel and sea water environment and is often much higher in the first few years of service. If the corrosion rate is uncertain, a conservative approach using the chain diameter excluding corrosion and wear margins should be considered in the fatigue analysis.

Corrosions of wire rope at connections to sockets could be excessive due to the galvanized wire acting as an anode for adjacent components. For permanent systems, it is recommended that either the wire be electrically isolated from the socket or the socket be isolated from the adjacent component. Additional corrosion protection can be achieved by adding sacrificial anodes to this area.

For the steel tendon system, a corrosion protection and control system should be used. Guidance on design of corrosion protection and control system for steel tendon system can be found in API RP 2T (2010).

5.3.15 Clearances

Clearances between a floating support structure or its mooring components and other offshore installations (e.g. platforms, pipelines, etc.) should be determined by the Owner when laying out the offshore wind farm configuration and verified by design analyses. Requirements of clearances specified in API RP 2SK (2008) should be satisfied.

5.3.16 Installation

The deployment of an FOWT mooring often requires the assistance of installation vessels such as a derrick barge or a specialized work boat. A portion of the mooring is often preset. As appropriate, special design features may be incorporated in the mooring design to facilitate deployment.

5.3.17 Inspection and Maintenance

Retrieving a permanent mooring for inspection may be expensive. As an alternative, and where conditions of access and visibility exist, suitably qualified divers or Remotely Operated Vehicles (ROVs) are often employed to perform the on-site inspection of a permanent mooring system.

5.3.18 Operating Manual

The operating manual for the stationkeeping system should be developed to specify the operating procedures and conditions that are consistent with the design information, criteria and limitations considered in the design of the stationkeeping system.

5.4 Environmental Conditions

5.4.1 General

The stationkeeping system should be designed to withstand all in-service operational and extreme environmental conditions at the site while the RNA is under various operating conditions.

Additionally, environmental conditions should be specified for verifying survivability of the FOWT stationkeeping system. Survival environmental conditions are those that produce responses having a very low probability of being exceeded during the design life and that the stationkeeping system can endure such responses without loss of their intended functions and structural integrity.

The stationkeeping system should also to be designed for all pre-service operations such as installation and commissioning.

The environmental conditions that influence pre-service and in-service operations of a stationkeeping system should be described in terms of relevant characteristic parameters. Statistical data and realistic statistical and mathematical models which represent the range of expected variations of environmental conditions should be used. Probabilistic methods for short-term, long-term and extreme value prediction should employ statistical distributions that are appropriate to the environmental phenomena under consideration, as evidenced by relevant statistical tests, confidence limits and other measures of statistical significance. Directional data and angular separation for wind, waves and current should be established. Hindcast methods and models should be fully documented if they are used to derive the environmental data.

5.4.2 Environmental Parameters

In general, the design of a stationkeeping system requires investigations of the following environmental parameters.

- Winds
- Waves
- Currents
- Tides, storm surges, and water level variations
- Seafloor and soil conditions

- Marine growth
- Air and sea temperatures
- Air density
- Seismicity
- Ice and snow accumulation
- Sea ice or lake ice

Other phenomena, such as tsunamis, submarine slides, seiche, abnormal composition of air and water, air humidity, salinity, ice drift, icebergs, ice scouring, etc., may also require investigations, depending upon the conditions of a specific installation site.

References should be made to IEC 61400-3 (2009) and ISO 19901-1 (2005) for requirements and recommended practices on the assessment of environmental conditions. API Bulletin 2INT-MET (2007) and API RP 2A-WSD (2007) provide guidance for offshore sites on the US OCS.

5.4.3 Environmental Criteria

The following three categories of environmental criteria should be considered when evaluating stationkeeping system strength and fatigue:

- Design environmental conditions
- Survival environmental conditions
- Fatigue environmental conditions

Environmental data, such as those for wind, wave, current and tide, having site-specific relationships governing their interactions should be considered in the assessment of site conditions. Of particular importance are the wind and wave, wave height and wave period, and wave and current relationships and their relative directions. The directions of various environmental phenomena are especially important for single point moorings.

Environment criteria should be determined considering appropriate metocean statistics and operational limits of the wind turbine. It is possible that some offshore areas are governed by special weather events such as squalls that may not be well represented by typical return period statistics. Such special weather events should be suitably considered in determining the environmental criteria.

For pre-service operations such as installation and commissioning, the environmental criteria defined in Section 5.5.2.2 Table 5.1 for the design load cases associated with the temporary conditions (DLC 8.1 and 8.2) should be considered in the stationkeeping system design.

The stationkeeping system should be assessed under the most unfavorable combinations of wind, wave and current directions that can be reasonably assumed to occur. The ability of the floating support structure to change its heading in response to changing environmental conditions may be considered.

5.4.3.1 Design Environmental Conditions

5.4.3.1.1 Operational Environmental Conditions

The operational environmental conditions are defined as the combinations of wind, wave, current and water level in which the wind turbine can assume specified operating modes such as start-up, power production and shut down. As a minimum, the combinations of the environmental conditions defined in Section 5.5.2.2 Table 5.1 for the design load cases associated with various turbine operating modes (DLC 1.3, 1.4, 1.5, 1.6, 2.1, 2.2, 2.3, 3.2, 3.3, 4.2, 4.3 and 5.1) should be considered in the stationkeeping system design.

5.4.3.1.2 Extreme Environmental Conditions

The extreme environmental conditions are defined as such that the parked wind turbine is subjected to various combinations of wind, wave, current and water level with specified return periods. The extreme environmental conditions associated with the design load cases DLC 6.1, 6.2, 6.3 and 7.1 as specified in Section 5.5.2.2 Table 5.1 are formed by combining:

- Extreme wind condition – EWM (Section 5.4.4.8)
- Extreme wave condition – ESS (Section 5.4.5.3)
- Extreme current condition – ECM (Section 5.4.6.3)
- Extreme water level range - EWLR (Section 5.4.7.3)

Since combining all individual extremes at the same return period is normally a conservative approach, the probability of joint occurrence of these environmental parameters should be taken into account when establishing extreme environmental conditions.

In the DLC 6.1, 6.2 where a minimum return period of 50 years is required, all environmental events with an annual joint exceedance possibility of 0.02 should theoretically be evaluated. In practice, as recommended in API Bulletin 2INT-MET (2007) as a minimum, the peak wind, the peak wave and the peak current conditions are normally assessed, which leads to the following three sets of 50-year return design environmental criteria:

- 50-year return wave with associated wind and current;
- 50-year return wind with associated wave and current; and
- 50-year return current with associated wave and wind.

The most severe directional combination of wind, wave and current should be specified for the FOWT being considered, consistent with the site's environmental conditions. Special attention should be given to certain floating support structures such as large ship-shaped structures, which are dominated by low frequency motions. Since low frequency motions increase with decreasing wave periods, the 50-year waves may not yield most severe mooring loads. Lower waves with shorter periods could instead cause larger low frequency motions and thus higher mooring loads.

If the design life of the mooring is substantially shorter than 20 years, a shorter recurrence interval may be justified. In this case, the recurrence interval should be determined by risk analyses taking into account the consequence of mooring failure.

When a different return period is used, for instance, in DLC 6.3 and 7.1 as specified in Section 5.5.2.2 Table 5.1, the extreme environmental conditions should be defined using the joint occurrence of relevant environmental parameters in a similar fashion to those with a 50-year return period.

For FOWTs with tendon systems or taut-line moorings, EWLR should be considered to evaluate the effect of water levels variations. For catenary or semi-taut moorings, on the other hand, the MSL may be applied.

5.4.3.2 Survival Environmental Conditions

The survival environmental conditions are defined as the combinations of wind, wave, current and water level for which the stationkeeping system is required to maintain its stationkeeping capability within specified limits. For the purpose of survival analysis, the wind turbine is considered in the parked conditions and the stationkeeping system is considered in the intact condition. The survival environmental conditions associated with the survival load cases specified in Section 5.5.2.3 are formed by combining:

- Survival wind condition – SurWM (Section 5.4.4.9)
- Survival wave condition – SurSS (Section 5.4.5.5)
- Survival current condition – SurCM (Section 5.4.6.4)
- Survival water level range - SurWLR (Section 5.4.7.4)

The probability of joint occurrence of these environmental parameters can be taken into account when establishing extreme metocean conditions, with the consideration of the peak wind, the peak wave and the peak current condition (see e.g. API Bulletin 2INT-MET, 2007). Combining all individual extremes at the same return period together is normally a conservative approach.

The survival load cases, as specified in Section 5.5.2.3, consider environmental events with a return period of 500 years. As a minimum, the peak wind, the peak wave and the peak current conditions should be assessed. This leads to the following three sets of 500-year return design environmental criteria:

- 500-year return wave with associated wind and current;
- 500-year return wind with associated wave and current; and
- 500-year return current with associated wave and wind.

For FOWTs with tendon systems or taut-line moorings, SurWLR should be considered to evaluate the effect of water levels variations. For catenary or semi-taut moorings, the MSL may be applied.

The most severe directional combination of wind, wave and current should be specified for the FOWT being considered, consistent with the site's environmental conditions. Special attention should be given to certain floating support structures such as large ship-shaped structures, which are dominated by low frequency motions. Since low frequency motions increase with decreasing wave periods, the 500-year waves may not yield most severe mooring loads. Lower waves with shorter periods could instead cause larger low frequency motions and thus higher mooring loads.

5.4.3.3 Fatigue Environmental Condition

Fatigue environmental conditions are those metocean conditions that occur day-to-day and used in a fatigue life assessment. As a minimum the combinations of the environmental conditions defined in Section 5.5.2.2 Table 5.1 for different fatigue design load cases (DLC 1.2, 2.4, 3.1, 4.1, 6.4, 7.2 and 8.3) should be considered in the stationkeeping system design. The durations of different turbine operational conditions should be determined and taken into account in the combination of fatigue damage.

5.4.4 Winds

5.4.4.1 General

Statistical wind data should normally include information about frequency of occurrence and duration and direction of various wind speeds at the location where an FOWT will be installed. If on-site measurements are taken, the duration of individual measurements and the height above sea-level of measuring devices should be stated. A wind speed value is only meaningful when qualified by its elevation and time-averaging duration. In the absence of site data, published data and data from nearby land and sea stations may be used as appropriate.

5.4.4.2 Wind Speed and Turbulence

A wind condition is typically represented by a mean wind speed and a standard deviation of wind speed. The turbulence intensity, which measures the variation of wind speed relative to the mean wind speed, is defined as the ratio of the wind speed standard deviation to the mean wind speed (i.e. coefficient of variation of wind speed).

In this guideline, the mean wind speed, denoted as V_{hub}, at turbine hub height with 10-minute averaging time duration is used to define the turbulent wind conditions in the design load conditions in Section 5.5.

The turbulence of wind over a time duration of 10 minutes is generally considered stationary and can be modeled by power spectral density functions and coherence functions. The turbulence model should include the effects of varying wind speeds, shears and directions and allow rotational sampling through varying shears. The three vector components of turbulent wind velocity are defined as:

- Longitudinal – Along the direction of the mean wind speed
- Lateral – Horizontal and normal to the longitudinal direction
- Upward – Normal to both the longitudinal and lateral directions and pointing upward

5.4.4.3 Wind Profile

The mean wind speed profile (vertical wind shear) should, in general, be defined by the power law:

$$V(z) = V_{hub}(z/z_{hub})^{\alpha}$$

where

$V(z)$	=	wind profile of the 10-minute mean wind speed as a function of height, z, above the SWL, in m/s (ft/s)
V_{hub}	=	10-minute mean wind speed at turbine hub height, in m/s (ft/s)
α	=	power law exponent, values of which are given in Section 5.4.4.7 and 5.4.4.8
z	=	height above the SWL, in m (ft)
z_{hub}	=	hub height above the SWL, in m (ft)

For tropical cyclone wind conditions at open ocean sites, the mean wind speed profile may be represented by the logarithmic wind shear law specified in API RP 2A-WSD (2007). This logarithmic wind shear law is expressed using the 1-hour mean wind speed at 10 m (32.8 ft) above the SWL.

Other wind profile models may also be used, provided that they can be justified by site-specific data.

5.4.4.4 Wind Spectrum and Spatial Coherence

Site-specific spectral density of wind speed and spatial coherence should be determined based on measured wind data.

Unless site conditions indicate otherwise, the Mann uniform shear turbulence model or the Kaimal spectrum and the exponential coherence model, as recommended in Annex B of IEC 61400-1 (2005), should be applied.

For the site where tropical cyclones govern the extreme wind condition, the NPD wind spectrum (also known as Frøya model) should be applied in conjunction with the two-point coherence function and the logarithmic wind shear law, as recommended in API RP 2A-WSD (2007).

5.4.4.5 Long-Term and Extreme Value Predictions

Long-term and extreme value predictions for sustained and gust winds should be based on recognized techniques and clearly described in the design documentation. Preferably, the statistical data used for the long-term distributions of wind speed should be based on the same averaging time duration of wind speed as that used for the determination of loads.

5.4.4.6 Wind Conditions

A wind condition for the FOWT stationkeeping system design is represented by a constant mean flow and associated turbulences. Wind conditions referred to in this design guideline are further categorized into:

- the normal wind conditions, which occur more frequently than once per year;
- the extreme wind conditions representing extreme wind conditions with a given return period; and
- the survival wind conditions for rare wind conditions with a given return period.

These wind conditions are further defined in Sections 5.4.4.7 through 5.4.4.9. The environmental criteria of Section 5.4.3 and the load case descriptions in Section 5.5 indicate which wind condition should be applied.

5.4.4.7 Normal Wind Conditions

i.) Normal Wind Profile Model (NWP)

The NWP model (vertical wind shear) is defined by the power law specified in Section 5.4.4.3, where the power law exponent $\alpha = 0.14$.

ii.) Normal Turbulence Model (NTM)

The NTM is applied together with the NWP model as defined above. The standard deviation of turbulence of the normal turbulence model is defined as the 90% quantile in the probability distribution of wind speed standard deviation, conditioned upon a given 10-minute mean wind speed at hub height (V_{hub}). The value of the turbulence standard deviation should be determined using appropriate statistical techniques applied to measured and preferably de-trended data. Where the site assessment is not available, the recommended approach provided in Section 12.3 of IEC 61400-3 (2009) may be used to estimate the standard deviation where applicable.

5.4.4.8 Extreme Wind Conditions

The extreme wind conditions are represented by extreme wind shear events, peak wind speeds due to storms, and rapid changes in wind speed and direction.

i.) Extreme Wind Speed Model (EWM)

The EWM model is defined by an extreme turbulent wind with a specified return period.

When site data are not available, the wind profile and turbulence spectrum for the EWM model should be defined according to Section 5.4.4.3 and 5.4.4.4. If the wind profile is assumed to follow the power law, the power law exponent $\alpha = 0.11$ and the standard deviation of longitudinal turbulent wind speed of extreme wind condition is taken as $0.11 \times V_{hub}$.

The EWM model is applied in combination with the Extreme Sea State (ESS) defined in Section 5.4.5.3 and the Extreme Current Model (ECM) defined in Section 5.4.6.3, with due consideration of their joint occurrence probabilities as required in Section 5.5.2.2, *xiii.)* and Section 5.5.2.3.

ii.) Other Extreme Wind Models

A number of other extreme wind models, as defined in IEC 61400-1 (2005) and further adapted in IEC 61400-3 (2009) and the criteria issued by several classification societies such as the ABS *FOWTI Guide* (2013), should be considered in the FOWT stationkeeping system design. A summary of those extreme wind models are listed as follows:

- Extreme Operating Gust (EOG)
- Extreme Turbulence Model (ETM)
- Extreme Direction Change (EDC)
- Extreme Coherent Gust with Direction Change (ECD)
- Extreme Wind Shear (EWS)

5.4.4.9 Survival Wind Conditions

Survival wind conditions are described by the Survival Wind Speed Model (SurWM).

The SurWM model is similar to the EWM model defined in Section 5.4.4.8, but with a higher return period as specified in Section 5.5.

When site data are not available, the wind profile and turbulence spectrum for the SurWM model should be defined according to Section 5.4.4.3 and 5.4.4.4. If the wind profile is assumed to follow the power law, the power law exponent $\alpha = 0.11$ and the standard deviation of longitudinal turbulent wind speed of extreme wind condition is taken as $0.11 \times V_{hub}$.

5.4.5 Waves

5.4.5.1 General

Wave data should reflect conditions at the installation site. Statistical wave data from which design parameters are determined are normally to include the frequency of occurrence of various wave heights and associated wave periods and directions. Published data and previously established design criteria for particular areas may be used where they exist. Hindcast techniques that adequately account for shoaling and fetch limited effects on wave conditions at the site may be used to augment available data. Analytical wave spectra employed to describe available data should reflect the shape and width of the data, and should be appropriate to the general site conditions.

As applicable, wave data should be developed in order to determine the following:

- Dynamic response of the FOWT stationkeeping system
- Maximum responses of stationkeeping system components
- Fatigue
- Provision for air gap
- Impact on the local structure

All long-term and extreme-value predictions of wave criteria should be fully described and based on recognized techniques. Because the wave-induced global responses may be increased due to the change of wave period and direction, consideration should be given to waves of less than the maximum height but with different periods and/or directions. Waves that cause the most unfavorable effects on the overall structure may also differ from waves having the most severe effects on individual structural components. In addition to extreme waves, frequent waves of smaller heights should also be investigated to assess their effect on the fatigue and dynamic responses.

The wave conditions for designing FOWT stationkeeping systems are defined in Section 5.4.5.2 through 5.4.5.5. The environmental criteria of Section 5.4.3 and the load case descriptions in Section 5.5 are specified using various wave conditions as described below in this section. The return periods for the severe, extreme and survival wave conditions are given in Section 5.5.

5.4.5.2 Normal Sea State (NSS)

The NSS model is represented by a significant wave height, a peak spectral period, a wave spectrum and a wave direction. It should preferably be determined based on site-specific long-term joint probability distribution of metocean parameters conditioned upon a given 10-minute mean wind speed at hub height (V_{hub}).

The NSS model is used in Section 5.5 to define several DLCs for either strength analysis or fatigue analysis. For fatigue calculations, the number and resolution of the normal sea states considered should be determined in such a manner that the fatigue damage associated with the full long-term distribution of metocean parameters can be sufficiently accounted for.

For strength calculations, the normal sea state can be characterized by the expected value of significant wave height, $H_{s,NSS}$, conditioned upon a given value of V_{hub} (i.e., $H_{s,NSS}$ = E[H_s|V_{hub}]). A range of peak period, T_p, associated with each significant wave height should be determined for consideration in the load calculations. The resultant most unfavorable responses should be used in the design of FOWT stationkeeping systems.

5.4.5.3 Extreme Sea State (ESS)

The ESS model describes extreme wave conditions with a specified return period.

The extreme sea state is represented by a significant wave height, a peak spectral period, a wave spectrum and a wave direction. The values of significant wave height should be determined from on-site measurements, hindcast data, or both for the installation site. Ranges of peak spectral periods appropriate to site conditions should be determined for load calculations. The resultant most unfavorable responses should be used in the design of FOWT stationkeeping systems.

The ESS model is applied in combination with the Extreme Wind Model (EWM) defined in Section 5.4.4.8 and the Extreme Current Model (ECM) defined in Section 5.4.6.3 and Extreme Water Level (EWLR) defined in Section 5.4.7.3, with due consideration of their joint occurrence probabilities as required in Section 5.5.2.2, *xiii.)* and Section 5.5.2.3.

5.4.5.4 Severe Sea State (SSS)

The SSS model is applied in combination with the normal wind conditions as specified in Section 5.4.4.7 for the strength analysis of FOWT stationkeeping systems.

The severe sea state is represented by a significant wave height ($H_{s,SSS}$), a peak spectral period, a wave spectrum and a wave direction. It should be determined by extrapolating site-specific long term joint probability distribution of metocean parameters to the extent that the combination of $H_{s,SSS}$ and a given value of 10-minute mean wind speed, V_{hub}, at hub height has the same return period as that of the Extreme Sea State defined in Section 5.4.5.3. A series of V_{hub} should be selected within the range of mean wind speed corresponding to the power production. As a conservative estimation, the significant wave height independent of wind speed may be used to approximate $H_{s,SSS}$.

A range of peak period associated with each significant wave height should be determined for load calculations. The resultant most unfavorable responses should be used in the design of FOWT stationkeeping systems

5.4.5.5 Survival Sea State (SurSS)

Survival Sea States are defined in a similar manner as the Extreme Sea State (ESS) in Section 5.4.5.3, but with a higher return period as specified in Section 5.5.

5.4.5.6 Breaking Waves

Where breaking waves are likely to occur at the installation site, the loads exerted by those breaking waves and their effects on the stationkeeping system, if deemed necessary, should be assessed in the design. Breaking wave criteria should be appropriate to the installation site and based on recognized methods. In shallow water the empirical limit of the wave height is approximately 0.78 times the local water depth. In deep water, a theoretical limit of wave steepness prior to breaking is 1/7. Guidance on breaking wave hydrodynamics can be found in IEC 61400-3, Annex C.

5.4.6 Currents

5.4.6.1 General

Data for currents should include information on current speed, direction and variation with depth. The extent of information needed should be commensurate with the expected severity of current conditions at the site in relation to other load causing phenomena, past experience in adjacent or analogous areas, and the type of structure and foundation to be installed. On-site data collection may be required for previously unstudied areas or areas expected to have unusual or severe conditions. Consideration should be given to the following types of current, as appropriate to the installation site:

- Wind-generated current
- Tide, density, circulation, and river-outflow generated sub-surface current
- Near shore, breaking wave induced surface currents running parallel to the coast

In the absence of site data, the speed of wind-generated surface current may be estimated as 2%–3% of the one-hour mean wind speed at 10 m (32.8 ft) above the SWL during tropical storms and hurricanes and 1% of the one-hour mean wind speed at 10 m (32.8 ft) above the SWL during winter storms or extra-tropical cyclones. The direction of wind generated surface current velocity may be assumed to be aligned with the wind direction.

Current velocity profiles with depth should be based on site-specific data or recognized empirical relationships. Unusual profiles due to bottom currents and stratified effects due to river out-flow currents should be accounted for. For the design of FOWTs in the U.S. offshore regions, the current profile may be determined in accordance with Sections 2.3.3 and 2.3.4 of API RP 2A-WSD (2007).

The current models for designing FOWT stationkeeping systems are specified in Sections 5.4.6.2 through 5.4.6.4. The environmental criteria of Section 5.4.3 and the load case descriptions in Section 5.5 indicate which current condition is applied in each DLC.

5.4.6.2 Normal Current Model (NCM)

For strength analyses, the NCM model should be defined to represent the site-specific wind-generated current conditioned upon a given 10-minute mean wind speed at hub height (i.e., V_{hub}). Tide and storm-generated sub-surface currents are not included.

For fatigue analyses, the NCM model should be determined in such a manner that the fatigue damage associated with the full long-term distribution of metocean parameters can be sufficiently accounted for.

The normal current model is applied in combination with the normal and severe sea states (NSS and SSS) defined in Section 5.4.5.2 and 5.4.5.4.

5.4.6.3 Extreme Current Model (ECM)

The ECM model is defined by site-specific currents with a given return period. The ECM model is applied in combination with the Extreme Wind Model (EWM) defined in Section 5.4.4.8, the Extreme Sea State (ESS) defined in Section 5.4.5.3 and Extreme Water Level (EWLR) defined in Section 5.4.7.3, with due consideration of their joint occurrence probabilities per Section 5.5.2.2, *xiii.)* and Section 5.5.2.3.

5.4.6.4 Survival Current Model (SurCM)

The Survival Current Model is defined in a similar manner as the Extreme Current Model (ECM), but with a higher return period per Section 5.5.

5.4.7 Tides, Storm Surges, and Water Levels

5.4.7.1 General

Tides can be classified as lunar or astronomical tides, wind tides, and pressure differential tides. The combination of the latter two is commonly called the storm surge. The water depth at any location consists of the mean depth, defined as the vertical distance between the sea floor and an appropriate near-surface datum, and a fluctuating component due to astronomical tides and storm surges. Astronomical tide variations are bounded by the highest astronomical tide (HAT) and the lowest astronomical tide (LAT). Storm surge is estimated from available statistics or by mathematical storm surge modeling. The still water level (SWL) in the air gap criterion should be taken as the highest still water level (HSWL), which is defined as the sum of the highest astronomical level and the positive storm surge. Definitions of various water levels referred to in this design guideline are illustrated in Figure 5.1.

The water level ranges for designing FOWT stationkeeping systems are given in Section 5.4.7.2 through Section 5.4.7.4. The load cases descriptions in Table 5.5 indicate which current condition is applied.

5.4.7.2 Normal Water Level Range (NWLR)

The normal water level range is defined as the variation in water level with a return period of one year. In the absence of site-specific long-term probability distribution of water levels, the normal water level range may be approximated by the variation between highest astronomical tide (HAT) and lowest astronomical tide (LAT).

Load calculations for the strength analysis should be performed based on the water level within the NWLR that results in the most unfavorable responses in the FOWT stationkeeping system. The influence of water level variation on fatigue loads should also be considered as appropriate.

5.4.7.3 Extreme Water Level Range (EWLR)

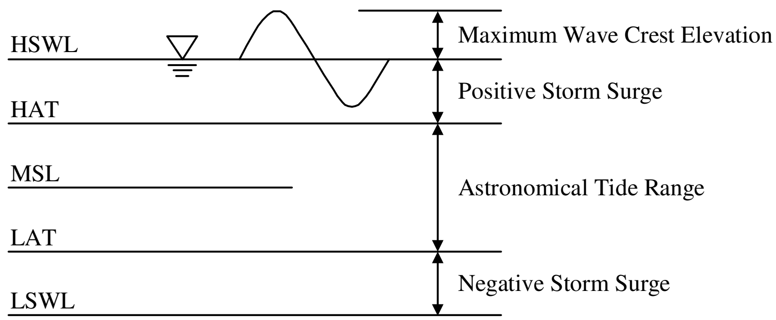
The extreme water level range for a particular return period is assumed for load cases associated with extreme waves (EWM). Load calculations for strength load cases should be performed based on the water level within the EWLR that results in the most unfavorable responses in the stationkeeping system.

In the absence of the long term joint probability distribution of metocean parameters including water level, the following water levels should be considered as a minimum:

- The Mean Sea Level (MSL)
- The highest still water level (HSWL), defined as a combination of highest astronomical tide (HAT) and positive storm surge, for a particular return period
- The lowest still water level (LSWL), defined as a combination of lowest astronomical tide (LAT) and negative storm surge, for a particular return period
- The water level associated with the highest breaking wave load, if relevant

5.4.7.4 Survival Water Level Range (SurWLR)

The Survival Water Level Range is defined in a similar manner as the Extreme Water Level Range (EWLR), but with a higher return period as specified in Section 5.5.



HSWL Highest Still Water Level

HAT Highest Astronomical Tide

MSL Mean Sea Level (Mean Still Water Level)

LAT Lowest Astronomical Tide

LSWL Lowest Still Water Level

Figure 5.1 Definitions of Water Levels

5.4.8 Water Depth

The design water depth for the stationkeeping system should account for sea level variations due to tides, storm surges, and seafloor subsidence, if applicable.

5.4.9 Seafloor and Soil Conditions

Site investigation should be performed and soil data should be taken in the vicinity of the tendon foundation or anchoring site. To establish the soil characteristics of the site, borings or probings should be taken at foundation or anchoring locations to a suitable depth of at least the anticipated depth of any piles or anchor penetrations plus a consideration for the soil variability. As an alternative, sub-bottom profile runs may be taken and correlated with at least two borings or probing in the vicinity of tendon foundation or anchoring locations and an interpretation may be made by a recognized geotechnical consultant to adequately establish the soil profile at all locations of interest. For the anchoring systems, the contours of the seafloor should be properly accounted for in the mooring analysis. A seabed hazard survey should also be performed.

General guidance on soil and sea floor condition assessment can be referred to:

- API RP 2GEO, Recommended Practice for Geotechnical and Foundation Design Considerations (2011);
- NAVFAC SP-2209-OCN, Handbook for Marine Geotechnical Engineering (2012)

5.4.9.1 Site Investigation for Spread and Single Point Mooring Anchoring Design

The areal extent of the foundation system of spread and single point mooring systems greatly exceeds that of fixed structures and TLPs. Requirements for site investigations should consider the type of anchors to be installed, the availability and quality of data from prior site surveys, and the potential consequences of a partial or complete foundation failure.

It is recommended that a high-quality, high-resolution geophysical survey be performed over the entire areal extent of the foundation. This survey should be subjected to a realistic geological interpretation and the results should be integrated with existing geotechnical data, if any, to assess constraints imposed on the design by geological features. Such an integrated study can then serve as a guide to develop the vertical and horizontal extent of the final geotechnical investigation (i.e. number, depth, and location of soil borings and/or in-situ tests) and to aid in the interpretation of the acquired geotechnical data. Previous site investigations and experience may allow a less extensive site investigation.

Further guidance on site investigation requirements and geotechnical design of drag, pile and plate anchors can be found in:

- API RP 2SK, Recommended Practice for Design and Analysis of Stationkeeping Systems for Floating Structures
- ISO 19901-7, Stationkeeping Systems for Floating Offshore Structures and Mobil Offshore Units
- Appropriate classification society criteria

5.4.9.2 Site Investigation for TLP Tendon Foundation Design

Detailed geological surveys, seafloor and sub-bottom geophysical surveys and geotechnical investigations should be carried out for TLP tendon foundation sites. Requirements for site investigations should be guided by the quality of data from prior site surveys and the potential consequence of foundation failure. For soil samples obtained from deep water sites, measured properties under laboratory conditions may be different from in-situ values due to relief of hydrostatic pore pressure and its associated effects on dissolved gases. Therefore, in-situ or special laboratory testing should be performed to determine soil properties for deep water sites. Since installation sites may be distant from areas for which site data are available, regional and local site studies may be required to adequately establish soil characteristics. A less extensive site investigation may be acceptable, provided that previous site investigation and experience are available.

TLP tendon foundations subjected to upward static and dynamic loadings are different from typical foundations of fixed jacket-type structures. In order to predict soil-structure interaction due to cyclic loading, soil tests should be carried out to define the both static and cyclic behavior of the soil. Additional tests should be carried out to determine the long-term soil-pile response due to the sustained and cyclic tensile loads that can result in tensile creep of the TLP tendon foundation. Consideration should also be given to the performance of permeability and consolidation tests to assist in the evaluation of the soil-pile setup.

Further guidance on soil investigation requirements and geotechnical design of TLP tendon foundations can be found in:

- API RP 2T, Recommended Practice for Planning, Designing, and Constructing Tension Leg Platforms
- API RP 2A-WSD, Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Structures – Working Stress Design

5.4.9.3 Site Investigation for Offshore Wind Farm Conditions

Site investigation should be in principle performed for each anchoring/foundation location in a wind farm per the requirements given in Section 5.4.9.1 and Section 5.4.9.2. A less extensive site investigation may be acceptable, provided that previous site investigations and experience are available or the type of foundation and the site conditions can justify a reduced scope of site investigation. As a minimum and an initial site investigation for an offshore wind farm, one cone penetration test (CPT) should be performed for each anchoring/foundation site of the FOWTs in the offshore wind farm. In addition, one boring to a sufficient penetration depth should be taken for each anchoring/foundation site of the FOWTs at each corner and in the middle of an offshore wind farm. Additional CPTs or borings may be required depending on the results of the initial site investigation.

5.4.10 Marine Growth

The design of the stationkeeping system should take into account the type and accumulation rate of marine growth at the site as they may affect mass, weight, hydrodynamic diameters, and drag coefficients of structural members and mooring lines. Estimates of the rate and extent of marine growth may be based on past experience and available field data. Particular attention should be paid to increases in hydrodynamic loading due to increased diameters and surface roughness of members caused by marine fouling as well as to the added weight and increased inertial mass of submerged structural members. The types of fouling likely to occur and their possible effects on corrosion protection coatings should be considered.

API RP 2A-WSD (2007) provides further guidance for considering marine growth in the design of offshore structures on the US OCS.

5.4.11 Other Conditions

5.4.11.1 Temperature

Extreme values of air, sea and seabed temperatures should be expressed in terms of return periods and associated highest and lowest values. Wind speed data are typically presented with respect to a specific reference temperature. Temperature data should also be used to evaluate the selection of air density, structural materials, ambient ranges and conditions for machinery and equipment design, and for determination of thermal stresses, if deemed relevant.

5.4.11.2 Air Density

The air density should be measured in conjunction with the wind conditions at the installation site. Where there are no site data for the air density, the value of air density should be determined according to ISO 2533 and corrected as appropriate for annual average temperature at the site.

5.4.11.3 Ice and Snow Accumulation

For offshore wind turbines intended to be installed in areas where ice and snow may accumulate, estimates should be made of the extent to which ice and snow may accumulate. Data should be derived from actual field measurements, laboratory data or data from analogous areas.

5.4.11.4 Seismicity and Earthquake Related Phenomena

The effects of earthquakes on the foundation of the tendon system of a TLP-type floating support structure located in areas known to be seismically active should be taken into account.

The magnitudes of the parameters characterizing the earthquakes with return periods appropriate to the design life of an FOWT should be determined. Two levels of earthquake conditions should be considered as described by API RP 2T (2010) to address the risk of damage and failure of tendon foundation, respectively:

- Strength Level Event (SLE): Ground motion which has a reasonable likelihood of not being exceeded at the site during the design life of an FOWT.
- Ductility Level Event (DLE): Ground motion for a rare, intense earthquake to be applied to evaluate the risk of failure of tendon foundation.

The anticipated seismicity of an area should, to the extent practicable, be established based on regional and site specific data such as:

- Magnitudes and recurrence intervals of seismic events
- Proximity to active faults
- Type of faulting
- Attenuation of ground motion between the faults and the site
- Subsurface soil conditions
- Records from past seismic events at the site where available, or from analogous sites

The seismic data should be used to establish the quantitative Strength Level and Ductility Level earthquake criteria describing the earthquake induced ground motion expected during the life of the FOWT. In addition to ground motion, and as applicable to the site in question, the following earthquake related phenomena should be taken into account.

- Liquefaction of subsurface soils submarine slides
- Tsunamis
- Acoustic overpressure shock waves

5.4.11.5 Sea Ice or Lake Ice

For an FOWT intended to be installed in areas where ice hazards may occur, the effects of sea ice or lake ice on the stationkeeping system should be taken into account in the design. Depending on the ice conditions at the site, the floating support structure and the stationkeeping system may encounter with moving ice and fast ice cover.

Statistical ice data at the site should be used as the basis for deriving the parameters such as ice thickness, ice crushing strength and pack ice concentration, etc., which are required for determining the ice loads.

Impact, both centric and eccentric, should be considered where moving ice may contact the floating support structure and the stationkeeping system. Impact of smaller ice masses, which are accelerated by storm waves, and of large masses (multi-year floes and icebergs) moving under the action of current, wind, and the Coriolis Effect should be considered in the design.

The interaction between ice and the FOWT produces responses in the ice, the floating support structure and the stationkeeping system, and this compliance should be taken into account as applicable.

Reference is made to API Bulletin 2N (1995) and ISO 19906 (2010) for ice conditions and the relevant design considerations.

5.5 Design Load Conditions and Load Calculations

5.5.1 General

This section addresses the design load conditions as well as loads and their calculations to be considered in the design of stationkeeping systems.

An FOWT is an integrated system consisting of the RNA, the turbine control system, the floating support structure, and the stationkeeping system. Loads on the stationkeeping systems are directly related to the load conditions for the floating support structure, to which the stationkeeping system is connected. In addition to the loads acting on the stationkeeping system directly, the motions and offsets of the floating support structure are the main contributors to stationkeeping system design.

5.5.2 Design Load Conditions

5.5.2.1 General

Design load conditions for FOWT stationkeeping systems should be represented by:

- Design Load Cases (DLCs), which are defined to verify the design adequacy of the stationkeeping system subjected to the combination of turbine operational conditions, site-specific environmental conditions, electrical network conditions and other applicable design conditions, such as specific transportation, assembly, maintenance or repair conditions.
- Survival Load Cases (SLCs), which are defined to verify the survivability of the stationkeeping system and the adequacy of air gap when the FOWT is subjected to the environmental conditions that are more severe than the extreme design environmental conditions.

The specifications of the load cases are given in the following Subsections.

5.5.2.2 Definition of Design Load Cases (DLCs)

Design Load Cases (DLCs) for FOWT stationkeeping systems should account for all relevant loading conditions with a reasonable probability of occurrence and covering the most significant conditions that an FOWT may experience.

As a minimum, the DLCs specified in Table 5.1 should be applied to the design of the stationkeeping system. The relevance of these DLCs is demonstrated by the case studies reported in Section 3 and further discussed in Section 4 in terms of critical design parameters. The final report of the BSEE TA&R 669 project (Yu and Chen, 2012) also explored the appropriateness of the proposed DLCs for both FOWT floating support structures and stationkeeping systems. Additional load cases should be considered, whenever they are deemed relevant to the integrity of the stationkeeping system. These additional load cases should include, but are not limited to, suitable considerations of the effect of the following:

- Global yawing moment exerted on the floating support structure due to unbalanced rotor aerodynamic loads caused by the shade effect or the wake effect of neighboring FOWTs and other adjacent structures,
- Vortex Induced Motion (VIM) of the floating support structure due to the site current conditions established in accordance with Section 5.4.6,
- Vortex Induced Vibration (VIV) fatigue due to the site current conditions established in accordance with Section 5.4.6, and
- Earthquake-induced effects on the design of the tendon system for the TLP-type FOWTs located in seismically active areas (see Section 5.4.11.4).

The descriptions and analysis requirements for the DLCs defined in Table 5.1, including the amendment of the original list of DLCs specified in IEC 61400-3 (2009), are adapted from the BSEE TA&R 669 final report (Yu and Chen, 2012) and the ABS *FOWTI Guide* and presented as follows. Further reference can be made to Section 7.4 and Section 7.5.4 of IEC 61400-3 (2009).

i.) The DLC serial numbers in Table 5.1 are generally in accordance with those specified in IEC 61400-3 (2009).

ii.) The DLCs defined in Table 5.1 are for the design of FOWT stationkeeping systems. As such, DLC 1.1 required by IEC 61400-3 (2009) for calculation of the ultimate loads acting on the RNA is not included in Table 5.1.

iii.) The DLCs associated with regular (deterministic) wave conditions as defined in IEC 61400-3 (2009) are not applicable to the design of the FOWT and therefore not included in Table 5.1. The indicators, ‘a’, ‘b’ and ‘c’, attached to the DLC serial numbers are also removed for the same reason.

iv.) As a new addition, DLC 4.3 is defined to address the normal shutdown process when the sea state exceeds the maximum operational limit. Depending upon the requirements of the operating manual, the emergency shutdown may need to be considered instead of the normal shutdown.

v.) The design environmental conditions referred in Table 5.1 for wind, wave, current, and water level range are in accordance with the definitions specified in Section 5.4 of this guideline. More detailed references are listed in the table notes.

vi.) Site-specific extreme wind speeds with various return periods are used to define the environmental conditions in DLC 6.1 to 6.4, DLC 7.1 and 7.2, and DLC 8.2 and 8.3 in Table 5.1. This differs from IEC 61400-3 (2009) where definitions of these DLCs are related to RNA's Reference Wind Speed (V_{ref}) and the conversion factors are prescribed for different return periods.

vii.) Currents are required to be considered in the fatigue design load cases.

viii.) The return period chosen for the extreme environmental conditions of DLC 6.1 and DLC 6.2 and for the severe wave conditions of DLC 1.6 should generally not be less than 50 years, unless appropriate justifications can be provided.

ix.) DLC 6.2 assumes a loss of connection to electrical power network at an early stage of the storm containing the extreme wind conditions. A nacelle yaw misalignment ranging between -180° and +180° is generally required to be considered in DLC 6.2. Load calculations should be based on the misalignment angle that results in the most unfavorable responses of the systems. The range of yaw misalignment may be reduced to account for the contribution from an active or passive yaw control system, provided that the designer can justify that

- such a system is capable of achieving the assumed reduction of yaw misalignment under site specific conditions; and
- an appropriate monitoring and maintenance program is implemented to maintain the effectiveness of yawing control during the design life of the FOWT.

x.) For those load cases, including DLC 6.1, 6.2, 6.3, 7.1 and 8.2, which in general require time-domain dynamic simulations for the combined extreme turbulent wind and stochastic storm waves, the simulation time duration may differ from the reference periods of wind speed and significant wave height. Two scaling factors, k_1 and k_2, are introduced in Table 5.1 for the 10-minute mean wind speed and the significant wave height of a storm wave respectively to take this time-scale difference into account.

IEC 61400-3 (2009), Section 7.4.6 recommends to use one hour as the simulation time duration. As a result, k_1 = 0.95 for the 10-minute mean wind speed and k_2 = 1.09 for the extreme significant wave height, assuming that the reference period of extreme wave condition is 3 hours; the wave heights follow the Rayleigh distribution; and the number of waves in 3 hours is approximately 1000. The turbulence standard deviation applied in the 1-hour simulation duration is increased by 0.2 m/s (0.66 ft/s) relative to the value associated with the 10-minute mean wind speed.

Depending upon the type of the floating support structure and the stationkeeping system of a specific design as well as site conditions, other simulation time durations may need to be used along with an appropriate adjustment to the wind model and/or wave model such that the extreme responses can be adequately estimated. Additional requirements of time-domain analyses are provided in Section 5.6.

xi.) Where a wind speed range is indicated in Table 5.1, wind speeds leading to the most unfavorable responses should be considered in the design. When the range of wind speeds is represented by a set of discrete values, the interval between two adjacent discrete wind speeds is not to be greater than 2 m/s (6.6 ft/s), In addition, the turbine Rated Wind Speed (V_r, see 5.2.2.34), where applicable, should be included as one of the discrete wind speeds used in the load calculation.

xii.) If site-specific directional data are not available, the direction of applied environmental conditions should be determined to produce the most unfavorable effect on the system. For DLC 6.1, 6.2, 6.3, 7.1 and 8.2, the misalignment between wind and wave directions should be considered up to 90° for extreme environmental conditions governed by tropical cyclones.

xiii.) Extreme metocean conditions in a specific load case (e.g. DLC 6.1, 6.2, 6.3, 7.1 and 8.2) are formed by combining the extreme wind (EWM), the extreme wave (ESS), the extreme current (ECM), and the extreme water level range (EWLR). The probability of joint occurrence of these environmental parameters should be taken into account when establishing extreme metocean conditions. Considerations should be given to the peak wind, peak wave and peak current condition (see e.g. API Bulletin 2INT-MET, 2007), as appropriate to site conditions and a specific design of the system. Combining all individual extremes with the same return period is normally a conservative approach.

xiv.) For those DLCs denoted by ‘S’ in the ‘Type of Analysis’ column in Table 5.1 for the structural strength design, the effect of environmental loads should be combined with the effect of other loads such as those due to gravity. Combinations of the load effects that produce the most severe local and global effects on the stationkeeping system should be used.

xv.) The description for DLC 8.x is revised to ‘Temporary (installation, maintenance and repair)’. For other ‘Temporary’ operations, the return period of design environmental conditions may be as specified by the Owner. The Owner is responsible for assuring that operational plans and environmental monitoring for these temporary phases are compatible with the environmental conditions used in the design.

Table 5.1 Design Load Cases

Turbine Condition	*DLC*	*Wind Condition*	*Waves*	*Wind and Wave Directionality*	*Sea Currents*	*Water Level*	*Other Conditions*	*Type of Analysis*
1) Power production	1.2	NTM $V_{in} \leq V_{hub} \leq V_{out}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	MIS, MUL	NCM	NWLR or $\geq$ MSL		F
	1.3	ETM $V_{in} \leq V_{hub} \leq V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL		S
	1.4	ECD $V_{hub} = V_r \pm 2$ m/s (6.6 ft/s)	NSS $H_s = E[H_s \vert V_{hub}]$	MIS, wind direction change	NCM	MSL		S
	1.5	EWS $V_{in} \leq V_{hub} \leq V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL		S
	1.6	NTM $V_{in} \leq V_{hub} \leq V_{out}$	SSS $H_s = H_{s,SSS}$	COD, UNI	NCM	NWLR		S
2) Power production plus occurrence of fault	2.1	NTM $V_{in} \leq V_{hub} \leq V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL	Control system fault or loss of electrical network	S
	2.2	NTM $V_{in} \leq V_{hub} \leq V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL	Protection system or preceding internal electrical fault	S
	2.3	EOG $V_{hub} = V_r \pm 2$ m/s (6.6 ft/s) and V_{out}	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL	External or internal electrical fault including loss of electrical network	S
	2.4	NTM $V_{in} \leq V_{hub} \leq V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	NWLR or $\geq$ MSL	Control, protection, or electrical system faults including loss of electrical network	F

Table 5.1 Design Load Cases (Continued)

Turbine Condition	*DLC*	*Wind Condition*	*Waves*	*Wind and Wave Directionality*	*Sea Currents*	*Water Level*	*Other Conditions*	*Type of Analysis*
3) Start-up	3.1	NTM $V_{in} \leq V_{hub} \leq V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	NWLR or $\geq$ MSL		F
	3.2	EOG $V_{hub} = V_{in}$, $V_r \pm 2$ m/s (6.6 ft/s) and V_{out}	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL		S
	3.3	EDC $V_{hub} = V_{in}$, $V_r \pm 2$ m/s (6.6 ft/s) and V_{out}	NSS $H_s = E[H_s \| V_{hub}]$	MIS, wind direction change	NCM	MSL		S
4) Normal shutdown	4.1	NTM $V_{in} \leq V_{hub} \leq V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	NWLR or $\geq$ MSL		F
	4.2	EOG $V_{hub} = V_r \pm 2$ m/s (6.6 ft/s) and V_{out}	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL		S
	4.3	NTM $V_{in} \leq V_{hub} \leq V_{out}$	SSS H_s = maximum operating limit	COD, UNI	NCM	NWLR	sea state exceeding the maximum operational limit	S
5) Emergency shutdown	5.1	NTM $V_{hub} = V_r \pm 2$ m/s (6.6 ft/s) and V_{out}	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL		S

Table 5.1 Design Load Cases (Continued)

Turbine Condition	*DLC*	*Wind Condition*	*Waves*	*Wind and Wave Directionality*	*Sea Currents*	*Water Level*	*Other Conditions*	*Type of Analysis*
6) Parked (standing still or idling)	6.1	EWM $V_{hub} = k_1 V_{10min,50\text{-}yr}$	ESS $H_s = k_2 H_{s,50\text{-}yr}$	MIS, MUL	ECM 50-yr Currents	EWLR 50-yr Water Level		S
	6.2	EWM $V_{hub} = k_1 V_{10min,50\text{-}yr}$	ESS $H_s = k_2 H_{s,50\text{-}yr}$	MIS, MUL	ECM 50-yr Currents	EWLR 50-yr Water Level	Loss of electrical network	S
	6.3	EWM $V_{hub} = k_1 V_{10min,1\text{-}yr}$	ESS $H_s = k_2 H_{s,1\text{-}yr}$	MIS, MUL	ECM 1-yr Current	NWLR	Extreme yaw misalignment	S
	6.4	NTM $V_{hub} \leq V_{10min,1\text{-}yr}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	MIS, MUL	NCM	NWLR or $\geq$ MSL		F
7) Parked and fault conditions	7.1	EWM $V_{hub} = k_1 V_{10min,\ 1\text{-}yr}$	ESS $H_s = k_2 H_{s,1\text{-}yr}$	MIS, MUL	ECM 1-yr Current	NWLR		S
	7.2	NTM $V_{hub} \leq V_{10min,1\text{-}yr}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	MIS, MUL	NCM	NWLR or $\geq$ MSL		F
8) Temporary (installation, maintenance and repair)	8.1	To be defined by the Fabricator or Owner						S
	8.2	EWM $V_{hub} = k_1 V_{10min,1\text{-}yr}$	ESS $H_s = k_2 H_{s,1\text{-}yr}$	COD, UNI	ECM 1-yr Current	NWLR		S
	8.3	NTM $V_{hub} \leq V_{10min,1\text{-}yr}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	MIS, MUL	NCM	NWLR or $\geq$ MSL	No grid during installation period	F

Table 5.1 Design Load Cases (Continued)

Notes:

1. The descriptions of the design load cases in the table are provided in Section 5.5.2.3.
2. The symbols and abbreviations used in the table are summarized as follows.

COD	co-directional (aligned) wind and wave direction
DLC	design load case
ECD	extreme coherent gust with direction change (5.4.4.8)
ECM	extreme current model (5.4.6.2)
EDC	extreme direction change (5.4.4.8)
EOG	extreme operating gust (5.4.4.8)
ESS	extreme sea state (5.4.5.3)
EWLR	extreme water level range (5.4.7.3)
EWM	extreme wind speed model (5.4.4.8)
EWS	extreme wind shear (5.4.4.8)
MIS	misaligned wind and wave directions
MSL	mean sea level (Figure 1)
MUL	multi-directional wind and wave
NCM	normal current model (5.4.6.2)
NTM	normal turbulence model (5.4.4.7)
NWLR	normal water level range (5.4.7.2)
NWP	normal wind profile model (5.4.4.7)
NSS	normal sea state (5.4.5.2)
SSS	severe sea state (5.4.5.4)
UNI	uni-directional wind and wave directions
F	fatigue (5.7.6 and 5.7.7)
S	strength (5.7.6 and 5.7.7)
H_s	significant wave height
$H_{s,1\text{-yr}}$	significant wave heights with a return period of 1 year
$H_{s,50\text{-yr}}$	significant wave heights with a return period of 50 years
k_1	simulation time scaling factors for 10-minute mean wind speed (5.5.2.3)
k_2	simulation time scaling factors for significant wave height (5.5.2.3)
T_p	peak period of wave spectrum
$V_{10\text{min},1\text{-yr}}$	10 minute average wind speed at hub height with a return period of 1 year
$V_{10\text{min},50\text{-yr}}$	10 minute average wind speed at hub height with a return period of 50 years
V_{hub}	10-minute mean wind speed at hub height
V_{in}	cut-in wind speed (5.2.2.1)
V_{out}	cut-out wind speed (5.2.2.6)
$V_r \pm 2$ m/s (6.6 ft/s)	sensitivity to the wind speeds in the range should be analyzed (5.5.2.3)

5.5.2.3 *Definition of Survival Load Cases (SLCs)*

The Survival Load Cases (SLCs) are used for the robustness check of the FOWT stationkeeping system and the air gap (also known as deck clearance or freeboard).

As a minimum, the SLCs specified in Table 5.2 adapted from the BSEE TA&R 669 final report (Yu and Chen, 2012) and the ABS *FOWTI Guide* should be assessed in the robustness check of FOWT stationkeeping systems. The probability of joint occurrence of environmental parameters should be taken into account when establishing survival metocean conditions, with the consideration of the peak wind, peak wave and peak current condition (see e.g. API Bulletin 2INT-MET). The effects of environmental loads should be combined with the effects of other relevant loads such as gravity. Combinations of the load effects that produce the most unfavorable responses of the stationkeeping system or the air gap should be used to assess the design adequacy.

For the TLP-type floating support structure, additional robustness checks of its stationkeeping system should include

i.) the assessment of the minimum tendon tension for the FOWT subjected to the SLCs defined in Table 5.2 and in accordance with API RP 2T (see Table 5.9);

ii.) the strength assessment of the ‘one-tendon removed’ case, if applicable, for the FOWT carrying the parked RNA and subjected to a 50-year return extreme environmental condition; and

iii.) the fatigue life assessment of the tendon system, in accordance with API RP 2T, for the FOWT carrying the parked RNA and subjected to a single extreme environmental event with a return period of 50 years.

Table 5.2 Survival Load Cases

Design Condition	*Wind Condition*	*Waves*	*Wind and Wave Directionality*	*Sea Currents*	*Water Level*
Parked RNA; Intact Blades; Intact Hull & Stationkeeping System	SurWM $V_{hub} = k_1 V_{10\text{min,n-yr}}$	SurSS $H_s = k_2 H_{s,\text{n-yr}}$	MIS, MUL	SurCM n-yr Currents	SurWLR n-yr Water Level
Parked RNA; Damaged Blade(s); Intact Hull & Stationkeeping System	SurWM $V_{hub} = k_1 V_{10\text{min,500-yr}}$	SurSS $H_s = k_2 H_{s,\text{500-yr}}$	MIS, MUL	SurCM 500-yr Currents	SurWLR 500-yr Water Level

Notes:

1. 'Parked RNA, Damaged Blade(s), Intact Hull & Stationkeeping System' case should be assessed if one turbine blade or multiple turbine blades cannot remain intact under the storm wind condition with a return period of 500 years (i.e. $n < 500$ years)
2. The symbols and abbreviations used in the table are summarized as follows

n-yr	maximum return period (n years) of the storm wind condition that turbine blades can sustain and remain intact or 500 years, whichever is less
$H_{s,\text{n-yr}}$	significant wave height with a return period of n years
$H_{s,\text{500-yr}}$	significant wave height with a return period of 500 years
$V_{10\text{min,n-yr}}$	10 minute mean wind speed at hub height with a return period of n years
$V_{10\text{min,500-yr}}$	10 minute mean wind speed at hub height with a return period of 500 years
SurWM	survival wind model (5.4.4.9)
SurSS	survival sea state (5.4.5.5)
SurCM	survival current model (5.4.6.4)
SurWLR	survival water level range (5.4.7.4)

Other symbols and abbreviations used in the table are defined in the Notes of Table 5.1.

5.5.3 Determination of Environmental Loads

5.5.3.1 General

Model or on-site test data may be employed to establish environmental loads. Alternatively, environmental loads may be determined using analytical methods compatible with the environmental condition models established in compliance with Section 5.4. Any recognized load calculation method may be employed provided it has proven sufficiently accurate in practice, and it is shown to be appropriate to the system's characteristics and site conditions.

5.5.3.2 Aerodynamic Loads on the RNA

Aerodynamic loads induced by airflow passing through the rotor are determined by the mean wind speed and turbulence across the rotor plane, rotor rotational speed, air density and aerodynamic shapes of wind turbine components as well as interactive effects such as aero-elasticity and rotational sampling. Aerodynamic loads due to these effects should be calculated using recognized methods and computer programs.

The 10-minute mean wind speed at hub height, i.e. V_{hub} as defined in Section 5.4.4.3, and the wind models defined in Section 5.4.4 are used in the definition of design load conditions in Section 5.5.2.

For FOWTs installed in a wind farm, the potential shadow effect and wake effect on the loads should be considered for both the strength and fatigue analyses. For large wind farms, an increase in the turbulence intensity or terrain roughness should be taken into account. The mutual influence of wind turbines through the wake interaction behind the rotor should be considered up to a distance of 10 times of rotor diameter. Reference can be made to IEC 61400-1 for guidance on the wake effects from neighboring wind turbines.

5.5.3.3 Environmental Loads on Mooring Lines

Mooring lines are typically modeled as slender cylindrical members. The environmental loads directly acting on mooring lines should be considered as follows:

i.) Current Induced Loads. Current loads could be particularly important for locations with high currents. Loads on mooring lines due to currents can be calculated as

$$F = 1/2 \rho_w C_d d v^2$$

where

F = force per unit length normal to the local mooring line, in N/m (lb/ft);

ρ_w = density of the seawater, in kg/m^3 (slug/ft^3);

C_d = drag coefficient, see appropriate classification society criteria;

d = nominal diameter of the mooring line, in m (ft);

v = component of current velocity normal to the local mooring line, in m/s (ft/s).

Where there are high currents, the drag coefficient should be adjusted for the presence of vortex-induced vibrations.

ii.) Ice-induced Loads. The effect of ice loads on the mooring system should be considered where applicable.

iii.) Vortex-induced vibrations of the mooring lines. For the smooth, cylindrical mooring lines, possible occurrences of vortex-induced vibration (VIV) and in particular its effect on the drag coefficients should be considered.

iv.) Direct wave loads on mooring lines may be neglected.

5.5.3.4 Environmental Loads on Floating Support Structures

Floating support structure offset and motions are the main source of indirect loads on FOWT stationkeeping systems. For the purpose of assessing their effects and relative influences on the stationkeeping system design, environmental loads and load effects of the floating support structures are categorized into following types according to their frequency range.

- Steady loads such as wind, current and wave drift forces that are constant in magnitude and direction for the duration of interest.
- Low-frequency cyclic loads (often referred to as slow drift) with characteristic periods between 1 min and 10 min. Low-frequency cyclic loads typically induce dynamic excitations of the floating support structures at their natural periods of surge, sway, yaw and, in the case of the Spar-type FOWTs, pitch and roll.
- Wave frequency cyclic loads with typical periods ranging from 3 to 30 seconds. Wave frequency cyclic loads result in wave frequency motions, which are normally independent of mooring stiffness. The approach of neglecting mooring stiffness in wave frequency motion calculations is considered relatively conservative. However for small floating structures such as buoys where the first order wave loads are not large, accounting for mooring stiffness can yield more realistic wave frequency motions. In addition, if the natural period of the FOWT is close to the wave periods, the wave frequency motions could be dependent on the mooring stiffness. In this case the effect of stiffness should be properly accounted for.
- High-frequency cyclic loads with characteristic periods between 1 to 5 seconds. High-frequency cyclic loads typically induce dynamic excitation of the TLP-type floating support structures at their natural periods of heave, roll and pitch.

- High frequency vibration excited by the tower and RNA dynamic loads with frequencies higher than 0.5 hz (periods lower than 2 seconds). Such high frequency loads may be transmitted to the TLP-type floating support structure and its tendon system.

Calculation of environmental loads on the floating offshore structure can be found in API RP2SK (2008), API RP 2T (2010), and ISO 19901-7 (2005), with general guidance given below.

5.5.3.4.1 Wind Loads

Wind loads and local wind pressures should be determined on the basis of analytical methods or wind tunnel tests on a representative model of an FOWT. Static and dynamic wind load effects generated directly by the inflowing wind and indirectly by the wind generated motions of the FOWT and the operations of the FOWT should be taken into account.

For wind drag loads normal to flat surfaces, such as nacelle and boat landing, or normal to the axis of members not having flat surfaces, such as the tower and the floating support structure, the wind loading can be considered either as a steady wind force or as a combination of steady and time-varying load calculated from a suitable wind spectrum. Where one structural member shields another from direct exposure to the wind, shielding may be taken into account. Generally, the two structural components should be separated by not more than seven times the width of the windward component for a reduction to be taken in the wind load on the leeward member.

Cyclic loads due to vortex induced vibrations of structural members should be investigated if applicable. Both drag and lift load components due to vortex induced vibrations should be taken into account. The effects of wind loading on structural members or components that are not normally exposed to wind loads after installation should be considered where applicable. This would especially apply to load-out or transportation phases.

5.5.3.4.2 Wave Loads

For structures consisting of slender members that do not significantly alter the incident wave field, semi-empirical formulations, such as Morison’s equation, may be used. For calculation of wave forces on structural configurations that significantly alter the incident wave field, appropriate methods which account for both the incident wave force (e.g., Froude-Krylov force) and the forces resulting from wave diffraction should be used. In general, Morison’s equation is applicable for structures comprising slender members with diameters (or equivalent diameters giving the same cross-sectional areas parallel to the flow) less than 20 percent of the wave lengths.

For the floating support structure consisting of large (columns and pontoons) and small (brace members) cylindrical members, a combination of diffraction and Morison's equation may be used for calculation of hydrodynamic characteristics and hydrodynamic loading. Alternatively, suitable model test results or full scale measurements can be used.

For installation sites where the ratio of water depth to wave length is less than 0.25, nonlinear effects of wave action should be taken into account. This may be fulfilled by modifying linear diffraction theory to account for nonlinear effects or by performing model tests. Wave force calculations should account for shallow water effects which increase current due to blockage effects, change the system natural frequency due to nonlinear behavior of moorings and alter wave kinematics.

5.5.3.4.3 Current Loads

Current induced loads on immersed structural members should be determined based on analytical methods, model test data or full-scale measurements. When currents and waves are superimposed, the current velocity should be added vectorially to the wave induced particle velocity prior to computation of the total force. Current profiles used in the design should be representative of the expected conditions at the installation site. Where appropriate, flutter and dynamic amplification due to vortex shedding should be taken into account.

5.5.3.4.4 Marine Growth

Marine growth could affect the hydrodynamic loads through:

- Increased hydrodynamic diameter
- Increased surface roughness used in the determination of hydrodynamic coefficients (e.g., lift, drag and inertia coefficients)
- Increased permanent load and inertial mass.

The amount of accumulation assumed for design should reflect the extent of and interval between cleaning of submerged structural parts.

5.5.3.4.5 Vortex-Induced Motions (VIM) of the Floating Support Structure

Floating support structures consisting of large diameter cylindrical components such as Spars, Semisubmersibles, and TLPs can experience low-frequency motions due to vortex shedding in the presence of currents. These vortex-induced motions (VIM) are most prominent for Spars where most of the industry experience has been acquired. Nevertheless, multi-column floating structures such as semisubmersibles and TLPs can also experience VIM and this effect should be taken into account in the design.

VIM could have three primary effects on the mooring design:

- Increase in the average in-line drag coefficient
- Large low frequency VIM motion amplitudes relative to the total floating support structure responses
- Additional low frequency oscillating mooring line tensions.

These effects should be taken into account for strength and fatigue design of FOWT stationkeeping systems. The occurrence of the Loop Current and associated eddies in the Gulf of Mexico make consideration of VIM particularly important for this geographic area. For example, unlike other extreme events, e.g. winter storms and hurricanes, the Loop Current and associated eddies could affect a particular site for an extended period of time and thus cause a significant fatigue damage accumulation in mooring components.

5.5.3.4.6 Directional Distribution

Offsets and motions of the floating support structure used in the stationkeeping system design should be evaluated for the most unfavorable combinations of wind directions, wave directions and current directions, consistent with the site-specific metocean characteristics. The ability of the floating support structure to change heading in response to changing environmental conditions may be taken into account.

5.5.3.5 Ice and Snow Accumulation Induced Loads

At locations where FOWTs are subjected to ice and snow accumulation, increased weight and change in effective area of structural members due to accumulated ice and snow should be considered. Particular attention should be paid to possible increases in aerodynamic and hydrodynamic loading due to the change in size and surface roughness of both non-rotating and rotating parts of an offshore wind turbine caused by ice and snow accumulation.

5.5.3.6 Earthquake Loads

For an FOWT supported by a tendon system and located in seismically active areas, the Strength Level and Ductility Level earthquake induced ground motions (see Section 5.4.11.4) should be determined based on seismic data applicable to the installation site. Reference should be made to API RP 2T (2010) for designing the tendon systems against earthquake loading.

Earthquake ground motions should be described by either applicable ground motion records or response spectra consistent with the return period appropriate to the design life of the structure. Available standardized spectra applicable to the region of the installation site are acceptable provided such spectra reflect site-specific conditions affecting frequency content, energy distribution, and duration. These conditions include

- The type of active faults in the region
- The proximity of the site to the potential source faults
- The attenuation or amplification of ground motion between the faults and the site
- The soil conditions at the site

As appropriate, effects of soil liquefaction, shear failure of soft mud and loads due to acceleration of the hydrodynamic added mass by the earthquake, submarine slide, tsunamis and earthquake generated acoustic shock waves should be taken into account.

5.5.3.7 Ice Loads

Ice loads acting on an FOWT are both static and dynamic loads. Static loads are normally generated by temperature fluctuations or changes in water level in a fast ice cover. Dynamic loads are caused by moving ice interactions with the floating support structure. The global forces exerted by ice on the global floating support structure and local concentrated loads on structural elements should be considered. The effects of rubble piles on the development of larger areas and their forces on the floating support structure should be considered. Further reference is made to API RP 2N (1995) and ISO 19906 (2010).

5.5.3.8 Wake Effects in an Offshore Wind Farm

For FOWTs in a wind farm, wind field perturbations in wake flow should be considered in the calculation of the extreme and fatigue loads. Both simple shadow effect and superimposed wake interaction should be assessed. For large wind farms, an increase in the environmental turbulence or terrain roughness should be taken into account. The wake effects induced load increase may be calculated using the effective turbulence intensity, I_{eff}, as defined in Annex D of IEC 61400-1.

As appropriate, the global yawing moment exerted on the floating support structure due to unbalanced rotor aerodynamic loads caused by the shade effect or the wake effect of neighboring FOWTs should also be considered. Such global yawing moment may be assessed separately and added to the total RNA aerodynamic loads.

5.6 Global Performance Analysis

5.6.1 General

Global performance analyses determine the global effects of environmental conditions and other loads on the FOWT and its components including the tower, hull structure, mooring lines or tendons, anchors, export electrical cable, etc. Global performance analyses should be carried out for all critical conditions in the pre-service and in-service phases, represented by the design load conditions specified in Section 5.5.

Because significant interactions could occur among the RNA and control system, the floating support structure and the stationkeeping system, an integrated ("coupled") model including all these components is recommended to be used for global performance analyses. An alternative method, where the dynamic analyses of the stationkeeping system are performed separately by using the responses of the floating support structure as boundary conditions, may also be acceptable, provided that the coupling effect of the stationkeeping system and the floating support structure is adequately taken into account.

The global performance analysis software should have the capability of considering complex interactions among aerodynamic loads, hydrodynamic loads, actions of turbine safety and control systems and structural dynamic responses of the FOWT. The analysis procedures should reflect the application limits of the selected software. Both publically available, industry-recognized software and in-house software may be used for the analyses. However, in-house software has to be adequately calibrated against model tests, field tests or the industry-recognized software.

General guidance on global performance analyses of the floating support structure and the stationkeeping systems can be found in:

- API RP 2T (2010), API RP 2FPS (2011) and ISO 19904-1 (2006) as well as appropriate classification society criteria for the design of floating offshore structures

- API RP 2SK (2008), API RP 2SM (2007) and ISO 19901-7 (2005) for catenary mooring and taut leg mooring systems as well as API RP 2T (2010) for TLP tendon systems. References may also be made to appropriate classification society criteria.

5.6.2 Global Responses Parameters

The global performance analyses are intended to determine the following parameters:

- Motions of the floating support structure in six degrees of freedom
- Mooring line or tendon tensions, including the maximum and minimum tensions and mooring line or tendon fatigue loads for the component design
- Tower base loads for the hull support structure analysis
- Tower top accelerations for the RNA design and selection
- Critical global forces and moments, or equivalent design wave heights and periods as appropriate, for the global structural analysis
- Hull hydrodynamic pressure loads for global structural analysis
- Accelerations for the determination of inertia loads
- Air gap (also known as deck clearance or freeboard)
- Separation of resonance peaks, if required

5.6.3 Wave-induced Motion Responses

The wave-induced response of an FOWT normally consists of three categories of response, i.e., first order (wave frequency) motions, low frequency or slowly varying motions and steady drift. For the TLP type floating support structure, high-frequency heave, roll and pitch motions of the floating support structures may also be excited.

i.) *First Order Motions*. These motions have six degrees of freedom (surge, sway, heave, roll, pitch and yaw) at wave frequencies that can be obtained from model tests in regular or random waves or by numerical analysis in the frequency or time domain.

ii.) *Low Frequency Motions*. These motions are induced by low frequency components of second order wave forces. The low frequency motions of surge, sway and yaw can be substantial, particularly at frequencies near the natural frequency of the floating support structure. The low frequency motion-induced loads in the mooring lines could be dominant design loads for the stationkeeping system. The low frequency motions should be calculated by using appropriate motion analysis software or by model tests.

iii.) *Steady (Mean) Drift*. An FOWT in waves experiences a steady drift along with the first and second order motions. The mean wave drift force and yawing moment are induced by the steady component of the second order wave forces. Mean drift forces and yawing moments should be calculated using appropriate motion analysis programs or extrapolated from model test results.

iv.) *High-frequency Responses*. High-frequency responses of the TLP-type floating support structure are significantly affected by various nonlinear excitation mechanisms. The relevant design guidance can be found in API RP 2T (2010).

5.6.4 Air Gap (Deck Clearance or Freeboard)

Unless topside deck structures, equipment on deck, and the tower, whenever relevant, are satisfactorily considered for direct passage of waves and wave impact, reasonable clearance between the wave crest and the structures for which wave forces are not considered in the design should be established for all afloat modes of operation.

A minimum air gap of 1.5 m (5 ft) should be provided between the 50-year return maximum wave crest elevation above the highest still water level (HSWL) (see Section 5.4.7) and the lowest edge of the floating support structure for which wave forces are not included in the design. Consideration should be given to the effect of wave run-up and motions of the floating support structure. Local wave crest elevation should be taken into account as appropriate. The requirement of air gap should be checked for the design load case DLC 1.6, DLC 6.1, and DLC 6.2 specified in Section 5.5.2.2.

Under the survival load cases, as specified in Section 5.5.2.3, the air gap is not to be less than zero. The air gap criterion should also be checked at various locations on the underside of a topside deck. If the air gap criterion for the survival load cases is not satisfied, the anticipated local and global wave forces (including slamming) should be suitably considered in the design of the stationkeeping system.

The air gap is normally determined by an appropriate model test. Alternatively, the air gap can also be calculated using a detailed global performance analysis that accounts for relative motions between the floating support structure and waves.

The following items should be considered in the determination of the air gap:

- Motions of floating support structure in six degrees of freedom
- Restraints provided by the stationkeeping system

- Nonlinearity of wave profile
- Wave diffraction and run-up
- Tide and water level effects, if applicable
- Various environmental headings
- Draft of the floating support structure

The air gap criteria should also be applied to the turbine blades.

5.6.5 Model Testing

Model testing provides an independent check of system responses under simulated environmental conditions. It is also used for deriving some of the design parameters, such as the air gap and nonlinear effects, particularly for an innovative design. Model testing and numerical analyses are not to replace, but are rather to complement each other. The primary objectives of model testing are:

- To determine the responses of a particular design, such as to calibrate low-frequency and high-frequency damping coefficients
- To verify analysis tools for prediction of system responses or to correlate the analysis results
- To derive some design information as a substitute for numerical analysis.

Appropriate environmental conditions should be selected in the model testing. Due consideration should be given to the model scaling for the FOWT where both hydrodynamic and aerodynamic load effects and, if deemed necessary, the tower elasticity need to be taken into account.

Additional guidance on hydrodynamic model tests for floating offshore structures can be found in in API RP 2T (2010) and ISO 19904-1 (2006).

5.6.6 Characteristics of FOWTs

5.6.6.1 General

An FOWT consists of a number of main subsystems including the floating support structure (hull structure and tower), the turbine RNA and safety and control system, as well as the stationkeeping system including mooring (or tendon) system and anchoring systems. This section describes the key issues and characteristics of the main FOWT subsystems relevant to global performance analyses. Representative coupling effects between the components of the FOWT are also identified.

5.6.6.2 Floating Supporting Structures

The floating support structure consists of the hull structure and the tower. A common feature of all types of the hull structures is that they utilize excess buoyancy to support the tower and the RNA and to provide mooring (or tendon) system tensions. For this reason, the design of the floating support structure tends to be weight sensitive.

Depending on specific site conditions, ocean waves typically contain first-order energy in the range 3 - 30s. For the floating support structure, the natural periods of different modes of motion are of primary interest and, to a large extent, reflect the design philosophy. Typical motion natural periods of different types of floating support structure are summarized in Table 5.3.

Table 5.3 Representative Natural Periods of Typical FOWT Floating Supporting Structures

Motions	*Natural Periods (seconds)*		
	Spar-Type	*Semisubmersible-Type*	*TLP-Type*
Surge	>40	>40	>40
Sway	>40	>40	>40
Heave	20-50	17-40	<5
Roll	25-60	25-50	<5
Pitch	25-60	25-50	<5
Yaw	>3	>3	>3

5.6.6.2.1 TLP-Type Floating Supporting Structures

A TLP-type floating support structure is a vertically moored, buoyant structural system wherein the excess buoyancy of the hull maintains tension in the stationkeeping system.

A TLP-type floating support structure consists of structural components of hull connecting to the tendon system. It may also include a column top frame and topside deck. The hull consists of buoyant pontoons and columns. The tops of the columns may be connected to the tower directly or to a column top frame or a topside deck forming the global strength of the hull. The tendon system consists of a vertical mooring system that forms the link between the hull and the foundation for the purpose of mooring the floating support structure. The foundation system is used to anchor the tendons to the seafloor.

The TLP-type floating support structure differs fundamentally from the other floating structure concepts, mostly because of the following reasons:

- Tendon stiffness, rather than the 'water-plane' stiffness, governs the vertical motions.
- It is normally very weight sensitive.
- It has low restraint to horizontal motions (surge, sway and yaw), but is highly restrained in the vertical direction (heave, roll and pitch).
- Higher order wave forces at different sum-frequencies may introduce resonant (springing) or transient (ringing) responses in the vertical direction. These effects may significantly increase tendon loads.
- Restrained by the tendon system, the TLP-type floating support structure moves along a spherical surface. This gives rise to the set-down effect, which is a kinematic coupling between the horizontal surge/sway motions and the vertical heave motion. The magnitude of the set-down affects the wave air-gap, tendon forces and electrical cable responses.

The TLP-type floating support structure generally experiences horizontal wave frequency motions of the same order of magnitude as those of a semisubmersible of comparable size. On the other hand, the TLP-type floating support structure behaves like a fixed structure with practically no wave frequency vertical motion responses, because the wave frequency forces are counteracted by the stiffness of the tendon system.

The flexibility of the tower could have significant influences on the natural periods of roll and pitch motions of the TLP-type floating support structure. The high frequency loads due to the rotor rotations and aeroelastic responses of the RNA and the tower could introduce resonant and/or transient responses in the vertical motions, which could significantly increase the tendon loads.

5.6.6.2.2 Spar-Type Floating Supporting Structures

A Spar-type floating support structure is a deep draft, vertical floating structure, usually of cylindrical shape, supporting the tower and a topside structure (if any) and moored to the seafloor.

A Spar-type floating support structure typically consists of an upper hull, mid-section and lower hull. The upper hull serves to provide buoyancy to support the topside and provides spaces for variable ballast. The mid-section connects the upper hull with the lower hull. The mid-section can be a cylindrical column or a truss space frame with heave plates. The heave plates are a series of horizontal decks between each bay of the truss space frame and are designed to limit heave motions by providing added mass and hydrodynamic damping. The lower hull normally consists of a fixed ballast tank and, in the case of a truss Spar, a flotation tank. The fixed ballast tank provides temporary buoyancy during a horizontal wet tow and provides the needed ballast in upending by flooding the tank. After upending, the ballast water may be replaced by fixed ballast (a substance with a density higher than water) to lower the Spar's center of gravity. The ballast in the fixed ballast tank results in a vertical center of gravity well below the center of buoyancy, which provides the Spar with sound stability, as well as desired motion characteristics. The flotation tank is located adjacent to the fixed ballast tank to provide additional buoyancy for wet tow and ballast in upending.

With a deep draft, the Spar-type floating support structure has a large area exposed to current forces, which is usually the dominant mean force on a Spar. Low frequency vortex induced oscillations may increase the effective drag leading to even higher mean current forces. By installing strakes on the Spar hull, the vortex induced cross-flow oscillation can be mitigated. However, the strakes increase the added mass and the drag forces on the Spar.

The Spar-type floating support structure is usually compliant to surge, sway, heave, roll, pitch and yaw motions. The natural periods of motions in all 6 degrees of freedom are usually outside the range of wave periods. In addition, the Spar-type floating support structure has a low level of vertical wave excitation due to its large draft, which exploits the fact that the first order wave motions and dynamic pressures decay exponentially with depth. These result in very small heave motions.

Due to relative small wave frequency motions, the Spar-type floating support structure is generally not subjected to large dynamic mooring line forces, although their actual effect have to be evaluated by considering the actual location of the fairlead and the increase in horizontal wave frequency motion towards the waterline.

The mooring system for the Spar-type floating support structure can be in the form of catenary moorings, semi-taut-line moorings or taut-line moorings. The motions and mooring loads of the catenary moored Spar-type floating support structure are normally insensitive to the high frequency loads generated by the rotor rotations and aeroelastic responses of the RNA and the tower.

Since the Spar-type floating support structure has a slender hull in vertical direction and the mooring system tends to have relatively low yaw stiffness, the Spar-type FOWT may experience yaw instability which should be avoided.

5.6.6.2.3 Column-Stabilized (Semi-submersible) Floating Supporting Structures

A column-stabilized floating support structure, also known as the Semi-Submersible floating support structure, consists of a topside structure connected to the underwater hull or footings by columns or caissons. The floating support structure depends upon the buoyancy of columns or caissons for flotation and stability. Lower hulls or footings are normally provided at the bottom of the columns for additional buoyancy. The topside structure can be of an enclosed hull type or an open space frame truss construction. The topside structure is interconnected with the stability columns of the hull to form the overall strength. The Tower may be connected directly to a column or caisson or to the topside structure.

Current forces could be significant on column-stabilized floating support structure due to the bluff shapes of their underwater columns and pontoons.

The column-stabilized floating support structure is characterized by having free modes of motion, which means that all natural periods of motion are outside the range of energetic wave periods. However, the wave frequency motions of the column-stabilized floating support structure are normally not insignificant, especially in extreme environmental conditions.

For the column-stabilized floating support structure, wave impact underneath the deck due to insufficient air-gap may influence the global motions and local structural responses.

The spread mooring system in the form of the catenary, semi-taut lines or taut lines is normally adopted as the stationkeeping system for the column-stabilized floating support structure. The column-stabilized floating support structure with the catenary mooring system may experience significant dynamic mooring loads due to the wave frequency responses. The motions and mooring loads of the catenary moored column-stabilized floating support structure are normally insensitive to the high frequency loads generated by the rotor rotations and aeroelastic responses of the RNA and the tower.

5.6.6.2.4 Other Types of Floating Supporting Structures

For the floating support structure having the hull configuration or the hull-mooring combination that does not belong to the those described above, general guidance may be referred to API RP 2FPS (2011), ISO 19904-1 (2006), API RP 2SK (2008) and ISO 19901-7 (2005), as well as appropriate classification society criteria for the design of floating offshore structures.

5.6.6.3 Stationkeeping Systems

5.6.6.3.1 General

An FOWT stationkeeping system is primarily designed to keep the FOWT within its position tolerances. It is also required to assist in achieving motion limits imposed by operational requirements of the RNA. Because the turbine RNA could exert large yaw moments to the floating support structure that normally has small yaw stiffness, the stationkeeping system may also need to be designed to provide sufficient yaw stiffness to mitigate the FOWT yaw motions.

A stationkeeping system includes a mooring (tendon) system and an anchoring system. The mooring system provides resistance to environmental loading by mobilizing reaction forces as the result of the gross change in mooring geometry. It essentially works as a collection of spring mechanisms where displacements of the floating support structure from its neutral equilibrium position introduce restoring forces to react the applied loading. Each mooring line acts as a tension spring and assumes its intended functions through one of the following two mechanisms:

- hanging catenary effect due to gravity acting vertically on the mooring line
- line elastic effect due to elastic stretch over the length of the mooring line

When FOWTs are expected to be deployed in relatively shallow water, in order for the mooring systems to have required stiffness, fiber ropes, clump weights and buoys may be used in addition to chains and wire ropes.

5.6.6.3.2 Catenary Moorings

The geometry of catenary moorings is related to the following parameters:

- submerged weight of the suspended lines;
- horizontal mooring load;
- line tension; and
- line slope at fairlead.

The compliance of the catenary mooring line allowing for wave-induced floating support structure motions is ensured by a combination of geometrical change and axial elasticity of the lines. Large line geometrical changes could lead to significant dynamic responses in the catenary mooring system due to the large transverse drag loads.

The mooring lines in a catenary mooring system are commonly composed of steel rope and chain segments. If necessary, clump weights and buoys may be used to achieve desired line configurations.

5.6.6.3.3 Taut Moorings

In a taut mooring system, the mooring lines are nearly straight between the anchor and the fairlead and an uplift force is exerted on the anchor. The compliance of the mooring line allowing for wave-induced floating support structure motions is provided mainly by line elasticity.

Transverse geometric changes in a taut mooring system are typically much smaller than those in a catenary mooring system. Therefore, dynamic effects due to line drag loads are moderate.

Synthetic ropes have been used as mooring lines in taut mooring systems to provide required stiffness and low weight. Compared to steel ropes, synthetic ropes exhibit more complex stiffness characteristics (e.g., hysteresis), which may significantly alter dynamic effects.

5.6.6.3.4 Tendons

The TLP tendons are the vertical mooring lines similar to those in taut mooring systems. The main difference is that tendons are traditionally made of tubes that are hardly compliant in the axial direction. The TLP tendon system acts as an inverted pendulum, where the stationkeeping capacity is governed by tendon length and pretension.

By restraining the FOWT at a draft deeper than what is required to balance its weight, the tendons are typically under a continuous tensile load that provides a horizontal restoring force when the hull is displaced laterally from its equilibrium position. With very high stiffness in the axial direction, the tendon system limits heave, pitch, and roll response of the hull to small amplitudes while its relatively compliant transverse restraints can be designed to achieve surge, sway, and yaw responses within operationally acceptable limits.

The tendons may take one of several forms, for example:

- *Tubular members with threaded or other mechanical connectors*. These members may be designed to be completely void, partially void, or fully flooded. The tubular member and the connectors may be fabricated as one piece, or assembled from separate tubular segments that are joined with threaded connectors. The tendon components may be made of metal or fiber reinforced composites, with either integral or metallic connectors.
- *Tubular or solid rod members with welded connections*. The tubular members are fabricated from seamless or rolled and welded steel and are designed to be welded together, prior to or during offshore installation, to form a continuous tendon element.
- *Tendon strands*. These tendons are fabricated from small diameter high tensile strength wire or fiber strands and are formed into bundles. These tendons are designed to be installed offshore using a continuous one-piece spooling operation to minimize the need for intermediate connectors.

5.6.6.4 RNA and Control and Safety Systems

The RNA consists of the rotor and nacelle assembly, which includes all the associated mechanical, electrical and control equipment and systems. A rotor may consist of two, three or more blades typically made of fiber reinforced composites. A minimum clearance between the rotor blades and other parts of the FOWT and the expected highest wave elevation should be maintained. A deformation analysis should be performed by dynamic and aeroelastic means. The motions of the FOWT should be accounted for.

The RNA control and safety system can optimize operations and keep the FOWT in a safe condition in the event of malfunction. The control system keeps the FOWT within the normal operating limits. The safety function of the system logically subordinates to the control function and is brought into action after safety-relevant limiting values have been exceeded or if the control function is incapable of keeping the FOWT within the normal operating limits. For detailed descriptions of control and safety system, refer to IEC 61400-1 and IEC 61400-3.

Due to its influence on mechanical loads, the performance of the control and safety system is critical not only for the safety of service personnel and normal operations but the structural integrity of the FOWT. The load-relevant functions of the control and safety system, which lead to various RNA operational conditions, should be considered in the load analysis.

5.6.7 Modeling of FOWT

5.6.7.1 General

In general, dynamic analyses should be carried out to evaluate dynamic responses of the FOWT subjected to site-specific external conditions and operating conditions. While various simplified analysis methods may be used in the preliminary design, an integrated (coupled) dynamic analysis approach is recommended for the final detailed design. Prototype tests and model tests may be used to supplement the load calculation.

For the purpose of motion and load calculations in the global performance analysis, modeling of an FOWT can be divided into the following areas:

- Modeling of hull structures
- Modeling of flexibility of the tower
- Modeling of stationkeeping systems
- Modeling of rotor blades and control and safety systems
- Modeling of dynamics of drive trains
- Modeling of wind farm wake effects

The external conditions to be considered in global performance analysis include:

- Environmental conditions
- Electrical network conditions

In addition, various fault conditions relevant to electrical system, control and safety system and mechanical components should be properly modeled in the analysis.

5.6.7.2 Modeling of Hull Structures

The hull structure in general can be modeled as a rigid body with 6 degrees of freedoms (6 DOFs) motions. Modeling of the hull structure should consider the following loads and load effects:

- Hydrostatic loads

- Gravitational and inertial loads
- Wind, wave and current loads
- Other load effects, such as hull VIM and VIV

5.6.7.2.1 Hydrostatic Loads

Balancing mass with buoyancy in the vertical direction is usually the starting point for hydrodynamic analyses. The vertical component of mooring pretensions is part of this load balancing.

Buoyancy of a large-volume floating structure can be calculated directly using the wetted surface of the panel element model created for radiation/diffraction analyses. When an analysis model includes both the panel elements and Morison elements, the buoyancy could still be calculated by most commercial software if actual locations and dimensions of the Morison elements are provided.

Correct modeling of metacentric heights (GM_L, GM_T) is just as important as modeling the location of the center of buoyancy. Free surface effects in partially filled internal tanks should be taken into account in determination of metacentric heights.

Stiffness contributions from moorings and cables should be appropriately taken into account. The mass distribution of the hull structure can be represented by either a global mass matrix or a detailed mass distribution (e.g. FE model). The input coordinate system normally depends on the software employed and its origin may be placed at the vertical center of gravity or on the still water plane. Proper input of roll and pitch radii of gyration are critical and require a correct definition of reference axis systems.

5.6.7.2.2 Wave Loads on Large-Volume Floating Structures

The typical hull structures are large-volume floating structures that are inertia-dominated with respect to global motion behavior. Radiation/diffraction analyses are commonly used to determine the wave loads on such hull structures. Some types of hull structure, for instance Semi-submersibles and truss Spars, may also have slender members/braces for which the Morison load model is more appropriate.

Linear radiation/diffraction analyses are usually sufficient. The term 'linear' means that the average wetted area of a floating structure (up to water line) is used in the analysis. The main output of a radiation/diffraction analysis gives first-order excitation forces, hydrostatics, potential damping, added mass, first-order motions in 6 DOFs and second-order drift forces/moments. Such an analysis can also provide information relevant to the slowly varying responses in roll and pitch that is important for FOWTs based on Spars or other deep-draft floating structures, large semisubmersibles and TLPs.

Low frequency vessel motions are caused, in part, by nonlinear second order drift forces. If the natural period of FOWT motions is high (for instance, larger than 25 seconds), a linear frequency-domain solution may be achieved by Newman's approximation, which eliminates the off-diagonal terms in the QTF (Quadratic Transfer Function) matrix. Newman's approximation generally gives satisfactory results for low frequency motions in the horizontal plane where the natural periods of FOWT motions are much larger than the wave periods. For low frequency motions in the vertical plane, for example the pitch motion of a spar, Newman's approximation may underestimate the second order drift forces. If such response is deemed important for the design, time-domain analyses using a full QTF matrix may be required. When the full QTF matrix approach is used, special attention should be paid to establishing a consistent damping level.

Second-order wave forces at the sum-frequencies in a random sea-state could excite resonant responses in heave, roll and pitch of the TLP-type FOWTs. Such resonant response, also known as springing, is a stationary time-harmonic oscillation of the TLP-type FOWTs at a resonance period of one of the vertical modes (heave, roll, pitch). In addition, the TLP-type FOWTs in deep water may experience very large resonant high frequency transient ringing response. Time-domain analysis is typically performed to evaluate these high frequency responses. There exist methods and computer tools for calculating the sum-frequency QTF. The important aspects to be considered for springing analyses include:

- discretization (mesh) of wetted surface geometry
- discretization of free surface and its extension
- number of frequency pairs in the QTF matrix
- damping level for the tendon axial response.

Wave periods and wave headings should be selected such that motions and forces/moments can be described as correctly as possible. Cancellation, amplification and resonance effects should be properly captured. Modeling principles related to the panel mesh (size) should in general be followed, e.g.:

- Diagonal length in panel elements should not to be larger 20% of the smallest wave length analyzed
- Fine panel mesh should be applied in areas with abrupt changes in geometry
- Finer panel mesh should be applied towards water-line in order to capture correct wave drift excitations

Hydrodynamic interactions between multiple floating support structures in close proximity may also be solved using radiation/diffraction analyses, where the floating support structures are normally solved in an integrated system with motions in 12 DOFs.

5.6.7.2.3 Wind Loads, Current Loads and Hull VIV

Wind loading is important for assessing global performance of the FOWT. Wind loading on the RNA usually is calculated using blade element method (BEM) or other appropriate methods. Wind loading on the hull structure is determined based on windage areas and appropriate drag coefficients and is often verified using wind tunnel tests.

Current conditions vary greatly in magnitude and direction at different site locations. In general, only measurements can provide sufficient background for determination of design current speeds and directions. Currents may induce VIV motions of the hull structure as well as VIV oscillations of the mooring lines and, therefore, has to be suitably considered. It is also important to apply appropriate drag coefficients with due attention to conditions of the loading area as well as the damping effect. Sensitivity checks using different sets of drag coefficients are therefore recommended.

Hull VIV motions (i.e. VIM) can affect the mooring system design as well as the electrical cable design in term of both extreme loading and fatigue loading. Since VIV is a strongly non-linear phenomenon, model testing has often been used to determine the hull VIV responses and calibrate the numerical simulations.

5.6.7.2.4 Instability

Mathieu's instability may occur for dynamic systems with time dependent stiffness. Several effects may cause such time dependent stiffness. Specifically for the FOWT, there are two scenarios that may trigger instability:

- non-constant heave stiffness caused by the geometric shape of the hull structure; and
- non-constant pitch stiffness caused by a nonlinear heave coupling term.

The heave/pitch-coupled instability in the second scenario could be critical for the single column hull structures with relatively low heave damping.

Instability can be identified through numerical simulations and/or model and field testing.

5.6.7.3 Modeling of Flexibility of Tower

The tower can generally be modeled based on linear elastic theory. However, non-linear relationships between loads and load effects should be properly accounted for, where they are deemed important. Structural damping of the tower should be properly determined.

The wind loads on the tower should be included. When wind loads on the FOWT are analyzed, the influence of the tower shadow or tower upwind effects on the wind field perturbation should be properly modeled.

The flexibility of the tower may be modeled by modal superposition. As a minimum the bending modes should be included. Sufficient modes should be included in the analysis. If the tower does not have sufficient torsional stiffness, torsional modes should also be included in the modeling. Modal analyses of the tower should take into account influences of floating foundations.

For some types of FOWTs, such as a catenary-moored Spar-type or Semi-submersible-type FOWT, the tower may be modeled as part of the rigid body of the floating support structure in preliminary mooring system designs. It is recommended that tower flexibility be properly modeled for the final detailed design.

5.6.7.4 Modeling of Stationkeeping System

5.6.7.4.1 General

There are mainly two approaches for mooring system analysis, i.e. quasi-static analysis and dynamic analysis. Both methods can be applied in either the frequency domain or the time domain. Time-domain dynamic analyses are usually required to account for nonlinearity and dynamic effects of the mooring (tendon) system.

The formulation for modeling the mooring (or tendon) system is mainly based on the finite element method (FEM) or the lumped-mass method.

5.6.7.4.2 Mooring Line Nonlinearity

There are four primary nonlinear effects that could greatly affect mooring line behaviors:

- *Nonlinear Stretching Behavior of the Mooring Line*. The strain or tangential stretch of the mooring line is a function of the tension magnitude. Nonlinearity occurs mostly in synthetic materials such as polyester, while chain and wire rope can be regarded as linear. In many cases, this nonlinearity is simplified by a linearized behavior using a representative tangent or secant modulus.
- *Changes in Geometry*. The geometric nonlinearity is associated with large variations of the mooring line shape.
- *Fluid Loading*. The Morison equation is most frequently used to represent fluid loading effects on mooring lines. The drag force on the line is nonlinear because it is proportional to the square of the relative velocity (between the fluid and the line).
- *Bottom Effects*. In many mooring designs, a considerable portion of the mooring line is in contact with the seafloor. The interaction between the line and the seafloor is usually considered to be a nonlinear frictional process. In addition, the length of grounded line segment constantly changes, causing an interaction between this nonlinearity and the geometric nonlinearity.

In the time-domain method, it is possible to model the non-linear effects described above - the elastic stretch can be mathematically modeled, the full Morison equation can be implemented, the position of the mooring line can be updated at each time step, and the bottom interaction can be simulated using a frictional model. Such time-domain analysis requires recalculating mass, damping, and stiffness matrices and loading at each time step. Hence, the computation can become complex and time consuming.

The frequency-domain method, on the other hand, is always linear because of the principle of linear superposition. Hence, all sources of non-linearity should be simplified by either a direct linearization approach or an iterative linearization approach.

5.6.7.4.3 Finite Element Analysis Approach

The Finite Element (FE) method can be an effective approach for the global performance analysis. The important features that are desirable for adequate modeling and analysis of mooring (or tendon) systems normally include:

- 3D formulation
- Conventional small strain slender beam and bar elements capable of considering material and geometric stiffness and nonlinear material properties
- Hull/mooring (or tendon) connection formulation
- Seafloor/mooring line contact formulation
- Seabed/tendon connection formulation
- Structural damping formulation
- Hydrodynamic loading according to the Morison equation expressed by the relative water/structure velocity and acceleration
- Regular and irregular loading due to waves and hull structure motions.
- Current modeling
- Capability of modeling mooring components such as swivels, hinges, buoyancy modules, clump weights, flex-joints, etc.
- Capability of modeling constant (or variable) line tension devices
- Nonlinear static analysis
- Eigenvalue analysis
- Nonlinear time-domain dynamic analysis.

The computational efforts of nonlinear time-domain dynamic analysis can be substantial. This is in particular the case for irregular analyses where long simulations are typically required to estimate extreme responses with sufficient statistical confidence. It is therefore beneficial to apply simplified analysis approaches as a supplement to achieve more efficient computer analyses (e.g. linearized time-domain analysis, frequency-domain analysis).

5.6.7.5 Modeling of Dynamics of Drive Trains

For the purpose of global performance analysis, drive train dynamics should be properly considered. As a minimum the torsional mode of the drive train should be included in the analysis.

The drive train includes all torque-transmitting components from the rotor to the generator including the elastic mounting of the drive train. The parameterization assumptions of the drive train model used in the global load calculation should be verified by the calculation using more detailed drive train models. In most cases, the controlling parameters are “resulting drive train stiffness” and “moment of inertia of generator rotor”. The verification can also be carried out through the comparison of the first eigen-frequency obtained from the detailed drive train model to the corresponding value derived from the global load simulation model. Other verification techniques can also be used, if appropriate.

5.6.7.6 Modeling of Rotor Blade and Control and Safety Systems

5.6.7.6.1 General

The rotor blades can in general be modeled based on linear elastic theory. However, non-linear relationships between loads and load effects should be properly accounted for, where they are deemed important. As a minimum, the edgewise and flapwise bending degrees of freedom should be considered in the evaluation of aero-elastic responses. Structural damping of the rotor blades should also be properly selected.

Modeling of rotor blades and control and safety systems should include the following loads and load effects:

- Gravitational and inertial loads
- Aerodynamic loads
- Actuation loads (or operational loads)
- Other loads (such as wake loads, impact loads, ice load, etc.)

The influence of the control system on the loads, especially aerodynamic loads should be properly modeled. The interaction of the turbine control system with the low-frequency motions of the hull structure should be incorporated into the control system design and load analysis.

Resonance and dynamic amplification of motions due to control system actions should be avoided.

The combined effects of inertial, gravitational and aerodynamic loads of the RNA for a three-blade horizontal axis wind turbine include the following frequency components:

- rotor rotation frequencies (1P)
- blade passing frequencies (3P)
- harmonics of 1P and 3P (2P, 6P, 9P, etc.)
- natural frequencies of rotor blades
- natural frequencies of other RNA components

5.6.7.6.2 Gravitational and Inertia Loads

Gravitational and inertial loads are static and dynamic loads that could be induced by gravity, vibrations, rotations and seismic activities.

In dynamic analyses, structural dynamics properties and the coupling of vibratory modes should be properly modeled. The following items should be taken into account:

- Elasticity of the blades
- Elasticity of the drive train and generator (drive train dynamics)
- Elasticity of the tower
- Global motions of the floating support structures
- Mass eccentricity of the rotor
- Helideck dynamics (if relevant)
- Stiffness of the floating support structure and mooring system (if relevant)
- Elastic mounting of the machinery, vibration dampers (if relevant)

5.6.7.6.3 Aerodynamic Loads

The aerodynamic loads on rotor blades are dependent upon:

- Rotational speed of the rotor
- Average wind speed across the rotor plane
- Turbulence intensity
- Density of the air

- Aerodynamic shapes of the offshore wind turbine components and their interactive effects, including the aeroelastic effects

The calculation method for aerodynamic loads on rotor blades is normally based on the blade element momentum theory (BEM). Other methods such as potential flow method, Computational Fluid Dynamics (CFD), etc. may also be used. In addition, aerodynamic loads on the nacelle should be taken into account, if deemed important.

The following aspects should be taken into account regarding wind loads on the RNA:

- Wind field perturbations due to the offshore wind turbine itself (wake-induced velocities, tower shadow, tower upwind effect etc.)
- The influence of three-dimensional flow on the blade aerodynamic characteristics (e.g. three-dimensional stall and aerodynamic tip loss)
- Dynamic stall effects of the airflow for the profiles used
- Unsteady aerodynamic effects
- Aeroelastic effects
- Aerodynamic asymmetries that can arise through production or assembly tolerances of the rotor blades.

5.6.7.6.4 Actuation Loads (Operational Loads)

Actuation loads (or operational loads) are generated by the operation and control of the RNA. The main source of actuation loads are the rotor speed control and/or the torque control through pitching the blades or adjusting other aerodynamic devices. Actuation loads also include the mechanical braking loads as well as the transient loads arising during the start and shutdown of the rotor, engagement and disengagement of the generator, and nacelle yaw movements. As a minimum, the following should be taken into account:

- Static and load-dependent bearing friction moments (especially those at the blade pitch bearing and the yaw bearing)
- Behavior of the control and safety systems of the RNA.

5.6.7.7 Modeling of Wind Farm Wake Effects

Within an offshore wind farm, the turbulence intensity associated with wake flow may be considerably higher than the ambient turbulence intensity. In addition, wake flow is characterized by a reduced mean wind speed and an increased shear profile. In the absence of detailed analysis of the wind characteristics within an offshore wind farm, the design calculation may be performed using increased turbulence intensity based on the past experience and recognized calculation methods.

The mutual influence of offshore wind turbines through the wake interaction behind the rotor should be considered in a wind farm configuration up to a distance of at least 10 rotor diameters from another FOWT.

5.6.8 Definition of Analysis Methodologies

5.6.8.1 Frequency-Domain and Time-Domain Analysis

5.6.8.1.1 Frequency-Domain Analysis

In this guideline, frequency-domain analyses refer to calculations of loads and responses in the frequency domain by solving the equations of motion using methods of harmonic analysis or methods of Laplace and Fourier transformations. It generally includes the following types of analysis:

- Wave load calculation in the frequency domain
- Mooring analysis in the frequency domain
- Motion analysis in the frequency domain
- Design wave analysis

In the calculation of FOWT wave-frequency responses, linear wave theory is usually employed, while more sophisticated methods may be employed to model finite amplitude waves. The low frequency motion analysis should be carried out to evaluate the responses to wind dynamics and wave drift forces. The damping levels used in such analyses should be properly determined and documented. For the TLP-type floating support structure, where second-order sum-frequency effects are deemed significant, the high frequency springing responses of the floating support structure and tendons should be evaluated.

Frequency-domain analyses for evaluating aerodynamic responses of the RNA and effects of turbine control systems should be properly formulated. Preferably, combined aerodynamic, hydrodynamic and control system actions in the frequency domain are used in the calculation of FOWT dynamic responses.

Frequency-domain analyses, by nature, cannot capture nonlinear dynamic interactions among the components and subsystems of the FOWT. They are also unable to take into account transient responses as well as nonlinear aerodynamic and hydrodynamic load effects. Because of these limitations, most of currently available simulation software for FOWTs is based on the time-domain analysis approach as described in Section 5.6.8.1.2. Frequency-domain analyses are normally performed to calculate the hydrodynamic coefficients which are used as input to time-domain analyses.

5.6.8.1.2 Time Domain Analysis

In this guideline, time domain analyses refer to calculations of the loads and responses in the time domain. It generally includes the following types of analysis:

- Mooring analysis in the time domain
- Motion analysis in the time domain
- Global structural analysis in the time domain

Time-domain analyses consist of numerically solving the equations of motion in the time domain for the FOWT subjected to environmental conditions and the RNA operational loads. As the input to time-domain analyses, time series of wind and wave conditions are generated to simulate turbulent wind conditions and stochastic wave elevations and kinematics.

Time-domain analyses are the preferable approach for FOWT global performance analyses, primarily because they can provide a rational means of modeling the nonlinear and transient effects in FOWT global responses. These nonlinear effects include, but are not limited to, hydrodynamic drag forces, finite wave amplitude effects, nonlinear restoring forces from moorings as described in Section 5.6.7.4.2, and effects of motion suppression devices or components (e.g. heave plates). Time-domain analyses also allow modeling of the coupling effects among responses of the turbine RNA, the floating support structure, the stationkeeping system and the export electrical cable.

Time-domain analyses should be carried out for a sufficiently long time to achieve stationary statistics, particularly for low frequency responses. Multiple realizations of an individual set of stochastic site conditions may be necessary in order to generate adequate data for statistical analysis and to verify consistency of the simulation. The most probable maximum responses should be predicted using appropriate distribution curve fitting or other recognized statistical techniques.

For the TLP-type floating support structure, the ringing (the high frequency vertical vibration excited by impulsive loading) and the springing (the high frequency vertical vibration excited by cyclic loading at or near the resonant periods) responses of the TLP hull and the tendon should be considered as appropriate. Further guidance on high frequency ringing and spring analyses can be found in API RP 2T.

The effect of Vortex Induced Motions (VIM, see Section 5.5.3.4.5) for the floating support structure in the form of Spar, single column TLP or other types of deep-draft hull structure should be taken into account as appropriate.

5.6.8.1.3 Combined Time-Domain and Frequency-Domain Analysis

In this guideline, combined time- and frequency-domain analyses refer to the approach where first-order wave frequency responses are computed in the frequency domain and all the other responses are computed in the time domain. Total responses are the combination of relevant responses obtained from frequency-domain and time-domain analyses. This approach can be used in the following analysis:

- Mooring analysis
- Motion analysis
- Air gap analysis
- Global structural analysis

To reduce the complexity and computational effort associated with full time-domain simulations, combined time- and frequency-domain analyses are often employed. Typically, the mean and low frequency responses (hull displacements, mooring line tensions, anchor loads, etc.) are computed in the time domain while the wave frequency responses are solved separately in the frequency domain. The frequency-domain solution of wave frequency responses is normally processed to obtain either statistical peak values or time series, which are then superimposed on the mean and low frequency responses.

5.6.8.2 Quasi-Static and Dynamic Analysis

5.6.8.2.1 Quasi-Static Analysis

In quasi-static analyses, the mooring system is modeled quasi-statically and wave actions are taken into account by statically offsetting the hull structure using wave-induced hull motions. Dynamic actions on the mooring lines associated with mass, damping and fluid accelerations are neglected. Past experience has shown that the reliability of mooring system designs based on quasi-static analyses can vary widely depending on the hull structure type, water depth and mooring line configuration.

5.6.8.2.2 Dynamic Analysis

Dynamic analysis of the mooring system accounts for the time-varying effects due to mass, damping and fluid accelerations. Time-varying fairlead motions are calculated from the hull structure's surge, sway, heave, roll, pitch and yaw motions. Dynamic models are used to predict the mooring line responses to fairlead motions.

Either frequency-domain or time-domain analyses can be used to predict dynamic responses of the mooring system. In the time-domain approach, the non-linear effects including line elongation, line geometry, fluid loading, and sea floor effects could be modeled. The frequency-domain approach, on the other hand, is a linear approach; methods of approximating nonlinearity in the frequency domain and their limitations should be investigated to justify that they can provide acceptable solutions for the intended application.

5.6.8.3 Coupled, Semi-Coupled and Uncoupled Analysis

5.6.8.3.1 Coupled Analysis

There are various types of interaction, also known as coupling, among subsystems of the FOWT as described in Section 5.6.9. In this guideline, a coupled analysis means a fully coupled analysis (or an integrated analysis) in the time domain. More specifically, the complete system of equations accounting for the rigid body model of the hull structure, elastic models of tower and turbine RNA, the slender body model for the cables and mooring lines, as well as the control system are solved simultaneously using a non-linear time-domain approach for dynamic analyses.

When an integrated (coupled) model is used for global performance analyses, coupling effects among responses of the turbine RNA, the floating support structure, the stationkeeping system and the subsea electrical cable can be taken into account at each incremental analysis time step. A more realistic simulation of the effects of the turbine control system and turbine's operating conditions can also be achieved using this approach.

5.6.8.3.2 Semi-Coupled Analysis

In a semi-coupled analysis, the coupling effects between aero-elastic and aero-control (servo) are neglected. The tower and the RNA are modeled as part of the hull structure as a rigid body. The aerodynamic loads are modeled by the wind forces applied at the top of the tower. Effects of control system can be considered in deriving the aerodynamic loads on the RNA. The aero-control (servo) coupling effects may be approximately represented by the rotor thrust force whose magnitude should be expressed as a function of wind speed and the RNA's operational condition. In the parked conditions, nacelle yaw misalignment may be included by using appropriate wind force drag coefficients and windage areas.

The hull, mooring system and, if needed, subsea cables are dynamically coupled in this approach.

5.6.8.3.3 Uncoupled Analysis

In an uncoupled analysis, the system of equations accounting for the rigid body motions is solved in the time domain. The tower and the RNA are modeled as part of the hull structure as a rigid body. The effect of the mooring and subsea cable systems are modeled quasi-statically using non-linear springs based on the quasi-static restoring force characteristics. All other coupling effects between the hull and the mooring system (e.g. contributions from damping and current loading on the mooring lines) need to be pre-calculated and provided as direct input to the analysis.

The same load model may be applied for the hull structure in coupled, semi-coupled or uncoupled analyses.

5.6.9 Coupling Effects

Coupling effects that should be considered in FOWT global performance analyses include:

- Aero-elastic coupling effects
- Aero-control coupling effects
- Tower-hull and mooring (or tendon) coupling effects
- Hull-mooring (or tendon) coupling effects
- Other coupling effects

The way of simulating these coupling effects is highly dependent on the actual software and analysis approaches employed in global performance analyses and has to be evaluated on a case by case basis.

5.6.9.1 Aero-elastic Coupling

Aero-elastic coupling are interactions between the aerodynamic loads on the rotor blades and the tower and the structural deformation due to the elasticity of the rotor blades, tower and drive train, etc. of the RNA. In the calculation of aerodynamic loads on rotor blades, the aero-elastic coupling effects should be considered.

5.6.9.2 Aero-control Coupling

Aero-control coupling are interactions between the behavior of the control system and aerodynamic loads on the rotor blade.

5.6.9.3 Tower-Hull and Mooring Coupling

The coupling between the tower-hull and the mooring system mainly includes:

- influences of the hull and the mooring system on the tower modal shapes and natural frequencies; and
- influences of the tower flexibility on the hull pitch and roll motion, particularly for the TLP-type FOWT.

5.6.9.4 Hull-Mooring Coupling

Hull-mooring coupling is the interaction between the mooring line restoring, damping and inertia forces and the hull mean position and dynamic responses.

- Restoring forces include static restoring force from the mooring and electrical cable system as a function of hull offset; current loading and its effects on the restoring force of the mooring and electrical cable system; and seafloor frictions if mooring lines and/or electrical cables have contact with the sea floor.
- Damping from the mooring lines and electrical cables due to their dynamics, current drag, etc.
- Additional inertia forces due to the mooring and electrical cable system.

More discussions on this coupling effect can be found in API RP 2SK (2008) for applications in floating offshore structures.

5.6.9.5 Other Coupling

Other coupling phenomena relevant to an FOWT may also exist, such as:

- Interaction between hull motions and behavior of the control system
- Interaction between hull motions and aerodynamic loads on the rotor blades
- Interaction between hull motions and wind, wave and current loads on the hull structure
- Change in hydrodynamic loads, added mass and damping on hull as the hull is offset and set-down
- Ringing and springing responses (TLP tendons)
- Loop current/VIV effects/responses.

5.6.10 Electrical Cable Considerations

The electrical cable system for exporting generated electricity could have a long suspended segment extending from its connecting point on the hull to the connection or contact on the seafloor. The electrical cable interacts with the floating support structure and the mooring in several aspects. Wave and current actions on the cable could increase the environmental actions to be resisted by the mooring, while the cable system stiffness provides assistance to the mooring. Furthermore, damping from the cable system decreases the low frequency motions and in turn reduces the mooring tensions. The net result of these effects depends on a number of factors such as type of the cable and water depth. Mooring design should consider the cable loads, stiffness and damping unless it can be demonstrated that neglecting the cable in global performance analyses result in a more conservative mooring design.

5.6.11 Damping

5.6.11.1 Damping of Low Frequency Motions

Low frequency motions of a moored FOWT are narrow banded in the frequency domain because they are dominated by the resonant responses at the natural frequency of the moored FOWT. Amplitudes of low frequency motions are highly dependent on the stiffness of the mooring system and damping. There is a substantial degree of uncertainty in the estimation of low frequency motions, particularly in the area of damping that could in general come from five sources:

- Aerodynamic damping
- Viscous damping of the floating support structure (tower and hull structure), including wind, wave, and current drag
- Wave drift damping of the floating support structure
- Mooring system damping
- Cable system damping

The technology for estimating viscous damping has well been established, and viscous damping is normally included in the low frequency motion calculations. Wave drift damping, mooring system damping, and cable system damping, however, are more complex and are sometimes neglected because of a lack of understanding. Nevertheless, these damping components could be important and neglecting them may lead to significant over-estimation of low frequency motions. Where low frequency motions are considered important, it may be warranted to evaluate the damping from all these sources either by appropriate analytical approaches or model testing.

5.6.11.2 Damping of High Frequency Motions

The TLP-type FOWT could experience high frequency motions and vibrations in the vertical motion modes including heave, roll and pitch motions. Damping in the vertical motion modes is affected by structural and soil damping, as well as hydrodynamic and aerodynamic damping, and should be estimated either by appropriate analytical approaches or model testing. This is especially important in the calculation of the springing and ringing responses, and the tower and the RNA induced vibrations that could contribute significantly to the tendon fatigue damage.

5.6.12 Global Motion Analysis

5.6.12.1 General

Dynamic global motions of FOWTs can be simulated using frequency-domain analyses, time-domain analyses or combined frequency and time-domain analyses, as described in Section 5.6.8. All three approaches include various techniques of approximation and therefore may not yield consistent results. It is recommended that the approach selected for the mooring design be verified by model testing, full-scale testing, or the use of a different analytical approach.

FOWT global motions contain the following components:

- Static and mean responses due to wind, wave and current
- Low frequency motions induced by wave/current effects and dynamic wind loads
- Wave frequency motions induced by wave
- High frequency motions induced by wave for the TLP-type floating support structures
- Vibrations induced by the loads exerted by the tower and the RNA, if applicable
- Hull VIM, if applicable (see Section 5.5.3.4.5)

The steady or mean forces result in the mean offset of the FOWT. The low frequency forces excite the motions which are at frequencies lower than wave frequencies but close to the surge, sway, or yaw natural frequencies of the floating support structure. The wave frequency forces excite wave frequency surge, and sway motions. Because of its weathervaning nature, the FOWT with a single point mooring may experience large low frequency yaw motions. These yaw motions may significantly affect FOWT and mooring system responses, and therefore should be taken into account in global motion analyses and model testing.

Global motion analyses are normally performed in conjunction with mooring (or tendon) analyses. However, they may also be separated when only global motions are of interest. In such case, either the quasi-static or the dynamic analysis approach can be used to model the mooring system in global motion analyses. If the quasi-static analysis approach is used, special attention should be given to the appropriate simulation of the coupling effects.

5.6.12.2 Static and Mean Responses

Static and mean response analyses are carried out to determine the static equilibrium position with no wind, wave, or current present as well as the mean positions with steady environmental loads acting on the FOWT. The determination of the equilibrium and mean positions is essential before any dynamic analyses.

The following steady forces should be taken into account in the analysis:

- *Mean Wind Forces*. Mean wind forces should be calculated using the average wind speed measured for an extended period, normally in the order of one hour, under a given design environmental conditions.

- *Current Forces*. The drag forces on the mooring lines (or tendons) and cables subject to the current under a given design environmental condition should be included in the calculation of total steady forces.
- *Steady Wave Drift Forces*: Steady wave drift forces acting on the hull structure due to wave diffractions and second-order viscous effects. The interaction between waves and currents can also result in steady forces which should be considered.

5.6.12.3 Low Frequency Motions

Low frequency motions of FOWTs can be modeled using either frequency-domain or time-domain analyses.

In frequency-domain analyses, assuming that low frequency wind and wave forces are independent, the total low frequency force spectrum is given by the sum of the low frequency wave force spectrum and the low frequency wind force spectrum. This total force spectrum can then be multiplied by appropriate motion transfer functions to obtain desired motions.

In time-domain analyses, because low frequency motions are dominated by the surge, sway and yaw resonances with natural periods typically ranging from 60 to 150 seconds, a long simulation duration is required to obtain a sufficient number of cycles for developing an accurate estimate of the statistical extreme. Time histories of low frequency forces could be generated either from wind and wave force spectra or directly from wind velocity and wave profile time histories.

The estimation of damping is important because low frequency motions are dominated by resonant responses. Further discussion of damping is provided in Section 5.6.11.

5.6.12.4 Wave Frequency Motions

Wave frequency motions are induced by first-order wave forces. Wave frequency motions can be modeled using either the frequency or time-domain analyses.

5.6.12.5 High Frequency Motions

High frequency motions are induced by second and higher order wave forces. High frequency motions can be modeled using either the frequency or time-domain methods.

5.6.12.6 Tower and Turbine RNA Load Induced Vibrations

Due to the flexibility of the tower and the RNA, there are high frequency load components at the natural frequencies of the tower and the RNA. These loads may be transmitted to the hull structure and result in the hull vibrations.

5.6.12.7 Analysis Methods

5.6.12.7.1 General

For global motion analysis the following approaches can be used:

- Frequency-domain analyses
- Time-domain analyses
- Combined time-domain and frequency-domain analyses

5.6.12.7.2 Time-domain Approach

The fully coupled, semi-coupled and un-coupled analysis methods can be used when FOWT global motion analyses are carried out in the time domain. In the case of semi-coupled and un-coupled analyses, the applied damping level should be calibrated by fully-coupled analyses and/or model testing. When the tower accelerations are of interest, fully coupled analyses should be used and flexibility of the tower should be properly modeled.

5.6.12.7.3 Frequency-Domain Approach

Mean, low-frequency, and wave frequency responses of FOWTs are calculated separately in frequency-domain analyses. The mean responses are calculated by the static equilibrium or mean position. The low-frequency motions and set-down associated with offset are calculated in the frequency domain with appropriate consideration of damping effects from wind and current and mooring/cable. The wave frequency responses due to wave radiation/diffraction and wave asymmetry effects are calculated with consideration of wave loads only. Damping effects from wind and current and mooring/cable should be properly modeled. Total motions are obtained by combining the mean, wave and low-frequency motions.

When the frequency-domain approach is used to compute the hull motion responses, the extreme values of the motion responses are defined as the mean plus or minus the maximum estimated value of the time-varying excursion due to combined wave-frequency and low-frequency structure motions.

The extreme values of the motion, S_{max} and S_{min} can be determined by:

$$S_{max} = S_{mean} + \mathrm{MAX}(S_{dyn1}, S_{dyn2})$$

$$S_{min} = S_{mean} - \mathrm{MAX}(S_{dyn1}, S_{dyn2})$$

$$S_{dyn1} = S_{lfmax} + S_{wfsig}$$

$$S_{dyn2} = S_{wfmax} + S_{lfsig}$$

where

MAX = the larger of the absolute values of the terms in parenthesis

S_{max} = maximum hull motion

S_{min} = minimum hull motion

S_{mean} = mean hull motion

S_{lfmax} = maximum expected value of low-frequency motion

S_{lfsig} = significant value of low-frequency motion

S_{wfmax} = maximum expected value of wave-frequency motion

S_{wfsig} = significant value of wave-frequency motion

The total offset should be defined as the vector sum of the individual offset components of different degrees-of-freedom (e.g. surge and sway). The total heel should be defined as the vector sum of the individual component angles of different degrees-of-freedom (e.g. roll and pitch).

5.6.12.7.4 Combined Time-Domain and Frequency-Domain Approach

FOWT mean, low-frequency and wave frequency responses are calculated separately when combined time-domain and frequency-domain analyses are employed in global motion analyses. The mean responses are calculated by the static equilibrium or mean position. The wave frequency responses due to wave radiation/diffraction and wave asymmetry effects are calculated with consideration of wave loads only. Damping effects from wind and current, and mooring/cable should be properly considered. The low-frequency motions and set-down associated with offset are calculated in the time domain. The total motions are obtained by combining the mean, wave and low-frequency motions.

5.6.13 Air Gap Analysis

Air gap analysis should be performed for the design load cases associated with the extreme environmental conditions (i.e. DLC 1.6, 6.2, 6.3 as defined in Table 5.1) and the survival load cases (i.e. Table 5.2). The most important parameter to be evaluated in the air gap analysis is the wave crest height and the hull roll, pitch and heave motions.

For the air gap analysis the following methods can be used:

- Time-domain analyses
- Frequency-domain analyses
- Combined time-domain and frequency-domain analyses

The dynamic effects and coupling may not be important for air gap analysis. As a result, all the above three methods could be used in both preliminary and final air gap analysis provided the platform roll, pitch and heave motions are properly calculated. In term of the TLP-type FOWT, the set-down effect should be considered.

For the TLP-type FOWT, the minimum air gap, also known as deck clearance, is governed by a combination of an increasing water level and an decreasing deck height. The increasing water level is caused by incident wave elevation, tide, storm surge, and radiation/diffraction effects from the hull. In very steep sea conditions, the diffraction effects could be significant. The decreasing deck elevation is caused by the hull set-down with offset. The hull set-down increases nonlinearly at large offsets, leading to a rapid decrease of the deck clearance with increasing environmental severity. In this case, the correction to the prediction of offset should be made.

Radiated or diffracted waves generally cause local wave impacts on the deck. In some cases, local impacts may need to be accounted for in design and, as a results, may lead to local structural stiffening, increased weight of the deck, and tendon ringing, which affects the peak loads in the tendons and the porch structure. Increased tendon load responses could also affect the minimum tension, which in turn affect the design pretension.

The deck height could significantly affect the vertical position of the center of gravity and, in turn, the maximum and minimum tendon tensions. The deck elevation also affects the wind load and wind overturning moments. In general, a higher deck contributes adversely to the tendon tensions. On the other hand, if the deck does not have a sufficient air gap, large tendon tension variations could occur when waves strike the deck.

In the air gap analysis, the following global hull motions should be considered:

- Static and mean responses due to wind, wave and current
- Low frequency motions induced by wave/current effects and dynamic wind loads
- Wave frequency motions induced by wave

The high frequency motions and vibrations, as well as the tower flexibility, may be neglected for the air gap analysis.

i.) Time-domain Analysis

Fully-coupled, semi-coupled and uncoupled time-domain analyses may be used. In the case of semi-coupled and uncoupled analyses, the applied damping level used in the analyses should be calibrated with fully coupled analysis and/or model testing. Wave surface elevations should be calculated with consideration of the wave radiation/diffraction effects and wave asymmetry effects.

ii.) Frequency-Domain Analysis

FOWT mean, low-frequency and wave-frequency responses are calculated separately in frequency-domain analyses. The mean responses are calculated by the static equilibrium or mean position. The low-frequency motions and set-down associated with offset are calculated in the frequency domain with appropriate consideration of damping effects from wind and current and mooring/cable. The wave-frequency responses due to wave radiation/diffraction and wave asymmetry effects are calculated with consideration of wave loads only. Damping effects from wind, current and mooring/cable should be properly modeled. Total motions are obtained by combining the mean, wave- and low-frequency motions. The air gap is determined based on relative wave elevation and the pitch, roll and set-down of the hull obtained from frequency-domain analyses.

iii.) Combined Time-Domain and Frequency-Domain Analysis

In this method, the wave elevation is calculated in the frequency domain with consideration of radiation/diffraction effects and wave asymmetry effects. The high frequency motions of roll, heave, and pitch for the TLP-type FOWTs may be neglected. The low-frequency surge, sway and yaw motions, and for the TLP-type FOWTs the set-down associated with offset, are calculated in the time domain. The air gap is determined based on relative wave elevation from frequency-domain analyses and the pitch, roll and set-down of the hull obtained from time-domain analyses.

5.6.14 Mooring Strength Analysis

5.6.14.1 General

Global performance analyses are performed to predict extreme responses such as line tensions, anchor loads, and hull offsets under the design environment and other external conditions. These extreme global responses are then used to check against allowable values to verify the strength of the system against overloading and the sufficiency of clearance to avoid interference with other structures.

Active control of the mooring system through mooring line adjustment may be used for certain operations. However, active mooring line adjustment should not be considered in the mooring analysis for the design load cases associated with the extreme environmental conditions and the survival load cases.

The mooring line diameter used in the mooring analysis should be the nominal value (i.e. inclusive of corrosion and wear allowance) when calculating mass, weight and hydrodynamic loads of the mooring line, unless otherwise noted. Installation tolerances of anchor placement and line length should be taken into account in the mooring system design.

Dynamic excitations originating from the floating support structure, including the tower and the hull structure and the RNA, could result in mooring system responses in the following distinct frequency bands:

- Mean responses;
- Low-frequency responses;
- Wave-frequency responses.
- High frequency responses for the tendons or taut lines; and

- Vibrations induced by the loads exerted by the tower and the RNA , if applicable.

Responses of the mooring system to mean forces can be predicted by a static model of the mooring system. In general, the responses to low frequency motions can also be predicted by a static model because of the long periods of these motions. The responses to wave and high frequency hull motions and hull vibrations may be predicted by either quasi-static or dynamic analyses. However, the quasi-static analysis method should only be used in preliminary designs. In final detailed designs, dynamic analyses should be employed.

5.6.14.2 Mooring Strength Analysis Methods

For the mooring strength analysis the following methods can be used:

- Frequency-domain analyses
- Time-domain analyses
- Combined time-domain and frequency-domain analyses

These methods incorporate different degrees of approximation and are affected by various limitations, and therefore do not necessarily yield consistent results. If verification of the approach selected for the mooring design is required, model test data or an alternative approach of similar reliability should be used.

Because there is no established analytical method for determining FOWT motion responses undergoing VIM, model testing should be in general be performed if VIM is deemed important in the design. In the case that current loads and VIM are determined to be important, it is usual practice to perform well planned model tests to determine motion amplitudes and drag coefficients for use in mooring designs. Full-scale in-field measurement data may be employed to confirm the scalability of model testing.

In general, time-domain analyses are recommended for the mooring strength analysis. When the effects of high frequency motions and vibrations are expected to be relatively insignificant, frequency-domain analyses may yield satisfactory results and the analysis procedures in this case are similar to those described in API RP 2SK (2008).

i.) Frequency-Domain Analyses for Spread Mooring Systems

When using frequency-domain analyses for the spread mooring system design, the mean position of the hull structure is first determined from static equilibrium calculations for surge, sway and yaw. The surge, sway and yaw responses to wave and low-frequency excitations are then calculated and superimposed to the mean position. The procedure outlined in API RP 2SK (2008) can be used.

Where the floating support structure has a small water plane area, alternative procedures incorporating all 6 DOFs of motion should be used.

To obtain extreme (maximum) values, the combination of different components of the motions and mooring line tensions can use the approach recommended in API RP 2SK (2008).

ii.) Frequency-Domain Analyses for Single Point Mooring Systems

When using frequency-domain analyses for a single point mooring system design, assumptions on the hull structure's design heading should first be made. The design headings at which the mooring system responses are to be calculated should be determined with consideration of the mean equilibrium heading and low-frequency yaw motions. The procedure outlined in API RP 2SK (2008) can be used.

iii.) Time-domain Analyses

The following three methods as defined in Section 5.6.8 can be used for the time-domain mooring strength analysis:

- Fully coupled analysis approach
- Semi-coupled analysis approach
- Uncoupled analysis approach

In general, the fully coupled (integrated) analysis approach is recommended for the following two important advantages:

- Low-frequency damping from the hull structure, mooring lines and cables can be internally generated in the simulation; and

- Coupling between the floating support structure, the turbine RNA and control system, the stationkeeping system, and the cable system can be fully accounted for.

The fully coupled analysis approach requires a time-domain mooring analysis tool that is capable of solving the equations of motion for the combined responses of the floating support structure, the turbine RNA and control system, the stationkeeping system, and, if applicable, the cable system.

iv.) Combined Time-Domain and Frequency-Domain Analyses

In this approach, the mean and low frequency responses are typically simulated in the time domain to model the nonlinearity of the stiffness of the mooring lines and cables and the nonlinearity of the hull forces due to quadratic terms and yaw angle variations. Constant or variable thruster forces may also be modeled in the time domain. Transient responses resulting from line breaking or thruster failure may be evaluated by specifying the time of failure in the time-domain analysis. Unlike the full time-domain approach, evaluation of low frequency damping cannot be included as part of such simulations because of the absence of wave frequency components. Damping must be evaluated separately and treated as an input parameter.

Wave frequency hull motions are calculated separately in the frequency domain using the hull structure's motion RAOs and a given wave spectrum. These wave frequency motions may be combined with the low frequency motions in two ways:

- *Method 1*: The frequency-domain solution of wave frequency hull motions is first transformed to a time history, which is then superimposed to the mean and low frequency hull displacement time histories to obtain the combined hull displacement. In this process, the seed values for generating the wave frequency and low frequency time histories should be the same.
- *Method 2*: The mean and low frequency motions time histories are statistically analyzed to determine the peak values, which are then combined with the peak values of the wave frequency motions to calculate the maximum hull offset, as described in API RP 2SK (2008).

v.) Maximum and Minimum Tendon Tensions

For the TLP-type FOWTs, the tendon tension can be calculated either in the frequency domain or the time domain. In addition to wind, wave and current loads, tidal effects, and weight variations, the calculation of maximum and minimum tendon tensions should also account for the effect of foundation mis-positioning, individual tendon load sharing differential and tendon VIV. Reference is made to API RP 2T (2010) for further guidance. It is recommended that time-domain fully coupled (integrated) analyses be used to calculate maximum and minimum tendon tensions.

5.6.14.3 Recommended Time-domain Analysis Procedure

A recommended procedure for FOWT global performance analyses in the time domain is outlined below:

i.) Determine environmental criteria relevant to the global performance analysis of a specific FOWT stationkeeping system (see Section 5.4.3)

ii.) Determine the external electrical network conditions

iii.) Identify the mooring pattern, the characteristics of chain, wire, and fiber rope to be deployed, and the initial tension

iv.) Define corrosion and wear allowance of the chain and wire rope used in analysis

v.) Determine the tower dimensions, properties, modal shapes, and wind force coefficients

vi.) Define the RNA and control system configuration and create the models to be used in the simulation

vii.) Identify the start-up and shut-down procedures and the associated settings of turbine RNA and control system

viii.) Identify the fault conditions in the RNA and control system

ix.) Define the hull structure's wind and current force coefficients, and create the hydrodynamic model of the FOWT system including the hull structure, stationkeeping system and, if necessary, electrical cables *x.)* Perform time-domain simulations for the expected storm duration using a time-domain mooring analysis program and applying different seed values for generating the wave and wind time histories.

xi.) Perform statistical analyses to establish expected extreme values of hull offset, line tension, anchor loads, and grounded line length.

xii.) Check the extreme hull offset, line tension, anchor load, and grounded line length from step *xi.)* against the design criteria in Section 5.7.

5.6.14.4 Design Checks

Extreme line tension values should be checked against the design criteria in Section 5.7. Minimum breaking strength of the chain should be determined based on the diameter excluding the corrosion and wear allowance.

For the TLP-type FOWT, minimum tendon tension should be checked against the design criteria in Section 5.7.

5.6.14.5 Line Length and Geometry Constraints

Depending on the type of mooring system, the type of anchors and the mooring line material, a number of line length and geometry parameters should be evaluated and assessed for compliance with design criteria.

For catenary moorings with drag anchors not specifically designed to withstand uplift forces, the minimum length of each grounded line, i.e. the mooring line segment always resting on the sea floor, should be computed and compared with a design criterion to be prescribed on a site-specific basis.

For anchors designed to withstand uplift forces, compliance with appropriate design criteria applicable to that specific type of anchors should be verified.

For some types of mooring line, the grounded line is highly undesirable and, therefore, the portion of the line closest to the anchor is typically replaced by a chain. In such cases, the minimum elevation of the line-to-chain connection should be computed and verified against a minimum elevation criterion prescribed on a site-specific basis.

For some types of mooring lines, exposure to the splash zone or to friction against the fairleads is undesirable and, therefore, the upper portion of the line is typically replaced by a chain. In such cases, the position of the upper termination should be evaluated and compared with a minimum depth criterion prescribed on a site-specific basis.

For the mooring lines in proximity to other underwater and surface installations, additional clearance requirements and geometric constraints may apply. In such cases, displacements at particular points of concern should be verified against applicable design criteria or be prescribed on a site-specific basis.

Guidance on line length and geometry constraints for fiber rope mooring lines can be found in API RP 2SM (2007) and appropriate classification societies criteria, such as the ABS Guidance Notes on the Application of Fiber Rope for Offshore Mooring.

5.6.14.6 Anchor Forces

The highest mooring line tension obtained from the mooring analysis should in general be used to predict the maximum anchor force. Additional considerations should also be given to the case where a smaller mooring line tension acts in a less favorable direction. The results should be verified against the design criteria in Section 5.8, as applicable.

5.6.15 Mooring Fatigue Analysis

5.6.15.1 General

Typical fatigue analysis procedures are presented below. Alternative procedures may be used, provided they can be demonstrated to achieve at least the same level of reliability to those presented herein.

Miner's Rule can be used to determine accumulated fatigue damage. For main components of the mooring lines (i.e. chain, wire rope and connecting links), Miner's Rule may be implemented in terms of tension range (the T-N curve approach) as described below, or stress range (the S-N curve approach). For other structural components of the stationkeeping system, such as anchor pile details and attachments, the S-N approach is normally used.

T-N curves for chain and wire rope can be found in API RP 2SK (2008). Special considerations of fiber rope fatigue analysis can be found in API RP 2SM (2007) and appropriate classification society criteria, such as the ABS Guidance Notes on the Application of Fiber Rope for Offshore Mooring.

In addition to the tension-tension induced fatigue, the tension-bending induced fatigue for chain and wire rope should be properly considered according to recognized industry criteria such as API RP 2SK (2008).

As indicated in Section 5.3.14, corrosion and wear should be suitably considered in the fatigue analysis.

In the mooring fatigue analysis, due consideration should be given to the following aspects:

- Dynamic wind effects
- Dynamic wave effects
- Mooring line/tendon VIV, if applicable
- Transient effects due to the start-up and shut-down of the RNA
- Coupling effects among the subsystems of the FOWT
- Number of the RNA start-ups and shut-downs in the FOWT design life
- Duration of each operation such as installation, start-up, power production, shut-down, parked, etc. that contributes to the mooring fatigue damage

Either time- or frequency-domain dynamic analysis approaches may be applied for mooring tension range predictions. It is recommended time-domain coupled analyses along with rain-flow counting method be used in the mooring fatigue analysis. Alternatively, mooring tension ranges may be obtained from model testing.

In general, quasi-static analyses should not be used to calculate tension ranges due to its deficiency in estimating wave frequency mooring tensions.

Guideline for the mooring fatigue analysis can be found in API RP 2SK (2008), API RP 2SM (2007), and API RP 2T (2010). Appendix H of API RP 2SK (2008) and API RP 2T (2010) provide guidance on the hull VIM induced mooring fatigue.

5.6.15.2 T-N Curve

The fatigue life of a mooring line component is calculated by comparing the long-term cyclic loading in that component with its resistance to fatigue damage. For mooring systems, the T-N curve approach is used to determine the number of cycles to failure for a specific mooring component as a function of constant normalized tension range. The T-N curve for a specific type of mooring component is established based on experimental results.

The equation for a representative T-N curve is:

$$N \cdot T^{m} = K$$

where

N	=	number of permissible cycles of tension range ratio, T
T	=	ratio of tension range (double amplitude) to the reference breaking strength of the component (see the guidance given below)
m	=	inverse slope of the T-N fatigue curve
K	=	constant coefficient or mean load dependent coefficient

When determining the reference breaking strength of the mooring chain or connecting links, the diameter should be taken as the nominal diameter minus half of the corrosion and wear allowance. The reference breaking strength for a wire rope should be its minimum breaking strength (MBS).

5.6.15.3 Accumulated Fatigue Damage

The total annual fatigue damage is the sum of the fatigue damage arising in a set of design states chosen to discretize the long-term environmental and operational conditions that the mooring system is subjected to:

$$D = \sum_{i=1}^{i=k} D_i$$

where

D_i	=	annual fatigue damage of the component in the design state i

The Miner's Rule should be used to calculate the annual cumulative fatigue damage ratio D_i:

$$D_i = \sum \frac{n_i}{N_i}$$

where

n_i = number of cycles per year within the tension range interval i

N_i = number of cycles to failure under the normalized tension range i as determined by the T-N curve

The discretization into i =1,…,k design states should have a sufficient resolution to avoid any significant error due to the discretization. Each design state is defined in terms of the wind, wave, and current parameters and directions as well as the RNA operating condition required to compute the mooring system responses. The probability of occurrence, P_i, should be determined for each design state. The calculated fatigue life of the mooring system is:

$$L = 1 / D \text{ (years)}$$

The annual fatigue damage accumulated in each individual design state can be computed as:

$$D_i = \frac{n_i}{K} E\left[R_i^m\right]$$

where

m and K are defined in Section 5.6.15.2

n_i = number of tension cycles encountered in the state i per year

$E\left[R_i^m\right]$ = expected value of the normalized tension range R_i raised to the power of m in the design state i per year

The number of tension cycles per year in each design state is:

$$n_i = v_i T_i = v_i P_i \cdot 3.15576 \times 10^7$$

where

v_i = zero up-crossing frequency of the tension spectrum in the design state i, in Hz

T_i = time (portion of years) spent in the design state i per year

P_i = probability of occurrence of the design state i

The effects of pretension and environmental loads due to wind, wave and current as well as the RNA operating conditions should be considered when determining the normalized tension ranges. Total fatigue damage should be calculated with consideration of the fatigue damage from various fatigue load cases as described in Section 5.5.2. When suitably qualified, previously used mooring components are considered for re-use, fatigue damage from previous operations should be taken into account.

5.6.15.4 Time-domain Fatigue Analysis Method

The tension ranges are obtained from time series as the results of time-domain dynamic analyses. The number of cycles should be obtained based on the rain-flow counting method.

5.6.15.5 Frequency-domain Fatigue Analysis Method

The frequency-domain dynamic analysis method may be used in the fatigue analysis provided the nonlinear effects are properly linearized. For further guidance on fatigue analyses in the frequency domain, refer to API RP 2SK (2008) and API RP 2T (2010).

5.6.15.6 Tendon Fatigue Analysis

Either the S-N-curve-based fatigue analysis approach or the fracture mechanics analysis method can be used for tendon fatigue analysis. Total fatigue damage should be calculated by considering the fatigue damage from various fatigue load cases as presented in Section 5.5.2.

In addition to the conventional fatigue life calculation using scatter diagrams and the turbine's operational conditions, the tendon components should demonstrate robustness against low-cycle, high-stress fatigue due to more prolonged events that exceed the probabilistic predictions.

In order to assure a minimum level of robustness, tendon fatigue damage should be assessed for all components considering a single event based on the 50-year return extreme storm, including the ramp-up and ramp down before and after the storm. The duration to consider should be determined by the designer based on the data available and the response characteristics of the components. The unfactored damage accumulated during this event should be no more than 0.02.

Other 50-year return period events that may induce substantial tendon fatigue, such as the Loop Currents in the Gulf of Mexico, should also be considered in the same manner.

Damage calculated for single event fatigue should not be added to the damage predicted in the long-term scatter-diagram-based fatigue analysis, nor compared to the associated safety factors. The intent, as a robustness check, is to screen for components that may incur excessive fatigue damage in prolonged extreme environmental conditions

Fatigue analysis for tendon components should consider local load effects in addition to global loads. Reference is made to API RP 2T (2010) for more details for tendon fatigue analysis.

5.6.15.7 Fatigue Design Checks

The calculated fatigue life, which is 1/D, should be greater than the design life multiplied by a fatigue design factor (FDF) defined in Section 5.7.

5.6.16 Recommendations for Numerical Simulations

5.6.16.1 General

In numerical simulations of global performance analyses, correct settings of the following parameters are crucial in order to obtain reliable results:

- Time step
- Transient time or ramp time
- Grid size and range for wind field data generation
- Number of wave components for generating random waves
- For the deterministic events, the onset time of the events
- For the stochastic events, the number of simulations with different random seeds and the time duration of each simulation
- For fatigue sea states, the discretization of fatigue bins
- Setting of the control system, generator, blade pitch, nacelle yaw, rotor azimuth angle, rotor speed and degrees-of-freedoms for drive train, tower and blade flexibilities for different turbine operating or parked conditions
- Parameters for the aerodynamic load calculation, especially the tower shadow model and the static or dynamic stall models
- Wind average speed, turbulence intensity, wind shear for different wind models used in the wind field data generation

Convergence test should be performed to determine:

- time steps in time-domain simulations;
- grid size and range for wind field; and
- number of wind, wave components and seed numbers.

Sensitivity analysis may be performed to determine the discretization of the fatigue bins.

For load cases involving start-up and shut-down of the RNA, analysis procedure should be consistent with the actual operational procedure of the RNA.

5.6.16.2 Time Step

Choice of time step is crucial for the stability and accuracy of time-domain solution, and is often dependent on the periods of the responses, degree of nonlinearity, and analysis formulation. Time step should be determined by a sensitivity check.

5.6.16.3 Initial Transient Response

The length of a time-domain simulation must allow for transient responses during the initial part of the simulation. The time required for dissipating transient responses is normally a function of the period and damping of the response.

Since initial conditions used for the dynamic analysis could affect the statistics of the response during the starting part of the simulation time duration, the first 5 seconds to 10 minutes (or longer, if necessary, depending on the period and damping of the response) of time history data should be discarded when stochastic wind and/or wave are applied.

5.6.16.4 Wind Generation and Grid Size

10-minute, 1-hour or 3-hour simulation time duration may be used in numerical simulations for the different DLCs (see Section 5.6.16.7). Since statistical values of wind conditions are normally based on 10-minute averaging time duration, input wind conditions should be adjusted for 1-hour and 3-hour numerical simulations in order to achieve statistical equivalence. In the absence of site-specific data for the wind conditions with an averaging time duration other than 10 minutes, Table 5.4 may be used to calculate the mean wind speed and turbulence intensity at hub height for 1-hour and 3-hour simulations by adjusting the 10-mintue wind conditions at hub height.

Table 5.4 Conversion of Wind Conditions with Different Averaging Time Durations

Simulation Time Duration	*10 minutes*	*1 hour*	*3 hours*
Correction factor applied to the 10-minute mean wind speed	1.00	0.95	0.90
Correction applied to the 10-minute turbulence intensity	1.00	σ_{10min}+0.2m/s	case-by-case

Notes:
1. Conversions are applied to the hub height wind conditions.
2. Correction for the turbulence intensity is valid for the wind spectra recommended in IEC 61400-3 (2009). For the API (NPD) wind spectrum, see Section 5.4.4.4.

When using the IEC-recommended wind spectrum to perform a 3-hour simulation, the following methods are recommended to generate wind field data:

- Method 1: use 1-hour mean wind speed and turbulence intensity to generate time series of a turbulent wind field for 3 hours
- Method 2: use 3-hour mean wind speed and adjust the turbulence intensity (or use site measurement data) to generate time series of turbulent wind filed for 3 hours such that the resultant maximum wind loads or load effects match those obtained using either 10-minute or 1-hour simulations.

The correction relative to the 10-minute turbulence intensity, as shown in Table 5.4, is applicable to the wind spectra recommended in IEC 61400-3 (2009). When the API (NPD) wind spectrum is used, the correction factor of the 1-hour average wind speed relative to 10-minute average wind speed still applies, but the turbulence intensity is a function of the 1-hour wind speed and is embedded in the wind spectrum formulation. When the API wind spectrum is used in 3-hour simulations, the mean wind speed and turbulence intensity may be taken the same as those used in 1-hour simulations.

The wind generation should consider the 3D effects. Sensitivity analysis may be required to determine an appropriate grid size of the 3D wind field.

5.6.16.5 Simulation of Wave Conditions

10-minute, 1-hour or 3-hour simulation time duration may be used in numerical simulations for the different DLCs (see Section 5.6.16.7). Since statistic values of wave conditions are normally based on 3-hour time window, input wave conditions should be adjusted for 10-minute and 1-

hour numerical simulations in order to achieve statistical equivalence. In absence of site-specific data, the conversion factors of 10-minute and 1-hour significant wave height relative to 3-hour wave conditions may follow Table 5.5.

Table 5.5 Conversion of the Significant Wave Height

Simulation Time Duration	*10 minutes*	*1 hour*	*3 hours*
Correction factor applied to the significant wave height *Hs*	1.00 (for using the constrained wave method; or 18 simulations otherwise)	1.09	1.0

For 10-minute simulations, the wave height is not factored. In order to obtained the same level of extreme value as 3-hour simulations, 18 simulations (a total of 3-hour length) with different seeds should be performed and maximum wave height is taken as maximum of 18 simulations. If the constrained wave method is used, the seed number may be reduced. The applicability of the constrained wave method should be verified with 3-hour simulations. The advantage of using 10-mintue simulations is that the wind conditions do not need the adjustment.

The number and range of discrete frequencies representing the hull transfer functions should be carefully chosen to cover the peaks in the transfer functions and the area of significant wave excitations. It is also important to identify how the employed computer program handles possible excitations outside the frequency range of the hull transfer functions since this can be a source of error. Small frequency spacing may be required to avoid repeating a time history within one simulation. Variable frequency spacing may also be used, but the repetition period of the time history is more difficult to assess. The number, range, and spacing of discrete frequencies should be determined and verified by sensitivity analyses.

5.6.16.6 Flexibility of RNA and Tower

For the tower, rotor blades and drive train, the mass distribution, stiffness, natural frequencies and damping used for the calculation should be specified. In general, the DOFs of the tower, rotor blades, and drive train should be modeled in accordance with Table 5.6, as a minimum.

The stability analysis normally is performed in the design of the RNA. This stability analysis should be used to assist in determining the modes that are important to the load calculations in global performance analyses.

Table 5.6 Minimum DOFs of Flexibility of the RNA and the Tower

Components	*DOFs*
Tower	1st and 2nd fore-aft and side-to-side bending modes If necessary, 1st torsional mode should be included.
Each Blade	1st edge-wise, 1st and 2nd flap-wise modes If necessary, torsional modes should be included.
Drive train	1st torsional mode

5.6.16.7 Simulation Length and Seed Number

For the design of floating offshore oil and gas platforms, 3-hour duration is often used for model testing and time-domain global performance analyses. This duration is generally sufficient for calculating the standard deviation of wave frequency responses because it represents about 1,000 cycles of response with a natural period of around 10 seconds. Low-frequency responses of floating systems, however, typically have natural periods on the order of several minutes. A 3-hour simulation may contain less than 50 cycles of a low frequency response and therefore is insufficient to provide a good statistical confidence to the calculated standard deviation. The required simulation time duration may even be longer for predicting extreme values of responses – in order to obtain statistically meaningful wave-frequency extreme responses, for instance, several 3-hour simulations may be needed.

An acceptable length of global performance simulation time duration depends on many factors, such as natural periods of wave- and low-frequency responses, contribution of wave- and low-frequency responses to the total response, degree of nonlinearity, system damping, etc. The simulation time duration should be determined and verified by sensitivity check. Recent studies indicate that, for typical floating oil and gas platforms in deep water, five to ten 3-hour simulations with different random seed numbers (equivalent to a continuous 15 to 30 hours simulation) may be needed in order to obtain standard deviations and extreme values of responses of good confidence.

For the design load conditions defined in Section 5.5.2, the time histories of turbulent wind and irregular wave conditions should be long enough to ensure statistical reliability of the estimate of the characteristic responses. In general, at least six 10-minute stochastic realizations (or a continuous 1-hour realization) should be generated for each turbulent wind condition and sea state considered in the simulations. Additional requirements as given below should also be satisfied:

- For the DLC 1.2, 1.3, 1.4, 1.5, 2.x, 3.x, 4.x, 5.1, as defined in Table 5.1, at least eighteen 10-miniute stochastic realizations should be generated for each wind condition and sea state considered in the simulations. This requirement may be relaxed and fewer realizations may be acceptable if the designer can demonstrate that the estimated extreme response is not less than that obtained with 3-hour realizations or a total of 3 hours of realizations.
- For the DLC 1.6, 6.1, 6.2, 6.3 and 7.1 and the SLCs, as defined in Table 5.1 and Table 5.2, at least six 1-hour stochastic realizations should be generated for each turbulent wind and sea state considered in the simulations. Six 3-hour simulations are recommended for the DLC 6.1, 6.2, 6.3 and 7.1 and the SLCs when the RNA is in the parked conditions. This requirement may be relaxed and shorter realizations may be assumed if the designer is able to demonstrate that the estimated extreme response is not less than that obtained with 1-hour or 3-hour realizations.

The values of mean wind speed, turbulence standard deviation and significant wave height referenced in the DLCs and the SLCs requiring dynamic simulations should be appropriate to the chosen simulation time duration. More specifically:

- For the DLC 1.6, 6.1, 6.2, 6.3 and 7.1 and the SLCs, as defined in Table 5.1 and Table 5.2, the values of mean wind speed, turbulence standard deviation and significant wave height should be adjusted for different simulation time durations in accordance with Section 5.6.16.4 and Section 5.6.16.5.
- For the load cases using 10-minute simulations, at least 18 simulations (a total of 3 hours) should be performed. No conversion is needed provided the wind conditions are based on a 10-mintue averaging time duration.

The recommended simulation time duration and random seed number for each DLC are summarized in Table 5.7. The statistical values for different load cases can be obtained as follows:

- For the DLC 1.4, 1.5, 2.1, 2.2, 2.3, 3.2, 3.3, 4.2, 4.3, and 5.1 with the occurrence of events such as fault, extreme wind gust, start-up, shut down, etc., the maximum value of a response should be determined based on the transient value computed in the worst case. The occurrence of the event can be at any moment during the simulation.

- For the DLC 1.3 with the turbulent wind together with irregular sea states, among all combinations of wind and wave conditions, the largest mean value of the top 1/3 of maximum responses of stochastic realizations should be taken.
- For the DLC 1.6, 6.1, 6.2, 6.3 and 7.1 with the turbulent wind together with irregular sea states, among all combinations of wind and wave conditions, the largest mean value of maximum responses of stochastic realizations should be taken.

Table 5.7 Recommended Simulation Time Duration and Seed Number for the DLCs

Turbine Condition	*DLC*	*Type of Analysis*	*Simulation Time Duration and Seed Number*
1) Power production	1.2	F	10-minute simulation with 18 seeds
	1.3	S	10-minute simulation with 18 seeds
	1.4	S	10-minute simulation with 18 seeds
	1.5	S	10-minute simulation with 18 seeds
	1.6	S	1-hour simulation with 6 seeds
2) Power production plus occurrence of fault	2.1	S	10-minute simulation with 18 seeds
	2.2	S	10-minute simulation with 18 seeds
	2.3	S	10-minute simulation with 18 seeds
	2.4	F	10-minute simulation with 18 seeds
3) Start-up	3.1	F	10-minute simulation with 18 seeds
	3.2	S	10-minute simulation with 18 seeds
	3.3	S	10-minute simulation with 18 seeds
4) Normal shutdown	4.1	F	10-minute simulation with 18 seeds
	4.2	S	10-minute simulation with 18 seeds
	4.3	S	10-minute simulation with 18 seeds
5) Emergency shutdown	5.1	S	10-minute simulation with 18 seeds
6) Parked (standing still or idling)	6.1	S	1-hour or 3-hour simulation with 6 seeds
	6.2	S	1-hour or 3-hour simulation with 6 seeds
	6.3	S	1-hour or 3-hour simulation with 6 seeds
	6.4	F	-
7) Parked and fault conditions	7.1	S	1-hour or 3-hour simulation with 6 seeds
	7.2	F	-
8) Temporary (installation, maintenance and repair)	8.1	S	-
	8.2	S	-
	8.3	F	-

5.6.16.8 Analysis Methods and Tools

The recommended analysis methods, especially for the final detailed design, are summarized in Table 5.8 for the DLCs in Table 5.1. The recommended analysis method for SLCs in Table 5.2 may follow those for the DLC 6.1. Although the time-domain fully coupled (integrated) dynamic analysis method is recommended, other global performance analysis software with less sophistication may still be used. In general, less sophisticated tools may be used in preliminary design stages.

Most existing FOWT global performance analysis software is based on the time-domain aero-hydro-servo-elastic coupled analysis approach. The simulation software is normally developed by combining aero-elastic codes originally developed for land-based turbines with hydrodynamic codes and mooring dynamic codes used for designing offshore oil and gas platforms. A typical aero-elastic code contains an aerodynamic part, which is mostly based on Blade Element Momentum (BEM) Method, and a structural part with various levels of complexity in modeling the drive train and elasticity of the blade and the tower. Control system modeling is usually designed by users and linked to the aero-elastic codes through a dynamic link library. Some simulation software models the mooring system quasi-statically rather than dynamically.

Table 5.8 Recommended Analysis Methods for the DLCs

Turbine Condition	*DLC*	*Type of Analysis*	*Analysis Methods*
1) Power production	1.2	F	Time-domain fully coupled analysis
	1.3	S	Time-domain fully coupled analysis Frequency-domain analysis in preliminary design stage
	1.4	S	Time-domain fully coupled analysis
	1.5	S	Time-domain fully coupled analysis
	1.6	S	Time-domain fully coupled analysis Frequency-domain analysis in preliminary design stage
2) Power production plus occurrence of fault	2.1	S	Time-domain fully coupled analysis
	2.2	S	Time-domain fully coupled analysis
	2.3	S	Time-domain fully coupled analysis
	2.4	F	Time-domain fully coupled analysis
3) Start-up	3.1	F	Time-domain fully coupled analysis
	3.2	S	Time-domain fully coupled analysis
	3.3	S	Time-domain fully coupled analysis
4) Normal shutdown	4.1	F	Time-domain fully coupled analysis
	4.2	S	Time-domain fully coupled analysis
	4.3	S	Time-domain fully coupled analysis
5) Emergency shutdown	5.1	S	Time-domain fully coupled analysis
6) Parked (standing still or idling)	6.1	S	Time-domain fully coupled analysis, or Frequency-domain analysis with dynamic effects, if applicable
	6.2	S	Time-domain fully coupled analysis, or Frequency-domain analysis with dynamic effects, if applicable
	6.3	S	Time-domain fully coupled analysis, or Frequency-domain analysis with dynamic effects, if applicable
	6.4	F	Time-domain fully coupled analysis, or Frequency-domain analysis with dynamic effects, if applicable
7) Parked and fault conditions	7.1	S	Time-domain fully coupled analysis, or Frequency-domain analysis with dynamic effects, if applicable
	7.2	F	Time-domain fully coupled analysis, or Frequency-domain analysis with dynamic effects, if applicable
8) Temporary (installation, maintenance and repair)	8.1	S	-
	8.2	S	-
	8.3	F	-

5.7 Strength and Fatigue Design Criteria of Mooring Lines and Tendons

5.7.1 General

Conventional stationkeeping systems for floating offshore oil and gas platforms include spread mooring, single point mooring, thruster-assisted systems and dynamic positioning systems (see API RP 2SK, 2008). The stationkeeping system for a TLP is commonly referred to as tendon systems (see API RP 2T, 2010). In the existing design of FOWTs, spread mooring systems and tendon systems, or the combination of both, have been adopted, depending on the type of floating support structures.

This section outlines general design considerations and acceptance criteria to be incorporated in the design of the stationkeeping system of an FOWT. The main focus of this section is placed on spreading mooring systems and tendon systems.

General guidance on the design and analysis of the stationkeeping system can be referred to API RP 2SK (2008), ISO 19901-7 (2005) and API RP 2T (2010), as well as appropriate classification society criteria. For the stationkeeping system using synthetic ropes, additional design considerations can be found in API RP 2SM (2007) and appropriate classification society criteria.

For innovative designs of the FOWT stationkeeping system or the components or equipment of the stationkeeping system that do not have proven application records, the application of this guideline or other relevant existing industry standards should be subject to case-by-case evaluation.

5.7.2 Loading Conditions

5.7.2.1 Design Load Cases

The design load cases for the strength and fatigue life assessment of the FOWT stationkeeping system should be in accordance with Section 5.5.2.2.

5.7.2.2 Survival Load Cases

The FOWT stationkeeping system should be designed to withstand the survival load cases, as specified in Section 5.5.2.3, without compromising its intended functions.

5.7.3 Design Conditions

5.7.3.1 Intact Condition

Intact Condition is the design condition of FOWT stationkeeping systems, where all components of the system are intact while the FOWT is exposed to the design load conditions (see Section 5.5.2).

5.7.3.2 Damaged Condition (with One Broken Mooring Line)

Damaged Condition is the design condition of FOWT stationkeeping systems, where any one of mooring lines is assumed to have been broken while the FOWT is subjected to the design load conditions (see Section 5.5.2). The floating support structure is assumed to oscillate around a new equilibrium position determined after taking into account the effect of a broken mooring line.

Breakage of the mooring line that sustains the maximum load in the intact condition might not lead to the worst broken mooring line case. The designer should determine the worst case by analyzing several scenarios of broken mooring line, including lead line broken and adjacent line broken cases.

Damaged Condition does not apply to the non-redundant stationkeeping system.

5.7.3.3 Transient Condition (with One Broken Mooring Line)

Transient Condition is the design condition of FOWT stationkeeping systems, where breakage of a mooring line (usually the lead line) causes the moored floating support structure to exhibit transient motions (overshooting) before it settles at a new equilibrium position.

The transient condition can be an important design consideration when a suitable clearance between the moored floating support structure and nearby structures is required. Global performance analyses for this transient condition subjected to the design load case associated with extreme design storm conditions, as defined by DLC 6.2 (see Section 5.5.2), should be performed. The effect of increased line tensions due to overshoot upon failure of one mooring lines should also be considered.

Transient Condition does not apply to the non-redundant stationkeeping systems.

5.7.4 Design Life

The minimum design life of the FOWT stationkeeping system should be determined in accordance with Section 5.3.3.

5.7.5 Analysis Methods

Global performance analyses for the purpose of designing FOWT stationkeeping systems should be in compliance with Section 5.6. The employed dynamic analysis method should suitably account for characteristics of dynamic responses of the FOWT.

Fatigue analyses should follow the procedure outlined in API RP 2T (2010) for tendon mooring and API RP 2SK (2008) for other types of mooring systems. The fatigue life of each mooring/tendon line component should be considered. Fatigue design curves for various line components should be based on fatigue test data and a regression analysis, or the recommended design curves in API RP 2SK (2008), API RP 2SM (2007), or appropriate classification society criteria, as deemed applicable.

5.7.6 Design Criteria for Steel Mooring Lines and Tendons

The mooring lines or tendons should be designed with safety factors not less than those specified in Table 5.9 and Table 5.10, with respect to the minimum breaking strength and fatigue characteristics of the mooring line or the tendon, respectively. These safety factors are dependent on the loading conditions as well as the design conditions and the redundancy of the stationkeeping system.

Fatigue damage in the tendons due to a single extreme event, as described in Section 5.6.15.6, should not be combined with the fatigue damage accumulation incurred by long-term environmental and operational loading. Reference is made to API RP 2T (2010) for further guidance.

Allowances for corrosion and abrasion of a mooring line should be taken into consideration in accordance with Section 5.3.14, Section 5.6.14 and Section 5.6.15 of this guideline as well as Section 3.1 of API RP 2SK (2008).

Table 5.9 Safety Factors for Steel Mooring Lines and Tendons

Loading Condition	*Redundancy of the Stationkeeping System*	*Design Condition of the Stationkeeping System*	*Safety Factor*
Design Load Cases	Redundant	Intact	1.67
		Damaged condition with one broken mooring line	1.05
		Transient condition with one broken mooring line (for DLC 6.2)	1.05
	Non-redundant	Intact	2.0
Survival Load Cases	Redundant or Non-redundant	Intact	1.05

Notes:

1. Dynamic mooring analyses should be performed in either the frequency domain or the time domain, or the combination of both.
2. Safety factors should be applied to the minimum breaking strength (MBS) of the mooring line.
3. Additional strength design criteria for tendons made up of steel tubulars are to comply with API RP 2T.
4. Requirements of tendon minimum tension check are to comply with API RP 2T in conjunction with the Design Load Cases and the Survival Load Cases as specified in Section 5.7.2.

Table 5.10 Safety Factors (Fatigue Design Factors) for Fatigue Life of Steel Mooring Lines and Tendons

Redundancy of the Stationkeeping System	*Inspectable and Repairable*	*Fatigue Design Factors*
Redundant	Yes	2
	No	5
Non-redundant	Yes	3
	No	10

5.7.7 Design Criteria for Synthetic Fiber Ropes

The design load cases for the strength and fatigue life assessments of the stationkeeping system using synthetic fiber ropes as mooring lines should be in accordance with Section 5.5.2.

The strength design should satisfy the requirements in the API RP 2SM (2007) or appropriate classification society criteria. For the non-redundant stationkeeping system, a 20% increase should be applied to those safety factors of strength design criteria for the redundant stationkeeping system under the intact design condition.

The fatigue life of synthetic fiber ropes used as mooring lines subjected to tension-tension cyclic loads should not be less than the design life of the stationkeeping system times the fatigue design factors (FDFs) specified in Table 5.10. Additional design requirements regarding creep and compressive fatigue should be in accordance with the API RP 2SM (2007) or appropriate classification society criteria.

For the robustness check of the strength of the mooring lines made of synthetic fiber ropes using the survival load cases, the safety factor should be at least 1.05.

For a synthetic fiber rope connected with a torque steel wire rope, the torque match should satisfy the applicable requirement as specified in the API RP 2SM (2007) or appropriate classification society criteria.

5.8 Stationkeeping System Hardware and Material Selection Criteria

5.8.1 General

Typical stationkeeping system components and equipment for the FOWT may include winches, windlasses, chain, wire rope, fiber rope, clump weight, in-line buoys, fairleads and chain stoppers. The foundation components for the stationkeeping system may include drag anchors, pile anchors, vertically loaded anchors (VLAs) or suction piles. Gravity boxes, grouted piles, templates, etc., may also be used.

The design of these components and equipment should be in accordance with API RP 2SK (2008), API RP 2SM (2007), API RP 2T (2010), ISO 19901-7 (2005) and appropriate classification society criteria, as well as other recognized industry standards. The design load cases for the strength and fatigue analysis of the stationkeeping system should be in accordance with Section 5.5.2.2. The robustness check using the survival load cases as specified in Section 5.5.2.3 should also be performed.

For the non-redundant stationkeeping system, a 20% increase should be applied to those safety factors of strength design criteria defined for components of the redundant stationkeeping system under the intact design condition.

Material, design, manufacture, and testing requirements for mooring line components such as wire rope, chain, synthetic fiber rope, in-line (spring) buoy and connecting link are given in Section 5.8.2. Design requirements for anchors can be found in Section 5.8.3. Requirements for other stationkeeping system components and equipment can be found in Section 5.8.4.

5.8.2 Mooring Line Components

5.8.2.1 General

Specifications and conditions of the mooring components should be in accordance with those assumed or required by the mooring analysis.

5.8.2.2 Wire Rope

Material, design, manufacture, and testing requirements of wire ropes and connecting hardware can be found in the following documents:

- API Spec 9A, Specification for Wire Rope
- API RP 9B, Recommended Practice for Application, Care, and Use of Wire Rope for Oil Field Service
- Appropriate classification society criteria for wire ropes

5.8.2.3 Chain and Accessories

Material, design, manufacture, and testing requirements of mooring chains and accessories can be found in the following documents:

- API Spec 2F, Specification for Mooring Chain
- Appropriate classification society criteria for offshore mooring chains

5.8.2.4 Fiber Rope

Material, design, manufacture, and testing requirements of fiber ropes and connecting hardware can be found in the following docuemtns:

- API RP 2SM, Recommended Practice for Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring
- Appropriate classification society criteria for offshore mooring fiber ropes

5.8.2.5 Clump Weight

Clump weights are sometimes incorporated into mooring legs to improve performance or reduce cost. By providing a concentrated weight to the mooring leg at a point close to the seabed, a clump weight can be used to replace a portion of chain and increase the restoring force of a mooring leg. Using clump weights in a mooring design requires careful consideration of potentially adverse effects, such as increased use of connecting hardware and installation complexity, undesirable dynamic response of the mooring line, and embedment of the clump weight in the seabed. In some mooring designs, heavy chain segments are used in place of clump weight for easy installation and lower cost.

Design of clump weight should meet the functional requirements of the stationkeeping system.

5.8.2.6 In-line (Spring) Buoy

In-line buoys are typically constructed from steel or synthetic materials. They should be rated for the maximum buoy submergence depth derived for the mooring system intact and one-line damage analysis. The maximum safe working depth for in-line buoys should be based on analyses and/or testing using applicable and recognized design and manufacturing codes. Further guideline for design of in-line (spring) buoy can be found in:

- API RP 2SK, Recommended Practice for Design and Analysis of Stationkeeping Systems for Floating Structures
- ISO 19901-7, Stationkeeping Systems for Floating Offshore Structures and Mobil Offshore Units

5.8.3 Anchoring Systems

5.8.3.1 General

Various options are available for anchoring the FOWT by using:

- drag anchors;
- anchor piles (driven, jetted, suction, drilled, grouted or dynamically installed); and
- other anchor types such as gravity anchors and plate anchors.

When selecting anchor options, consideration should be given to required system performance, soil conditions, reliability, installation feasibility and test load application. The structural strength of an anchor should be demonstrated to be adequate with respect to the required foundation capacities.

Recommended design criteria for drag anchors, conventional pile anchors, vertically loaded drag anchors (VLAs), suction piles, suction embedded plate anchors (SEPLA) and dynamically installed pile anchors (torpedo piles) are given in this section.

5.8.3.2 Drag Anchor

For a catenary mooring system with drag anchors, the mooring line length should be sufficiently long such that there is in general no uplift angle between the mooring line and the sea floor in any design condition, as described in Section 5.7. For soft clay condition, a small angle for the intact condition in extreme storms or the damaged condition with one broken line may be considered on a case-by-case basis.

Drag anchor holding power depends on the anchor type, as well as the anchor deployment conditions such as penetration of the flukes, opening of the flukes, depth of burial, stability of the anchor during dragging, soil behavior with the flukes, etc. The designer should evaluate the performance data for a specific anchor type and site-specific soil conditions for the estimation of the ultimate holding capacity (UHC) of an anchor design. Because of uncertainties and wide variations of anchor characteristics, exact holding power should be determined after the anchor is deployed and load tested.

The anchor load, F_{anchor}, should be calculated as follows for the cases where a single line has constant W_{sub} and without buoys or clump weights. Appropriate adjustments are required for other cases. The maximum anchor load should be determined by evaluating all design conditions described in Section 5.7. The safety factors for the holding capacity of a drag anchor are specified in Table 5.11. For anchors used in a non-redundant stationkeeping system, a 20% increase should be applied to the safety factor required for the redundant system using the same type of anchors and under the intact design condition.

$$F_{anchor} = P_{line} - W_{sub} D_{water} - F_{friction}$$
$$F_{friction} = f L W_{sub}$$

where

F_{anchor}	=	anchor load, in N (lb)
P_{line}	=	mooring line tension at any design condition, in N (lb)
W_{sub}	=	submerged unit weight of the mooring line, in N/m (lb/ft)
D_{water}	=	water depth, in m (ft)
$F_{friction}$	=	holding power of the mooring line on the sea floor, in N (lb)
f	=	coefficient of friction of the mooring line on the sea floor, (dimensionless)
L	=	length of the mooring line on the sea floor, not to exceed 20 percent of the total length of a mooring line, in m (ft)

The coefficient of friction, f, depends on the soil condition and the type of mooring line. For soft mud, sand and clay, the values of f recommended by API RP 2SK for wire ropes and chains are listed in Table 5.12. The static (starting) friction coefficients are normally used to determine the holding power of the mooring line on the sea floor, while the sliding friction coefficients are normally used to compute the friction force on the mooring line during mooring deployment.

Table 5.11 Safety Factors for Drag Anchor Holding Capacity

Loading Condition	*Redundancy of the Stationkeeping System*	*Design Condition of the Stationkeeping System*	*Safety Factor*
Design Load Cases	Redundant	Intact	1.5
		Damaged condition with one broken mooring line	1.0
		Transient condition with one broken mooring line	N/A
	Non-redundant	Intact	1.8
Survival Load Cases	Redundant or Non-redundant	Intact	1.05

Table 5.12 Coefficient of Friction of the Mooring Line on the Sea Floor

	Coefficient of Friction, f	
	Static	*Sliding*
Chain	1.00	0.70
Wire Rope	0.60	0.25

5.8.3.3 Vertically Loaded Drag Anchor (VLA)

VLAs can be used in a taut line mooring system with an angle of approximately 35 to 45 degrees between the sea floor and the mooring line. These anchors are designed to withstand both vertical and horizontal loads imposed by the mooring line. The design documentation should include the ultimate holding capacity and the anchor's burial depth beneath the sea floor. Additionally, strength and fatigue assessment of the anchor and the connectors joining the VLA to the mooring line should be performed.

The safety factors of VLA anchors' holding capacity are specified in Table 5.13.

Table 5.13 Safety Factors for Vertically Loaded Drag Anchor (VLA) Holding Capacity

Loading Condition	*Redundancy of the Stationkeeping System*	*Design Condition of the Stationkeeping System*	*Safety Factor*
Design Load Cases	Redundant	Intact	2.0
		Damaged condition with one broken mooring line	1.5
		Transient condition with one broken mooring line	N/A
	Non-redundant	Intact	2.4
Survival Load Cases	Redundant or Non-redundant	Intact	1.05

5.8.3.4 Conventional Pile

Conventional pile anchors are capable of withstanding uplift and lateral forces at the same time. Strength and fatigue assessment of the pile anchor structure should be performed. The analyses for different types of soil using soil resistance and deflection (*p-y*) curves should follow the API RP 2A, API RP 2SK, API RP 2T, or appropriate classification society criteria.

The safety factors for the holding capacity of a conventional pile anchor are specified in Table 5.14.

Table 5.14 Safety Factors for Pile Anchor Holding Capacity

Loading Condition	*Redundancy of the Stationkeeping System*	*Design Condition of the Stationkeeping System*	*Safety Factor*
Design Load Cases	Redundant	Intact	Refer to API RP 2T for the tendon foundation or API RP2 SK otherwise
		Damaged condition with one broken mooring line	Refer to API RP 2T for the tendon foundation or API RP2 SK otherwise
		Transient condition with one broken mooring line	Refer to API RP 2T for the tendon foundation
	Non-redundant	Intact	20% increase in the safety factor required for the redundant system using the same type of anchors and under the intact design condition
Survival Load Cases	Redundant or Non-redundant	Intact	1.05

5.8.3.5 Suction Pile

Suction pile anchors are caisson foundations that are penetrated to a target depth by pumping out water inside the pile to create under-pressure within the pile. Suction piles generally have larger diameters and are shorter in length than conventional piles. A suction pile typically consists of a stiffened cylindrical shell with a cover plate at the top and an open bottom. A suction pile can be designed to have a permanent top or a retrievable top depending on the required vertical holding capacity. The padeye for the mooring line connection can be at the top or at an intermediate level depending on the application of a suction pile.

Suction pile anchors are capable of withstanding uplift and lateral forces. Because of the distinctive geometry of suction piles, soil failure modes may be different than those applicable to long slender conventional piles.

Geotechnical holding capacity and structural adequacy of the suction pile should be determined to demonstrate its adequacy to withstand in-service and installation loads. Fatigue assessment of the suction pile should also be performed.

The recommended safety factors for the suction pile holding capacity are given in Table 5.15. Additionally, installation analyses should verify that the suction pile can achieve the design penetration and that the suction pile can be retrieved, if necessary. It is suggested that a ratio of at least 1.5 between the force that would cause uplift of the soil-plug inside the pile and the effective pile installation force be considered in the penetration analysis.

Table 5.15 Safety Factors for Suction Pile Holding Capacity

Loading Condition	*Redundancy of the Stationkeeping System*	*Design Condition of the Stationkeeping System*	*Safety Factor*
Design Load Cases	Redundant	Intact	1.5 to 2.0* For the tendon foundation, refer to API RP 2T
		Damaged condition with one broken mooring line	1.2 to 1.5* For the tendon foundation, refer to API RP 2T
		Transient condition with one broken mooring line	Refer to API RP 2T for the tendon foundation
	Non-redundant	Intact	20% increase in the safety factor required for the redundant system using the same type of anchors and under the intact design condition
Survival Load Cases	Redundant or Non-redundant	Intact	1.05

Notes:

* The safety factor to be used in the design should be based on the extent of the geotechnical investigation, confidence in the prediction of soil-pile behavior, experience with the design and behavior of suction piles in the area of interest, and the inclination of the mooring line load.

5.8.3.6 Suction Embedded Plate Anchor (SEPLA)

SEPLAs and VLAs are all considered as plate anchors, which can be broadly categorized into drag embedded and direct embedded plate anchors. Same as VLAs, SEPLAs can be used in a taut line mooring system with an angle of approximately 35 to 45 degrees between the sea floor and the mooring line. SEPLA's fluke is embedded in a vertical position. Adequate fluke rotation is achieved during a keying process by pulling on the mooring line.

SEPLAs are designed to withstand both the vertical and horizontal loads imposed by the mooring line. The design documentation should include the ultimate holding capacity and the anchor's burial depth beneath the sea floor. Additionally, strength and fatigue assessment of the anchor and the connectors joining the SEPLA to the mooring line should be performed.

The safety factors of SEPLA anchors' holding capacity are specified in Table 5.16.

Table 5.16 Safety Factors for Suction Embedded Plate Anchor (SEPLA) Holding Capacity

Loading Condition	*Redundancy of the Stationkeeping System*	*Design Condition of the Stationkeeping System*	*Safety Factor*
Design Load Cases	Redundant	Intact	2.0
		Damaged condition with one broken mooring line	1.5
		Transient condition with one broken mooring line	N/A
	Non-redundant	Intact	2.4
Survival Load Cases	Redundant or Non-redundant	Intact	1.05

5.8.3.7 Dynamically Installed Pile Anchor (Torpedo Pile)

Torpedo pile anchors are capable of withstanding uplift and lateral forces at the same time. Strength assessment of the pile anchor structure should be performed. Fatigue assessment may also be required in particularly for the mooring or tendon line attachment padeye or lug. The holding capacity of a torpedo pile anchor should in general be determined by direct analyses using Finite Element Method with consideration of three-dimensional pile-soil interactions. When the pile includes fins and/or appendages to increase its holding capacity, an equivalent pile diameter appropriate for the loading direction may be derived for the holding capacity analysis. When calculating the ultimate capacity of the pile, the pile axial deformation should in general not exceed 10% of the pile diameter or, if applicable, the equivalent pile diameter. In addition, the lateral deformation should in general not exceed 10% of the pile's main body width/diameter. The safety factors for holding capacity are the same as those specified in Table 5.14 for conventional piles.

5.8.3.8 Field Test

After a mooring system is deployed, each mooring line should in general be test loaded in accordance with Section 7.4.3 of API RP 2SK. For all types of anchors, the attainment of design-required minimum soil penetration depth should be verified at the site.

5.8.4 Other Components and Equipment

Chain and accessories, wire rope, and fiber rope design requirements are addressed in Section 5.8.2. Anchor design criteria are addressed in Section 5.8.3. Other stationkeeping system components and equipment should be in accordance with appropriate classification society criteria or recognized industry standards. The design load conditions for the strength and fatigue analysis of the stationkeeping system components should be in accordance with Section 5.5.2. For the chain stopper, fairlead or tendon porch and its connection to the floating support structure, the design load is normally taken as the breaking strength of the mooring line or tendon.

For the non-redundant stationkeeping system, a 20% increase should be applied to those safety factors of strength design criteria defined for components of the redundant stationkeeping system under the intact design condition.

For the robustness check of strength using the survival load cases (see Section 5.7.2), the safety factor should be at least 1.05.

The fatigue life of the chain stopper, fairlead or tendon porch and its connection to the floating support structure, and tendon foundation components is not to be less than the design life of the stationkeeping system times the fatigue design factors (FDFs) specified in Table 5.10.

The chain stoppers should be function tested at the specified proof load.

6 Summary and Recommendations

Four major tasks are accomplished in this project. They include:

- Conducting a state-of-the-art review of technologies relevant to the design of Floating Offshore Wind Turbine (FOWT) stationkeeping systems
- Performing extensive case studies to explore the global response characteristics of typical FOWT conceptual designs with a particular focus on the sensitivity of FOWT global responses to various design and analysis parameters
- Identifying important design parameters and technical challenges for the design of FOWT stationkeeping systems
- Proposing a design guideline to provide recommended practices for FOWT stationkeeping systems

The design guideline is proposed based on the knowledge garnered through this project and BSEE TA&R Project 669, as well as applicable experience adapted from the offshore oil and gas industry and the offshore wind energy industry. While a comprehensive literature review and extensive case studies using representative data and designs have been carried out in order to provide a sound technical basis for the proposed design guideline, additional work and particularly the input from regulators and subject-matter experts from industry are essential to establish consensus and to finalize the design guideline. The proposed design guideline in this report should be considered “draft” recommended practices.

In addition to what has been accomplished in this project, the following subjects relevant to the present study are believed to be of great importance and thus recommended for further studies.

Validation of Global Performance Analysis Tools

Existing global performance analysis software for FOWTs lacks essential calibrations using model test data or full-scale field measurements. Although extensive code-to-code comparisons have been made, the validity of the software is still not fully confirmed. Further research is recommended to collect relevant model test data and field measurements and use these data to verify and enhance the capability and robustness of global performance analysis software for FOWTs. It will also be valuable for the industry to establish a common standard for software verification and to develop a set of reliable benchmark analysis cases that can be used for validating software capabilities.

FOWT Model Testing Method

Even with latest global performance analysis capabilities, model tests may still be needed to supplement and verify the numerical calculations, especially when a new component, a new combination of existing components, or an unfamiliar set of site conditions is involved. Although there are well-established offshore basins which have accumulated abundant knowledge of ocean environment modeling, scale model test for floating structures and data processing methodologies, model tests for FOWTs introduce many new challenges, such as the scaling method, turbulent wind simulation in an offshore basin, etc., that need to be appropriately addressed. Further research on FOWT model testing procedures and methods is important not only for validating simulation software but facilitating the industrial application of innovative design concepts.

Study on FOWT Design Load Cases (DLCs)

There are about 25 DLCs in the design guideline proposed in this report. They are developed based on best industry practice and past research, and are verified to the extent that the case studies carried out in this project can achieve. Potential revisions to the definition of DLCs may occur when more experience is garnered. The source of such experience could come from the enhancement of simulation capabilities; more high quality model test data and in-field measurements; and further understanding of the FOWT's load and response characteristics. Future revision of the list of required DLCs may see either an increase in their number because important design conditions have not yet been identified, or a decrease of the number of DLCs because some of the DLCs listed herein may prove to be inconsequential.

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