**FINAL REPORT**

# Floating Wind Turbines

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*Prepared by*

**American Bureau of Shipping**
**Corporate Offshore Technology, Renewables**
**16855 Northchase Drive**
**Houston, Texas 77060**
**www.eagle.org**

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**U.S. Department of the Interior**
**Bureau of Safety and Environmental Enforcement**
**381 Elden Street**
**Herndon, Virginia 20170-4817**

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This report is prepared by Qing Yu (qyu@eagle.org) and Xiaohong Chen at ABS Corporate Offshore Technology, Renewables Group. The project coordinator is Lars Samuelsson at ABSG Consulting.

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# Executive Summary

The main objectives of this project are to:

- Conduct a state-of-the-art review of floating offshore wind turbine technologies
- Explore technical challenges of deploying floating wind turbines on the US OCS
- Propose a draft design guideline for the floating support structures and the stationkeeping systems of floating offshore wind turbines

This report presents the research findings obtained from an extensive literature review and the case studies using three conceptual designs of floating offshore wind turbines adapted from the existing designs available in the public domain. The report also provides an evaluation of the critical design considerations, a proposal of the design guideline, and recommendations for future research for floating offshore wind turbines.

This project starts with a state-of-the-art review of the existing knowledge relevant to floating offshore wind turbines. The subjects of interest include existing design concepts, simulation tools, effects of turbine control systems, and the development of design standards.

Extensive case studies are conducted to evaluate the characteristic load conditions and global responses of floating offshore wind turbines. Emphasis is given to both the relevant load cases specified in IEC 61400-3 (2009) for bottom-founded offshore wind turbines and those that are not specified in the IEC standards, but considered essential for the purpose of developing the design guideline for floating offshore wind turbines. 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 OCS are applied in the case studies. The case studies are performed using the state-of-the-art simulation software for the fully coupled aero-hydro-servo-elastic analysis of the integrated turbine Rotor Nacelle Assembly (RNA) and its control system, floating support structure and stationkeeping systems. Parametric studies are performed to evaluate the relative importance of various design parameters, including the site location, the return period and

directionality of environmental conditions, the turbine operating modes, the hurricane wind models, and the effect of fault conditions in the turbine's nacelle yaw control system and blade pitch control system.

Technical challenges in the design of floating offshore wind turbines are identified based upon the results of the state-of-the-art review and the case studies, as well as experience from the offshore wind industry and common practices of designing offshore oil and gas production installations. A draft design guideline is proposed to provide recommended design methods and acceptance criteria, which are calibrated to the extent of the case studies, for the design of floating support structures and their stationkeeping systems. It is expected that the proposed design guideline and the calibrations carried out in this project will lay the foundation for further development.

Recommendations are made for future research on the simulation software, design and analysis methods, design standard development, and hurricane wind modeling for floating offshore wind turbines, as well as the cooperation with the IEC TC88 workgroup.

# 1 Introduction

A significant portion of offshore wind energy resources in the United States is available in water depths greater than 30 m in the offshore regions near highly populated costal states. At this and potentially deeper water depths, floating offshore wind turbines (FOWTs) could become more economical than bottom-founded designs. Various concepts of FOWTs have been proposed in the past. It was not until recently that technological advances and policy supports have made FOWTs a viable solution for harnessing ocean energy resources.

Existing design concepts of floating support structures and stationkeeping systems for FOWTs are mostly developed based on experience from the offshore oil and gas industry, which has witnessed almost 60 years of designing and operating numerous floating offshore structures. There is a wealth of knowledge about hydrocarbon-related offshore structures installed on the US Outer Continental Shelf (OCS). A series of Recommended Practices published through American Petroleum Institute (API) under their Subcommittee on Offshore Structures provides a comprehensive basis for the design of offshore structures and stationkeeping systems on the US OCS. What make FOWTs unique, however, are the presence of wind turbines that follow a very different design approach. Strong interactions among the wind turbine rotor, turbine control systems, floating support structure and stationkeeping system also pose a great challenge to the design of FOWTs. Economic considerations for typically un-crewed FOWTs further require leaner designs, serial production and mass deployment. In this regard, it may not be technically sound or economically acceptable to transfer the technology from floating oil and gas production installations directly to FOWTs without further calibrations and possible modifications.

This project is aimed to provide a thorough review of existing technologies relevant to the design of the floating support structures and the stationkeeping systems of FOWTs, and to evaluate global load and response characteristics using the latest simulation methods for FOWTs. A draft design guideline for the floating support structures and the stationkeeping systems of FOWTs is proposed based on the research findings garnered through this project, as well as applicable experience adapted from the offshore oil and gas industry and the wind energy industry.

The report is organized into five main sections, which present

- the results of the state-of-the-art review,
- the case studies for three FOWT conceptual designs assumed to be installed on the US OCS,

- discussions of design challenges in the design of FOWTs,
- a proposed draft design guideline, and
- recommendations for future research.

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

- existing design concepts,
- design and analysis software, and
- effects of turbine control systems.

The results of literature review are categorized into these four subjects in order to establish a general overview of what information is available, and where most past effort has been focused.

Section 3 is dedicated to the case studies using 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 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 being installed in the East, West and Gulf of Mexico coastal regions on the US OCS respectively, are selected for the case studies. The modeling, methodology, and results of extensive global performance analyses are described in this section. The section is concluded by the parametric analysis results for assessing the sensitivity of the selected FOWT conceptual designs to various design parameters, including the site location, the return period and directionality of environmental conditions, the turbine operating modes, the hurricane wind models, and the effect of fault conditions in the control system regulating nacelle yaw and blade pitch angles.

Section 4 provides an overview of critical design issues that need to be addressed in the draft design guideline. 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 the common practices from the offshore oil and gas industry and the offshore wind industry. The main focus is on identifying the distinctive technical areas that could potentially impact the safe operation of FOWTs on the US OCS and proposing recommended solutions to tackle these challenges.

Section 5 presents a draft design guideline which includes the recommended design methods and acceptance criteria for the floating support structure and the stationkeeping systems of FOWTs. The main contents of this draft design guideline covers

- general design philosophy and intended safety levels;
- design environmental conditions and design load conditions;
- recommended practices for global performance analysis;
- structural analysis methods and design criteria;
- design requirements for the stationkeeping systems; and
- design requirements for systems and equipment.

Main conclusions and recommendations for future research are presented in Section 6.

# 2 State-of-the-Art Review

The state-of-the-art review is conducted for various subjects relevant to the design of floating offshore wind turbines (FOWTs). Numerous publications have been collected, reviewed and commented. Emphasis is given to the following technical areas:

- Floating wind turbine prototypes and design concepts (Section 2.1)
- Design tools and software verifications (Section 2.2)
- Effect of turbine control systems on the global motions of FOWTs (Section 2.3)

## 2.1 Prototypes and Design Concepts of Floating Offshore Wind Turbine

### 2.1.1 Overview

Over the past fifteen years, many design concepts of FOWT have been proposed (Henderson, et al., 2009, Wang, et al., 2010). It was not until 2008, the first scaled prototype, Blue H, was installed offshore Italy at the water depth of 113 m (Bastick, 2009). By the time this state-of-the-art review was completed, two full-scale FOWTs, including the Spar-type Hywind (Bratland, 2009) and the Semi-submersible-based WindFloat (Weinstein, 2009), had been deployed for concept demonstrations. In addition to that, several scaled prototype FOWTs have also been installed for field testing.

### 2.1.2 Design Philosophy, Concepts and Technical Challenges

Henderson and Vugts (2001) conducted a review of exploratory studies of FOWTs during the 1990s. Advantages and disadvantages of various design concepts were evaluated by comparing the configuration of main support structure, number of supported turbines (single or multiple), materials used in platform construction (steel or concrete), and types of moorings. The conceptual designs studied in the paper included the semi-submersible, TLP, spar-buoy and space frame type of support structures.

The following technical challenges were highlighted in the paper:

- Dimensions – Floating wind turbines might require a large amount of materials, which would make them uneconomic.
- Wave loads – The large areas projected by multiple-turbine-floaters to the water surface could result in very high wave loads which might be beyond the structural bearing capabilities of any appropriate (i.e. economic) materials.
- Stability – The turbine thrust multiplied by the tower moment arm could result in large overturning moments.
- Motion response – To minimize the fatigue damage due to gyroscopic loads, floater motion responses must be minimized. It was noted that this requirement was contradictory to the requirement of minimizing structural loads.
- Anchorage – Anchoring in shallow water could be difficult and expensive. The commonly used catenary moorings could perform poorly.

The authors concluded that the prospects of floating offshore wind farms were not yet assured (at the time when the paper was published in 2001).

As a part of the FloatWind project, Henderson, et al. (2003, 2004) provided an overview of the feasibility study, the concept generation, the evaluation and selection process and other relevant aspects such as grid connection, operation and maintenance relevant to FOWTs. The paper also reported detailed case analyses of a design concept, which was considered the most suitable for the assumed shallow water conditions in the study. The authors concluded that, although the FOWT technology might not be ready for commercial applications, the gap to economic viability was closing.

In a more recent paper by Henderson, et al. (2009), the authors discussed the benefits of using floating support structures and offered a new look at the technical challenges for FOWTs, as summarized as follows:

- Minimization of turbine and wave induced motions
- Additional complexity in the design process, including understanding and modeling the coupling between the floating support structure and the wind turbine
- Design requirements for the electrical infrastructure and the potential cost increase, especially from using flexible subsea cables

- Construction, installation, operation and maintenance procedures, where similar level of attentions should be paid to installation as to the operation
- Design of FOWT control systems, which need to address the effects of negative aerodynamic damping caused by active blade pitch control and the yaw stability of the floating support structure as a consequence of nacelle yaw control.

The paper summarized design principles and challenges for the spar buoy concept, TLP concept and semi-submersible concept. The potential world market of the floating wind turbine technology was also discussed.

Musial, et al. (2003) provided a general introduction of technical challenges and cost estimations for the FOWT design concepts. Various design options, including multiple- or single-turbine floaters, catenary or vertical/taut mooring systems, and different anchoring systems, were considered in the study. The authors conducted a cost comparison for the Dutch Tri-floater (Semi-submersible-based) FOWT and the NREL TLP-based FOWT, assuming both were supporting a generic 5-MW wind turbine. Based on the cost comparison results, the authors reached the conclusion that the cost of power production of the two design concepts could be brought down to $0.05/kWh, which is DOE's target for large-scale deployment of offshore wind turbines. It was also concluded that the differences between floating offshore oil & gas platforms and FOWTs would allow the necessary cost reductions. The paper indicated that

- For crewed offshore oil and gas platforms, additional safety margin must be included to provide permanent residences for personnel. This was not a concern for FOWTs which were most likely designed as un-crewed offshore structures.
- Offshore oil and gas platforms must provide additional safety margin and stability for spill prevention. This was not a concern for FOWTs.
- FOWTs would be expected to be deployed in water depth up to 600 ft (182.4-m). Floating oil and gas platforms were typically deployed in depth from 1500 ft (456-m) to 8000 ft (2432-m) (as of the time when the paper was published).
- FOWT were designed to minimize the exposure to wave loading. Floating oil and gas platforms were often focused on maximizing the above-water deck/payload area.
- Wind platforms would be mass-produced and would benefit from a steep learning curve.

Kuo and Sukovoy (2004) concluded that knowledge from naval architecture could be transferred to wind farm development. The paper started with a brief examination of the interest in offshore renewable energy converters. Criteria for successful development were outlined. Attention was given to those areas where contributions from existing knowledge could be made. The experience in the design, construction, operation and decommissioning phases during the installation's life-cycle were considered the most relevant. The main conclusion was that there was considerable amount of knowledge that could be transferred from naval architecture to the development of offshore wind farms.

Butterfield, et al. (2007) developed a classification method to categorize the floating support structures into three general groups based on how the static stability is achieved, i.e. ballast (spar-buoy), mooring lines (TLP) and buoyancy (barge). The paper concluded that the overall architecture of a floating platform would be determined by the first-order static stability analysis, although there were many other critical factors that would determine the size and character of the final design. The paper outlined the critical design parameters for three stability categories and suggested the goals that would lead to economically viable development of FOWTs.

Wang, et al. (2010) conducted a literature survey on the research and development on FOWTs. The paper categorized FOWTs into four types: Spar-buoy type, Tension-leg platform (TLP) type, Semi-submersible type (Column-stabilized) and Pontoon-type (Barge-type). Various concepts were described and design principles were summarized. The paper concluded with recommendations for future work.

Ronold, et al. (2010) introduced an on-going development of a guideline for the design of FOWT support structures and stationkeeping systems. The general design philosophy, acceptance criteria, analysis requirements and hydrostatic stability requirements were discussed.

Cordle (2011) provided a brief review of design standards or guidelines relevant to FOWTs. Applicability of those design standards or guidelines, mostly based on the experience of bottom-founded wind turbines and floating offshore structures for oil and gas production, was assessed. The author also identified potentially critical technical areas that need to be addressed in the development of design guideline for FOWTs. Recommendations were made for possible extensions of IEC 61400-3 (2009) to cover FOWTs.

### 2.1.3 FLOAT Concept Design in UK (1991-1993)

The FLOAT concept was the first Spar-based FOWT concept that can be found in the literature. The FLOAT study was conducted in UK from 1991 to1993 (Quarton, 2004). The reported research evaluated the feasibility of various hull configurations, including the cylindrical buoy, barge, donut buoy, satellite buoy, semi-submersible, and twin-hull catamaran. It was concluded that the cylindrical buoy significantly outscored other configurations. Cost estimations, numerical analyses and model tests were performed for the selected conceptual design. The results indicated that the Spar-based concept was technically feasible and the cost reduction was achievable.

### 2.1.4 Dutch Tri-Floater Concept Design in the Netherlands (2001-2002)

The Dutch tri-floater concept is a semi-submersible-based FOWT. The concept design was developed in the Netherlands during 2001-2002. The research project, known as DrijfWind or FloatWind, was to develop FOWTs suitable for the shallow water with a water depth of 50 m in the Dutch sector of the North Sea. Bulder, et al. (2003) summarized the FloatWind feasibility study. Henderson, et al. (2003, 2004) provided an overview of the feasibility study and technical challenges for FOWTs in shallow water. More details were presented in the final project report (Bulder, et al., 2002), where the literature study, design criteria, boundary conditions and references for FOWTs were presented.

A number of concepts for FOWTs were proposed through brainstorm sessions. For some of the concepts, primary dimensions were determined using the knowledge-based software system called Quaestor, which allowed relationships among weight, costs, dimensions, stability etc. to be defined and then used to search for an optimum solution. Of all the concepts evaluated in the early part of the project, a tri-floater appeared to be statically and dynamically stable. It also offered the greatest potential for the installation site under consideration and, therefore, was selected for the further study.

Motion response calculations for the tri-floater concept showed that it was technically feasible in terms of motions. A more thorough analysis on the strength and costs of production and installation was performed. A preliminary design of the mooring system was also performed. An electrical system analysis was made for a 500-MW wind farm consisting of 100 turbines. Several permutations of transmission technologies and layouts were also evaluated. Furthermore, the maintenance cost of an offshore wind farm was estimated, and an optimal maintenance strategy was defined by considering component failure rates, repair time "weather windows", and choice of transport equipment, etc.

For floating support structures in the Dutch sector of the North Sea with a relatively shallow water depth, the following technical and cost challenges were identified by Henderson, et al. (2003, 2004):

- Minimizing wave induced motions
- Coping with additional complexity of the wind turbine design process
- Understanding the coupling between the floating support structure and the wind turbine
- Streamlining the construction, installation, operation and maintenance procedures
- Achieving stability
- Designing appropriate moorings

### 2.1.5 MUFOW (Multiple-Unit Floating Offshore Wind farm) Concept

As acknowledged by Henderson and Patel (2003), the idea for the MUFOW (multiple-unit floating offshore wind farm) concept was originally developed at the University College London in the early 1990s. The paper evaluated the feasibility of the MUFOW concept, which consisted of a semi-submersible hull structure supporting five wind turbines. The semi-submersible concept was featured by its main structures located below the water surface in order to reduce wave loads and global motion. A simplified method was proposed for analyzing the effect of deterministic motion of a floating foundation on the wind turbine performance and the fatigue loads. Modeling of aerodynamic loads on turbine blades and inertial loads due to global motions was discussed.

It was shown that motions of MUFOW had a minimal effect on the total loads experienced by the turbine rotor. This was mainly because the aerodynamic loads, which were not affected significantly by global motions, were dominant for this part of the turbine. On the other hand, the nacelle and the tower base connection were more affected by inertia loads and, therefore, additional inertia loads due to global motions could result in a significant load increase at these locations. It was concluded that unless the floating support structure was very stable, the tower would need to be strengthened. The exact details and the extent of potential changes in the nacelle design would need to be examined using a more advanced simulation method.

### 2.1.6 FOWT Concept Development at NREL

NREL has been leading the development of offshore wind energy technology in the US. Significant amount of research and concept development for FOWTs were performed or sponsored by NREL. A brief review of some key publications from NREL on the FOWT concept development is presented in this subsection.

Musial, et al. (2003) introduced a NREL TLP concept and presented a cost comparison between the Dutch Tri-floater (Semi-Sub) and the NREL TLP, assuming both were supporting a generic 5-MW wind turbine. Butterfield, et al. (2007) explored different types of FOWT concepts and the engineering challenges. See Section 2.1.2 for the review of these two publications.

Fulton, et al. (2007) summarized a conceptual design study to examine the feasibility of various semi-submersible platform configurations expected to be used to support a large offshore wind turbine. A 5-MW wind turbine and a semi-submerged triangular platform with tension legs and gravity anchors were selected for detailed analyses. Three analysis programs, including Bladed, FAST, and Orcaflex, were used for the dynamic modeling. The analysis results indicated that the rotor and nacelle loads associated with deep water offshore operations were similar to those of land-based wind turbines. However, the tower loads were significantly higher because of the platform's motions.

Jonkman (2009) reviewed four FOWT concepts including Hywind, Blue H, WindFloat and Sway. Discussions were made about the design challenges as well as the advantages and disadvantages of typical TLP, Spar and barge design concepts of the floating support structure. The author introduced the simulation capabilities of the FAST program for the coupled aero-hydro-servo-elastic analyses as well as the analysis process for FOWTs. The analysis results of three examples, including MIT/NREL TLP, OC3-Hywind Spar Buoy and ITI Energy Barge, were reported for the DLC1.2 (Normal Operation), DLC6.2a (idling) side-by-side instabilities and DLC2.1 & 7.1a (idling) yaw instabilities. The presentation also outlined the ongoing work and future plan of IEA Wind Task 23-2 (OC3).

Matha (2010) and Matha, et al. (2010) conducted a review of previous studies on FOWTs and discussed their limitations. The advantages and disadvantages of TLP, Spar and barge based concepts of the floating support structure were evaluated. The primary focus of the study was to assess the modeling, loads, and dynamic responses of a TLP concept, which was originally developed at MIT and was later modified and renamed to MIT/NREL TLP. The coupled aero-hydro-servo-elastic analysis program, FAST, was used in the global performance analysis. The motion RAOs calculated by FAST based on the assumption of rigid tower-blade model were verified by the results from WAMIT. Differences were observed in the RAOs calculated using the rigid and flexible FAST models respectively. It was suggested that at least one tower fore-aft bending degree of freedom should be added to the frequency-domain model to account for the tower flexibility.

Global performance analyses for the selected design load cases from the IEC 61400-3 (2009) were performed for the MIT/NREL TLP design concept and, for a comparative study, the OC3-Hywind Spar design concept. Response statistics, ultimate loads, fatigue loads and instabilities were analyzed. Compared to a reference land-based wind turbine, the ultimate loads on the MIT/NREL TLP design concept were increased by 25% for the tower and over 10% for the blades, while the fatigue DELs (damage-equivalent loads) were increased by 60% for the tower-base bending moment. Severe aerodynamic instability was observed in the platform pitch, platform roll, and tower and blade bending modes when the MIT/NREL TLP design concept was idling in high winds with all the blades feathered at 90º and the nacelle at certain yaw misalignment angles. The platform yaw instability also occurred when the MIT/NREL TLP design concept was idling in high winds with one blade seized at 0º pitch and the other two blades feathered at 90º.

The authors indicated that the modeling and analysis process developed in the study could serve as a general framework for future analysis of new FOWT design concepts. It was concluded that further work on the TLP design concept, turbine controller improvements, and mitigation of instabilities was essential for the development of an economically feasible FOWT that could withstand extreme conditions in a deepwater offshore environment.

Jonkman and Matha (2010) presented the results of dynamic response analyses of the three conceptual designs, including the MIT/NREL TLP, the OC3-Hywind Spar and the ITI Energy barge design concept which were configured to support the NREL 5-MW baseline offshore wind turbine. The three FOWT conceptual designs achieved hydrostatic stability mainly through mooring, ballast and water-plan area, respectively. Load and stability analyses were performed for each model using the FAST program suite. A northern North Sea location was selected as the reference site where metocean data were derived. The three FOWT conceptual designs were evaluated based on the FAST calculation results of ultimate loads, fatigue loads and instabilities. Comparisons were also made with a land-based support structure to identify the distinctive response characteristics of FOWTs. In summary, all the FOWT conceptual designs showed increased loads on turbine components as compared to those of the land-based case. The ultimate and fatigue loads induced by the global motions of the floating support structure were found the greatest in the ITI Energy barge concept. The MIT/NREL TLP and the OC3-Hywind Spar were found having comparable ultimate and fatigue loads, except for the loads on the tower, which appeared higher in the OC3-Hywind Spar. Instabilities in all three design concepts were also studied.

Robertson and Jonkman (2011) reported extensive numerical simulations carried out for six FOWT design concepts. Three of the floating support structures, including the MIT/NREL TLP, the OC3-Hywind Spar, and the ITI Energy Barge, had been studied previously by Jonkman and Matha (2010). The three new models were created based on the conceptual designs from the DeepCwind Consortium and labeled as the UMaine TLP, the UMaine-Hywind Spar and the UMaine Semi-submersible. All DeepCwind Consortium concepts were developed for the water depth of 200 m, which represents the water depth of a prospective FOWT test site in the Gulf of Maine. Each of the six models was assumed to support the same NREL 5-MW baseline offshore wind turbine. The global responses of these conceptual designs were compared to those of a benchmark land-based monopile support structure carrying the same turbine RNA. Selected load cases based on IEC 61400-3 (2009) were evaluated using the aero-hydro-servo-elastic analysis program FAST, with the assumption that these design load cases specified in IEC 61400-3 (2009) for bottom-founded offshore wind turbines could still be applied to FOWTs.

The simulations results were presented for the ultimate strength analyses with the turbine in normal operation and the fatigue analyses. Load cases for the extreme wind and wave conditions were also studied, but the results were considered unrealistic due to the presence of instability and thus not reported in the paper. Reference was made to Jonkman and Matha (2010) for further discussions about the instability. It was observed that all the FOWTs showed increased loads on turbine components in comparison with the land-based turbine. The turbine loads of the barge-based FOWT were found the highest among all the conceptual designs. The differences in the loads among the TLP, the Spar, and the Semi-submersible based FOWTs were insignificant, except for the tower loads which appeared relatively higher in the Spar and Semi-submersible cases.

### 2.1.7 Research and Concept Development at MIT

Several design concepts were developed by a research team at MIT. A summary of the relevant publications are listed below, followed by a brief review of key publications.

- Withee (2004), Sclavounos (2005) and Lee, et al. (2005) presented studies on a TLP-based floating support structure carrying a 1.5-MW turbine.
- Lee (2005), Sclavounos (2005) and Lee, et al. (2005) studied two concepts including a TLP and a spar buoy type FOWTs with a taut-leg mooring system and a 1.5-MW wind turbine.
- Wayman (2006) and Wayman, et al. (2006) studied several different concepts including barges and TLPs supporting the NREL 5-MW baseline offshore wind turbine.
- Parker (2007) performed a parametric study of a TLP concept supporting the NREL 5-MW baseline offshore wind turbine, which was initially studied by Wayman (2006) and Wayman, et al. (2006).
- Tracy (2007) and Sclavounos, et al. (2008) used a parametric analysis approach to optimize the TLP and spar buoy concepts supporting the NREL 5-MW baseline offshore wind turbine and with the slack and taut catenary mooring systems. One of the TLP designs was later modified and renamed as MIT/NREL TLP by Jonkman and Matha (2010).
- Lee (2008) performed a sensitivity study for a spar buoy supporting the NREL 5-MW baseline offshore wind turbine and with different mooring configurations using synthetic ropes.
- Sclavounos (2008) discussed the development of two types of floating support structure, TLP and spar buoy, for supporting a 5-MW wind turbine.
- Sclavounos, et al. (2010) presented two low-weight, motion-resistant FOWT concepts, including a Taught Leg Buoy (TLB) with inclined taught mooring lines and a Tension Leg Platform (TLP) system with vertical tethers. The design concepts were intended to support 3-MW – 5-MW wind turbines to be deployed in water depths ranging from 30 to several hundred meters and in seastates with wave heights up to 30 meters.

Withee (2004) developed a fully coupled dynamic analysis technique to predict the response of a FOWT system in a stochastic wind and wave environment. This technique incorporated both nonlinear wave loading on the submerged floater and the aerodynamic loading on the wind turbine. Hydrodynamic loads were computed by the GI Taylor's equation and Morison's equation. In the time-domain analysis, the nonlinear hydrodynamic forces were calculated by the summation of forces up to wave elevations. The hydrodynamic program module was interfaced with the wind turbine design program FAST and ADAMS. Tethers were modeled as restoring coefficients. A tension leg spar buoy (mono-column TLP with 4 legs) with very high stiffness in roll and pitch motion was designed to support a 1.5-MW wind turbine. A linear frequency domain analysis was first performed to evaluate floater motions, followed by a more detailed time domain analysis. Damping properties of the FOWT concept were evaluated by simulating free decay tests in the six degrees of freedom. Both normal operations and the extreme wind and wave conditions were considered in the study. The results of the analysis demonstrated that the tension leg spar buoy had a good potential to support a large wind turbine in the offshore environment.

Lee (2005) introduced two FOWT conceptual designs and studied their performance in combined wind and wave conditions. The two concepts were based on a TLP and a spar buoy floating support structure with a taut-leg mooring system. Both were designed for a 1.5-MW wind turbine and operating in 100 m water depth. The SWIM module of SWIM-MOTIONS-LINES (SWL) program suite was used for the linear frequency-domain analysis. The LINES module was used to compute static tension and linear restoring (stiffness) matrices for the mooring system. The system was modeled as a rigid body and only steady wind loads (thrust) were considered. The wind loads (thrust) was approximated by the actuator disc. The axial flow induction factor was tuned to yield a similar result as that from the NREL FAST program. Compared to the spar buoy concept, the TLP concept was stiffer in roll, pitch and heave modes and softer in surge, sway and yaw modes. The natural frequencies of two conceptual designs were outside the frequency band containing most wave energy. Static and a linear seakeeping analyses were performed in 5 sea states. It was found that the RMS (root-mean-square) values of roll and pitch motions were less than one degree even in the most severe sea state. The thesis also presented a new approach to compute the nonlinear wave excitation in the time domain. The results showed the excitation of higher harmonics in the TLP design concept. The author concluded that it might be important to consider these higher harmonics, particularly to avoid resonances with the turbine rotor and the tower.

Wayman (2006) developed the floating support structure conceptual designs which were intended to support a 5-MW wind turbine for water depths of 30-300 m in U.S. waters. In order to optimize the designs, stability and static analyses of the floating support structures subjected to wind loads were performed by considering restoring forces from water-plane area, ballast and mooring system. A cost analysis was conducted for the optimized support structures. Frequency domain dynamic analyses were performed to calculate natural frequencies as well as motion RAOs and standard deviations in different sea states. A 6-DOF motion equation was established using the hydrodynamic coefficients and forces of the floating support structure calculated by WAMIT and the wind turbine mass, damping and stiffness matrices calculated by FAST. The contributions from aerodynamics and gyroscopics were accounted for. Mooring forces were considered as restoring matrices. Two general conclusions were drawn in this study: *i.*) Coupled modes of excitation were important for a compliant FOWT, but not as important for a stiff FOWT; *ii.*) The global responses could be largely tuned by designing the floating support structure for particular natural frequencies.

Tracy (2007) presented a parametric analysis approach for the design of the floating support structure of an FOWT. Frequency domain analyses were performed by using the LINES program to calculate the line tensions. A restoring matrix was defined to represent the mooring system. The WAMIT program was employed to calculate the hydrodynamic coefficients, while the FAST program was used to calculate the linearized dynamic properties of the NREL 5-MW baseline offshore wind turbine. Static responses (steady state offset, static line tension and static stability) and dynamic responses (RAOs, RMS, dynamic line tensions, free surface elevations and natural frequencies) were evaluated for numerous combinations of the mooring system (vertical, taut and slack catenary), the size of floater (in 60m and 200m water depths), and the sea state (Hs=6m and 10m). Design solutions were compared in terms of the line tension, displacement and nacelle RMS acceleration.

Sclavounos (2008) presented the technologies and the economics associated with the development of motion-resistant FOWTs. Both the TLP and spar buoy based FOWTs supporting a 5-MW wind turbine were discussed. These concepts were aimed at achieving low accelerations at the nacelle and small cumulative dynamic tensions in the anchors when the FOWTs were subjected to severe environmental conditions. The author indicated that the standard deviation of the acceleration at the nacelle was about 0.1g for both types of floating support structures in severe storms. Under mild environmental conditions, the estimated accelerations were found negligible. The author further stated that the water depths at which FOWTs were able to be deployed could range from about 30 m to several hundred meters. The cost of the floating support structure, ballast and mooring system were found not affected materially by the water depth, but could increase linearly with the size of wind turbine.

Sclavounos, et al. (2010) presented the development of a new generation of FOWT concepts supporting 3-MW – 5-MW wind turbines. The frequency-domain simulation results of the responses of a Taught Leg Buoy (TLB) based FOWT with inclined taught mooring lines and a TLP-based FOWT with vertical tethers were reported in the paper. The water depth ranged from 30 m to 150 m. Three seastates with significant wave heights of 6 m, 10 m and 14 m respectively were considered. The wind turbine was assumed to operate at the maximum rated power and the corresponding maximum thrust in all seastates. Global performance analyses were performed for the two designs, each of which was assumed to support a 3-MW and a 5-MW wind turbine, respectively. The nacelle acceleration and the mooring line dynamic tension were considered as important performance metrics for FOWTs. The sensitivity of the two performance metrics to the TLB and TLP design parameters, wind turbine weight, water depth and wave environment were evaluated. It was concluded that the TLB was the preferred system for a water depth less than about 50 m, while the TLP was superior for a water depth greater than 50 m.

### 2.1.8 Hywind Design Concept by Statoil

The Hywind concept is the first FOWT that reached the stage of full-scale prototype testing. The prototype was installed offshore Norway in 2009 for a two-year testing program. The Hywind concept consists of a concrete or steel cylinder with ballast. The base draft is 120 m. The stationkeeping system is a 3-point catenary mooring system. Extensive studies have been carried out on the concept development, model test, software tools and numerical simulations as well as the issue with the negative damping induced by the conventional blade pitch controller.

A general introduction of Hywind concept can be found in Gjørv (2006) and Larsen (2008). Bratland (2009) introduced the development of the Hywind concept and provided the key data and characteristics of the full-scale prototype.

Nielsen, et al. (2006) described the integrated dynamic analysis for the Hywind concept using two simulation programs, SIMO/RIFLEX and HywindSim. The authors stated that SIMO/RIFLEX developed by Marintek was a state-of-the-art code for the dynamic analysis for integrated rigid and flexible floating bodies. The elastic behavior of the tower could therefore be taken into account. HywindSim, an in-house MATLAB/Simulink program, was able to use the analysis results from the WAMIT program and Morison's equation to calculate wave loads, while a quasi-static approach with the consideration of multi-body motions was implemented for calculating mooring forces. A simplified wind turbine model was assumed in both simulation programs and was based on a look-up table of the thrust force coefficient derived from a conventional pitch-regulated turbine.

The paper indicated that, for the water depth above 100 m, a deep draft hull was a promising solution for the floating support structures. A slender deep draft hull made the static stability requirements relatively easy to fulfill. The wave loads were moderate on a deep slender structure and efficient, low cost production was possible. The Hywind concept supporting a 5-MW wind turbine was used in the dynamic analyses. Results were compared with the small scale model test results. The model test results of wave-induced motions agreed reasonably well with those obtained in the simulations. However, the responses around the natural frequencies were in most cases overestimated by the simulations, and this was believed an indication of higher damping in the experiments than in the simulations.

Various environmental conditions and wind turbine control schemes were tested. The maximum power control strategy was applied when wind velocities are below the rated wind speed of the wind turbine, while the constant power control strategy was achieved by controlling the blade pitch angle when wind velocities are above the rated wind speed. It was observed that the conventional blade pitch controller for wind velocities above the rated wind speed introduced negative damping in the global motions. This negative damping resulted in resonant responses associated with spar's pitch natural frequency and could lead to unacceptably large tower motions. This issue was resolved by adopting an alternative blade pitch control algorithm which took the feedback from the measurement of tower velocity. The new blade pitch control algorithm was shown to be effective in both simulations and model tests.

Skaare, et al. (2007) and Larsen and Hanson (2007a, 2007b) conducted further investigations into the effect of negative damping on the tower vibration, which was considered as one of the key technical challenges in the development of the Hywind concept.

Based on the Hywind concept, many studies were further carried out to assess the load and response characteristics of FOWTs. It was selected by the IEA Wind Task 23 Offshore Code Comparison Collaboration (OC3) for software tool comparisons. Based on the conceptual design data, modifications were made so that the Hywind concept could be used to support the NREL 5-MW baseline offshore wind turbine. The modified Hywind was named “OC3-Hywind” to distinguish it from Statoil’s original Hywind concept. The definition of the OC3-Hywind was given in Jonkman (2010).

### 2.1.9 WindFloat Concept Design by Principle Power

The WindFloat concept is developed by Principle Power, Inc. The floating support structure of the WindFloat concept is based on the Column-Stabilized MiniFloat design described in Cermelli, et al. (2004). Several variations were developed to accommodate different design requirements. A full-scale prototype was installed offshore Portugal in 2011.

Roddier, et al. (2009) summarized the feasibility study on the WindFloat concept for a site on the US West Coast, with the primary focus on the design basis for floating wind turbine support structure. The WindFloat considered in the study was a three-column floating foundation designed to accommodate one wind turbine, 5-MW or larger, on top of one of the columns of the hull structure. The mooring system considered in the feasibility study consisted of 6 mooring lines with 60-degree separation between each line. A closed-loop active ballast system was designed to transfer ballast water between columns to keep the platform upright as the wind direction changes. The 100-year return extreme wave event was considered in the design basis. The authors argued that the design of the hull structure for a large FOWT should be based on common practices of the offshore oil and gas industry, in addition to the consideration of the design requirements and functionality of wind turbines.

Cermelli, et al. (2009) presented the results of hydrodynamic analysis of the floating support structure as well as ongoing work on the simulation of coupling effects between hull hydrodynamic responses and turbine aerodynamic loading. Time-domain simulations of the hydrodynamic response of the floating support structure were performed using an in-house program called TimeFloat, which calculated turbine loads based on an equivalent drag model. Gyroscopic effects of the rotor coupled with global hull motions were also included. Intact and damaged stability were assessed based on a range of thrust coefficients of the wind turbine. A worst case scenario (failure mode) defined by a combination of wind overturning moment and a faulty active ballast system was evaluated.

In the preliminary design phase, the design load cases were determined based on the design standards for floating offshore oil and gas production installations and bottom-founded offshore wind turbines. The design load cases that were considered to be the most onerous for the floating support structure motions were analyzed, including the 100-year return storm (13.5m Hs), the extreme coherent gust (ECG), and the extreme operating gust (EOG). In addition, a number of operating cases were also evaluated for the turbine subjected to the maximum thrust wind speed and to the cut-off wind speed along with their associated waves, respectively.

The results of a 1:105 scale model test were discussed. A circular disk with one third of the sweep area of the rotor was installed on the model to simulate the wind force. An electrical motor was also installed at the top of the tower to model the gyroscopic effect. An equivalent mooring model was applied to simulate the horizontal stiffness of the six-line catenary mooring system. A 3-hour realization of a 100-year return wave was generated. The associated wind was 25 m/s, which was the turbine's maximum allowed operational wind speed. Under the 100-year return storm, a satisfactory agreement was found between the model test results and numerical simulations performed using the TimeFloat program.

In order to perform fully coupled aero-hydro-dynamic simulations, the TimeFloat program was further enhanced by integrating an interface program that can communicate with NREL's FAST program. Preliminary results showed that the interactions between the wind turbine control system and the floating support structure generated small rotational oscillations with long periods (~30 seconds), which, in some cases, could result in slightly reduced power output.

Aubault, et al. (2009) described the structural analysis and design as a part of the feasibility study for WindFloat design concept. The preliminary scantling design was discussed and the strength and fatigue analysis methodologies were described. The structural analysis was mainly based on experience from the offshore oil and gas industry, including the ABS Rules for Mobile Offshore Drilling Units and the API RP 2A-WSD. The design environmental conditions were obtained for the seastates in the wave scatter diagram. For each peak period in the wave scatter diagram, the seastate with the highest significant wave-height was identified. The twelve resulting seastates were then used in the strength and fatigue analyses. For each of the sea-states, a 1-hour time-domain analysis was performed. It was concluded that the accurate prediction of wind force was essential to the calculation of structural responses of the WindFloat because its contribution to the bending stress of the structural members was significant.

Cermelli, et al. (2010) discussed the qualification process for the floating support structure and the stationkeeping system of the WindFloat concept. A combination of design standards developed for floating oil and gas platforms and bottom-founded offshore wind turbines was adopted. Existing classification society criteria for the design of Mobile Offshore Drilling Units (MODU) were followed to verify intact and damaged stability of the WindFloat concept. The design of the mooring and electrical cable was based on the results of fully coupled global performance analyses. In contrast to the 6-line mooring system used in the previous feasibility study, a 4-point mooring configuration was selected. Issues associated with the redundancy of the stationkeeping system were highlighted. Adjustment of the design criteria associated with the damaged mooring case was recommended based on the consideration of overall reliability. The authors concluded that it was important to develop a coupled analysis algorithm, which should be capable of taking into account the interactions among the aero-servo-elastic responses of the turbine RNA, tower and control system and the hydrodynamic responses of the floating support structure.

Roddier, et al. (2011) described the sizing and performance of a generic WindFloat hull structure supporting the NREL 5-MW baseline offshore wind turbine. This generic design was mainly developed for validations and comparisons of design software. Typical environment conditions were used for the sizing. The main dimensions and weight of the hull structure and mooring system were provided in the paper.

### 2.1.10 FOWT Concept Development in Japan

Various FOWT design concepts were proposed with the primary focus on potential application in Japanese waters. A summary of the related publications is given below.

- Henderson, et al. (2002) conducted a review of different FOWT design concepts developed in 1990s.
- Kosugi, et al. (2002) proposed a mat-like mega-float with multiple wind turbines.
- Suzuki and Sato (2007), Matsukuma and Utsunomiya (2008), Utsunomiya, et al. (2009a, 2009b, 2010) studied several Spar-type concepts.
- Ishihara, et al. (2007), Shimada, et al. (2007) and Ishihara (2008) studied a Semi-submersible concept that could accommodate three wind turbines.

- Ishihara, et al. (2009) and Waris, et al. (2010) evaluated a Semi-submersible based concept.
- Shimada, et al. (2010) and Suzuki, et al. (2010) developed a TLP-type concept.
- Fujiwara, et al. (2011) studied gyro-effects of rotating blade on the FOWT.

Henderson, et al. (2002) reviewed the FOWT-related technology development in Japan between early 1990s and 2002. A prognosis for future development and an estimate of potential wind energy resources in Japanese waters were presented. Several promising candidates of floating support structures (Semi-submersibles, TLPs, Spar-buoys and space-frame) suitable for supporting offshore wind turbines were reviewed. Simple quantitative calculations were performed for a generic variable-speed, pitch-regulated 3.5-MW turbine subjected to wave induced loads on the turbine and tower. It was concluded that the effects of the wave-induced motion on turbine loads would be similar to the fixed-foundation designs, while tower base loads were found dependent upon wave induced motions, which are further related to the specific type of floating structure.

Kosugi, et al. (2002) explored the feasibility of developing an offshore floating wind farm off Japanese coast. The farm consisted of multiple wind turbines supported by a mat-like mega-float with a single point mooring which allowed weathervaning. Detailed cost analysis revealed that wind power production cost of a proposed 300-MW wind farm was higher than that of a bottom-founded wind farm with the same production capacity and far higher than that of a conventional power generation systems with the same production capacity. Constructions of floating structures and associated mooring systems were considered as the main cause of cost increase.

Suzuki and Sato (2007) investigated the effect of motions of an FOWT on the strength of turbine blade and floating support structure. A Spar-based FOWT was selected for the detailed analysis. The calculation of inertial loads on turbine blade due to motions of the FOWT were formulated and verified by scaled model tests. Aerodynamic loads were calculated based on the blade element momentum (BEM) theory. Ultimate strength of the wind turbine was assessed for the maximum wind load with a 50-year return period. For the fatigue design, the maximum fatigue load due to wind shear in the operational condition was analyzed. It was shown that the maximum load on blades was increased by 10% for 5 degrees of pitch motion, while the sectional modulus had to be increased by 50% in order to provide sufficient fatigue resistance. It was found that the increase in the maximum load on blades due to FOWT motions were insignificant. However, fatigue loads appeared to be very sensitive to FOWT motions. It was suggested that the amplitude of pitch motion of the FOWT should be less than a few degrees in order to allow the land-based wind turbine to be installed on the floating support structure with minimum modifications.

Ishihara, et al. (2007) developed a FEM code to predict the dynamic responses of FOWTs in the time domain. Morison's equation was employed to calculate the hydrodynamic drag forces and inertia forces on the floating support structure. Quasi-steady theory was implemented to calculate the aerodynamic forces on wind turbines. Wave particle velocities and accelerations were generated by the Airy theory for linear waves and the stream functions for nonlinear waves. The mooring system was simplified by longitudinal linear springs. A Semi-submersible floating support structure was modeled using beam elements to evaluate the performance of the developed FEM code. Eigenvalue analyses were performed to calculate the natural frequencies and modes of the floating structure. Model tests were carried out using a 1:150 scale model. The motion of the central column and the strains of the horizontal brace were measured. Dynamic response analyses were also conducted under the same condition applied in the experiment. It was found that

- Both hydrodynamic damping and wind-induced damping were important in predicting responses in resonant regions.
- Elastic deformation played an important role in the dynamic responses of the floating support structure. The predicted responses were underestimated when the elastic deformation was ignored.

The authors also concluded that the nonlinearity of wave induced loads became significant for a water depth less than 100m, and the elastic modes might be resonant with higher order harmonic components of nonlinear waves, which could result in the increase of dynamic response of the floating support structure.

Shimada, et al. (2007) proposed a semi-submersible floating structure to host three wind turbines. The results of numerical computations and 1:150 scale rigid model experiments in a wave tank were presented. In the numerical computations, the nonlinear damping effect due to drag forces was modeled using Morison's equation. The linear hydrodynamic forces were determined by the Green's function model. It was shown that the response characteristics around the resonant frequency region were favorable. In addition to these relatively simple evaluations, random wave induced motions were analyzed for the design concept, with the assumption that the FOWT was located at the water depth of 100 m and subjected to the "extreme wind speed condition" (50-year return storm wind speed) and "operational wind speed condition" (turbine's rated wind speed).

Safety of the mooring system under the extreme wind speed condition was found satisfactory. The tilting angle was ascertained to be small enough to maintain the efficient power production. The fatigue analysis results showed that the structure had sufficient fatigue strength, although large fatigue damage was identified at some local connections.

Matsukuma and Utsunomiya (2008) presented the motion analysis results of a Spar-type FOWT supporting a 2-MW downwind turbine. The blade element momentum theory was implemented for the calculation of wind loads acting on the rotor blades. The multi-body dynamics was employed to calculate the dynamic responses of the FOWT system, with the consideration of the effect of gyro-moment generated by the rotating rotor. It was observed that the motions in sway, roll and yaw directions occurred at the same time because of the effect of the gyro-moment. The authors indicated that such a complex coupling behavior could be captured only when the rotor rotation was included in the analysis. In this study, the steady wind was assumed. The wind turbulence, mooring nonlinear restoring forces, waves, currents and tides were not considered.

Utsunomiya, et al. (2009a) studied a Spar-type FOWT foundation made of reinforced concrete. The floating foundation was designed to support a 2-MW wind turbine. The equation of motion of three degrees-of-freedom was derived. Wave forces were evaluated using Morison’s equation and the potential theory. The nonlinear mooring forces were evaluated using the catenary-line theory. Regular and irregular wave experiments were performed using 1:100 scale models of the three prototype designs, including a uniform cylinder moored at the gravity center, a uniform cylinder moored at the upper position, and a stepped floating cylinder moored at the upper position. The experimental results were compared with numerical predictions of RAOs in regular waves and significant values in irregular waves. The stepped floating cylinder moored at the upper position showed the smallest motions.

Utsunomiya, et al. (2009b) examined motions of a 2-MW Spar-type FOWT subjected to wave loadings. In the numerical simulation program used in the study, Morison’s equation was employed to calculate wave forces. Water particle velocities and accelerations were evaluated at instantaneous positions, while the extrapolated linear wave theory was used for the integration of wave forces along the floating body. The equations of motion for a six degrees-of-freedom rigid body were solved in the time domain. The mooring lines were modeled as linear springs, and the damping force acting in each mooring line was calculated by an empirical formula. The motion of the FOWT subjected to regular and irregular waves, respectively, along with steady horizontal forces simulating the effect of steady wind, were calculated. Wave tank experiments using a 1:22.5 scale model were performed in the deep sea wave basin at NMRI (National Maritime Research Institute). The RAOs obtained from numerical simulations were found in fairly good agreement with the experiment results, although the discrepancies in RAOs at longer wave periods remained to be resolved. The ratios of the significant values of motions in irregular waves in the experiment to the corresponding simulation results were within 0.46-1.21. In order to improve the accuracy of the numerical prediction, it would be necessary to improve the damping force evaluations in the numerical simulation code.

Ishihara, et al. (2009) investigated the influence of heave plates on the dynamic responses of a semi-submersible type FOWT. Wave tank experiments using a 1:100 scale model were performed for three different designs, i.e. a semi-submersible floater without heave plate, with heave plates of 12 m diameter and with heave plates of 16 m diameter. A range of periods (6 s – 30 s) for two wave heights of 4 m and 12 m, corresponding to rated and extreme sea condition respectively, were applied. Wind was not considered in this experiment. Dynamic responses of the FOWT were calculated using a time-domain FEM program. Hydrodynamic forces were calculated using Morison's equation. The mooring system was simplified as linear stiffness. The floater was modeled by beam and truss elements. It was found in the model test that the use of heave plates increased the natural period of heave and reduced heave response in both the rated and the extreme sea states. Numerical predictions of motion RAOs showed a good agreement with model test results. The influence of considering the actual mooring system instead of the simplified mooring stiffness in the numerical simulation was discussed. It was concluded that the simplified method reduced the prediction accuracy.

Utsunomiya, et al. (2010) presented a field experiment using a 1:10 scale model of a steel-concrete hybrid Spar-type floating support structure. The prototype Spar support structure was moored by a catenary mooring system using anchor chains and was designed to support a 2-MW downwind horizontal-axis wind turbine at 70 m draft. The experiment process included the construction, dry-towing, installation at the offshore site in a sheltered harbor, generating electric power using a 1 kW downwind turbine, and decommission from the site. During the field experiment, the environmental conditions, the motions of the model FOWT, the tension in a mooring chain, and the strains in the tower and the Spar foundation were measured. Numerical analyses were performed to predict the motions of the testing model. The wind force was applied horizontally in the measured wind direction at the hub height and on the center axis of the tower.

A constant thrust force coefficient was assumed, while the gyroscopic moment induced by the rotating rotor was not applied. A fairly good agreement was observed between the experimental data and the simulation results.

Waris, et al. (2010) developed a fully coupled nonlinear FEM model for predicting dynamic responses of FOWTs. The analysis model was used to compare the linear and nonlinear method for calculating mooring forces and to identify potential limitations of the linear model. It was found that the linear model overestimated the surge response near the resonance peak and would provide realistic results only when the wave period was less than half of the natural period of an FOWT. Using the linear model outside such application limit could result in conservative designs.

Shimada, et al. (2010) demonstrated a design procedure for determining the configuration of a TLP-type floating support structure. The TLP floating foundation was designed to support a 2.4-MW wind turbine. The initial tendon tensions were estimated. Various sizes of the structural elements of the TLP were examined in order to evaluate their effects on the tendon tensions and the accelerations at tower top. Numerical model was based on Morison's equation and the diffraction theory and was solved in the frequency domain. Nonlinear drag forces were incorporated through a linearization process. External forces were assumed to be collinear with wind, wave and current. The maximum wind load and mean current load were modeled as steady forces. The paper concluded that although the increase in diameter of peripheral column and its height reduced the acceleration response, the tendon tensions were increased. On the other hand, the increase in span length appeared to be able to reduce both the tendon tensions and the tower top accelerations.

Suzuki, et al. (2010) carried out an initial design of a TLP for a 2.4-MW wind turbine. The installation site was assumed to be off the Japanese coast. Three environmental conditions associated with the rated, cut-out and extreme wind speed conditions were considered. The following design requirements were followed:

- Rated condition: The average inclination should be no larger than 5 degrees.
- Cut-out condition: The maximum acceleration of the nacelle should be no larger than 0.2g.
- Extreme condition: Blades must not touch the wave surface. Under the tendon tension, sufficient safety margins (safety factor 3.0) above the tendon breaking limit should always be maintained. Tendon tensions should always remain positive.

Numerical analyses were performed to calculate the dynamic responses of TLP, tendon tensions, natural frequencies of vibration and dynamic responses to seismic forces. It was found that the proposed TLP was a very promising solution of the floating support structure. It was also found that the proposed design had a sufficient safety margin to cope with the extreme environmental conditions including earthquake, and was free from resonance with the turbine.

Fujiwara, et al. (2011) studied the gyroscopic effect of a rotating rotor on the responses of the floating support structure. A pontoon model with a fishing line as mooring and an automatic revolving disk on the top was examined in experiment. The pitching motion reduction of the floating pontoon model due to the effect of the revolving disk was observed in experiments. Numerical results of the pontoon model revealed that the peak frequencies of surge and pitch motion and wave drift force in surge direction were all shifted to higher frequency side because of the presence of the revolving disk on the top. The revolving disk also induced yaw motions due to the gyroscopic effect. In spite of bilaterally symmetric body, the sway drift force and yaw moment were still generated in following waves. The wave generated yaw moment could change its direction depending on wave period. Additional numerical analyses were performed for a 1:158 scale spar buoy model supporting a revolving disk on the top. A smaller damping was observed, and the gyroscopic effect on wave drift forces and yaw moment were found insignificant.

### 2.1.11 Semi-submersible Concept for Supporting Multiple Wind Turbines

Zambrano, et al. (2006) presented the simulation results of a MiniFloat type (see Cermelli and Roddier, 2004) support structure fitted with three wind turbines. The GOM storm conditions were applied in the analysis. The WAMIT program was used to calculate the wave forces. Time-domain platform-mooring coupled analyses were performed using an in-house program. The effect of wind turbine was simplified to a quadratic drag term, with considering the dynamic coupling between the turbines and the floating support structure. Two different wind turbines with the blade diameter of 17 m and 27 m and power output of 90 KW and 225 KW, respectively, were selected for the study. The responses of the design concept subjected to four different hurricane conditions with up to 25-year return period were evaluated. Results were presented in the forms of motion RAOs and statistics of motions and mooring line tensions. The winds and waves were assumed to be collinear, and the platform was assumed to have one column heading towards waves. The platform was sized to have less than 5º of mean pitch and ±15º of dynamic amplitude. A safety factor of 2 was applied to the dynamic mooring loads. Analysis results showed that the system was able to survive the 25-year return hurricane condition.

Lefranc (2007) presented a conceptual design intended to be installed in the Norwegian sector of the North Sea. The proposed floating support structure consisted of 3 vertical columns connected by frames. At the lower level of the frame, a three-arm star was designed to connect the hull to the stationkeeping system. Three mooring lines were connected at the symmetric centre of the floating support structure and to a vertical axis, allowing free rotations of the floater relative to the stationkeeping system. The author stated that the design standards and experience from the offshore oil and gas industry would help result in a rational design of the wind turbine floating support structure. Design criteria for the multi-turbine FOWT were discussed in the paper. Since the proposed FOWT concept would be un-crewed most of the time and would not discharge any hydrocarbon in significant amount, the loss of an installation would not represent a major economical incident. Based on this consequence assessment, the author proposed to reduce the load factors for permanent loads from 1.3, which was used for the design of offshore oil and gas platforms, to 1.15. The proposal was also made to reduce the load factor from 1.3 to 1.15 for environmental loads. Reduction of the material factor was considered possible, i.e. using 1.1 instead of 1.15, although this reduction was not applied in the study reported in the paper. A collision impact with energy input of 4 MJ might be applied. The part of the platform to be designed for this impact should include those structures located between -1 and 2 meters measured from the sea level based on the experience from the offshore oil and gas industry.

Lefranc and Torud (2011) presented the latest development of the WindSea design concept. The semi-submersible type support structure had three columns supporting three turbines, with two turbines in the front (up-wind) and one turbine in the rear (down-wind). The support structure was anchored through a “turret” at its geometrical centre. Model tests confirmed that the support structure could always position itself toward the wind and oscillated with very slow motions around the equilibrium position. These slow motions could be controlled by applying a suitable regulation of the turbines. The wake effects produced by the two upwind turbines on the downwind turbine was estimated by the CFD analysis and further verified by the model test in wind tunnel. Interactions between wave-induced motions and wind action were evaluated using computer simulations and scaled model tests in wave basin. Based on the data collected in the model tests, a design concept intended to support three 3.6-MW turbines was sized for a location in the southern part of the North Sea. The cost for fabrication and installation as well as the annual energy production based on specific wind data were estimated. The production loss on the rear turbine was verified to be only 25% of the theoretical maximum capacity. The upwind turbines, on the other hand, experienced no loss. The authors indicated that the WindSea concept was considered feasible in water depths of 45 m and deeper.

Larsen, et al. (2011) presented a comparison between simulated and measured loads and dynamic motions for the hybrid wave-wind energy converter named after Poseidon. A 37 m wide prototype was deployed offshore Denmark. Three 11 kW turbines were installed on the prototype, which consisted of a floating wave energy extraction platform and a turret mooring system allowing the platform to be weathervaning. These two-blade turbines had a down-wind configuration with the teeter hinge and fixed pitch stall control. The passive yaw system was enabled so that the rotor can be aligned with incoming winds. The platform has been heavily instrumented to record turbine loads, platform global motions and wind and wave characteristics. The prototype was found to align well with the incoming wind. This reduced the risk of operation since the turbine in the rear was operating in full or partial wake generated by two upstream turbines. The authors indicated that the simulation for the integrated system using the HAWC2 and WAMSIM program worked well, assuming the hull structure was rigid.

### 2.1.12 Mono-column Three-leg TLP Concept

Zambrano, et al. (2007) described the design of a floating structure and its mooring system for supporting a small wind turbine (1 KW) in a semi-protected offshore environment. The engineering basis, the hydrodynamic load calculations as well as the installation and commissioning sequences were discussed. Calculations were performed using WAMIT and TimeFloat. Aerodynamic loads were not considered in the analysis, while the turbine generated loads were simplified as a wind drag force.

Moon and Nordstrom (2010) provided a general overview of a TLP-type design concept and its environmental criteria and design criteria. A new design process, along with a discussion of the tools used for design and analysis, was also presented. The TLP concept presented in this paper was designed to a combination of guidelines and criteria that were considered suitable for a first principles “working stress design” approach and a quick design cycle. These relevant design guidelines include API RP-2A, API RP-2T, API RP-2SK, ABS Floating Production Installation, ABS MODU Rules and ABS Steel Vessel Rules. The conceptual design reported in the paper was based on the metocean conditions at a location in the UK Round 3 Development Area. The 50-year return significant wave height of 8.5 meters with an associated peak period of 12.5 seconds was selected. For operational (wind turbine operating) load cases, significant wave height and peak periods were determined as a function of the wind speed measured at 10 m above the sea surface. For ultimate limit state analysis subjected to 50-year return environmental conditions, the wind, wave and current were assumed to be collinear, while both aligned and misaligned wind, wave and current were considered for operational load cases. The chosen water depth for the conceptual design was 55 m.

Henderson, et al. (2010) proposed a TLP concept for German waters. The authors evaluated the prospect of developing floating support structures suitable for deployment in the German sectors of the North and Baltic Seas, with the consideration of technology principles, challenges and the potential wind resource. Since the German sectors of the North and Baltic Seas are relatively shallow and most potential offshore wind farm sites have water depth shallower than 50 m, the authors suggested that TLP-based concepts were the most suitable for German waters in the longer term. Preliminary design assessments of the TLP-based concept supporting the NREL 5-MW baseline offshore wind turbine were carried out. The dimensions of the center column and bottom arms of the TLP as well as the tendon diameter were chosen to minimize the overall cost of the structure but still satisfy with the design requirements on structural dimensions, heel angle, natural frequencies and strength. The TLP concept was analyzed using the Bladed program for the operational load cases and a few non-operational extreme events according to IEC61400-3 (2009).

### 2.1.13 Blue H Concept

Bastick (2009) provided a general overview of the Blue H concept. A scaled prototype of Blue H was deployed offshore Italy in 2008 for a 6-month testing program. The primary purpose of the Blue H prototype was to test the concept, design, assembly, transportation and position methods. The prototype was not designed to be connected to the grid. The author highlighted the economic advantage of the Blue H and indicated that the Blue H concept did not require assembly at the offshore site, expensive marine services equipment, or sea bed preparation and were expected to have low decommissioning cost.

### 2.1.14 SWAY Concept

Forland (2009) introduced the history of the SWAY concept, which consists of a deep draft single column with ballast in the lower end. Similar to the Spar, the center of gravity of the SWAY concept is designed to be far below the center of buoyancy of the column to provide the required stability and the intended hydrodynamic characteristics. The floating tower is anchored to the seabed using a single tendon and a suction anchor. The SWAY concept is developed for supporting the downwind horizontal axis wind turbine. When the wind changes direction, the entire support structure can yaw around a subsea swivel, which enables passive weathervaning. The first scaled prototype of the SWAY concept was installed offshore Norway in 2011 for a two-year field testing program. The prototype lost stability in late 2011 amid a severe storm which exceeded the design limit.

### 2.1.15 Vertical Axis Wind Turbines Concept

Cahay, et al. (2011) presented the recent development of a vertical axis wind turbine (VAWT) concept for the Vertiwind project. The paper reviewed the existing design concepts of VAWTs including the Savonius wind turbine, Darrieus wind turbine and Giromill wind turbine. It was concluded that the VAWT could reduce the number of mechanical components because yaw control, pitch control and gear box were not required. The VAWT also had a lower center of gravity, which increased afloat stability. The authors reported that the floating support structure was based on a semi-submersible specifically designed to accommodate the VAWT. The floating structure would be supported by a minimum of three mooring lines and the turbine would be connected to the grid by a dynamic subsea cable. The Vertiwind prototype is expected to be installed in French Mediterranean Sea. The design of the turbine and the floating support structure was reported being carried out according to the IEC 61400-3 load cases.

### 2.1.16 Other Study on the Response Characteristics of Existing Design Concepts

Chen, et al. (2009) studied the mechanical characteristics of three deepwater offshore FOWT concepts, i.e. NREL TLP, Dutch Tri-floater, and Japanese SPAR, supporting a 5-MW wind turbine. The authors explored the role of the restoring ability, blade pitch controller and wave loads in reducing motions of the floating support structure. It was found that the blade pitch control might help minimize the response.

The three concepts were simplified to 2D models. Steady wind loads on the turbine were calculated using the blade element momentum (BEM) method. Thrust was assumed to be steady wind loads acting at the center of the rotor. The results showed that the maximum thrust under the operation conditions (11 m/s wind speed) was about 1200 kN, while the thrust under the shutdown conditions (25 m/s wind speed) was about 360 kN. The static analysis results of NREL TLP and Dutch Tri-floater were compared.

A 2-D NREL TLP model was selected for further dynamic analysis. Wave loads were calculated using Morison's equation. Airy's linear wave theory and Wheeler's stretching method were applied to compute the wave kinematics. The analysis results were also verified by the dynamic analysis using the HAWC program developed by Riso. Significant resonance was observed at the tower top when the irregular wave condition was applied. The resonance between high frequency wave components and the fundamental eigen-frequency of the wind turbine was considered as the main reason. The output power would oscillate between 1-MW to 4-MW because the relative wind velocity applied to the wind turbine varied between 7 m/s and 11 m/s. The authors concluded that control or damping of such large power output fluctuation caused by motions of the floating support structure would be a major task for the further study.

Jensen (2009) proposed a stochastic procedure for predicting extreme values of wave and wind induced stochastic loads on a tension-leg FOWT. The method was based on the First Order Reliability Method (FORM) and required only short time-domain simulations. A simplified 2-D analytical TLP model was used in the study. The procedure was used previously for wave induced loads only and was extended in this paper for combined wave and wind loads. The author indicated that non-linearity could be appropriately taken into account by the propose method.

Johanning (2009) presented the hydrodynamic analysis and test results of a surface piercing, bottom pivoted circular cylinder. The resulting load and damping characteristics were applied in the calculation of the responses of the pile and compared with the experimental results. Main focus was the response of the cylinder subject to steep wave actions in the pitching mode. It was concluded that the wave radiation damping was the dominant damping source over the tested frequency range, while the acoustic damping was approximately three magnitudes smaller than viscous damping. Small scale experiments were conducted in the wave tank using a cylindrical model whose natural frequency was 2-3 times the wave frequency. It was found linear excitation forces were dominant in moderate waves, resulting in responses at the excitation frequency; while non-linear excitation forces were dominant for steep waves, exciting the motion at the cylinder's natural frequency.

Jagdale and Ma (2010) described a numerical time domain modeling approach for simulating the dynamic behavior of a TLP support structure. Wave forces were computed by Morison's equation and integrated on the instantaneous wetted part of the FOWT. Wave kinematics were computed using the linear wave theory. Each mooring line was considered as a linear spring. A limited comparison of the numerical results with the experimental data was presented to demonstrate the accuracy of the model. The TLP support structure used in the case study was similar to the one used by Shim and Kim (2008). The effect of the changes in the platform configuration on its dynamic responses to wave loading was examined in detail. It was concluded that the variation in spar length, spoke length, spoke cross section sizes and number of mooring lines could lead to different dynamic responses.

Karimirad and Moan (2010a) presented a study on a catenary moored Spar hosting the NREL 5-MW baseline offshore wind turbine. The FOWT model used in the study was similar to the Hywind concept from Statoil. The purpose of the study was to investigate the coupled aero-servo-hydro-elastic dynamic response analysis of a moored FOWT in the time domain. Dynamic responses of the Spar were calculated using the DeepC program, while the HAWC2 program was employed to calculate the response of the wind turbine. A simplified theory of aerodynamic and hydrodynamic damping was developed in order to demonstrate the importance of various design parameters affecting the motion responses and power generation. The main observations of the study are summarized as follows:

- Nacelle resonant surge motion was reduced by increasing the drag coefficient.
- Wave-wind induced resonant surge motion of the nacelle was smaller than that under the wave only (no wind) condition. It appeared that the aerodynamic damping was more effective in reducing the resonant global pitch motion than the hydrodynamic damping, probably because the magnitude of aerodynamic forces was much larger than that of hydrodynamic forces, and the aerodynamic forces were acting at the top of tower.
- For the case with the wind speed below turbine's rated wind speed, the low frequency responses (surge and pitch) of the FOWT hosting a rotating rotor were smaller than those of the FOWT with a parked rotor. The wave frequency response was found almost the same.

- For the case with the wind speed above turbine's rated wind speed, the low frequency responses (surge and pitch) of the FOWT with the parked turbine were smaller than those of the FOWT when the rotor was rotating. However, the wave frequency responses (surge and pitch) are higher when the rotor was parked.
- The dependence of FOWT motion upon the turbine operational modes could be explained by: *i.*) the above-rated wind speed increased the magnitude of aerodynamic forces, which excited the resonant responses, but reduced the wave frequency motions due to the action of blade controller; *ii.*) the nacelle surge motion under the rated wind speed condition was greater than that under the above-rated wind speed condition because of larger excitation forces from the maximum thrust which occurred under the rated wind speed condition.
- In order to improve the quality (steadiness) of generated power, the wave frequency responses as well as the resonant responses should be reduced.

Karimirad and Moan (2010b) focused on the determination of extreme responses for ultimate strength design. A Spar-type FOWT, which was the same as the model in Karimira (2010), was employed for the case study. The HAWC2 program was used for analyzing dynamic responses of the FOWT. The mooring system was modeled as nonlinear spring stiffness. The responses of the parked turbine under the survival condition were compared with those obtained under the operational condition. It was found that the maximum nacelle surge motion under the survival condition was comparable to that under the operational condition. However, the maximum and standard deviation of the bending moment at the tower-hull interface were found much larger in the survival case. This was mainly because the wind induced resonant responses (mostly platform pitch resonance) were dominant under the survival condition.

The structural responses were found close to Gaussian and the process appeared wide banded. The critical structural responses were determined using the coupled aero-hydro-elastic time domain simulation. Based on different simulation schemes, the mean up-crossing rate was calculated and then used to predict the extreme structural responses. The most probable extreme value of the bending moment was found to be in a good agreement with the bending moment with the up-crossing rate of $10^{-4}$. It was further observed that the minimum total number of simulations (realizations or seeds) required for obtaining converged results was highly correlated to the target up-crossing rate. One 1-hour or 2-hour simulation was found not able to provide sufficient information for the $10^{-4}$ up-crossing rate. Comparisons among different simulation time lengths indicated that 20 1-hour simulations might be required to predict the extreme bending moment occurring within a 3-hour time duration, provided that the proper extrapolation of up-crossing rate was used.

Myhr et al. (2011) studied the Tension-Leg-Buoy (TLB) type floating wind turbine support structure, which was moored by two taut legs and used both net buoyancy and mooring line stiffness to control the global motions. The eigen-periods were around 5 s, below the energetic part of the wave spectrum. Wave tank experiments for two TLBs and one Spar were conducted and compared with the numerical computations using the 3Dfloat program, developed by the Norwegian University of Life Sciences (UMB), and ANSYS. In comparison with the Spar-type support structure, the TLB concept appeared to have smaller motions, lower tower loads and the higher anchor loads.

Shin (2011) studied motion characteristics of the OC3-Hywind Spar. A 1:128 scale model was built. The hull, mooring system and wind turbine followed the Froude scaling. The model test was carried out in various sea states and the effect of rotating rotor was taken into account. The results of the model tests were compared with those calculated using the FAST program and the MOSES program. The experiment confirmed that natural frequencies of surge, heave and pitch motion were not affected by wave, wind and rotating rotor despite the difference in peak RAO values. Motions of OC3-Hywind Spar in irregular waves were represented by the significant amplitude at the center of mass and the center of nacelle for different sea states. It was found that the significant amplitudes of motion responses measured in the model tests were larger than those from numerical simulations.

Courbois, et al. (2011) described the development of a turbulent wind field generation system suitable for the application in FOWT model tests. A CFD simulation was also performed to verify the wind field in the wave basin. The wind generation system was based on several centrifuge fans located behind the wavemaker. Flexible air ducts were used to tunnel airflow to the location close to FOWT models.

## 2.2 Development of Global Performance Analysis Tools for FOWTs

### 2.2.1 NREL FAST Program

Jonkman and Sclavounos (2006) presented an enhanced FAST program for analyzing FOWTs. Prior to this development, the NREL's FAST program had been used only for predicting the extreme and fatigue loads of land-based and bottom-founded offshore wind turbines. This new version of FAST allowed considering platform kinematics and kinetics, linear hydrodynamic loading, and mooring system dynamics. The mooring loads were obtained by interfacing FAST with LINES, which is a program module developed by MIT. Contributions from inertia, restoring forces, and viscous separation damping effects, as well as the elastic responses of mooring lines and their interaction with the seabed, can be taken into account in the mooring load calculation in the LINES program. It was noted that the bending stiffness of mooring lines could not be modeled. The hydrodynamic loads on the floating support structure were calculated using SWIM or WAMIT, which served as a preprocessor. The capability of considering the effect of nonlinear slow-drift and sum-frequency excitations and high-order wave kinematics were not included.

Jonkman and Buhl (2007a) continued the work initiated by Jonkman and Sclavounos (2006) to develop a simulation program that could model fully coupled aero-hydro-servo-elastic responses of FOWTs. The program was originally an integration of WAMIT or SWIM for calculating hydrodynamic loads on the floating support structure, LINES for calculating mooring loads, and AeroDyn-FAST for calculating aerodynamic and servo-elastic loads and responses of the RNA and tower. Subsequent studies revealed numerical instability in the coupled LINES and FAST program. The LINES program was then replaced by a built-in quasi-static module in FAST to simulate nonlinear restoring loads from the mooring system. The new mooring module could be used to model an array of homogenous taut or slack catenary mooring lines. It also had the capability to consider the apparent weight in fluid, elastic stretching, and seabed friction of each mooring line, while the bending stiffness, inertia and damping of the mooring line were neglected.

Jonkman and Buhl (2007b) used the FAST program to perform the load analyses for the NREL 5-MW baseline offshore wind turbine supported by a floating barge and a catenary mooring system. The barge was assumed to be located in the northern North Sea at 160 m water depth. For the 1-year return storm condition, the significant wave height was 10.8 m and the hub height 10-minute mean wind speed was 40 m/s. For the 50-year return storm condition, the significant wave height was 13.8 m and the hub height 10-minute mean wind speed was 50 m/s. A number of operating and extreme design load cases (DLCs) were evaluated. The coupling between the wind turbine responses and the barge pitch motions, in particular, was found to produce larger extreme loads in the turbine, especially in its tower and blades. The barge was also found to be susceptible to excessive pitching in the extreme wave conditions. Comparing to the land-based support structure, the added compliance of the barge led to the instability of overall FOWT system when the rotor was idling with a faulted blade. The compliance of the barge did however eliminate the tower side-to-side instability observed in the land-based wind turbine. Design modifications to reduce the barge motions, improve the turbine responses, and eliminate the instabilities were recommended.

Jonkman's Ph.D. dissertation (2007) detailed the theoretical basis of a fully coupled aero-hydro-servo-elastic simulation tool for both bottom-founded and floating offshore wind turbines. FAST and ADAMS were updated to include a quasi-static mooring analysis program and an interface with WAMIT or SWIM for calculating hydrodynamic coefficients for FOWTs. The upgraded software also included a new time-domain hydrodynamic module, HydroDyn, for generating wave fields and calculating hydrodynamic loads on the offshore support structure. The effects of VIV, sea ice loads, and the nonlinear effects of slow-drift and sum-frequency excitation and high-order wave kinematics were not considered. The program also neglected the bending stiffness of the mooring lines and the inertia and damping of the mooring system. A number of case studies were performed using the latest FAST program. The influence of the conventional wind turbine blade-pitch control on the pitch damping of floating turbine was also assessed.

Bir and Jonkman (2008) studied the modal dynamics of floating and monopile-supported offshore wind turbines. A new version of the finite-element program, BModes, was used in the analyses. The program was capable to calculate coupled vibration modes either for a rotating blade or for a mono-column support structure. The program considered the effects of hydrodynamic inertia, hydrostatic restoring and mooring lines stiffness on the floating platform. It also took into account the distributed hydrodynamic mass on the submerged part of the support structure and the effect of elastic foundation surrounding the monopile. Comparative analyses were performed for three turbine configurations including a land-based turbine, a monopile-supported offshore wind turbine and an FOWT. The NREL 5-MW baseline offshore turbine was assumed to be installed on each support structure. In the FOWT configuration, a preliminary barge design was adopted. To account for the hydrodynamic and hydrostatic effects on the floating support structure, the 6x6 inertia (added mass) and 6x6 restoring (stiffness) matrices, obtained from the hydrodynamic analysis using WAMIT, were imported as an input to BModes. A 6x6 matrix accounting for the mooring system stiffness can be defined by the user as an input to BModes. This matrix was calculated by numerically linearizing the nonlinear mooring system. The paper concluded that the hydrodynamic response and elastic or moving foundation had a significant influence on the turbine modal dynamics.

Jonkman (2009) described the formulations for the hydrodynamic and mooring system analysis implemented in HydroDyn, which is part of the FAST program. The quasi-static mooring line module was capable of considering the elastic stretching of an array of homogenous taut or slack catenary lines and the effect of seabed-mooring line interaction. The hydrodynamics module was developed to taken into account

- linear hydrostatic restoring forces
- nonlinear viscous drag due to incident-wave kinematics
- sea currents
- platform motions
- incident wave excitations due to linear diffraction in regular or irregular waves.
- added-mass and damping induced by the wave radiation and free-surface memory effects

The updated FAST program was verified by comparing its calculation results to those obtained using other methods, including the frequency domain models.

### 2.2.2 CHARM3D + FAST

Shim (2007) and Shim and Kim (2008) reported the development of a fully coupled dynamic analysis program based on the two existing programs, CHARM3D and FAST, for FOWTs. CHARM3D is a time-domain global performance analysis program for integrated floating hull-mooring-riser/cable systems. The floating hull structure is assumed as a rigid body subjected to the actions of wave, wind and current. The hydrodynamic forces on the floating hull structure were evaluated using the diffraction theory. The mooring, riser and cable were modeled as rod elements using the nonlinear finite element formulations. FAST, which was interfaced with AeroDyn, is the aero-servo-elastic wind turbine analysis software developed by NREL. A data passing scheme was developed to link CHARM3D and FAST. The 6-DOF motions were calculated for the floating support structure subjected to ocean environmental conditions and turbine loads at the interface between the hull structure and the tower. The turbine loads were supplied by FAST aerodynamic analysis output. The balanced platform motions at the hull-tower interface were fed back to FAST to compute the dynamic loads on the turbine supported at the moving foundation and also update the hull-tower interface loads.

A 1.5-MW wind turbine with 70 m long blades and a 5-MW wind turbine with 126 m long blades were evaluated. The TLP support structure selected for this study was similar to the one used by Withee (2004). Comparisons were made between the coupled and uncoupled dynamic analyses. In the uncoupled dynamic analysis, the wind loads on the projected area of stationary blades were assumed, while a more realistic rotor dynamic modeling, which was able to consider the dynamic forces and inertia loading, were included in the coupled analysis. It was shown that the dynamic coupling between the floating support structure and mooring lines became stronger under an increasing wind speed and/or with a larger blade size. The significant coupling effect could also lead to higher dynamic tensions in the TLP tendons.

Bae, et al. (2010) further enhanced the fully coupled FOWT analysis program developed by integrating CHARM3D and FAST. The hydrodynamic coefficients including added mass, radiation damping, wave forces, and mean drift forces of FOWT were calculated by a frequency domain diffraction/radiation preprocessor (WAMIT, by default, or other equivalent programs). These coefficients were then used as part of the input data for the time domain analysis in CHARM3D. The mooring dynamics coupled with hull motions were solved at each time step by a generalized-coordinate-based FEM formulation using high-order rod elements. The wind turbine dynamics, excluding the effect of 6-DOF inertia and gravity loads which were considered by CHARM3D, were calculated by the FAST program. The resultant aerodynamic forces and the forces due to elastic deformation of the tower were lumped at the interface between the tower base and the hull structure and were then exported as an external force input to the CHARM3D analysis. When calculating the tower base loads in FAST, the 6-DOF hull motions calculated by CHARM3D were passed on to FAST at every time step. These instantaneous motions were supplied as initial displacements of tower base for the incremental time domain analysis in FAST within each time step of the hull global motion analysis. In the case studies, the time step of Charm3D global motion analysis was chosen as 0.05s, while the internal time step for FAST analysis was chosen as 0.005s. That means at every time interval of 0.05 second used in

Charm3D, FAST calculates 10 internal time steps before returning the resultant hull-tower interface loads back to CHARM3D.

Case studies were carried out using a mono-column TLP designed for two different water depths (80 m and 200 m). A 1.5-MW turbine was selected for the case studies. The TLP became stiffer in both horizontal and vertical planes at the shallower water depth. It was shown that the coupling effects between the rotor and the floating support structure could lead to a higher maximum tendon tension even if they appeared insignificant for the selected blade size. The maximum tendon tension was slightly larger in the relatively shallow water in spite of the fact that the system was stiffer. The rotor dynamics and elastic modes also caused additional high-frequency vibrations of the TLP. These high frequency excitations could reduce tendon's fatigue life. The authors indicated that the rotor-floater coupling effect would become more significant for longer blades or under higher wind speeds.

A new coupling scheme between CHARM3D and FAST were introduced in Bae and Kim (2011) and Bae, et al. (2011a, 2011b), where FAST was used to calculate all the dynamic responses of the turbine components, tower and floating hull structure, while CHARM3D was employed to determine 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 used the forces calculated by CHARM3D and lumped at the hull-tower interface 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 were passed on to CHARM3D for the next step calculation of the hull-tower interface forces.

Bae, et al. (2011a) and Bae and Kim (2011) studied the significance of the coupling effect of hull-mooring-turbine to FOWT global performances. Two case studies were carried out, respectively, using the OC3-Hywind Spar supporting the NREL 5-MW baseline offshore wind turbine at 320 m water depth and a mono-column mini TLP supporting a 1.5-MW turbine at 80 m water depth. Global performance analyses were undertaken using coupled turbine-tower-hull-mooring simulation models and the CHARM3D-FAST program. The "uncoupled" analyses, where the tower-RNA was modeled by a rigid body subjected to the equivalent quasi-static wind load, were also carried out for the comparative study. The equivalent quasi-static wind load on the swept area of blades was determined by adjusting the blade drag coefficient used in the uncoupled analysis to match the mean aerodynamic load obtained in the coupled analysis. The results of those uncoupled analyses served as the benchmark in evaluating the significance of the coupling effect. In case studies, collinear wind and wave conditions were assumed, while currents were not applied. The turbine was assumed being in the normal operating condition. A sea state with the significant wave height of 5 m and peak wave period of 8.69s and a 1-hour mean wind speed (at 10 m height) of 13 m/s were applied. Based on the case study results, the authors concluded that

- For the floating support structure with a soft mooring system, such as Spar or Semi-submersible, the low-frequency excitations related to blade pitch-angle control could cause large-amplitude slowly varying hull motions.
- For the TLP-type support structures, which were much stiffer in the vertical direction compared to other types of the floating support structure, the effects of rotor-induced or tower-flexibility-induced excitations could be important for both strength and fatigue design.
- The accurate estimation of the coupling effect among the dynamics of the floating support structure, the RNA-tower dynamics and the turbine control scheme were very important in the optimal design of FOWTs.

### 2.2.3 SIMO/RIFLEX + HAWC2

Skaare, et al. (2007) presented an analysis approach based on the integration of SIMO/RIFLEX developed by Marintek and HAWC2 developed by Risø National Laboratory for the Hywind project. The analysis results were verified using the scaled model test data.

HAWC2 is an aero-elastic simulation program capable of calculating the dynamic structural responses of a wind turbine subjected to aerodynamic loading and control actions. The core of HAWC2 is a multi-body implementation of beam finite elements. The multi-bodies used to model the wind turbine structure, e.g. the tower structure or the shaft structure, were connected using algebraic constraint equations. Different types of constraint equations enable the user to define rigid connections, joints and bearings for an operating wind turbine. The SIMO/RIFLEX program consists of two modules, i.e. SIMO and RIFLEX. SIMO is designed for calculating motions and station-keeping performance of floating structures, whereas RIFLEX is for static and dynamic analyses of slender marine structures such as flexible risers, mooring lines and pipelines. In the integrated SIMO/RIFLEX and HAWC2 program, a data exchange mechanism was developed to connect the two programs. The user can decide whether to put the interface point at sea level or other locations on the foundation. HAWC2 provides external forces at a specified interface point to SIMO/RIFLEX based on the prescribed motion at the interface. These reaction forces were passed on to SIMO/RIFLEX where they enter into the equilibrium equation of motions, whose solutions provide the updated motion at the interface for the next step HAWC2 analysis.

The integrated HAWC2 and SIMO/RIFLEX program were used for modeling the Hywind design concept. The main challenges were related to the combined wave and wind loads and the choice of blade-pitch control strategy. Using conventional wind turbine control strategies could result in large motions of FOWTs due to the unfavorable coupling of aerodynamic loads and wave induced motions. A comparative study was conducted to evaluate the critical operation regime above the rated wind speed and the performance of the conventional blade pitch control strategy with and without active damping. The active damping control included an additional input determined by measurements of tower motions. The authors concluded that the development of a coupled simulation program based on HAWC2 and SIMO/RIFLEX was a success. The verification analysis using the scaled wind turbine model for the Hywind concept appeared to give promising results.

### 2.2.4 Flex 5

The Flex5 program was originally developed at Risø National Laboratory. It is capable of simulating the dynamic behavior of wind turbines in turbulent wind fields by taking into account aerodynamic loads, elastic structural responses and actions of other sub-modules (generator, tower, foundation). The aerodynamic analysis is based on the BEM method assisted by empirical corrections for stall, wake development and tip effects. The aero-elastic model can accommodate a maximum of 28 degrees of freedom in the simulations, although fewer degrees of freedom are usually used. The solution is carried out in the time domain.

Knauer and Hagen (2007) described a coupled floater-turbine analysis approach that consisted of the integration of a simplified hydrodynamic subroutine into Flex5. The hydrodynamic subroutine for the floating foundation was implemented to calculate the motions of turbine tower base. The irregular wave environment was modeled with the Pierson-Moskowitz spectrum. A simple drag model was implemented and constant added masses coefficients were assumed in the calculation of hydrodynamic forces. The pre-tensioned mooring system was simulated using a set of functions to represent the mooring line forces. The program was demonstrated through a case study using the Hywind concept supporting a 5-MW variable-speed, pitch-regulated turbine. The floating foundation consisted of a cylindrical concrete/steel floating support structure and a catenary mooring system. Simulations were carried out using different irregular wave spectra combined with deterministic and turbulent wind conditions. It was concluded that the integrated program was numerically robust. The analysis results showed a good agreement with test data, despite the simplifications implemented in the hydrodynamic analysis subroutine. Differences did occur at the high wind speeds, where the blade pitch control could have big impact on the global responses. The authors indicated that the program would be developed further, with the focus on new control strategy and more advanced hydrodynamic modeling.

### 2.2.5 GH Bladed

GH Bladed, developed by Garrad Hassan (Bossanyi, 2003), is capable of performing the coupled aero-hydro-servo-elastic simulation for both bottom-founded and floating offshore wind turbines. The structural dynamics of an FOWT are calculated using the modal superposition method. A newer version of the program based on multi-body dynamics formulations is also available. The aerodynamic forces on the rotor are determined using the blade element momentum theory, while the hydrodynamic loads on the turbine support structure are calculated using Morison’s equation. The mooring lines are not directly modeled in GH Bladed. Instead, a user-defined force-displacement relationship needs to be provided as an input.

In the study reported by Henderson, et al. (2010), the GH Bladed program was used to calculate the dynamic responses of a TLP-based FOWT concept subjected to the operational load cases and extreme conditions specified in IEC61400-3 (2009). The program has also been used in the IEA OC3 code-to-code comparative study (Jonkman, et al., 2010).

### 2.2.6 TimeFloat + FAST

TimeFloat, developed by Principle Power, Inc. (Roddier, et al., 2009), is a time-domain global performance analysis program for floating offshore structures and mooring systems. An interface program has been developed to link the FAST program to TimeFloat, which was used in the development of the WindFloat concept. More details about the application of this integrated TimeFloat and FAST program can be found in Section 2.1.9.

### 2.2.7 Other Simulation Tools and Modeling Methods for FOWTs

Cordle (2010) and Cordle and Jonkman (2011) reviewed the simulation software capable of performing dynamic analyses for FOWTs. Both the modeling techniques and the capabilities of these software, including the FAST program, Charm3D+FAST, TimeFloat+FAST, ADAMS+AeroDyn+HyroDyn, GH Bladed, SIMO/RIFLEX+HAWC2, 3Dfloat, and a special version of SIMPACK were summarized. An overview of the testing and validation of these tools was also presented. Conclusions were drawn on the development needs and future verification activities. The authors further indicated that a full design optimization would not be possible without taking into account the coupled responses of an integrated FOWT system.

Karimirad (2010) reported a study on the global performance analysis of a FOWT subjected to storm wave and wind conditions. A Spar platform designed for supporting the NREL 5-MW baseline offshore wind turbine was analyzed. Global performance analyses were carried out with the consideration of the coupling effect among the turbine, the Spar hull structure and the mooring. Equations of motion for the coupled hull and the mooring lines were solved simultaneously using the DeepC program developed by Marintek. The aerodynamic forces on a parked turbine were first calculated based on the strip theory, and then imported to the DeepC program through a MATLAB interface. At each time step, the wind velocity relative to the global motions was calculated. Various load conditions (with different combinations of wind, wave and turbulence) were analyzed to evaluate the response of the FOWT. It was found that the wind force could excite resonant responses at the natural frequencies of pitch and surge motions.

Quesnel, et al. (2010) presented the hydrodynamic modeling of FOWTs. The reported study was part of a broader effort to develop a fast, flexible aero-hydro-servo-elastic simulation tool. A set of requirements and specifications for developing a hydrodynamic simulation module for FOWTs was discussed. As the first implementation step, the development and validation of the wave kinematics module were detailed. Finite depth linear kinematics, delta and Wheeler’s stretching were implemented and validated.

Sebastian and Lackner (2010) presented a comparison of different first-order aerodynamic analysis methods for FOWTs. In contrast to land-based and bottom-founded offshore wind turbines, FOWTs were found to operate in three distinctive aerodynamic conditions, i.e.

- nearly constant non-axial flow field,
- significantly non-uniform wind field across the rotor disk, and
- angular and translational motions that result in turbulent transient conditions similar to vortex ring state (VRS) and dynamic stall.

Responses of an example floating horizontal axis wind turbine were calculated using three selected first-order aerodynamic analysis tools, including an in-house code based on the blade element momentum (BEM) theory, the AeroDyn subroutine used by NREL's FAST program, and a program based on the free vortex method developed at the Delft University of Technology. The results suggested that existing methods for predicting the aerodynamic loads acting on an FOWT might not be sufficient, although the free vortex method (FVM) might provide a framework that could accurately describe the physics of the flow field.

In a subsequent study by Sebastian and Lackner (2011), a program based on the free vortex wake model, Wake Induced Dynamics Simulator (WInDS), was developed. It was shown that the program could provide better predictions than other commonly used wind turbine aerodynamic analysis programs. The author indicated that simply extrapolating empirical techniques to new operating conditions, such as those experienced by FOWTs, was not appropriate. Most existing wind turbine analysis and design software were found to rely on the momentum balance assumption, which might break down for FOWTs. The authors further stated that the free vortex method represented one of the most promising aerodynamic analysis techniques for FOWTs.

Myhr et al. (2011) studied the Tension-Leg-Buoy (TLB) based floating support structures using 3Dfloat and ANSYS. 3Dfloat is an aero-hydro-servo-elastic analysis program developed at the Norwegian University of Life Sciences for the modeling of FOWTs. The finite element method was implemented to model the structural dynamics of FOWT support structures using beam elements. The rotor aerodynamics was calculated using the blade element momentum theory. Morison's equation was employed to calculate the hydrodynamic loads on slender members. The mooring lines were modeled using linear finite elements without considering bending stiffness.

Ku, et al. (2011) developed a dynamics kernel for a multi-body system subjected to wave and wind loads, and applied it to the dynamic response analysis of an FOWT. The kinematic relations between the rigid bodies were imposed by defining various types of joints. All the components of the wind turbine were regarded as rigid bodies. An external calculation module was developed for calculating the hydrostatic forces, the linearized hydrodynamic force using the 3D Rankine panel method, the mooring forces, and the aerodynamic force on the rotor based on the blade element momentum theory.

Sweetman and Wang (2011) described theoretical development of a new approach to compute large-angle rigid body rotations of FOWTs in the time domain. The floating support structure and the RNA were considered as two rotational rigid bodies in space, for which two sets of Euler angles were used to develop the equations of motion. Transformations between the various coordinate systems were derived in order to solve for the motions of the floating support structure subjected to gyroscopic, environmental and restoring forces. A quasi-static model for the wind load calculation and Morison's equation were implemented. Under the assumption of small-angle vibrations, the new approach was validated by the FAST program. With the consideration of large-angle rigid body motions, the authors showed that two major components of gyroscopic loading on a free floating support structure - one due to precession velocity of the spin axis and another due to rotation velocity - could be substantial.

Kallesøe and Hansen (2011) studied the performance of various mooring line models in hydro-aero-elastic simulations of FOWTs. The authors extended the capability of the HAWC2 program (see Larsen and Hansen, 2009) by implementing a dynamic mooring line modeling approach. The flexible mooring line was model using a general cable element formulation. The enhanced HAWC2 was used to analyze the effect of mooring models on a Hywind Spar-type FOWT. The mooring system consists of three catenary mooring lines, with two delta lines splitting each catenary line into two connection points on the hull. In the quasi-static modeling approach, these delta lines were neglected such that the main line was extended and connected directly to the hull. In the dynamic modeling approach, on the other hand, two models were developed for the delta line configuration, i.e. extending each main line to the hull in the same way as in the quasi-static model and modeling the delta lines explicitly. The yaw stiffness for the FOWT was apparently different in the two dynamic mooring models because the delta lines of the second model substantially increased the yaw stiffness. The simulation results showed that the dynamic mooring line model did not affect the blade extreme or fatigue loads, nor did it affect the extreme loads on the hull structure. However, the bending equivalent load at the tower-hull interface was reduced by 5%-20 % in some load cases and thus the equivalent fatigue load is reduced by 5%-10 %. The authors observed that the mooring system could affect the floating support structure loads, but it appeared conservative to use the quasi-static modeling approach for the mooring system. It should be noted that the load cases analyzed in this study only include the normal operational condition with a collinear wind and wave and no nacelle yaw misalignment. The conclusions made in this paper regarding the effect of modeling fidelity of mooring system on the FOWT should not be generalized until a full set of load cases are evaluated.

Matha, et al. (2011) discussed modeling challenges for FOWT design tools and explored the important physical effects not yet addressed by existing simulation software. Comparisons were also made among various modeling methods and their applicability to the development of FOWT design tools.

### 2.2.8 FOWT Simulation Software Verifications

Jonkman, et al. (2010) presented the latest results of the code-to-code verifications conducted by the Offshore Code Comparison Collaboration (OC3), which was operated under Subtask 2 of the International Energy Agency (IEA) Wind Task 23. In the final phase (Phase IV) of the project, the coupled dynamic response was studied for the NREL 5-MW baseline offshore wind turbine installed on a Spar-type floating support structure, which was named “OC3-Hywind” in order to distinguish it from Statoil’s original Hywind concept. The OC3-Hywind was featured by a deep draft, slender spar buoy restrained by three catenary mooring lines.

A number of load cases were selected to evaluate different modeling approaches for the OC3-Hywind. The results from participating software were compared at various levels of details, including full-system eigen-values, free decay motions, hydro-elastic responses in regular waves and irregular waves, and aero-hydro-servo-elastic responses to combined turbulent winds and regular waves. This “code-to-code” comparison resulted in a greater understanding of FOWT dynamics and modeling techniques, as well as the validity of various approximations. The software used in the OC3 study included FAST, GH Bladed, ADAMS, HAWC2, 3Dfloat, SIMO/RIFLEX and SEASAM/DeepC. In the new IEA Wind Task 30 (OC4), more simulation tools including CHARM3D+FAST and PHATAS among others were also involved.

Cordle and Jonkman (2011) provided an overview of existing simulation software having the capability of modeling FOWTs. Verification results of several simulation programs were also summarized in the paper. Although some software was verified by model tests and/or field measurements, there were very few data available in the public domain. More dedicated model tests and field measurements of full-scale installations were therefore considered highly desirable. At present, the simulation software for the design of FOWTs was mostly validated through code-to-code comparisons, among which the most extensive effort was made by the IEA Wind Task 23 (OC3) and the on-going IEA Wind Task 30 (OC4).

## 2.3 Control Systems for Floating Offshore Wind Turbines

Larsen and Hanson (2007) used SIMO/RIFLEX+HAWC2, an integrated simulation software capable of performing coupled aero-hydro-servo-elastic analyses, to study the effect of blade pitch control on the performance of Hywind Spar supporting a 5-MW pitch regulated wind turbine. It was observed that since the first natural frequency of the Hywind FOWT was very low compared to that of a traditional bottom-founded offshore wind turbine, the pitch controller would adjust the blade pitch angle during the motion and thereby reduce the thrust when the motion was against the wind and vice versa. The aerodynamic damping could therefore become negative when the pitch control was acting above certain frequency. The solution proposed in this paper was an adjustment of control parameters to reduce the control activity, or in other words, a reduction of the pitch controller's natural frequency. This approach led to the positive aerodynamic damping, but was found to cause a noticeable increase in the rotor speed variation. To limit the rotor speed variation, the generator control was changed from the constant power control to the constant torque control. The new blade pitch controller was shown to perform well, especially for maintaining the tower motion stability and structural responses. The unfavorable variations in the rotor speed (and thus electrical power output) were found to reach up to 30% of the nominal speed, while a bottom-founded turbine typically would have a variation up to 10%. The authors further indicated that the significant variation in electrical power might be less important if the turbine was operated in a wind farm, where the overall power output would be smoothed by averaging the production of individual turbines. Discussions were also made about using stall controlled turbines to mitigate the instability.

Skaare, et al. (2007) calculated the fatigue life of the Hywind FOWT using SIMO/RIFLEX+HAWC2. The effect of using two different blade pitch control strategies, i.e. a conventional control scheme and an estimator based control scheme, were assessed. Seven fatigue load cases were analyzed to calculate the fatigue life of the tower and the rotor. The global performance was evaluated for the Hywind FOWT in normal operation and subjected to the wind speed higher than turbine's rate wind speed. It was found that the fatigue resistance of the FOWT was significantly improved when the estimator based control scheme was applied. However, as less favorable consequences, the estimator based control scheme led to a modest reduction in the average power output and higher variation in the power output and the rotor speed.

Jonkman (2008) studied the influence of turbine's blade pitch control on the global pitch motion of a floating barge supporting the NREL 5-MW baseline offshore wind turbine. The negative damping of global pitch motion due to the reduction of steady-state rotor thrust was observed when the wind speed went above turbine's rated speed. This negative damping resulted in large global pitch motions of the floating support structure. The control system of the turbine was then modified to improve the damping of global pitch motion. The solutions included

- adding a second blade-pitch control loop using the feedback of tower-top acceleration;
- changing from the variable pitch-to-feather to variable pitch-to-stall rotor speed control; and
- de-tuning the gains in the variable blade pitch-to-feather rotor speed controller.

The author evaluated each of these solutions separately. It was shown that neither the addition of a control loop using the feedback of tower-top acceleration nor the modification to the pitch-to-stall rotor speed regulation could improve the pitch motion of the barge. Detuning the gains in the blade-pitch-to-feather controller showed some improvement, but still could not entirely resolve the instability issue of the barge pitch motion.

Lackner (2009) studied two approaches for designing the rotor control system of an FOWT in order to reduce the loads on the floating support structure and the turbine blades. The first approach was to control the collective blade pitch and reduce the pitch motion of the floating support structure. The rated generator speed was assumed to be a function of the pitch velocity of the floating support structure. When the floating support structure pitched upwind, the generator speed was set to a larger value, and vice versa. For a constant generator torque, this approach essentially made the rated power a variable that depends on the pitch motion velocity of the floating support structure. It was shown that substantial reductions in the pitch motion of the floating support structure could be achieved at the cost of minor increases in the power variability. The second design approach was to design an individual blade pitch controller. It was found that this individual pitch control could not reduce the blade loads of the FOWT.

Luo, et al. (2011) developed a dynamic load mitigation method based on semi-active control techniques, which was featured by installing the tuned liquid column dampers at the tower top. The tuned liquid column dampers were designed to suppress wind-induced motions by dissipating energy through motions of the liquid mass in a U-shaped tube. The damper in its original form was passive. With the addition of a controllable valve, it became a semi-active damper. By using a suitable control algorithm, the authors showed that it was possible to adapt the orifice opening according to the structure responses and loading conditions.

Bae, et al. (2011) evaluated the effect of various rotor control schemes on the global responses and the power output of the NREL 5-MW baseline offshore wind turbine installed on a Spar-type support structure. It was demonstrated that for Spar-type FOWTs, the rotor control scheme could significantly alter the hull and mooring dynamics, especially when the control system induced instability (e.g. resonant response) occurred. The authors compared the effectiveness of two different control schemes, including a conventional rotor control scheme typically used for land-based wind turbines and a modified control strategy designed specifically for the FOWT under consideration. The coupling effects between the variations of blade pitch angle and the global hull motions were taken into account through coupled aero-hydro-servo-elastic analyses using the CHARM3D-FAST program. The resonance in the Spar motion responses was observed when the conventional control scheme was applied, while the modified control scheme appeared able to noticeably reduce the Spar motions and improve the quality of power output.

# 3 Case Studies Using Conceptual Designs

## 3.1 Overview

One of the major challenges in the design of an FOWT is the prediction of dynamic loads and responses of the FOWT. The design load cases specified in the existing design standards, represented by IEC 61400-3 (2009), were developed for bottom-founded offshore wind turbines and based primarily on the experience gained in shallow waters. The adequacy and applicability of these design load cases for FOWTs have to be evaluated with due account being taken for the unique load and response characteristics of FOWTs.

This section presents the models, methodologies and results of the case studies using three representative FOWT conceptual designs available in the public domain. The 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, the floating support structure and the stationkeeping system. Representative environmental conditions of the Northeast Coast, West Coast and Gulf of Mexico on the US OCS are applied in the case studies. The load cases evaluated in the study are defined using the combination of turbine operating conditions and environmental conditions. Typical turbine operating conditions, including the normal power production, start-up, shut down, and parked conditions, are considered in the definition of the load cases. For the turbine in normal power production, the sensitivity of global responses to different blade pitch control schemes is evaluated. For the parked turbine conditions, global performance analyses are carried out for both 50-year and 100-year return storm conditions, and the effects of the nacelle yaw fault as well as the directionality of wind and wave conditions are assessed. Parametric studies are performed to evaluate the relative importance of various design parameters. A robustness check is also carried out for selected load conditions.

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 to the extend 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, tower, floating hull structure, and stationkeeping system;
- to assess the applicability of relevant load cases originally defined in IEC 61400-3 (2009) for bottom-founded offshore wind turbines;
- to explore other potentially critical load cases for FOWTs to be deployed in hurricane prone areas on the US OCS; and
- to evaluate the sensitivity of global responses of FOWTs to the variations of external conditions on the US OCS.

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

- Return period of extreme design environmental conditions
- Turbine operating conditions
- Configuration of the floating support structure
- Site variation
- Wind-wave misalignment

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 generic WindFloat Semi-submersible 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 100-year return hurricane conditions in the Gulf of Mexico (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 being installed on each conceptual design for 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 the one 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 are determined based on API Bulletin 2INT-MET (2007). For the US West Coast, site-specific metocean data are derived from the records of the NOAA buoy and the water level station located offshore northern California. For the US Northeast coast, site-specific metocean data are derived using the records of the NOAA buoy and the water level station off the coast of Maine.

A general description of the load cases 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 Cases Descriptions for the Case Studies**

| *Turbine Condition* | *Wind condition* | *Wave* | *Wind and wave directionality* | *Current* | *Water level* | *Yaw Control* | *Turbine Operating Mode* |
|---|---|---|---|---|---|---|---|
| Power production (DLC1.3) | Extreme turbulent wind<br>$V_{in} \leq V_{hub} \leq V_{out}$ | Normal Sea State<br>$H_s = E[H_s \vert V_{hub}]$ | Collinear | Normal currents | Mean Sea Level | Yaw misalignment $\varphi=0^0$ | Normal |
| Start-up (DLC3.2) | Extreme Operating Gust<br>$V_{hub} = V_{in}$, $V_r$±2 m/s and $V_{out}$ | Normal Sea State (Normal Wave Height)<br>$H=H_s=E[H_s \vert V_{hub}]$ | Collinear | Normal currents | Mean Sea Level | Yaw misalignment $\varphi=0^0$ | Normal |
| Emergency shut down (DLC5.1) | Normal turbulent wind<br>$V_{hub} = V_r$±2 m/s and $V_{out}$ | Normal Sea State<br>$H_s = E[H_s \vert V_{hub}]$ | Collinear | Normal currents | Mean Sea Level | Yaw misalignment $\varphi=0^0$ | Normal |
| Parked (Idling) | Extreme turbulent wind<br>$V_{hub} = 0.95\times V_{10min,10\text{-}yr}$ | 10-yr return wave<br>$H_s = 1.09\times H_{s,10\text{-}yr}$ | Collinear<br>$\pm30^0$ cross waves<br>$\pm90^0$ cross waves | 10-yr Currents | 10-yr Water Level | Yaw misalignment $\varphi=\pm20^0$ | Normal |
| | Extreme turbulent wind<br>$V_{hub} = 0.95\times V_{10min,50\text{-}yr}$ | 50-yr return wave<br>$H_s = 1.09\times H_{s,50\text{-}yr}$ | Collinear<br>$\pm30^0$ cross waves<br>$\pm90^0$ cross waves | 50-yr Currents | 50-yr Water Level | Yaw misalignment $\varphi=\pm8^0$ | Normal |
| | Extreme turbulent wind<br>$V_{hub} = 0.95\times V_{10min,100\text{-}yr}$ | 100-yr return wave<br>$H_s = 1.09\times H_{s,100\text{-}yr}$ | Collinear<br>$\pm30^0$ cross waves<br>$\pm90^0$ cross waves | 100-yr Currents | 100-yr Water Level | Yaw misalignment $\varphi=\pm8^0$ | Normal |
| | Extreme turbulent wind<br>$V_{hub} = 0.95\times V_{10min,50\text{-}yr}$ | 50-yr return wave<br>$H_s = 1.09\times H_{s,50\text{-}yr}$ | Collinear<br>$\pm30^0$ cross waves<br>$\pm90^0$ cross waves | 50-yr Currents | 50-yr Water Level | Yaw misalignment $-180^0\leq\varphi <180^0$ | Abnormal |
| | Extreme turbulent wind<br>$V_{hub} = 0.95\times V_{10min,100\text{-}yr}$ | 100-yr return wave<br>$H_s = 1.09\times H_{s,100\text{-}yr}$ | Collinear<br>$\pm30^0$ cross waves<br>$\pm90^0$ cross waves | 100-yr Currents | 100-yr Water Level | Yaw misalignment $-180^0\leq\varphi <180^0$ | Abnormal |

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

| *Turbine Condition* | *Wind condition* | *Wave* | *Wind and wave directionality* | *Current* | *Water level* | *Yaw Control* | *Turbine Operating Mode* |
|---|---|---|---|---|---|---|---|
| Parked (Idling) and Fault | Extreme turbulent wind $V_{hub} = 0.95\times V_{10min,10\text{-}yr}$ | 10-yr return wave $H_s = 1.09\times H_{s,10\text{-}yr}$ | Collinear<br>$\pm 30^0$ cross waves<br>$\pm 90^0$ cross waves | 10-yr Currents | 10-yr Water Level | Yaw misalignment $-180^0 \leq \varphi < 180^0$ | Abnormal |

Notes:

1. $V_{hub}$ is the mean wind speed at hub height.
2. $V_{10min,10\text{-}yr}$ is the 10-year return 10-minute average wind speed at hub height.
3. $V_{10min,50\text{-}yr}$ is the 50-year return 10-minute average wind speed at hub height.
4. $V_{10min,100\text{-}yr}$ is the 100-year return 10-minute average wind speed at hub height.
5. $H_s$ is the significant wave height.
6. $H_{s,10\text{-}yr}$ is the 10-year return significant wave height.
7. $H_{s,50\text{-}yr}$ is the 50-year return significant wave height.
8. $H_{s,100\text{-}yr}$ is the 100-year return significant wave height.
9. The normal and abnormal turbine operating modes correspond to different safety factors for the design of the floating support structure.

## 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 the Texas A&M University by integrating the CHARM3D program from the Texas A&M University and the FAST program from NREL. Reference is made to Section 2.2.2 for more details about the development and applications of CHARM3D-FAST.

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 on 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 referenced in IEC 61400-1 (2005) are applied to generate the turbulent wind field. For the parked turbine subjected to the 10-year, 50-year or 100-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. Sensitivity analyses are performed for the selected extreme wind conditions to evaluate the effect of using different (API vs. IEC-Kaimal) turbulent wind models.

The quasi-static wind loads on the floating hull structure above still water level (SWL) is modeled as wind drag loads and used as an input of global static force in CHARM3D-FAST simulations. The wind shear law recommended in API RP 2A-WSD (2007) is applied in the calculation of the wind drag load. 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. In the post-processing of analysis results, the quasi-static wind loads on the nacelle and tower are modeled as wind drag loads and superimposed to 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 rigid foundation. The mass properties of the turbine RNA are included in modal analyses using the BModes (v.3.00.00) program, which is a finite-element code developed by NREL for calculating the mode shapes and natural frequencies of a tower or a single turbine blade.

The 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 Cost and Northeast Coast, respectively, are assessed and applied in the case studies. The water depths for the three locations are assumed to be 320 m. Each site location is assumed to accommodate the three conceptual designs, namely the Spar, Semi-submersible and TLP based FOWTs, which results in 9 site-FOWT combinations.

#### *3.3.2.1 GoM Central Region*

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 10, 50, and 100 years are derived for a water depth of 320 m. Both the peak wind conditions and peak wave conditions are used in the case studies. For the turbine operating conditions with wind speeds lower than 10-yr 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 (Edition 2005) are used to derive the associated waves.

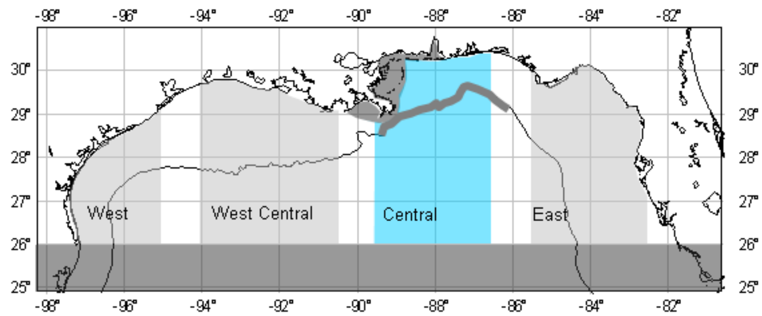



**Figure 3.1 GoM Central Region**

### *3.3.2.2 An Offshore Site on the US West Cost*

The site-specific metocean condition assessment on the US West Cost and Northeast Coast 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 US West Coast, the site metocean data are derived based on the historical data analysis using the measurements from the NOAA NDBC buoy (Station 46022) and NOAA NOS water level station (Station 9418767) located off the coast of northern California as shown in Figure 3.2. Wind and wave data analyses based on the measurements from Station 46022 are further verified by the historical data analysis using the measurements of the nearby NOAA NDBC Station 46027.

The extreme wind speed and significant wave height at the site are derived using the buoy measurements (Station 46022) between 1982 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 10-year, 50-year and 100-year return wind speeds and wave heights as shown in Figure 3.3 and Figure 3.4. 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 3.5. 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 9418767) between 1993 and 2010. Gumbel curve fitting is used to determine the 10-year, 50-year and 100-year return water levels as shown in Figure 3.7. The current speed and profile with return periods of 10, 50, and 100 years are derived based on ISO-19901.

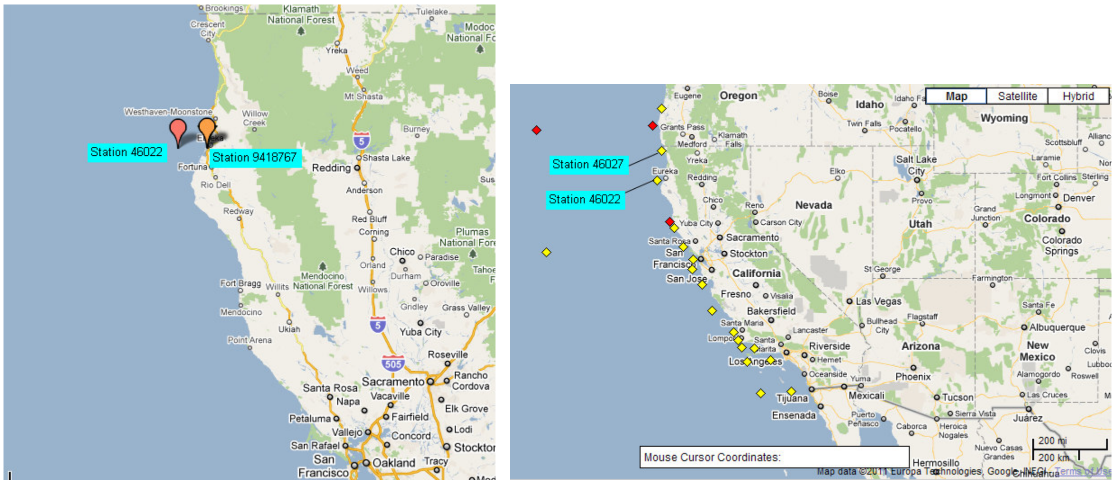



**Figure 3.2 Locations of NOAA Stations Selected for the US West Coast Case Study**

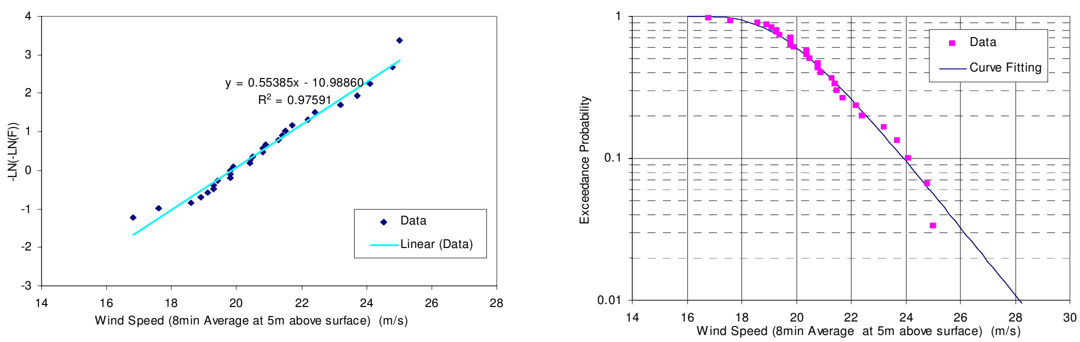



**Figure 3.3 Gumbel Curve Fitting for the Buoy Wind Data (Station 46022)**

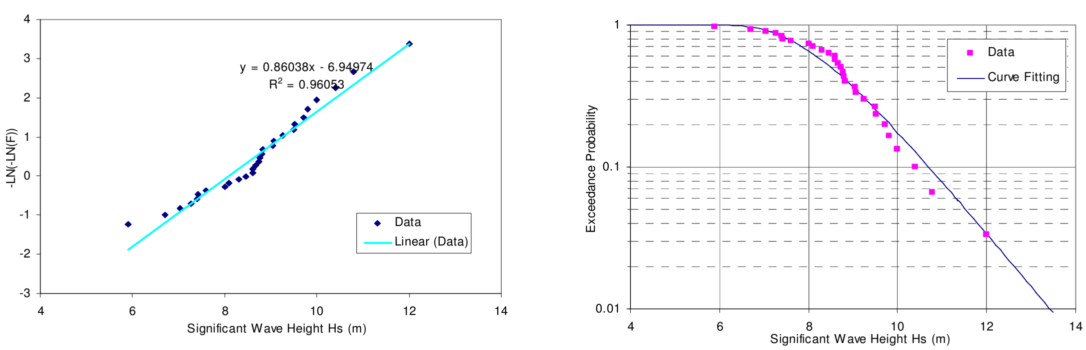



**Figure 3.4 Gumbel Curve Fitting for the Buoy Wave Data (Station 46022)**

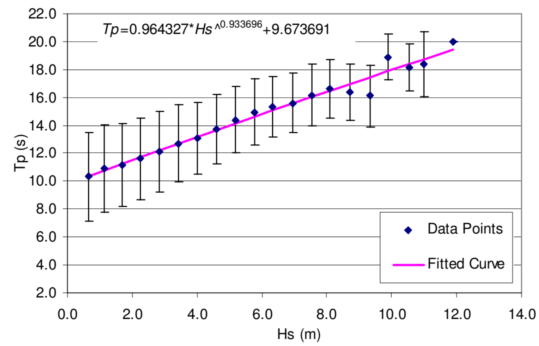



**Figure 3.5 Correlation of $T_p$ and $H_s$ Using the Binned Buoy Data (Station 46022)**

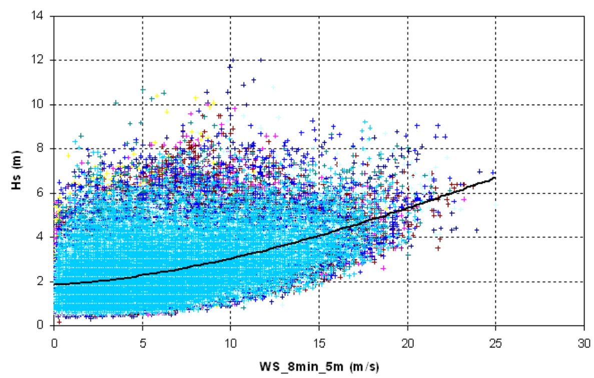



**Figure 3.6 Correlation of $H_s$ and $W_s$ (Station 46022)**

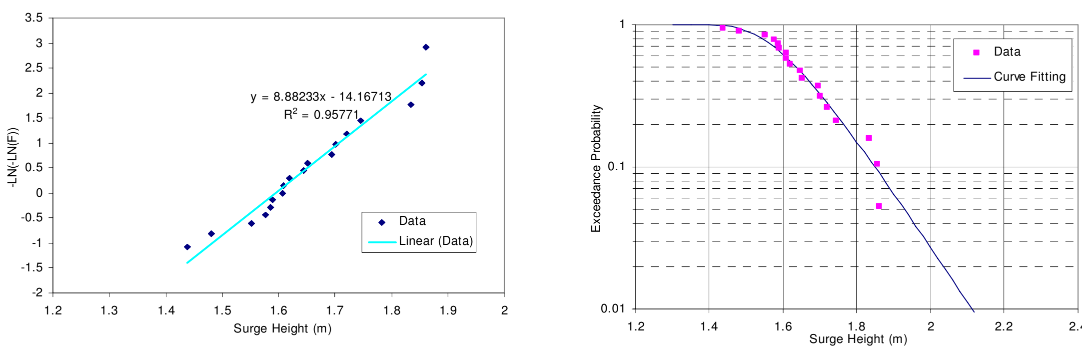



**Figure 3.7 Gumbel Curve Fitting for the Water Level Data (Station 9418767)**

#### 3.3.2.3 An Offshore Site on the US Northeast Cost

For the US Northeast Coast, 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 10-year, 50-year and 100-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. The correlation between the significant wave height and the wind speed ($W_s$, 8-minute wind speed at 5 m elevation) is derived using the buoy data as shown in Figure 3.12. 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 10-year, 50-year and 100-year return water levels as shown in Figure 3.13. The current speed and profile with return periods of 10, 50, and 100 years are derived based on API RP-2A-WSD (2007).

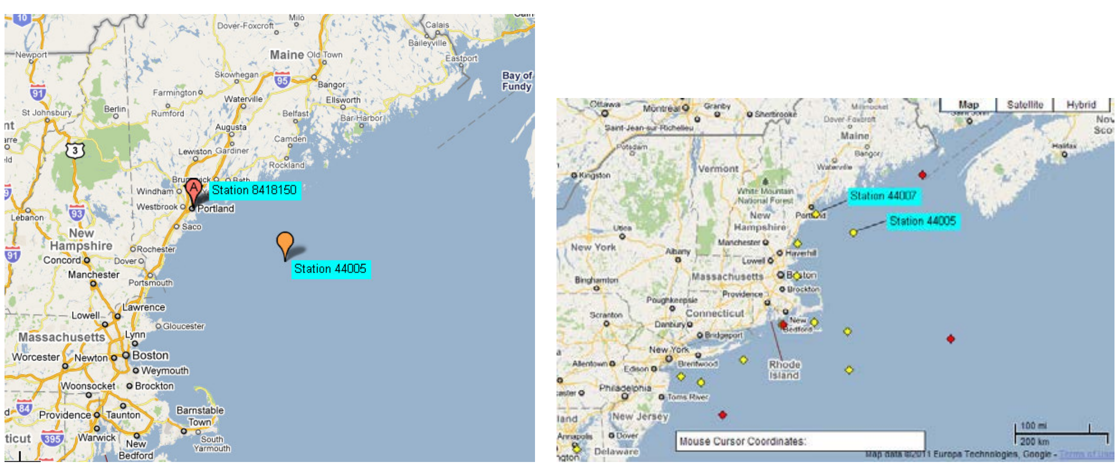



**Figure 3.8 Locations of NOAA Stations Selected for the US Northeast Coast Case Study**

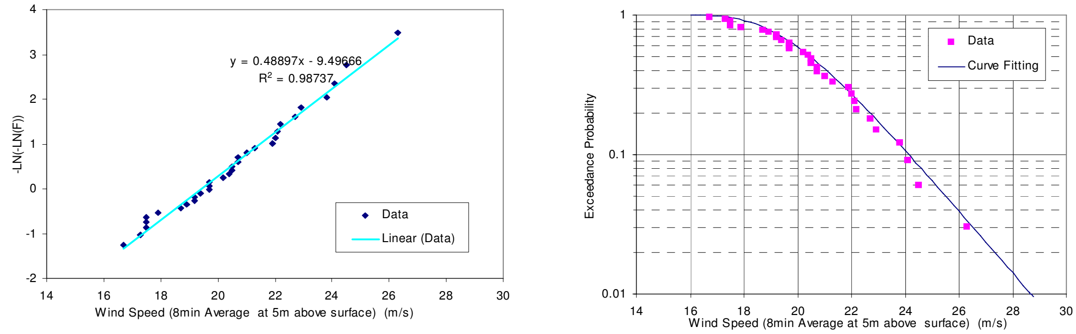



**Figure 3.9 Gumbel Curve Fitting for the Buoy Wind Data (Station 44005)**

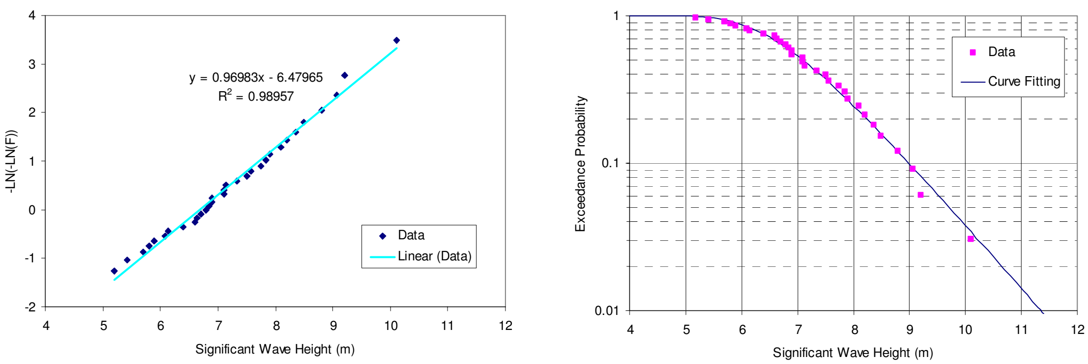



**Figure 3.10 Gumbel Curve Fitting for the Buoy Wave Data (Station 44005)**

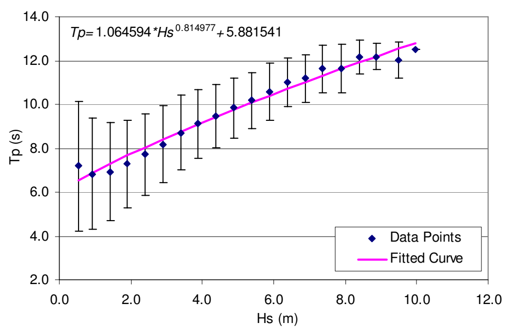



**Figure 3.11 Correlation of $T_p$ and $H_s$ Using the Binned Buoy Data (Station 44005)**

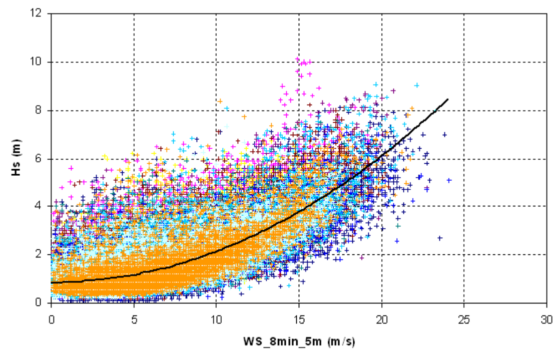



**Figure 3.12 Correlation of $H_s$ and $W_s$ (Station 44005)**

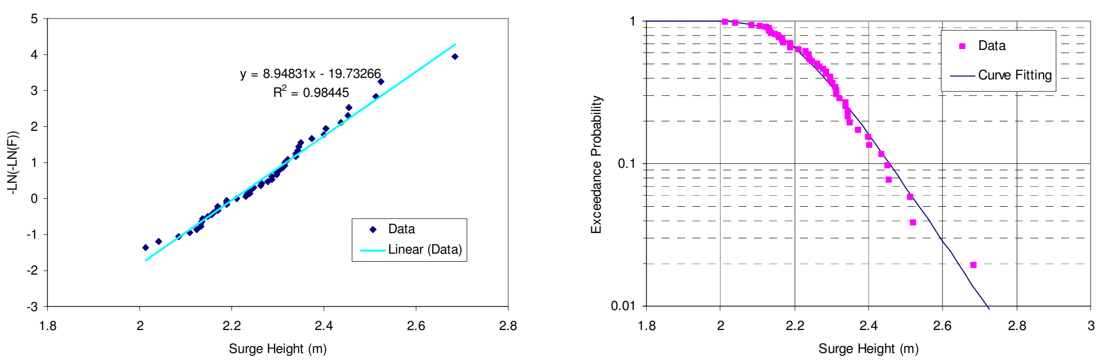



**Figure 3.13 Gumbel Curve Fitting for the Water Level Data (Station 8418150)**

### *3.3.2.4 Current Speeds and Profiles in the Normal Current Model (NCM)*

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, the current speed and profile are derived based on the 1-year winter storm generated current as defined in ISO-19901. For the US Northeast Coast, 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 by 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

For DLCs 1.3 (Power Production), 3.2 (Start-up) and 5.1 (Emergency Shut down), the statistics of the following generator and rotor responses are also calculated in addition those parameters listed above:

- Generator power
- Generator torque
- Rotor speed
- Generator Speed
- Rotor Thrust
- Rotor Torque
- Blade Pitch

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 DLC 1.3 (Power Production), twenty 10-mintue simulations are performed for the wind speed at the cut-in ($V_{in}$), rated ($V_r$) and cut-out ($V_{out}$) wind speed, respectively. The mean wind, wave and current conditions associated with the turbine in operation are used in the simulation. The turbulence model used for the wind is the IEC Extreme Turbulence Model (ETM). A 200s ramp time is applied in the analysis, and the total simulation time is 800s for one simulation. Statistics are obtained based on time series from 200s to 800s. 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 3.2 (start-up), the IEC Extreme Operating Gust (EOG) is applied. Since the wind is deterministic, the normal wave conditions used are regular wave with Normal Wave Height (NWH). Six 10-minute simulations are performed at the cut-in ($V_{in}$), rated ($V_r$) and cut-out ($V_{out}$) wind speed, respectively. Statistics are obtained based on time series from 200s to 800s. The maximum value is the maximum of all 10-minute simulations. The minimum value is the minimum of all 10-minute simulations.

For DLC 5.1 (Emergency Shut Down), twenty 10-mintue simulations are conducted at the rated ($V_r$) and cut-out ($V_{out}$) wind speed, respectively. The turbulence model used for the wind is the IEC Normal Turbulence Model (NTM). Statistics are obtained based on time series from 200s to 800s. The maximum value is the maximum of all 10-minute simulations. The minimum value is the minimum of all 10-minute simulations.

In the emergency shut-down, 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 260s. The blade starts to pitch to feather at 260.2s. Both the rated ($V_r$) and cut-out ($V_{out}$) wind speed are considered at the beginning of shut-down.

For the parked (idling) condition, 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 turbulence model used is the API (NPD) recommended wind model. Each simulation is 4000s with a 400s ramp. Statistics are obtained based on time series from 400s to 4000s. Design statistics (maximum, mean, minimum and standard deviation) are averages of corresponding statistics of 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 represented by NOAA NDBC Station 46022 is shown in Figure 3.2, while the site location on the US Northeast Coast represented by NOAA NDBC Station 44005 is shown in Figure 3.8.

Both the peak wind and the peak wave conditions at the 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 10-year, 50-year and 100-year return storm conditions for the US West Coast and Northeast Coast 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 wave conditions.

The operational wave conditions in association the cut-in, rated and cut-out wind speeds 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.

**Table 3.2 Hurricane Conditions in GoM Central – Peak Wind**

| Return Period (Years) | | 10 | 50 | 100 |
|---|---|---|---|---|
| Wind (10m Elevation) | 1-hour Mean Wind Speed (m/s) | 33.0 | 44.4 | 48.0 |
| | 10-min Mean Wind Speed (m/s) | 36.5 | 50.1 | 54.5 |
| | 1-min Mean Wind Speed (m/s) | 41.0 | 57.4 | 62.8 |
| | 3-sec Gust (m/s) | 46.9 | 66.9 | 73.7 |
| Wave | Significant Wave Height (m) | 9.90 | 13.87 | 14.73 |
| | Maximum Wave Height (m) | 17.40 | 24.51 | 26.22 |
| | Peak Spectral Period (s) | 13.00 | 14.62 | 15.01 |
| | Period of Maximum Wave (s) | 11.70 | 13.16 | 13.55 |
| Current Profile | Current Speed (m/s) | 1.32 at 0.0 m | 1.67 at 0.0 m | 1.80 at 0.0 m |
| | Current Speed (m/s) | 0.99 at 27.7 m | 1.25 at 34.95 m | 1.35 at 37.8 m |
| | Current Speed (m/s) | 0.0 at 55.4 m | 0.0 at 69.90 m | 0.0 at 75.6 m |
| Water Level | Storm Surge (m) | 0.30 | 0.47 | 0.57 |
| | Tidal Amplitude (m) | 0.42 | 0.42 | 0.42 |
| | Surge and Tide (m) | 0.72 | 0.89 | 0.99 |

**Table 3.3 Hurricane Conditions in GoM Central – Peak Wave**

| Return Period (Years) | | 10 | 50 | 100 |
|---|---|---|---|---|
| Wind (10m Elevation) | 1-hour Mean Wind Speed (m/s) | 33.0 | 42.2 | 45.6 |
| | 10-min Mean Wind Speed (m/s) | 36.5 | 47.4 | 51.6 |
| | 1-min Mean Wind Speed (m/s) | 41.0 | 54.1 | 59.2 |
| | 3-sec Gust (m/s) | 46.9 | 62.9 | 69.1 |
| Wave | Significant Wave Height (m) | 9.90 | 14.60 | 15.50 |
| | Maximum Wave Height (m) | 17.40 | 25.80 | 27.60 |
| | Peak Spectral Period (s) | 13.00 | 15.00 | 15.40 |
| | Period of Maximum Wave (s) | 11.70 | 13.50 | 13.90 |
| Current Profile | Current Speed (m/s) | 1.32 at 0.0 m | 1.67 at 0.0 m | 1.80 at 0.0 m |
| | Current Speed (m/s) | 0.99 at 27.7 m | 1.25 at 34.95 m | 1.35 at 37.8 m |
| | Current Speed (m/s) | 0.0 at 55.4 m | 0.0 at 69.90 m | 0.0 at 75.6 m |
| Water Level | Storm Surge (m) | 0.30 | 0.47 | 0.57 |
| | Tidal Amplitude (m) | 0.42 | 0.42 | 0.42 |
| | Surge and Tide (m) | 0.72 | 0.89 | 0.99 |

**Table 3.4 Storm Conditions in US West Coast**

| Return Period (Years) | | 10 | 50 | 100 |
|---|---|---|---|---|
| Wind (10m Elevation) | 1-hour Mean Wind Speed (m/s) | 23.49 | 26.27 | 27.48 |
| | 10-min Mean Wind Speed (m/s) | 25.57 | 28.74 | 30.12 |
| | 1-min Mean Wind Speed (m/s) | 28.25 | 31.90 | 33.52 |
| | 3-sec Gust (m/s) | 31.73 | 36.03 | 37.94 |
| Wave | Significant Wave Height (m) | 10.75 | 12.62 | 13.43 |
| | Maximum Wave Height (m) | 20.00 | 23.48 | 24.98 |
| | Peak Spectral Period (s) | 18.53 | 19.96 | 20.58 |
| | Period of Maximum Wave (s) | 16.83 | 18.13 | 18.69 |
| Current Profile | Current Speed (m/s) at 0.0 m | 0.70 | 0.80 | 0.80 |
| | Current Speed (m/s) at 90.0 m | 0.60 | 0.70 | 0.70 |
| | Current Speed (m/s) at 319.0 m | 0.60 | 0.70 | 0.70 |
| Water Level | Storm Surge (m) | 0.35 | 0.53 | 0.61 |
| | Tidal Amplitude (m) | 1.51 | 1.51 | 1.51 |
| | Surge and Tide (m) | 1.85 | 2.04 | 2.11 |

**Table 3.5 Storm Conditions in US Northeast Coast**

| Return Period (Years) | | 10 | 50 | 100 |
|---|---|---|---|---|
| Wind (10m Elevation) | 1-hour Mean Wind Speed (m/s) | 23.71 | 26.70 | 27.98 |
| | 10-min Mean Wind Speed (m/s) | 25.82 | 29.23 | 30.70 |
| | 1-min Mean Wind Speed (m/s) | 28.53 | 32.48 | 34.19 |
| | 3-sec Gust (m/s) | 32.06 | 36.70 | 38.73 |
| Wave | Significant Wave Height (m) | 9.04 | 10.66 | 11.36 |
| | Maximum Wave Height (m) | 16.82 | 19.83 | 21.12 |
| | Peak Spectral Period (s) | 12.29 | 13.21 | 13.59 |
| | Period of Maximum Wave (s) | 11.16 | 11.99 | 12.35 |
| Current Profile | Current Speed (m/s) at 0.0 m | 0.54 | 0.57 | 0.58 |
| | Current Speed (m/s) at 61.0 m | 0.54 | 0.57 | 0.58 |
| | 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) | 0.40 | 0.58 | 0.66 |
| | Tidal Amplitude (m) | 2.06 | 2.06 | 2.06 |
| | Surge and Tide (m) | 2.46 | 2.64 | 2.72 |

**Table 3.6 Operational Wind-Wave Conditions – GoM Central**

| *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 |
| 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 |
| 18.00 | 14.06 | 4.02 | 8.96 |
| 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**

| *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 | 2.01 | 11.52 |
| 4.00 | 3.35 | 2.09 | 11.59 |
| 8.00 | 6.55 | 2.50 | 11.94 |
| 9.40 | 7.64 | 2.67 | 12.09 |
| 11.40 (rated speed) | 9.17 | 2.93 | 12.31 |
| 13.40 | 10.68 | 3.21 | 12.54 |
| 18.00 | 14.06 | 3.93 | 13.13 |
| 24.00 | 18.32 | 4.97 | 13.98 |
| 25.00 (cut-out speed) | 19.02 | 5.16 | 14.13 |

**Table 3.8 Operational Wind-Wave Conditions – US Northeast Coast**

| *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* | | *US West Coast* | | *US Northeast Coast* | |
|---|---|---|---|---|---|
| *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 Configurations

The three conceptual designs of the floating support structure are adapted from the OC3-Hywind Spar, the MIT/NREL mono-column TLP and the generic WindFloat Semi-submersible concepts. Figure 3.14 depicts the schematic images of the three FOWT conceptual designs used in the case studies. 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 100-year return storm conditions in the GoM Central Region. Main modifications are summarized below. More descriptions of the modified floating support structures can be found in Section 3.4.2.1 through 3.4.2.3.

- In all the three cases, the tower base is raised to 24.6m above the still water level to provide a sufficient air gap. The height of the tower is changed to 68 m, which leads to a hub height of 95 m.
- For the OC3-Hywind Spar, the weight of spar hull is increased to accommodate the increase in the tower base elevation and hub height. The total weight of the hull and the tower remains the same as that of original OC3-Hywind Spar.
- For the OC3-Hywind Spar in the GoM Central Region, the mooring line size and pretension are increased to provide sufficient yaw stiffness such that the yaw instability can be eliminated. Hull size is also slightly increased to provide enough buoyancy to balance the increased mooring pretension.
- For the generic WindFloat Semi-submersible, the chain size is increased from 3 inch to 4 inch in order to meet strength requirement for mooring lines. Pretensions are also increased to prevent contact of polyester rope with the sea floor.
- It is found that the tendons used in the original MIT/NREL TLP could become slack under the GoM hurricane conditions. The slack-line issue is resolved by increasing the tendon fairlead radius (see Section 3.4.2.3) and tendon pretensions. Material properties of 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.

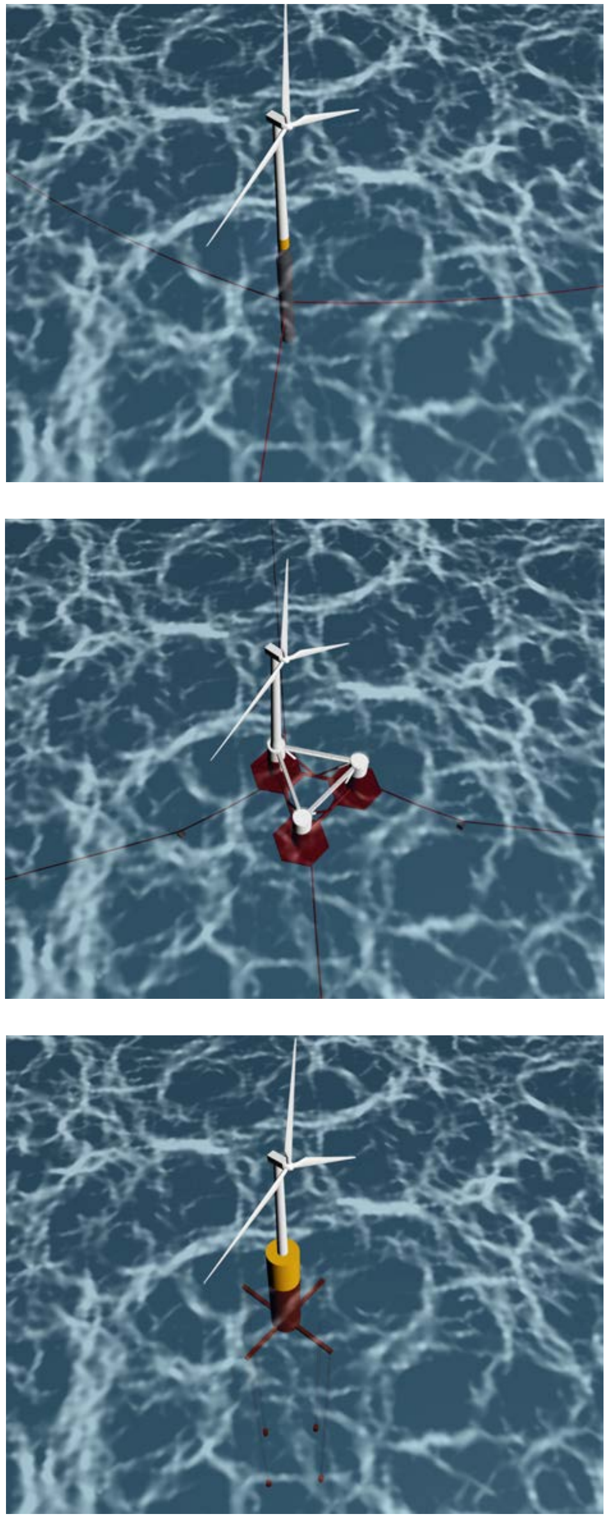
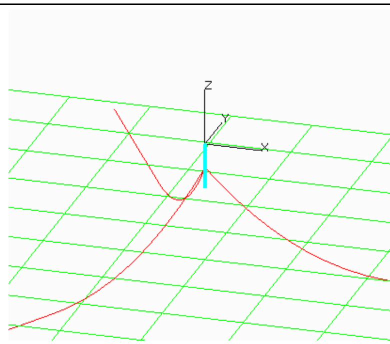
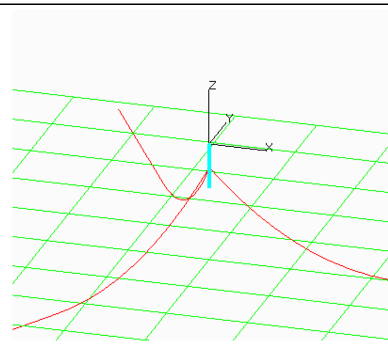
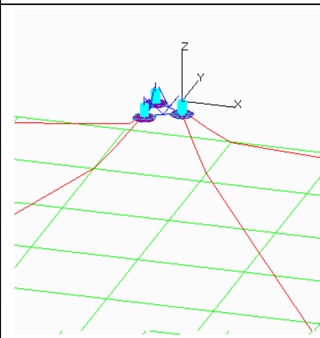
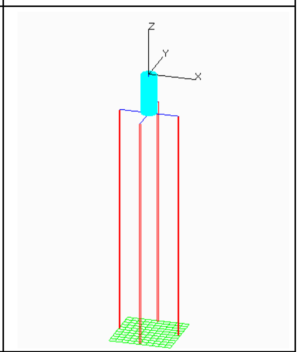


**Figure 3.14 Schemetic Images of the FOWT Conceptual Designs Used in the Case Studies**

**Table 3.10 Main Particulars of Floating Support Structures**

| | *Spar*<br>*(for West and Northeast Coasts)* | *Spar*<br>*(for GoM Central Region)* | *Semi-Submersible*<br>*(for all sites)* | *TLP*<br>*(for all sites)* |
|---|---|---|---|---|
| Draft | 120 m | 120 m | 17 m | 47.89 m |
| Displacement | 8230 ton | 10279 ton | 4640 ton | 12485 ton |
| Column Diameter | 6.5 m – 9.4 m (tapered) | 6.5 m – 10.6 m (tapered) | 10 m | 18 m |
| Center of Gravity below SWL | 89.474 m | 89.56 m | 8.098 m | 38.154 m |
| Mooring or Tendon System | 3 lines<br>902.2 m length each line<br>77.7 kg/m dry weight per unit length<br>970 kN pretensions | 3 lines<br>1000 m length each line<br>68.7 kg/m dry weight per unit length<br>3000 kN pretensions<br>45 ton clump weight on each line | 4 lines<br>80 m 4-inch top chain<br>30 ton clump weight<br>718 m 5-inch polyester rope<br>80 m 4-inch bottom chain<br>975 kN – 1000 kN Pretension | 8 lines<br>163 mm spiral wire rope<br>35 m tendon fairlead radius<br>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 is used in the present case studies. The Spar hull diameter and draft are kept the same as the original design, while 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 higher tower base elevation and hub height, while the total weight of the hull and the tower remains the same as the original design. The coordinate system and mooring line numbering for the Spar 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.

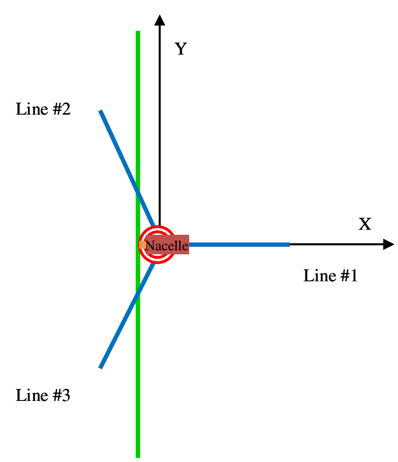



**Figure 3.15 Coordinate System and Numbering of Mooring Lines – Spar FOWT**

The modified OC3-Hywind FOWT is able to remain stable under the storm conditions at the other two site locations. However, it encounters the yaw instability under both the 50-year return and the 100-year return hurricane conditions in the GoM Central Region. Figure 3.16 depicts a sudden blow-out of Spar’s sway, roll, yaw, motions and tower top side-to-side motion, respectively, observed from the Spar FOWT subjected to the 100-year return hurricane conditions in the GoM Central Region.

The simulation results show that the horizontal dimension of the wind turbine rotors and unsymmetrical pattern of the blades result in large yaw moment on the yaw bearing. This yaw moment is transmitted through the yaw bearing to the Spar hull and causes the hull to yaw. To provide both static and dynamic yaw stability, the mooring system must be designed to provide sufficient amount of yaw stiffness. Increasing hull size and yaw damping will also help to mitigate the yaw instability. For the case studies of Spar FOWT in the GoM, the additional yaw stiffness is achieved by applying higher mooring line pretensions and increasing the mooring line size. 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. Table 3.11 summarizes these further modifications to the Hywind concept assumed being deployed in the GoM Central Region.

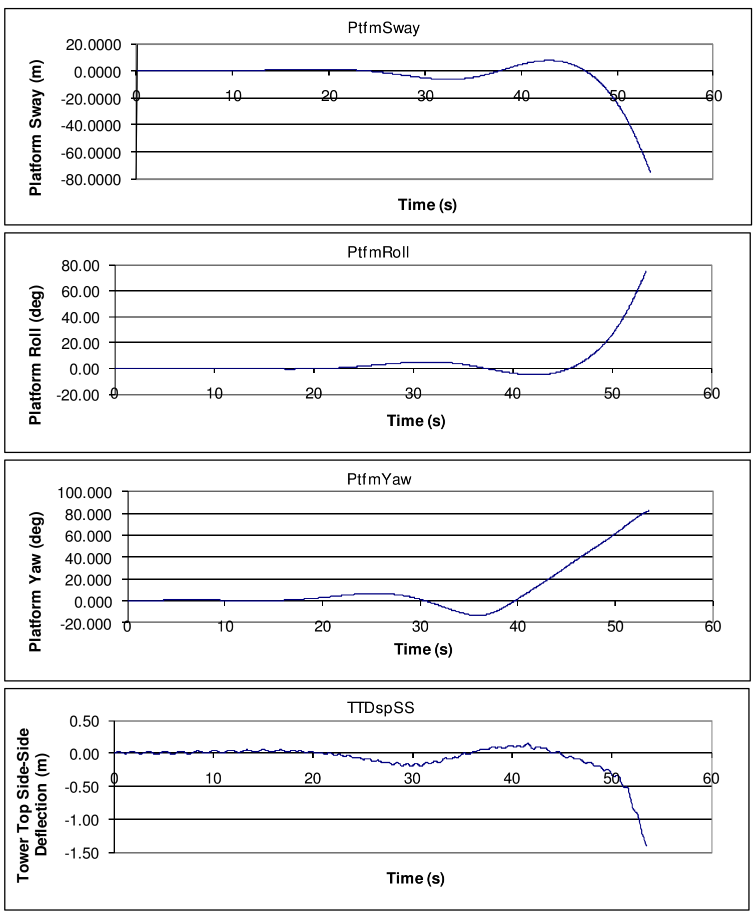



**Figure 3.16 Spar Yaw Instability in 100-year Hurricane in the GoM Central Region**

**Table 3.11 Particulars of the Spar for the GoM Central Region**

| | *Particulars* | *OC3-Hywind* | *New Spar FOWT for the GoM Central Region* |
|---|---|---|---|
| *Hull and Tower* | Lower Hull Diameter (m) | 9.4 | 10.6 |
| | Draft (m) | 120 | 120 |
| | Diameter at waterline (m) | 6.5 | 6.5 |
| | Displacement (m-ton) | 8230 | 10279 |
| | CG below still waterline (m) | 89.92 | 89.56 |
| | Tower base elevation above waterline (m) | 10 | 24.6 |
| *Mooring* | Diameter (mm) | 90 | 127 |
| | Length (m) | 902.2 | 1000 |
| | Dry Weight (kg/m) | 77.71 | 68.7 |
| | Clump Weight (ton) | included in the rope unit length weight | 45 |
| | Pretension (kN) | 970 | 3000 |
| | Additional Mooring Yaw Stiffness (crow-foot) (kN-m/rad) | 98,340 | 500,000 |

### *3.4.2.2 Semi-submersible Hull and Mooring System*

The generic WindFloat 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 four mooring lines. Each mooring line has a three-segment chain-polyester rope-chain configuration. A clump weight is attached to the upper chain section and the polyester rope.

For the present case studies, the tower base of the generic WindFloat design is raised to 24.6m 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 increased due to the higher tower base elevation and hub height. A 68 m high tower is mounted at the top of one column.

The generic WindFloat concept features an active ballast system, which is designed to keep the mean angular position of the tower vertical. In the case studies, the active ballast is modeled by applying a static overturning moment on the Semi-submersible hull structure. For the load cases where the turbine is in either the power production or the parked conditions, the mean heel angle of the hull is adjusted to even keel. For the load cases where the turbine is in either the start-up or the emergency shut down condition, the hull is adjusted to an even keel condition before initiating the start-up or shut-down process in the time domain simulation.

The coordinate system and mooring line numbering for the Semi-submersible is depicted in Figure 3.17. The origin is at the crossing of the still water level and the tower center line with z-axis pointing upwards.

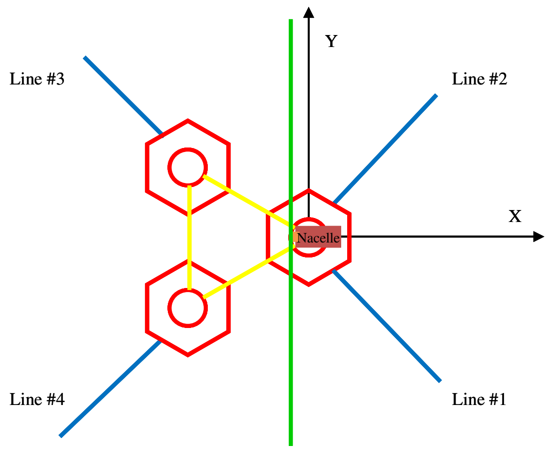



**Figure 3.17 Coordinate System and Numbering of Mooring Lines – Semi-Submersible FOWT**

### *3.4.2.3 TLP Hull and Mooring System*

The MIT/NREL TLP supporting the NREL 5-MW baseline offshore wind turbine is basically 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 massless 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 24.6m above the still water level. A 68 m high tower is mounted at the top 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 being 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 3.18. 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.

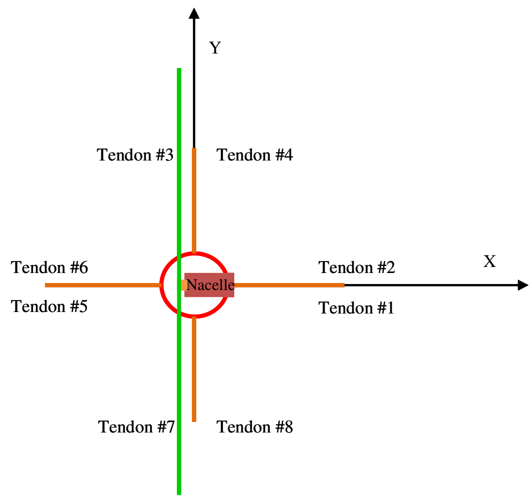



**Figure 3.18 Coordinate System and Numbering of Tendon – TLP FOWT**

### 3.4.3 Tower Specifications and Mode Shapes

The tower of the three conceptual designs is adapted from the OC3 Hywind. 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, while 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 3.12.

**Table 3.12 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 rigid 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 3.19 and the natural frequencies are listed in Table 3.13.

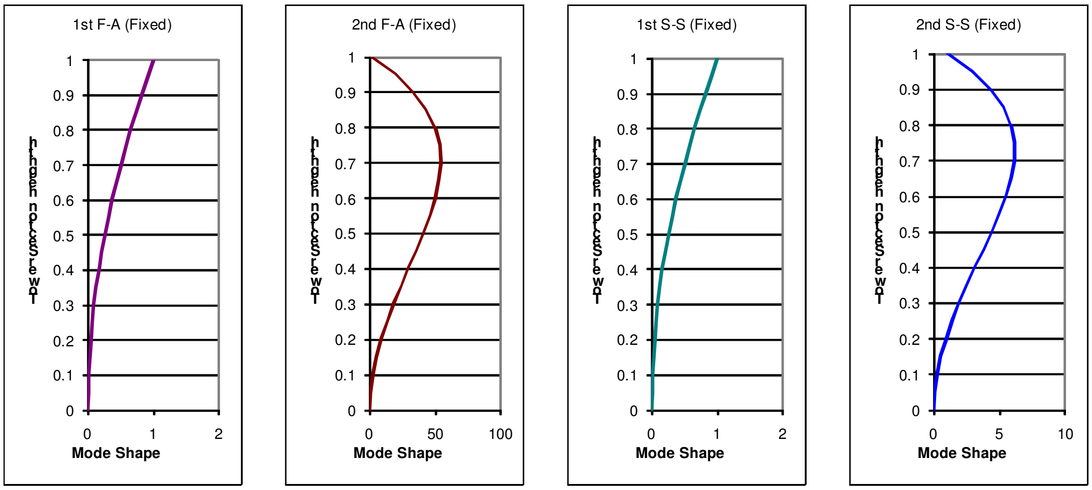



**Figure 3.19 Tower 1st & 2nd Fore-Aft and Side-to-Side Bending Mode Shapes**

**Table 3.13 Tower Modal Frequency**

| *Mode* | *Frequency (Hz)* | *Radial Frequency (rad/s)* | *Period (s)* |
|---|---|---|---|
| 1st Fore-Aft | 0.390 | 2.450 | 2.564 |
| 2nd Fore-Aft | 2.436 | 15.306 | 0.411 |
| 1st Side-to-Side | 0.385 | 2.419 | 2.597 |
| 2nd Side-to-Side | 1.969 | 12.372 | 0.508 |

### 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 turbine RNA and blades are listed in Table 3.14 and Table 3.15.

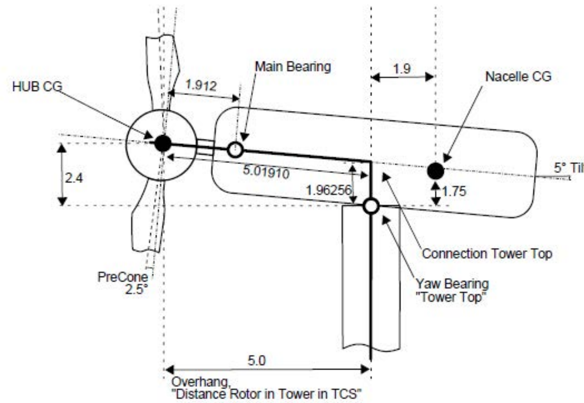



**Figure 3.20 RNA of NREL 5-MW Baseline Offshore Wind Turbine (Jonkman et al., 2009)**

**Table 3.14 Properties of the RNA of 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 3.15 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 Preconed 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, on the other hand, 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.

For the modified WindFloat Semi-submersible concept used in the present study, the platform pitch natural period is about 45 s. Following the approach proposed in Jonkman, et al. (2010), the controller response natural frequency is further reduced to 0.1 rad/s. This frequency is used along with the damping ratio of 0.7 to derive the reduced proportional gain at minimum blade-pitch setting and the reduced integral gain at minimum blade-pitch setting. The new control system properties for the Semi-submersible FOWT evaluated in this project, together with those of the conventional control system (land-based) and the OC3 Hywind control system, are listed in Table 3.16. These control system properties are applied through a dynamic link library (DLL) in CHARM3D-FAST simulations.

The control scheme of the land-based turbine and the new control scheme modified from the OC3 Hywind control scheme for the Semi-submersible FOWT are intended to be used only in the sensitivity study presented in Section 3.4.7.3.

**Table 3.16 Control System Properties for the NREL 5-MW Baseline Offshore Wind Turbine**

| | *For the Land Based Turbine* | *For the OC3 Hywind* | *For the Semi-submersible FOWT* |
|---|---|---|---|
| Controller natural frequency | 0.6 rad/s | 0.2 rad/s | 0.1 rad/s |
| Damping Ratio | 0.7 | 0.7 | 0.7 |
| Proportional Gain, Kp | 0.01882681 s | 0.006275604 s | 0.00313780 s |
| Integral Gain, KI | 0.00806863 | 0.0008965149 | 0.00022413 |
| Generator-torque control | Constant Power | Constant Torque | 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 10-year, 50-year and 100-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. The IEC (Kaimal) wind spectrum is applied for the selected load cases involving the extreme wind conditions and used only in the sensitivity analysis.

For operational wind conditions, the IEC (Kaimal) wind spectrum is used to generating turbulent wind field data.

The API and IEC wind spectra for the 100-year peak wind and 100-year peak wave hurricanes in the GoM Central Region, as well as the 100-year storm conditions on the US West Coast and Northeast Coast are depicted in Figure 3.21 and Figure 3.22. It is shown that the API wind model has more energetic wind in the low frequency range. In the relatively higher frequency range, on the other hand, the IEC wind model shows much higher power spectral densities than those from using the API model. The significance of the difference between the API and IEC turbulent wind model to the global response of FOWTs is dependent upon the relative importance of hydrodynamic loads and aerodynamic loads. Further discussions can be found in the sensitivity analysis presented in Section 3.4.7.1.

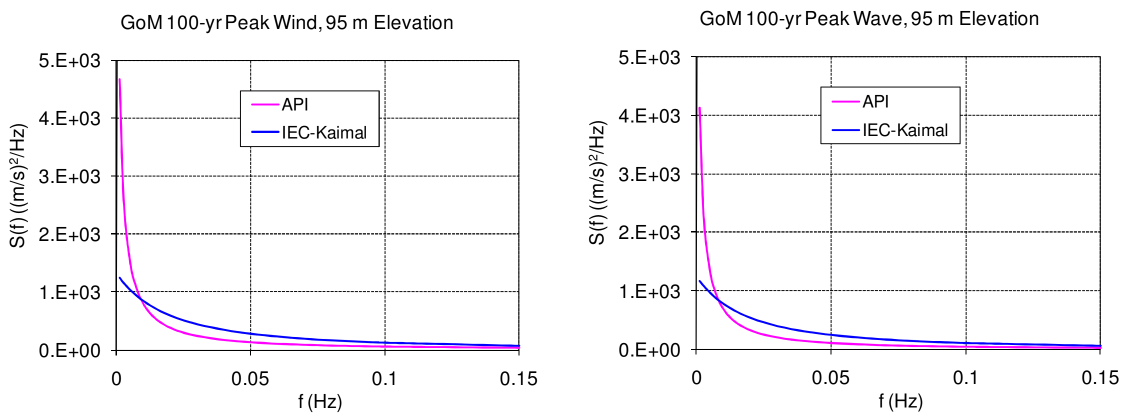



**Figure 3.21 Comparison of API and IEC Spectra for GoM Central 100-year Peak Wind and Peak Wave Conditions**

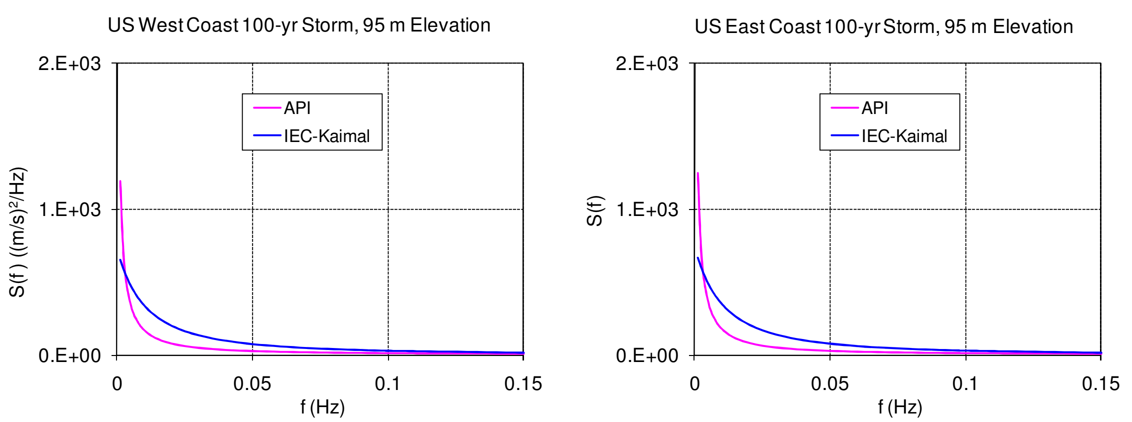



**Figure 3.22 Comparison of API and IEC Spectra for US West Coast and Northeast Coast 100-year Storm**

A grid size of 51×9 for a 139.98 m (height) by 260.00 m (width) domain centered at hub height is used in the simulation for both the API (NPD) and IEC (Kaimal) wind spectra. An alternative grid size 20×26 for a 189.98 m (height) by 250.00 m (width) domain centered at hub height is also used for the IEC (Kaimal) wind spectrum in order to evaluate the sensitivity of global responses to the changing wind field grid size and shape.

The 10-minute mean wind speeds at hub height ($V_{hub}$, 95m above the still water level) are calculated using the API wind shear law and the 1-hour mean wind speeds at 10 m elevation. The turbulence intensity for the IEC wind spectrum is calculated using the 10-minute mean wind speed at hub height and increased by 0.2 for 1-hour simulations, as recommended by IEC 61400-3 (2009). The results of the mean wind speed and turbulence intensities ($I_u$) are listed in Table 3.17.

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

For DLC 1.3 (Power Production), twenty 10-mintue simulations are performed for the cut-in ($V_{in}$), rated ($V_r$) and cut-out ($V_{out}$) wind speeds. The turbulence model used for the wind is the IEC Extreme Turbulence Model (ETM).

For DLC 5.1 (Emergency Shut Down), twenty 10-mintue simulations are conducted the rated ($V_r$) and cut-out ($V_{out}$) wind speed. The turbulence model used for the wind is the IEC Normal Turbulence Model (NTM).

For DLC 3.2 (Start-up), the wind model used in the simulation is the IEC Extreme Operating Gust (EOG), for which the wind field data are generated by IECWind at the cut-in ($V_{in}$), rated ($V_r$) and cut-out ($V_{out}$) wind speed. Each simulation lasts 800s, in which the first 200s is used as ramp time in CHARM3D-FAST simulations. Six simulations are performed for three wind speeds by setting different starting time of the gust. The gust lasts for 10.5s.

**Table 3.17 Wind Speed and Turbulence Intensity**

| *Location* | *Return Period* | *API/IEC* *10-min Mean Wind Speed at Hub Height ($V_{hub}$)* | *API* *1- hour Mean Wind Speed at 10m above MSL* | *API* *1- hour Mean Wind Speed at Hub Height* | *API* *1- min Mean Wind Speed at Hub Height* | *API* *3-sec Mean Wind Speed at Hub Height* | *IEC* *1- hour Mean Wind Speed at Hub Height ($0.95V_{hub}$)* | *IEC* *1 -hour, Iu at Hub Height (% of $0.95V_{hub}$)* |
|---|---|---|---|---|---|---|---|---|
| GoM Central (Peak Wind) | 10-year | 46.2 | 33.0 | 43.4 | 49.8 | 54.5 | 43.9 | 12.03% |
| | 50-year | 65.0 | 44.4 | 60.3 | 71.0 | 78.9 | 61.7 | 11.90% |
| | 100-year | 71.1 | 48.0 | 65.7 | 78.1 | 87.1 | 67.6 | 11.87% |
| GoM Central (Peak Wave) | 10-year | 46.2 | 33.0 | 43.4 | 49.8 | 54.5 | 43.9 | 12.03% |
| | 50-year | 61.2 | 42.2 | 56.9 | 66.7 | 73.9 | 58.1 | 11.92% |
| | 100-year | 67.0 | 45.6 | 62.1 | 73.4 | 81.6 | 63.7 | 11.89% |
| US West Coast (See Section 3.3.2.2) | 10-year | 31.6 | 23.5 | 29.9 | 33.6 | 36.3 | 30.0 | 12.25% |
| | 50-year | 35.7 | 26.3 | 33.8 | 38.2 | 41.5 | 33.9 | 12.17% |
| | 100-year | 37.6 | 27.5 | 35.5 | 40.3 | 43.7 | 35.7 | 12.14% |
| US Northeast Coast (See Section 3.3.2.3) | 10-year | 31.9 | 23.7 | 30.2 | 34.0 | 36.7 | 30.3 | 12.24% |
| | 50-year | 36.4 | 26.7 | 34.4 | 38.9 | 42.3 | 34.6 | 12.16% |
| | 100-year | 38.4 | 28.0 | 36.2 | 41.1 | 44.7 | 36.4 | 12.13% |

### 3.4.7 Sensitivity Study on Modeling Parameters

Sensitivity studies are carried out to evaluate the significance of the following modeling parameters to the global response.

- 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 semi-submersible concept).

#### *3.4.7.1 Wind Model and Grid Size*

A sensitivity analysis is performed to evaluate the impact of using different turbulent wind models and different grid size of the turbulent wind field. The wind field data are generated according to Section 3.4.6. For the100-year conditions, the API wind model with a grid size of 51×9 and the IEC wind model with a grid size of 51×9 and 20×26, respectively, are used to generate 3-D turbulent wind fields for the sensitivity analysis.

Global performance analyses are carried out for the Spar, Semi-submersible and TLP FOWTs subjected to the 100-year return extreme storm with the turbine RNA in the parked condition. The 100-year return peak wind hurricane condition in the GoM Central Region is applied to each conceptual design. The metocean data are provided in Section 3.4.1. It is assumed that the wind, wave and current are collinear. A total of six 1-hour simulations with different random seeds are performed for each analysis case. One simulation is also performed for the analysis cases where only the storm wind (no wave or current) is applied in order to quantify the relative importance of the wind loads to the wave loads. Yaw error, i.e. the misalignment between the incoming wind direction and the nacelle axis, is assumed as 0 degree (aligned) in the sensitivity analysis.

The effects of the using different wind spectra and grid sizes on the global responses of the Spar, Semi-submersible and TLP FOWTs are depicted in Figure 3.23 through Figure 3.25. It is shown that:

- The IEC wind model results in higher tower loads, including the tower top acceleration, tower base shear, and tower base overturning moment, than the API wind model. This is mainly because the IEC wind model has much higher power spectral densities than the API model in the frequency range that covers the tower natural frequency (see Figure 3.21). Under the same mean wind conditions, this difference implies that the IEC wind spectral model could excite larger global responses in the tower than the API wind model.

- The IEC wind model results in larger yaw motions for the Spar and TLP than the API wind model. For the Semi-submersible, however, the IEC wind model gives larger yaw motions.
- The offset and heel of the hull and the mooring line top tensions are not sensitive to the variation of wind model or grid size, because the aerodynamic loads appear to have relatively small contribution to the low frequency motions compared to the wave loads.

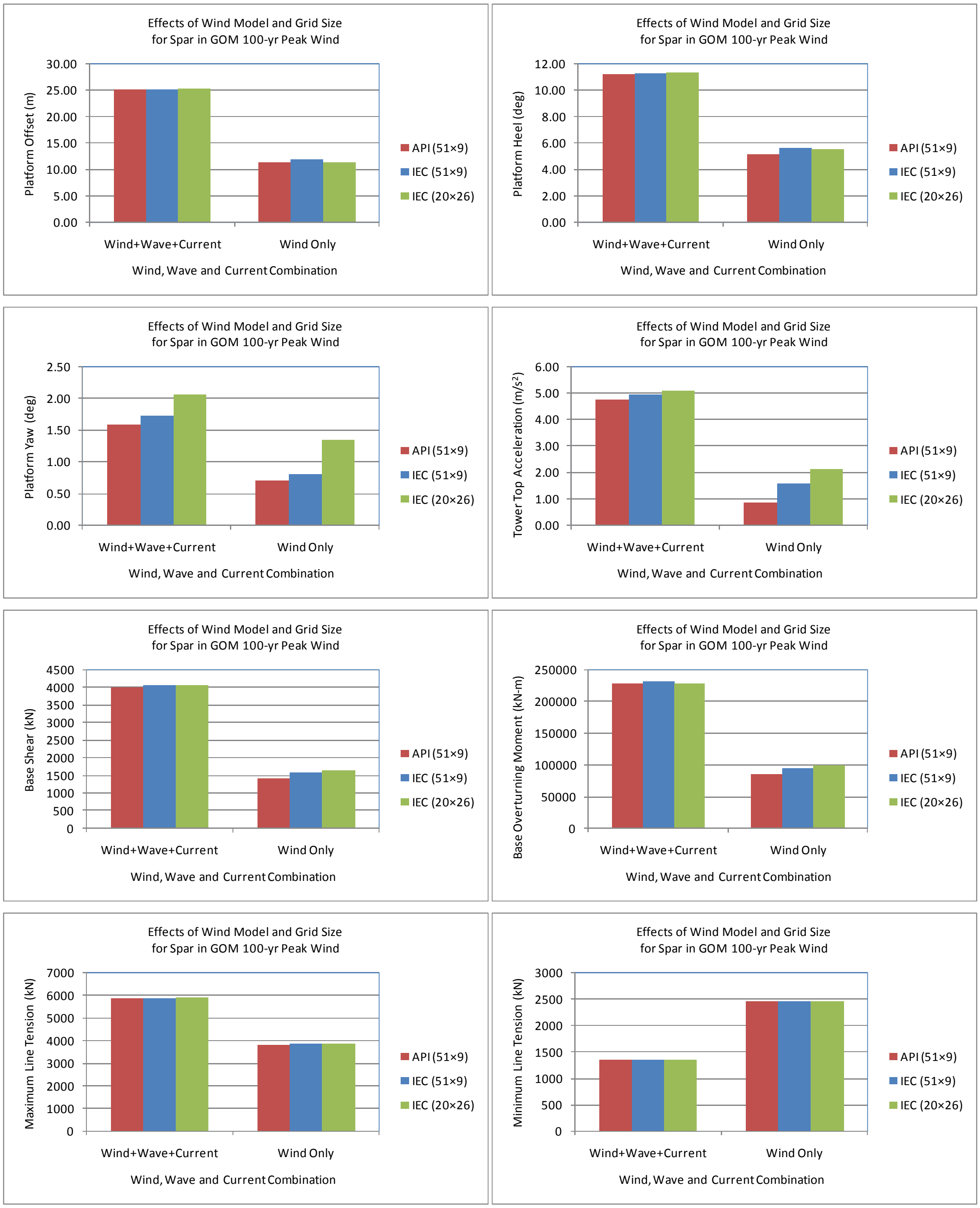



**Figure 3.23 Effects of Wind Model and Grid Size – Spar FOWT**

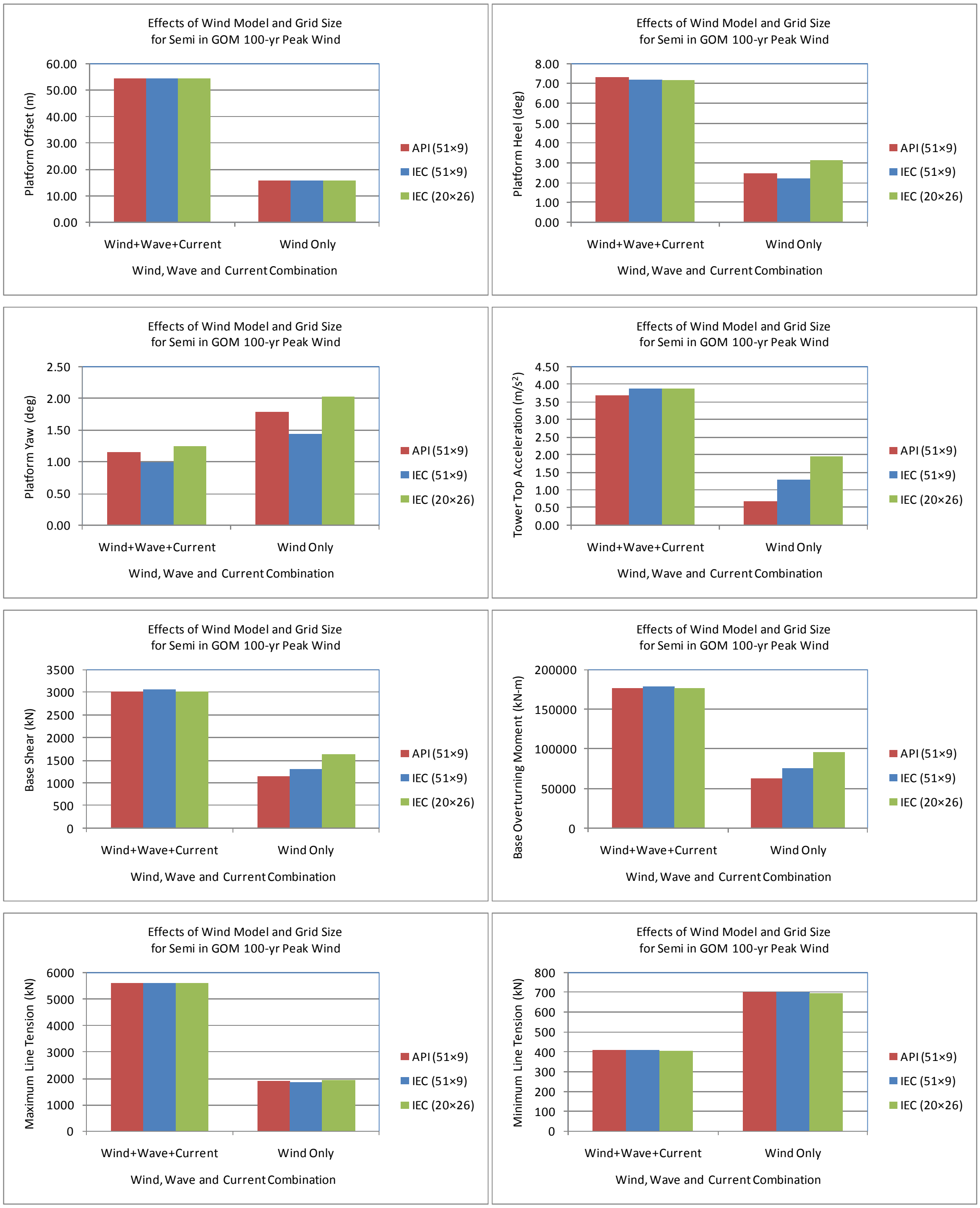



**Figure 3.24 Effects of Wind Model and Grid Size – Semi-submersible FOWT**

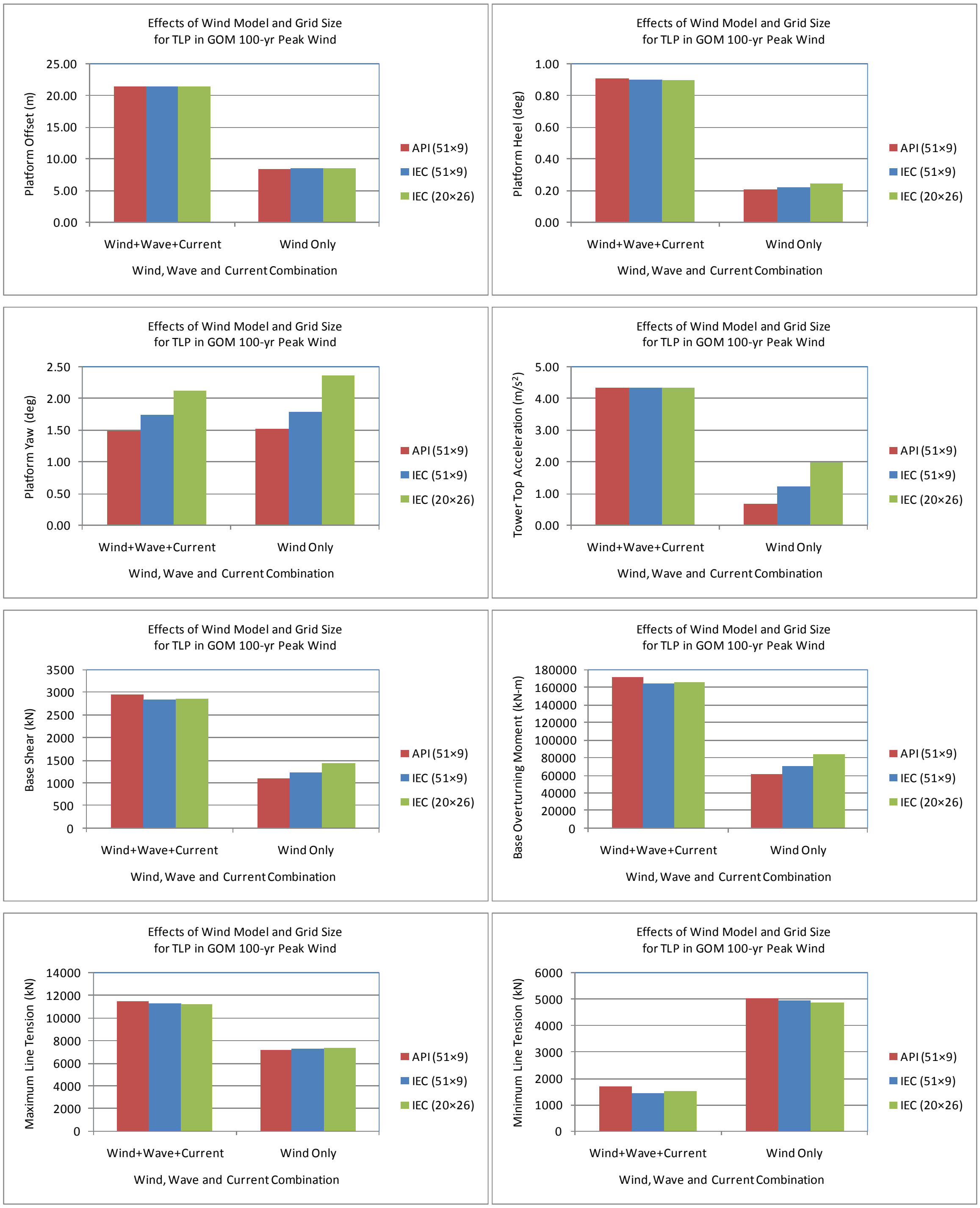



**Figure 3.25 Effects of Wind Model and Grid Size – TLP FOWT**

### 3.4.7.2 *Gust Duration*

To assess the effect of gust duration on the global responses of FOWT, the design load case DLC3.2, which represents the turbine start-up in the extreme operating gust (EOG), is analyzed for the Spar FOWT in the GoM Central Region. The 10-miniute average wind speed is assumed to be the rated wind speed ($V_r$ =11.4 m/s) and the maximum wind gust speed is taken as ($V_r$ +4) m/s.

Six gust rising-falling time durations of 12s, 20s, 30s, 40s, 50s and 60s are used in the analysis. The ramp time for the simulation is 200s. The wind turbine is started at 205s by changing blade pitch from the feathered position. The gust event starts at 205s and lasts for a given time duration. The associated wave and current conditions are for the operational conditions in the GoM Central Region.

The gust events with different rising-falling time durations are plotted in Figure 3.26. The resultant global responses of the Spar are presented in Figure 3.27. It can be seen that the effects of gust time duration on the global responses of the Spar FOWT are insignificant.

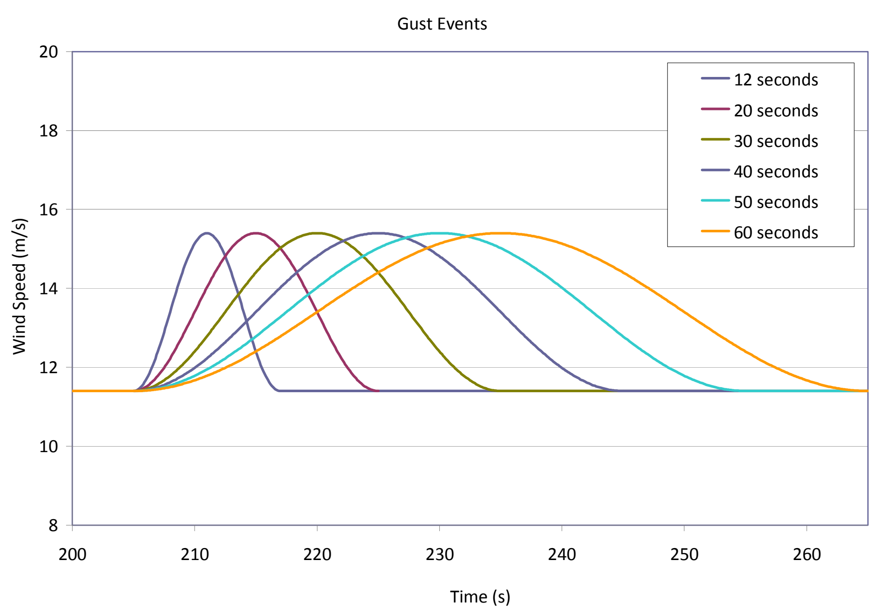



**Figure 3.26 Gust Events with Different Rising-Falling Time Durations**

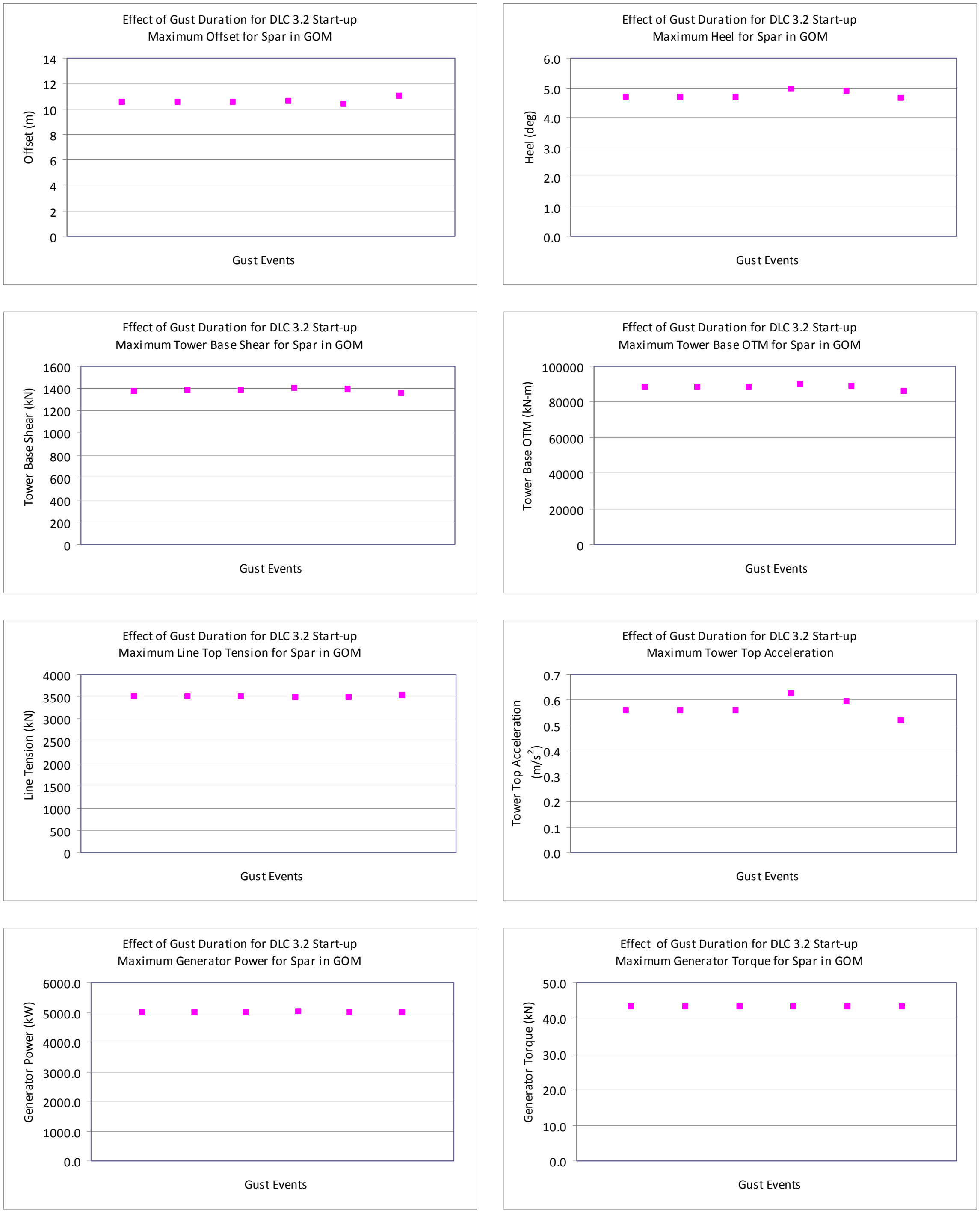



**Figure 3.27 Responses of the Spar FOWT in the GoM Central for DLC3.2 (Start-up with Different Gust Durations)**

### *3.4.7.3 Control Scheme for Power Production*

For the Spar FOWT, it is found that the conventional bladed pitch control system used by the land-based turbines can cause significant hull pitch motions when the average wind speed exceeds the rated wind speed. A comparative study is performed using two blade pitch control schemes. The average wind speed is assumed to be 17 m/s and the turbine is in the normal power production. The global performance analysis results are plotted in Figure 3.28, which shows that the blade pitch angle changes frequently when the land-based control scheme is applied. The rapid change of blade pitch angle reduces the rotor thrust force when the Spar pitches into the wind, and therefore may cause negative damping and resonant Spar pitch and surge motions. The OC3-Hywind control scheme shows a better performance in term of avoiding the negative damping effects.

The sensitivity of the global responses to the different blade pitch control schemes for regulating the power production are evaluated for the Spar, Semi-submersible and TLP FOWTs. The power production load case with the Extreme Turbulent Model (DLC 1.3, see Table 3.1) is chosen for the sensitivity study. The hub height wind speed is assumed at the rated and cut-out wind speed, respectively. The maximum value of global responses and power output are presented in Figure 3.29 to Figure 3.31. The following observations can be made:

- In all the cases, the land based control scheme produces fewer variations in the generator power output than the OC3 Hywind control.
- For the Spar FOWT, the land based control scheme results in larger hull pitch motions; larger tower, rotor and generator loads; and larger blade pitch angle than the OC3 Hywind control scheme.
- For the Semi-submersible FOWT, the land based control scheme induced relatively smaller hull pitch motion compared to the Spar concept, mainly because of the high viscous damping from the heave plates fitted to the Semi-submersible hull. The land based scheme results in larger tower, rotor and generator loads and larger blade pitch angles than the OC3 Hywind control. The modified OC3 Hywind control scheme (see Section 3.4.5) reduces the hull pitch motion at the cut-out wind speed, but increases the hull pitch motion at the rated wind speed.
- For the TLP concept, using different control schemes appears to have an insignificant effect on the TLP pitch motion, while the land based scheme results in the larger tower, rotor and generator loads and larger blade pitch than the OC3 Hywind control scheme.

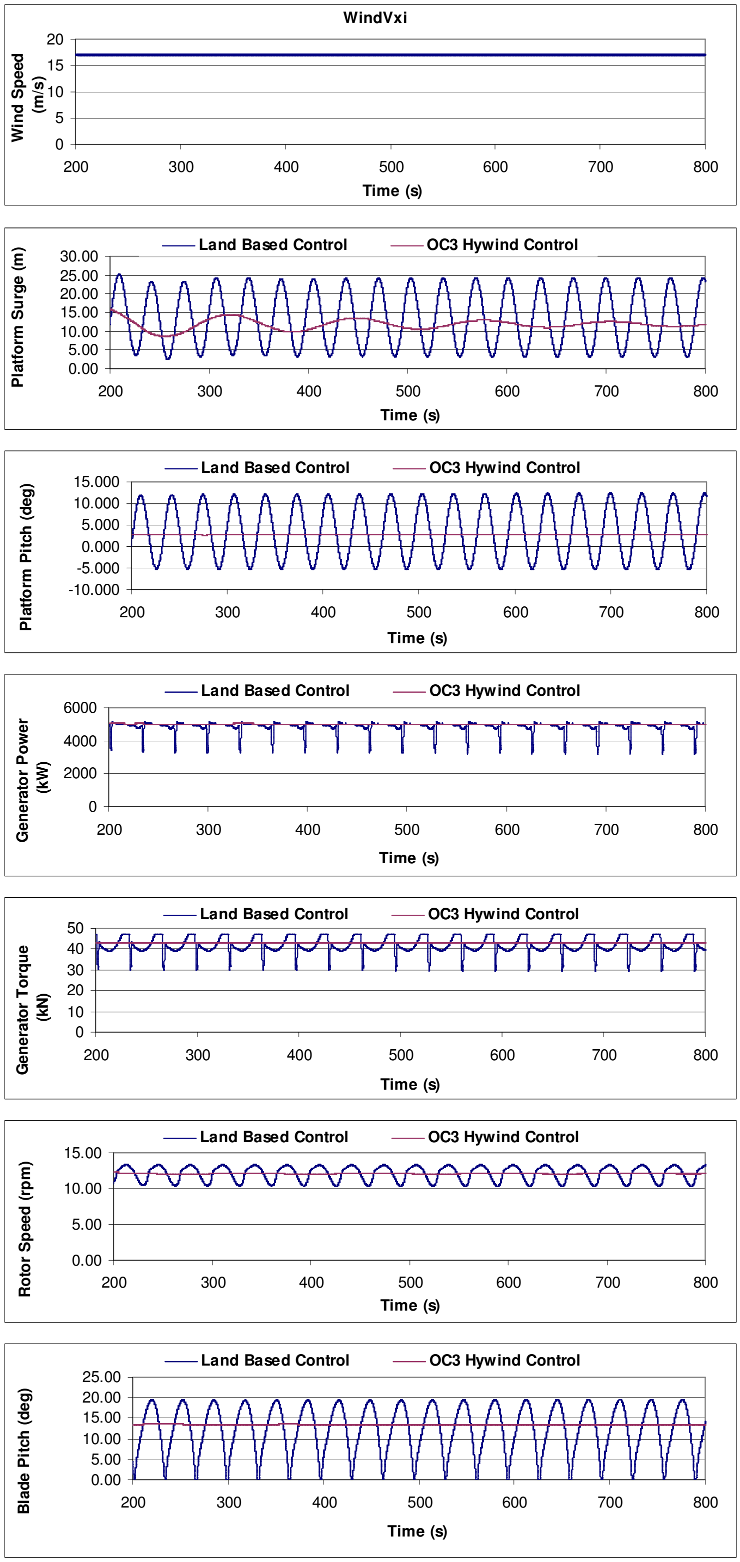



**Figure 3.28 Comparison of Control Scheme for Spar in Steady Wind (17 m/s)**

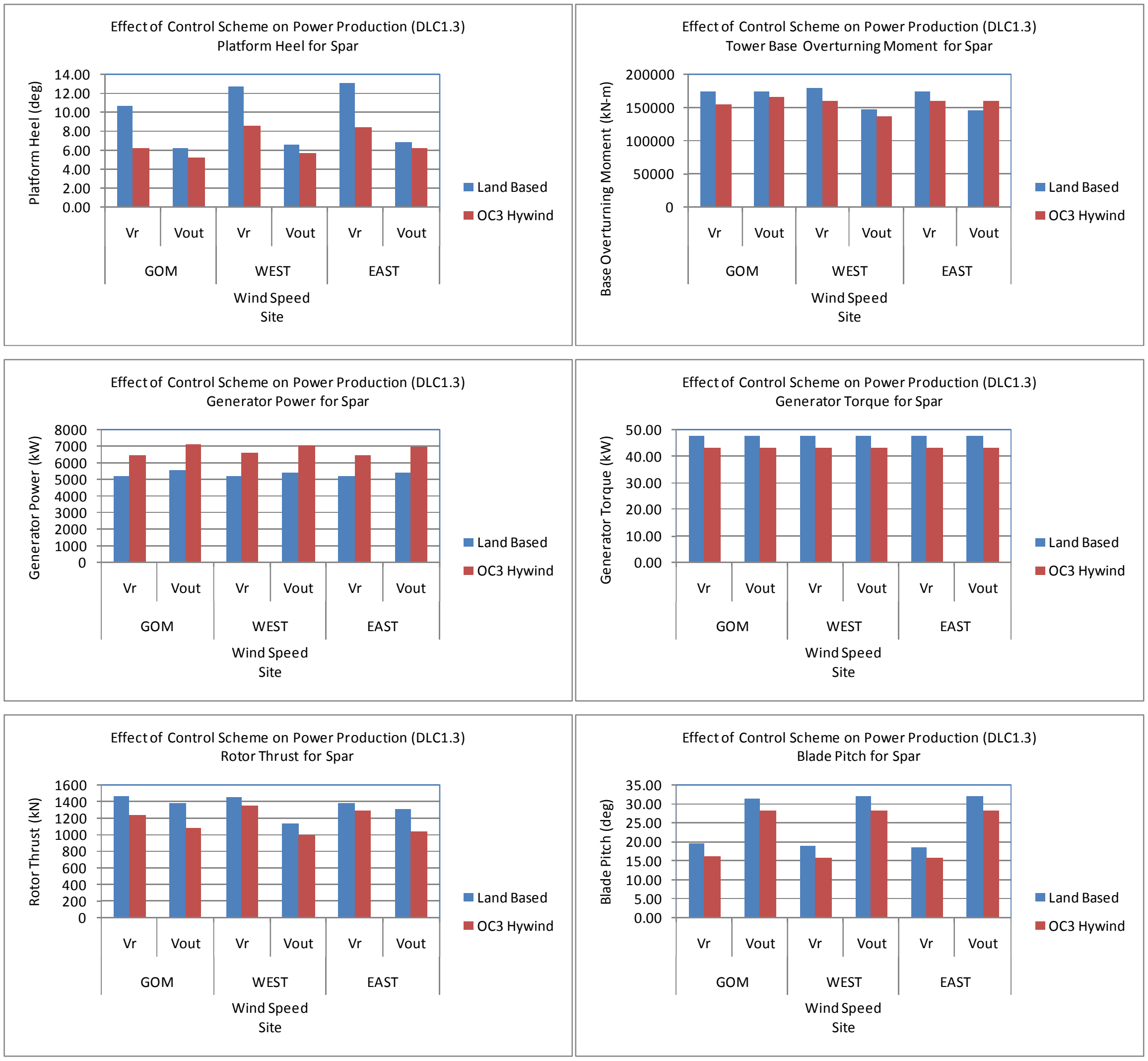



**Figure 3.29 Effects of Control Scheme for Power Production of Spar FOWT**

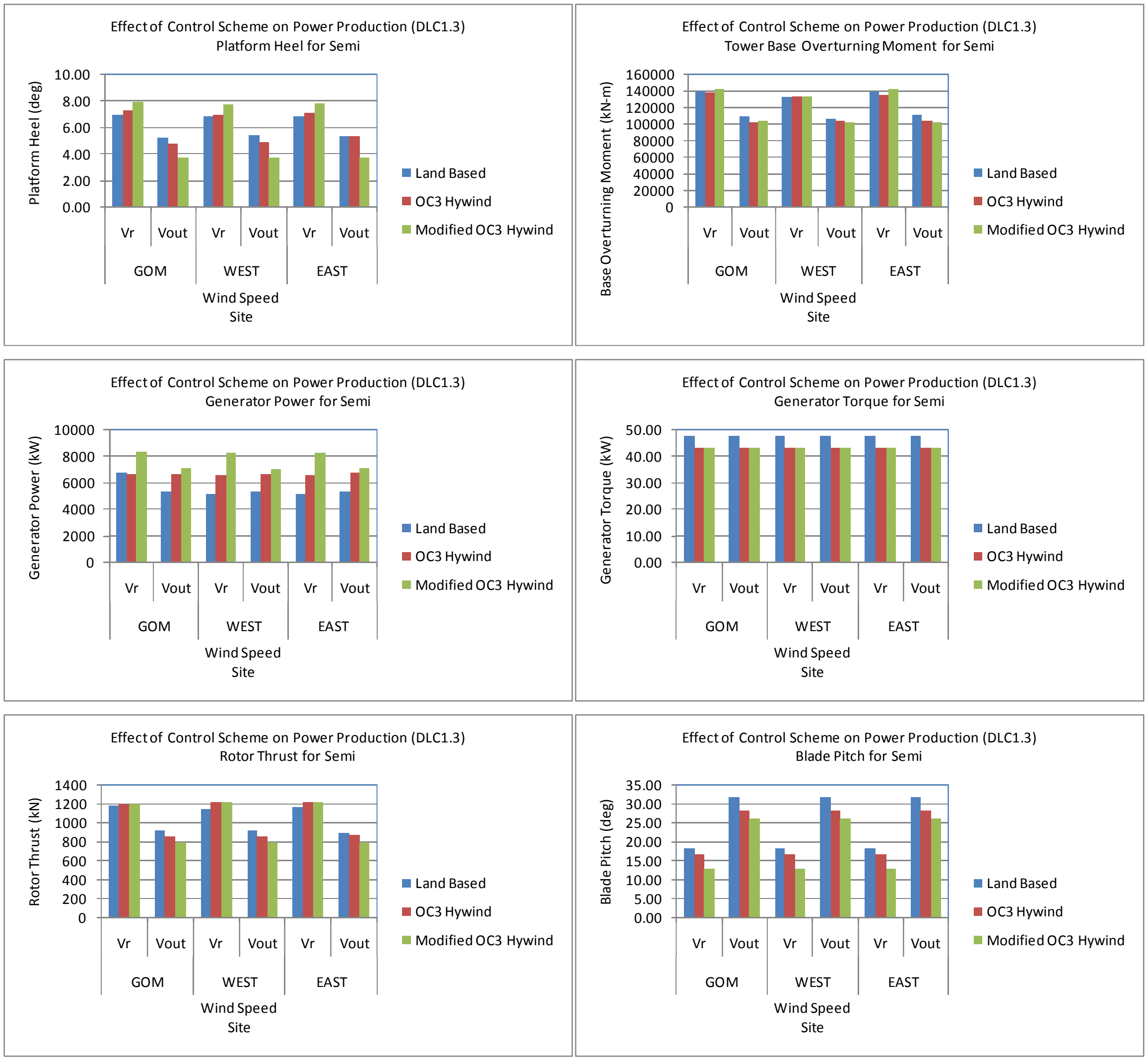



**Figure 3.30 Effects of Control Scheme for Power Production of Semi-submersible FOWT**

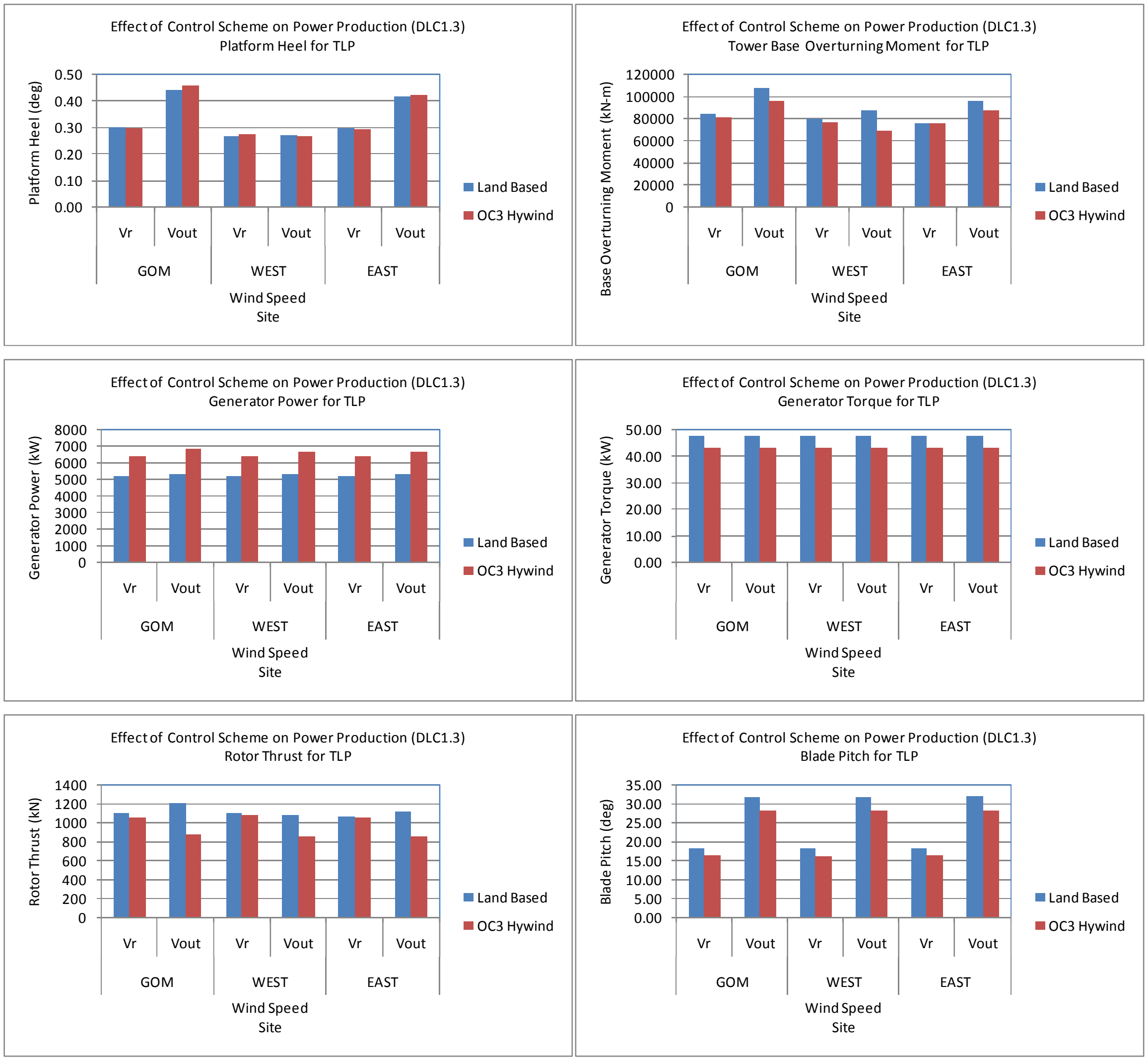



**Figure 3.31 Effects of Control Scheme for Power Production of TLP**

The time-series of one of the simulations of DLC1.3 for the Spar FOWT in the GoM Central Region with the turbine subjected to the rated wind speed are plotted in Figure 3.32 and Figure 3.33. These figures show that the conventional control scheme for land-based turbines produces fewer variations in the generator power output, but induces larger tower, rotor and generator loads and larger variations in blade pitch than the OC3 Hywind control.

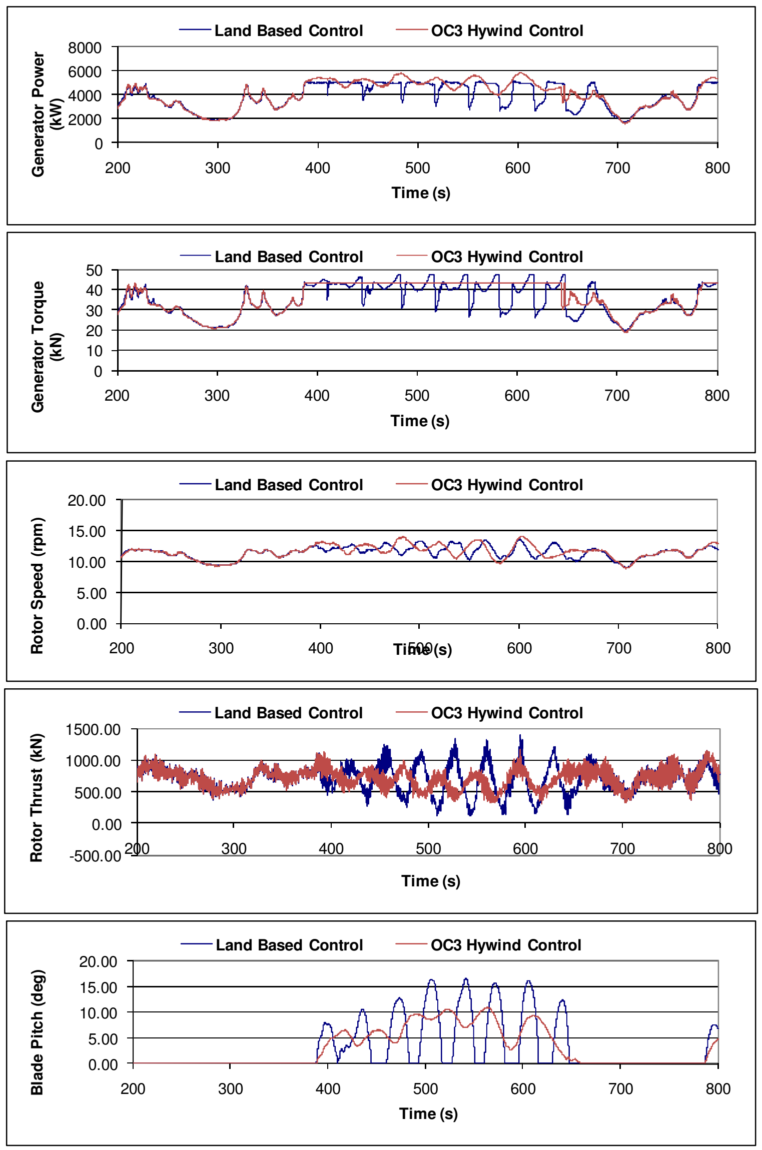



**Figure 3.32 RNA Responses – Spar FOWT in the Power Production Condition (DLC1.3 at $V_r$) in the GoM Central Region**

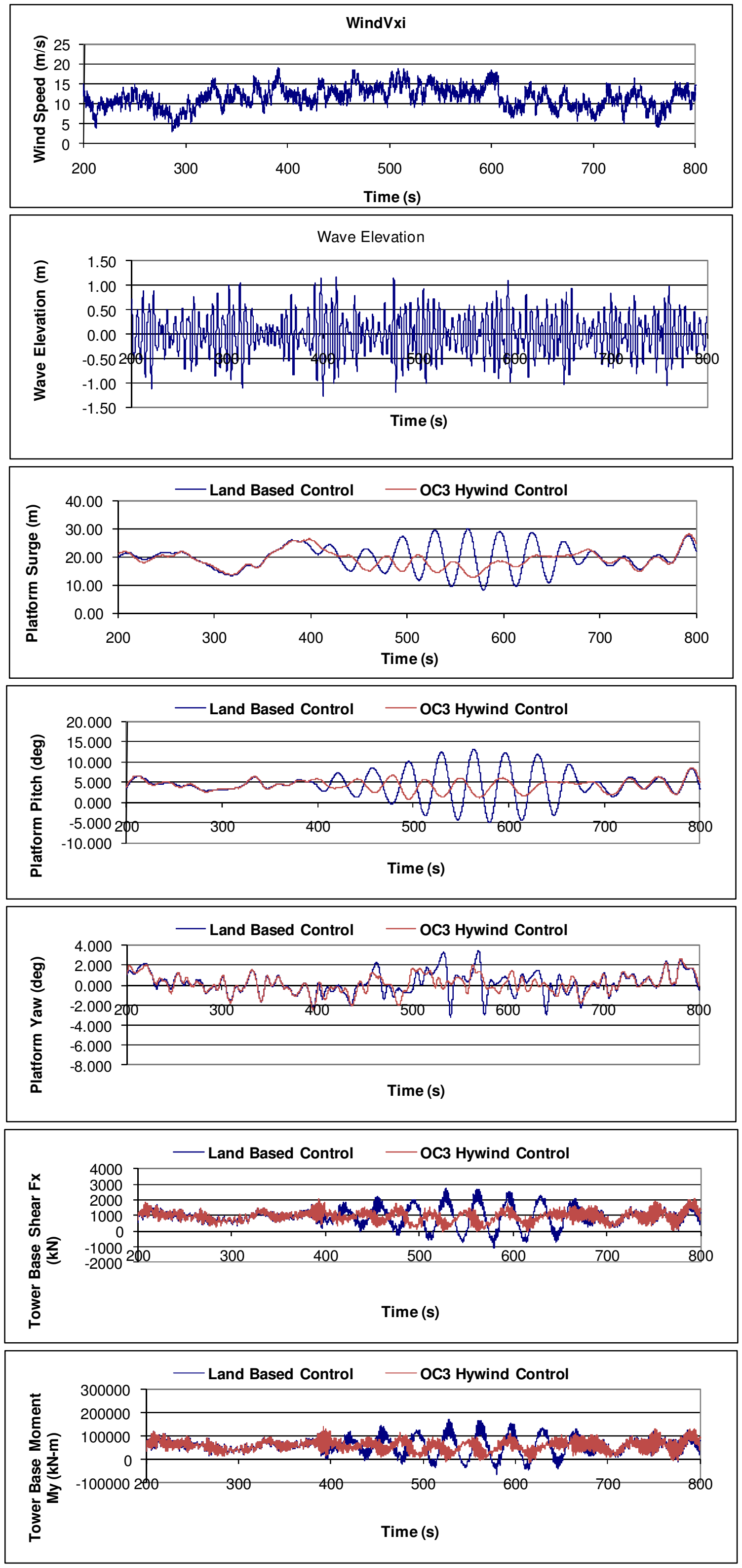



**Figure 3.33 Global Motions of Spar Hull – Spar FOWT in the Power Production Condition (DLC1.3 at $V_r$) in the GoM Central Region**

### *3.4.7.4 Polyester Rope Stiffness*

The polyester rope stiffness used in the generic WindFloat concept is 100,000 kN (Roddier, 2011). In order to investigate the effects of rope stiffness on the global responses of the Semi-submersible FOWT, sensitivity analyses using the upper bound stiffness with 3 times the original stiffness value, which is considered as a lower bound, are performed. The Semi-submersible FOWT is assumed to be located in the GoM Central Region. The OC3 Hywind control scheme is applied in the power production condition. The global performance analysis results are depicted in Figure 3.34 for the power production condition (DLC 1.3) and Figure 3.35 for the parked turbine subjected to the 100-year return hurricane peak wind condition. The following observations can be made.

- For the power production condition (DLC1.3) shown in Figure 3.34, the upper bound stiffness results in the smaller platform offset but higher maximum line top tension than the lower bound stiffness. The rope stiffness appears have insignificant influences on the platform heel, tower base loads, generator loads and power output.
- For the parked (idling) turbine under the 100-year return hurricane peak wind condition, as shown in Figure 3.35, the upper bound stiffness leads to the smaller platform offset and yaw motion but the higher line top tension. The upper bound stiffness also results in a slightly higher platform heel motion.
- Figure 3.35 shows that the nacelle yaw error appears to have insignificant effect on the hull offset and the mooring line tensions. However, the larger tower loads (base shear force, base bending moment and top acceleration) and the hull yaw and heel motions are observed for the 30-degree nacelle yaw error, which results in significantly higher aerodynamic loads than the 8-degree nacelle yaw error.
- Figure 3.35 also reveals that, with the nacelle yaw error of 30 degrees, the tower loads (base shear force, base bending moment and top acceleration) are mostly determined by the aerodynamic forces generated by the parked turbine subjected to the extreme storm condition. The stiffness of mooring line, as well as the global hull motions, has insignificant effect on the tower loads. It should be noted that this observation is made from the results of this specific study and may not be applicable to other hull forms or other load conditions.

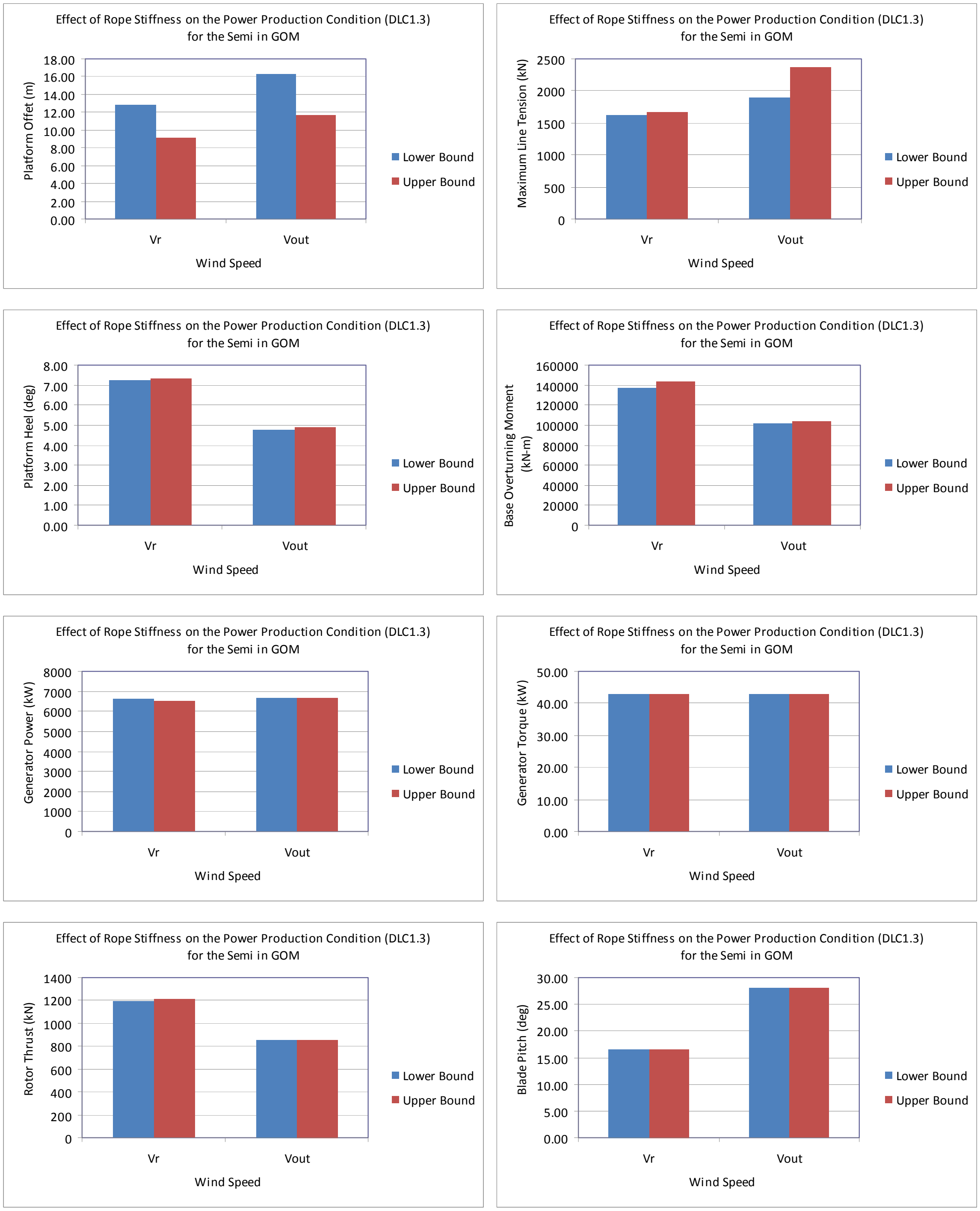



**Figure 3.34 Effect of Rope Stiffness on the Semi-submersible FOWT – Power Production (DLC 1.3)**

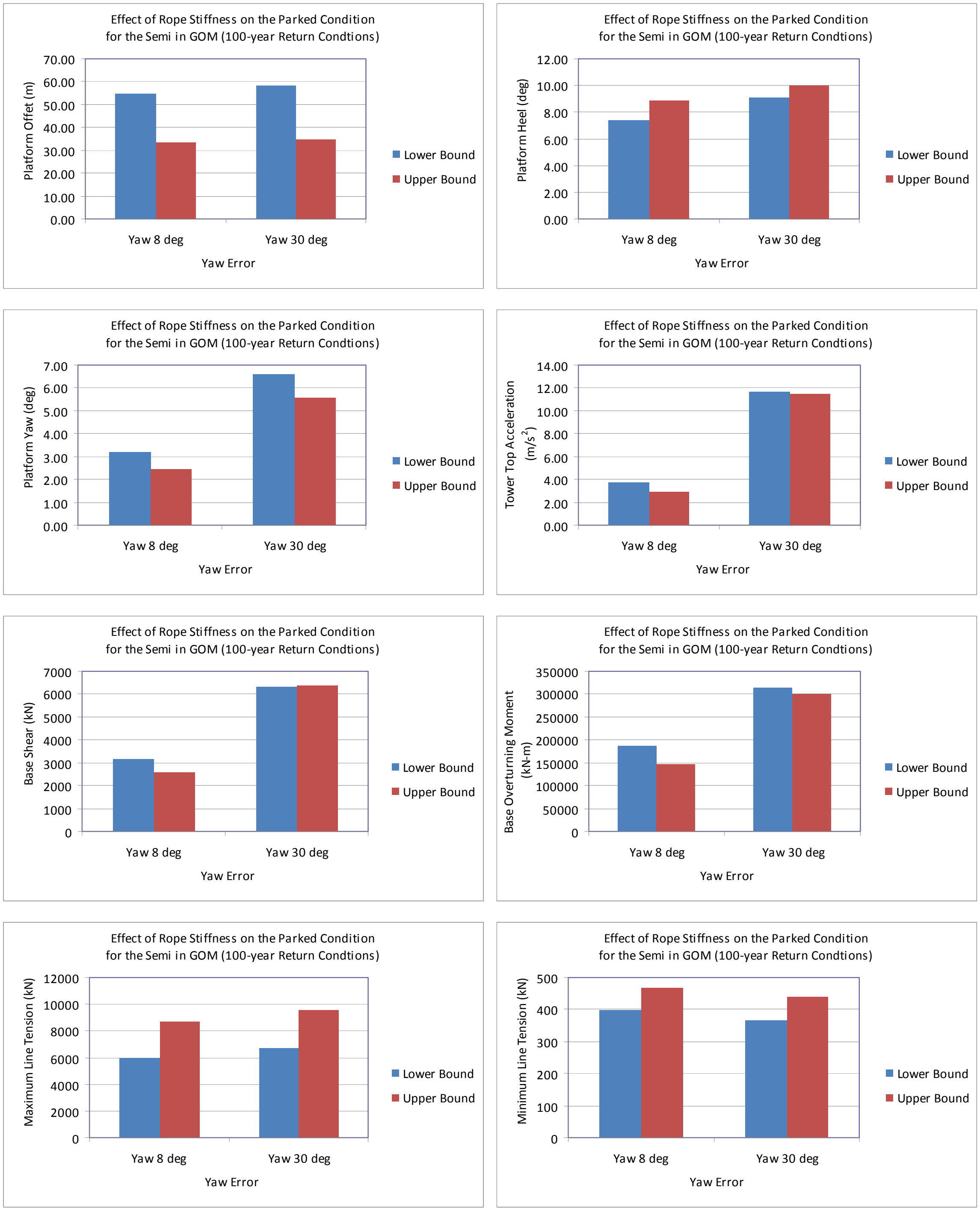



**Figure 3.35 Effect of Rope Stiffness on the Semi-submersible FOWT – Parked Condition**

## 3.5 Spar Floating Wind Turbine

### 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 94 load cases are defined to evaluate the global responses of the Spar FOWT with the consideration of 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 3.18.

For the Spar FOWT with the parked turbine subjected to the 100-year or 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 and current heading is always 0 degree, while the wave heading is taken as 30 degrees and 90 degrees, respectively. The definitions of the headings are depicted in Figure 3.36.

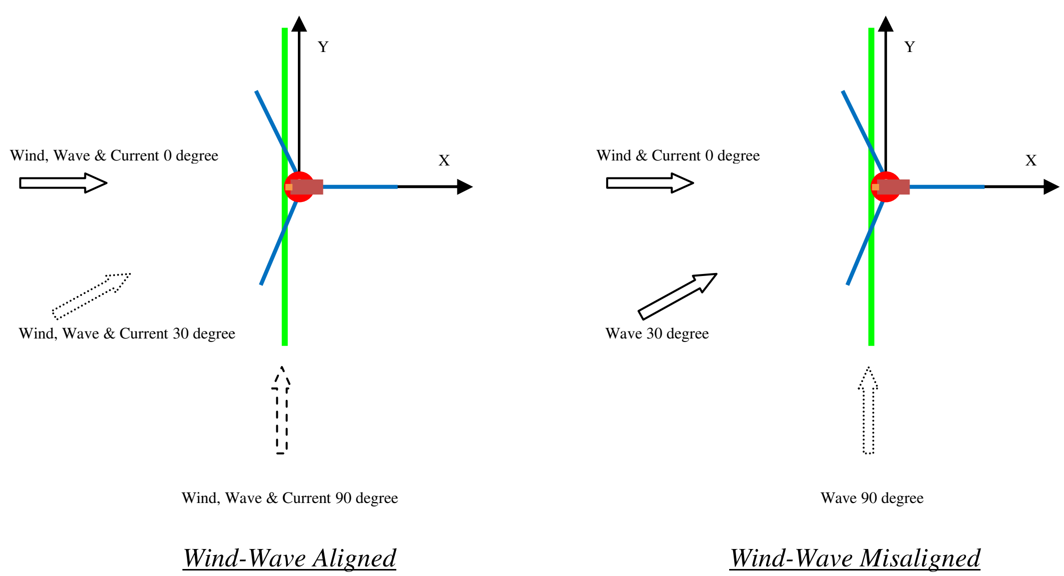



**Figure 3.36 Definition of Wind, Wave and Current Directionality – Spar FOWT**

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 3750×4 panels (3750 panels on one quarter of the hull, considering x- and y-symmetry), is created for the hydrodynamic analysis in WAMIT (see Figure 3.37).

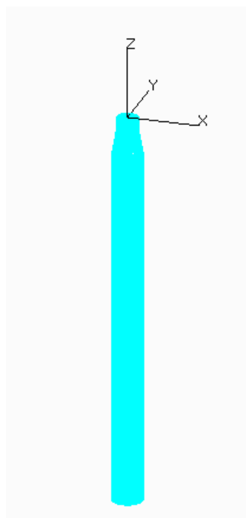



**Figure 3.37 Hydrodynamic Panel Model of the Spar Floating Support Structure**

The integrated hull-mooring model for the CHARM3D-FAST time-domain analysis is shown in Figure 3.38 (wind turbine not shown). Each mooring line is modeled by 20 high-order cable elements.

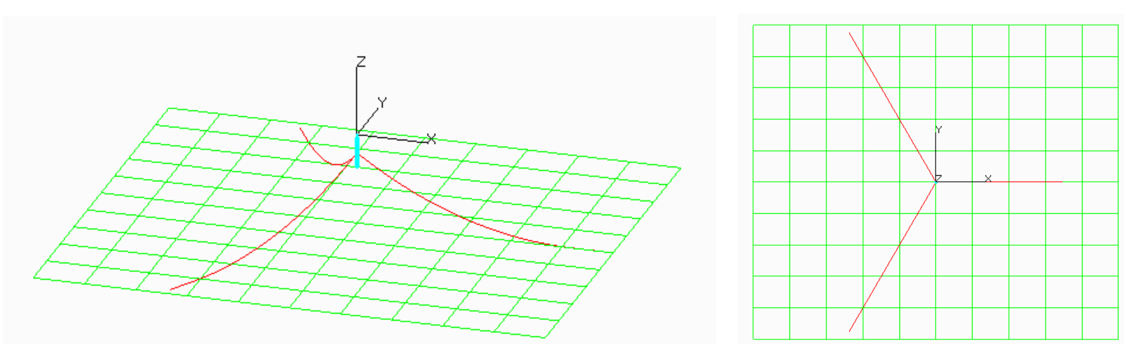



**Figure 3.38 Integrated Spar-Mooring Model**

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* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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 | Spar | GOM | ETM, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 0.13 | 1.61 | 0.40 | MSL |
| | Spar | GOM | ETM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.71 | 5.84 | 0.40 | MSL |
| | Spar | GOM | ETM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 7.35 | 12.12 | 0.40 | MSL |
| | Spar | WEST | ETM, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 2.01 | 11.52 | 0.60 | MSL |
| | Spar | WEST | ETM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 2.93 | 12.31 | 0.60 | MSL |
| | Spar | WEST | ETM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.16 | 14.13 | 0.60 | MSL |
| | Spar | EAST | ETM, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 0.95 | 6.90 | 0.50 | MSL |
| | Spar | EAST | ETM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.98 | 7.74 | 0.50 | MSL |
| | Spar | EAST | ETM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.79 | 10.33 | 0.50 | MSL |
| Start-up | Spar | GOM | EOG, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 0.13 | 1.61 | 0.40 | MSL |
| | Spar | GOM | EOG, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.71 | 5.84 | 0.40 | MSL |
| | Spar | GOM | EOG, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 7.35 | 12.12 | 0.40 | MSL |
| | Spar | WEST | EOG, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 2.01 | 11.52 | 0.60 | MSL |
| | Spar | WEST | EOG, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 2.93 | 12.31 | 0.60 | MSL |
| | Spar | WEST | EOG, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.16 | 14.13 | 0.60 | MSL |
| | Spar | EAST | EOG, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 0.95 | 6.90 | 0.50 | MSL |
| | Spar | EAST | EOG, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.98 | 7.74 | 0.50 | MSL |
| | Spar | EAST | EOG, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.79 | 10.33 | 0.50 | MSL |

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

| *Turbine Operational Mode* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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) | |
| Emergency shut down | Spar | GOM | NTM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.71 | 5.84 | 0.50 | MSL |
| | Spar | GOM | NTM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 7.35 | 12.12 | 0.50 | MSL |
| | Spar | WEST | NTM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 2.93 | 12.31 | 0.40 | MSL |
| | Spar | WEST | NTM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.16 | 14.13 | 0.40 | MSL |
| | Spar | EAST | NTM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.98 | 7.74 | 0.60 | MSL |
| | Spar | EAST | NTM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.79 | 10.33 | 0.60 | MSL |
| Parked (Idling) | Spar | GOM | 100yr peak wind | 0 | 0 | 0 | 0 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wave | 0 | 0 | 0 | 0 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wind | 30 | 30 | 30 | 0 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wave | 30 | 30 | 30 | 0 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wind | 90 | 90 | 90 | 0 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wave | 90 | 90 | 90 | 0 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wind | 0 | 30 | 0 | 30 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wave | 0 | 30 | 0 | 30 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wind | 0 | 90 | 0 | 90 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wave | 0 | 90 | 0 | 90 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wind | 0 | 0 | 0 | 0 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wave | 0 | 0 | 0 | 0 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |

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

| *Turbine Operational Mode* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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) | Spar | GOM | 100yr peak wind | 30 | 30 | 30 | 0 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wave | 30 | 30 | 30 | 0 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wind | 90 | 90 | 90 | 0 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wave | 90 | 90 | 90 | 0 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wind | 0 | 30 | 0 | 30 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wave | 0 | 30 | 0 | 30 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wind | 0 | 90 | 0 | 90 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Spar | GOM | 100yr peak wave | 0 | 90 | 0 | 90 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Spar | WEST | 100yr storm | 0 | 0 | 0 | 0 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Spar | WEST | 100yr storm | 30 | 30 | 30 | 0 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Spar | WEST | 100yr storm | 90 | 90 | 90 | 0 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Spar | WEST | 100yr storm | 0 | 30 | 0 | 30 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Spar | WEST | 100yr storm | 0 | 90 | 0 | 90 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Spar | WEST | 100yr storm | 0 | 0 | 0 | 0 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Spar | WEST | 100yr storm | 30 | 30 | 30 | 0 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Spar | WEST | 100yr storm | 90 | 90 | 90 | 0 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Spar | WEST | 100yr storm | 0 | 30 | 0 | 30 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Spar | WEST | 100yr storm | 0 | 90 | 0 | 90 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Spar | EAST | 100yr storm | 30 | 30 | 30 | 0 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Spar | EAST | 100yr storm | 90 | 90 | 90 | 0 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |

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

| *Turbine Operational Mode* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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) | Spar | EAST | 100yr storm | 0 | 0 | 0 | 0 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Spar | EAST | 100yr storm | 0 | 30 | 0 | 30 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Spar | EAST | 100yr storm | 0 | 90 | 0 | 90 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Spar | EAST | 100yr storm | 0 | 0 | 0 | 0 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Spar | EAST | 100yr storm | 30 | 30 | 30 | 0 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Spar | EAST | 100yr storm | 90 | 90 | 90 | 0 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Spar | EAST | 100yr storm | 0 | 30 | 0 | 30 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Spar | EAST | 100yr storm | 0 | 90 | 0 | 90 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| Parked (Idling) | Spar | GOM | 50yr peak wind | 0 | 0 | 0 | 0 | 8 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wave | 0 | 0 | 0 | 0 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wind | 30 | 30 | 30 | 0 | 8 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wave | 30 | 30 | 30 | 0 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wind | 90 | 90 | 90 | 0 | 8 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wave | 90 | 90 | 90 | 0 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wind | 0 | 30 | 0 | 30 | 8 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wave | 0 | 30 | 0 | 30 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wind | 0 | 90 | 0 | 90 | 8 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wave | 0 | 90 | 0 | 90 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wind | 0 | 0 | 0 | 0 | 30 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wave | 0 | 0 | 0 | 0 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |

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

| *Turbine Operational Mode* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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) | Spar | GOM | 50yr peak wind | 30 | 30 | 30 | 0 | 30 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wave | 30 | 30 | 30 | 0 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wind | 90 | 90 | 90 | 0 | 30 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wave | 90 | 90 | 90 | 0 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wind | 0 | 30 | 0 | 30 | 30 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wave | 0 | 30 | 0 | 30 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wind | 0 | 90 | 0 | 90 | 30 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Spar | GOM | 50yr peak wave | 0 | 90 | 0 | 90 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Spar | WEST | 50yr storm | 0 | 0 | 0 | 0 | 8 | 26.27 | 35.74 | 12.62 | 19.96 | 0.80 | MSL |
| | Spar | WEST | 50yr storm | 0 | 0 | 0 | 0 | 30 | 26.27 | 35.74 | 12.62 | 19.96 | 0.80 | MSL |
| | Spar | EAST | 50yr storm | 0 | 0 | 0 | 0 | 8 | 26.70 | 36.39 | 10.66 | 13.21 | 0.57 | MSL |
| | Spar | EAST | 50yr storm | 0 | 0 | 0 | 0 | 30 | 26.70 | 36.39 | 10.66 | 13.21 | 0.57 | MSL |
| Parked (Idling) | Spar | GOM | 10yr hurricane | 0 | 0 | 0 | 0 | 20 | 33.00 | 46.20 | 9.90 | 13.00 | 1.32 | MSL |
| | Spar | GOM | 10yr hurricane | 0 | 0 | 0 | 0 | 30 | 33.00 | 46.20 | 9.90 | 13.00 | 1.32 | MSL |
| | Spar | WEST | 10yr storm | 0 | 0 | 0 | 0 | 20 | 23.49 | 31.55 | 10.75 | 18.53 | 0.70 | MSL |
| | Spar | WEST | 10yr storm | 0 | 0 | 0 | 0 | 30 | 23.49 | 31.55 | 10.75 | 18.53 | 0.70 | MSL |
| | Spar | EAST | 10yr storm | 0 | 0 | 0 | 0 | 20 | 23.71 | 31.88 | 9.04 | 12.29 | 0.54 | MSL |
| | Spar | EAST | 10yr storm | 0 | 0 | 0 | 0 | 30 | 23.71 | 31.88 | 9.04 | 12.29 | 0.54 | MSL |

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

*Notes:*

1. API wind models are used for the 10-yr, 50-yr and 100-yr condition for turbine parked.
2. IEC wind models are used for power production, start-up and emergency shut down.
3. For Start-up, NWH (normal wave height) wave model is used.
4. GOM: GOM Central Region
5. WEST: US West Coast
6. EAST: US Northeast Coast
7. ETM: Extreme Turbulence Model
8. EOG: Extreme Operating Gust
9. NTM: Normal Turbulence Model
10. $V_{in}$ is the cut-in wind speed at hub height.
11. $V_r$ is the rated wind speed at hub height.
12. $V_{out}$ is the cut-out wind speed at hub height.
13. $H_s$ and $T_p$ are the significant wave height and the peak period of wave spectrum
14. Current Speed are given at water surface
15. 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 motion 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 3.39 for the Spar FOWT on the US West Coast and Northeast Coast and in Figure 3.40 for the modified Spar in the GOM Central Region.

**Table 3.19 Natural Periods of Spar Hull Motions**

| *Mode of Motion* | *Natural Periods (seconds)* | |
|---|---|---|
| | *Spar on the US West and Northeast Coast* | *Modified Spar in the GOM Central Region* |
| Surge | 119.5 | 62.6 |
| Sway | 118.4 | 62.2 |
| Heave | 31.3 | 34.4 |
| Roll | 30.5 | 27.4 |
| Pitch | 30.5 | 27.4 |
| Yaw | 8.2 | 4.3 |

### 3.5.3 Spar FOWT Case Study Results

Global responses, including the Spar hull motions, tower top acceleration, tower base shear and overturning moment, and maximum and minimum line top tensions at fairlead, are obtained for each load case specified in Section 3.5.1. In addition, for the power production load cases (DLC 1.3), the maximum generator power output, generator torque, rotor speed, generator speed, rotor thrust, rotor torque and blade pitch are also obtained. For start-up (DLC 3.2), the maximum generator power output and generator torque are derived.

All these Spar case study results are compiled for the parametric study presented in Section 3.8.

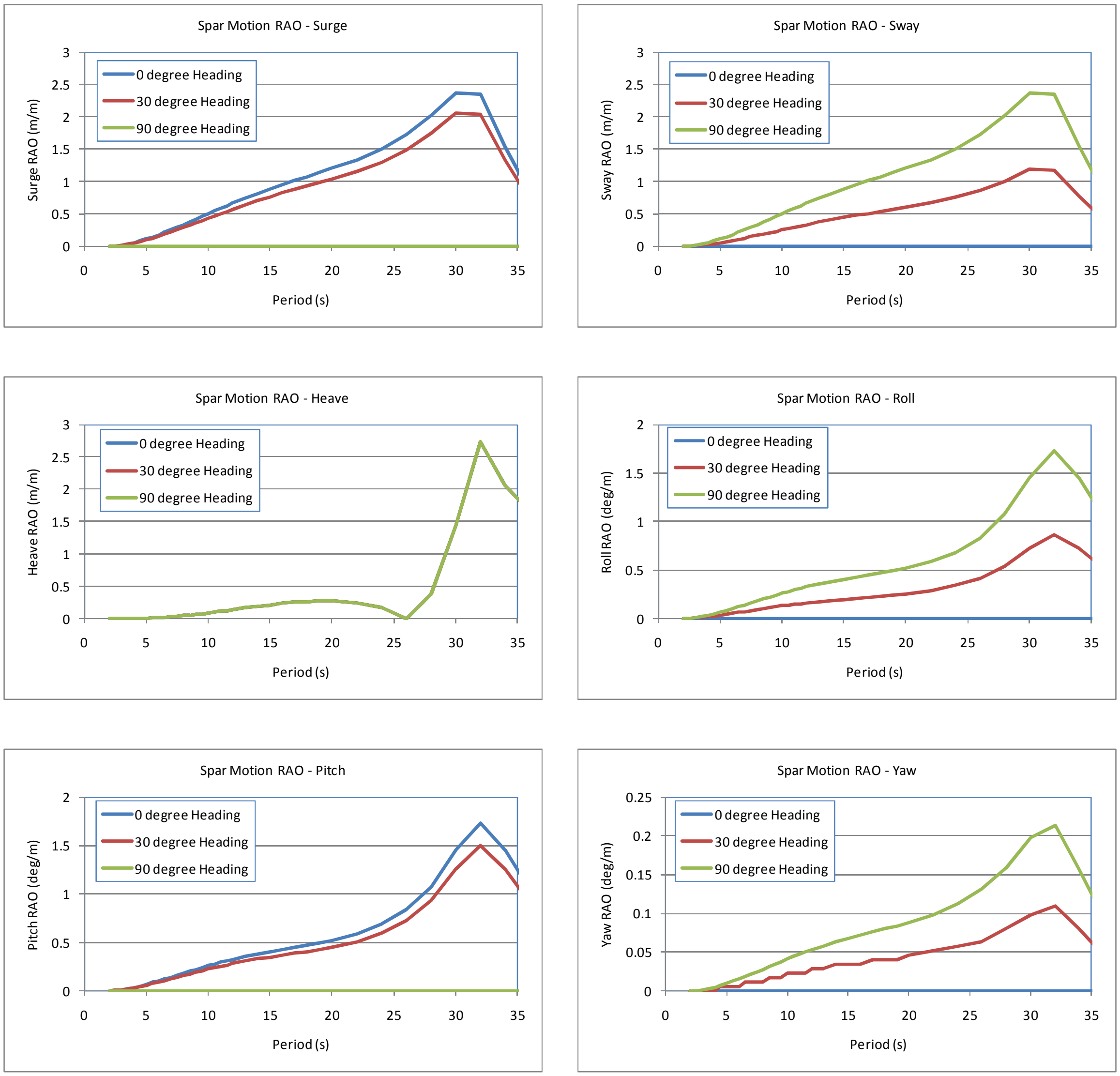



**Figure 3.39 Motion RAOs for the Spar Floating Support Structure on the US West Coast and Northeast Coast**

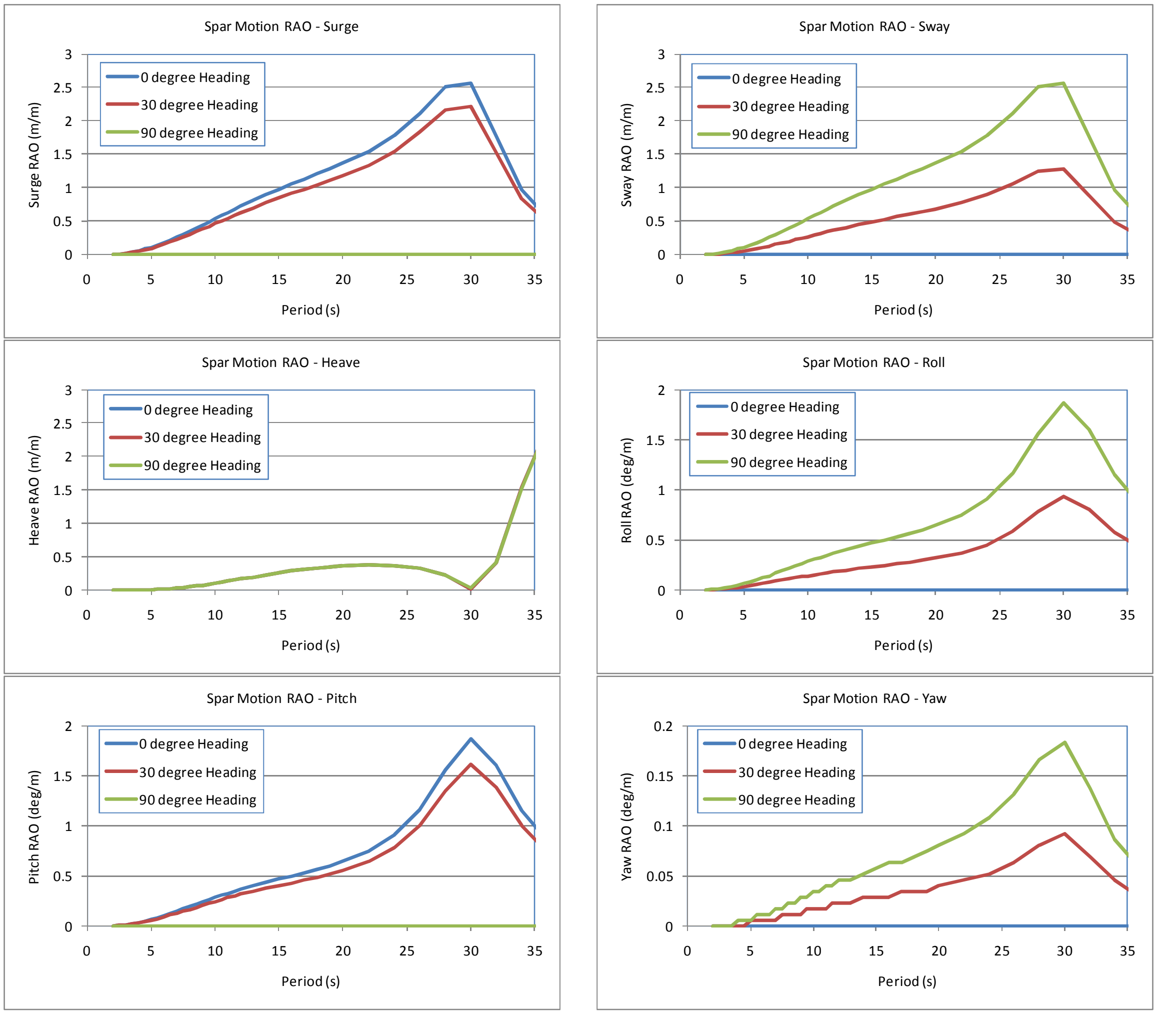



**Figure 3.40 Motion RAOs for the Modified Spar Floating Support Structure in the GOM Central Region**

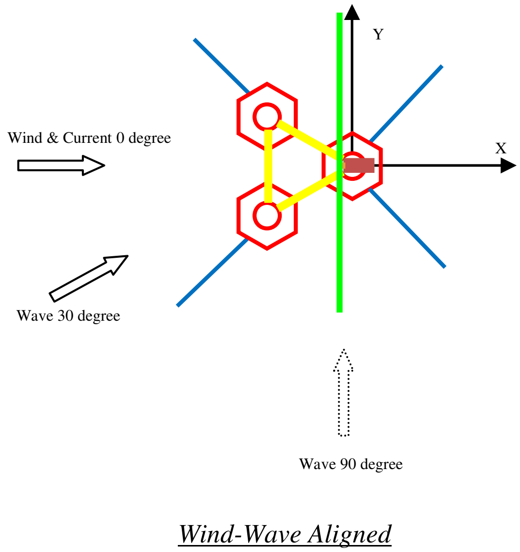
## 3.6 Semi-submersible Floating Wind Turbine

### 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. Sensitivity analyses have been performed for the Semi-submersible FOWT using the land-based, original OC3-Hywind and modified OC3-Hywind control schemes (see Figure 3.30). The turbulent and deterministic wind field data for the aerodynamic analysis in FAST are generated according to Section 3.4.6.

A total of 94 load cases are defined to evaluate the global responses of the Semi-submersible FOWT with the consideration of 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 3.20. All the load cases presented in this section are using the lower bound stiffness for the polyester ropes. A sensitivity analysis using the upper bound rope stiffness is presented in Section 3.4.7.4.

For the Semi-submersible FOWT with the parked turbine subjected to the 100-year or 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 and current heading is always 0 degree, while the wave heading is taken as 30 degrees and 90 degrees, respectively. The definitions of the headings are depicted in Figure 3.41.



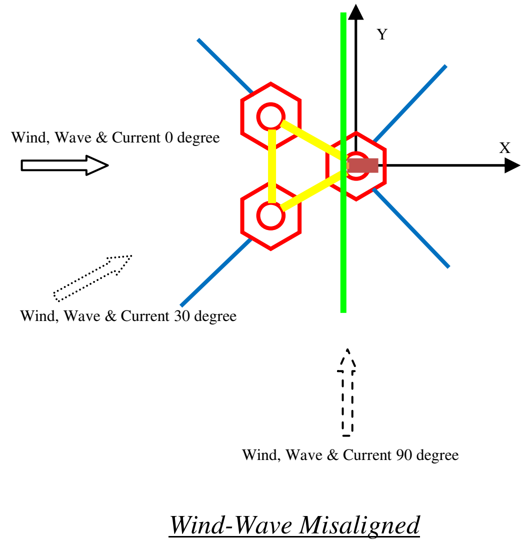




**Figure 3.41 Definition of Wind, Wave and Current Directionality – Semi-submersible FOWT**

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 2722×2 panels (with 2722 panels on half of the hull and considering the y-symmetry with respect to the x-z plane) as plotted in Figure 3.42, is created for the hydrodynamic analysis in WAMIT.

The integrated hull-mooring model for the CHARM3D-FAST time-domain analysis is shown in Figure 3.43 (wind turbine not shown). Each mooring line is modeled by 20 high-order cable elements.

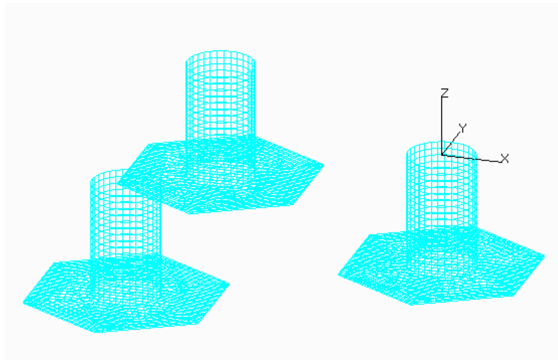



**Figure 3.42 Hydrodynamic Panel Model of the Semi-submersible Floating Support Structure**

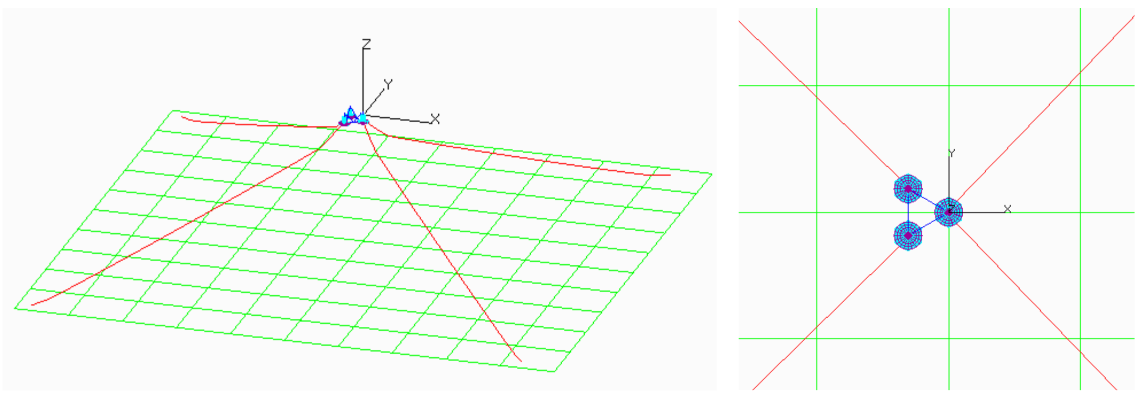



**Figure 3.43 Integrated Semi-submersible-Mooring Model**

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 1.2. The drag coefficient for the heave plate is assumed to be 5.0. The added-mass and drag coefficients of the truss members are taken as 1.0 and 0.6, 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* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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 | Semi | GOM | ETM, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 0.13 | 1.61 | 0.40 | MSL |
| | Semi | GOM | ETM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.71 | 5.84 | 0.40 | MSL |
| | Semi | GOM | ETM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 7.35 | 12.12 | 0.40 | MSL |
| | Semi | WEST | ETM, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 2.01 | 11.52 | 0.60 | MSL |
| | Semi | WEST | ETM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 2.93 | 12.31 | 0.60 | MSL |
| | Semi | WEST | ETM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.16 | 14.13 | 0.60 | MSL |
| | Semi | EAST | ETM, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 0.95 | 6.90 | 0.50 | MSL |
| | Semi | EAST | ETM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.98 | 7.74 | 0.50 | MSL |
| | Semi | EAST | ETM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.79 | 10.33 | 0.50 | MSL |
| Start-up | Semi | GOM | EOG, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 0.13 | 1.61 | 0.40 | MSL |
| | 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 |
| | Semi | WEST | EOG, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 2.01 | 11.52 | 0.60 | MSL |
| | Semi | WEST | EOG, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 2.93 | 12.31 | 0.60 | MSL |
| | Semi | WEST | EOG, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.16 | 14.13 | 0.60 | MSL |
| | Semi | EAST | EOG, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 0.95 | 6.90 | 0.50 | MSL |
| | Semi | EAST | EOG, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.98 | 7.74 | 0.50 | MSL |
| | Semi | EAST | EOG, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.79 | 10.33 | 0.50 | MSL |

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

| *Turbine Operational Mode* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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) | |
| Emergency shut down | Semi | GOM | NTM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.71 | 5.84 | 0.50 | MSL |
| | Semi | GOM | NTM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 7.35 | 12.12 | 0.50 | MSL |
| | Semi | WEST | NTM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 2.93 | 12.31 | 0.40 | MSL |
| | Semi | WEST | NTM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.16 | 14.13 | 0.40 | MSL |
| | Semi | EAST | NTM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.98 | 7.74 | 0.60 | MSL |
| | Semi | EAST | NTM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.79 | 10.33 | 0.60 | MSL |
| Parked (Idling) | Semi | GOM | 100yr peak wind | 0 | 0 | 0 | 0 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wave | 0 | 0 | 0 | 0 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wind | 30 | 30 | 30 | 0 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wave | 30 | 30 | 30 | 0 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wind | 90 | 90 | 90 | 0 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wave | 90 | 90 | 90 | 0 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wind | 0 | 30 | 0 | 30 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wave | 0 | 30 | 0 | 30 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wind | 0 | 90 | 0 | 90 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wave | 0 | 90 | 0 | 90 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wind | 0 | 0 | 0 | 0 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wave | 0 | 0 | 0 | 0 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |

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

| *Turbine Operational Mode* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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) | Semi | GOM | 100yr peak wind | 30 | 30 | 30 | 0 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wave | 30 | 30 | 30 | 0 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wind | 90 | 90 | 90 | 0 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wave | 90 | 90 | 90 | 0 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wind | 0 | 30 | 0 | 30 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wave | 0 | 30 | 0 | 30 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wind | 0 | 90 | 0 | 90 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | Semi | GOM | 100yr peak wave | 0 | 90 | 0 | 90 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | Semi | WEST | 100yr storm | 0 | 0 | 0 | 0 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Semi | WEST | 100yr storm | 30 | 30 | 30 | 0 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Semi | WEST | 100yr storm | 90 | 90 | 90 | 0 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Semi | WEST | 100yr storm | 0 | 30 | 0 | 30 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Semi | WEST | 100yr storm | 0 | 90 | 0 | 90 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Semi | WEST | 100yr storm | 0 | 0 | 0 | 0 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Semi | WEST | 100yr storm | 30 | 30 | 30 | 0 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Semi | WEST | 100yr storm | 90 | 90 | 90 | 0 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Semi | WEST | 100yr storm | 0 | 30 | 0 | 30 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Semi | WEST | 100yr storm | 0 | 90 | 0 | 90 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | Semi | EAST | 100yr storm | 30 | 30 | 30 | 0 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Semi | EAST | 100yr storm | 90 | 90 | 90 | 0 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |

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

| *Turbine Operational Mode* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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) | Semi | EAST | 100yr storm | 0 | 0 | 0 | 0 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Semi | EAST | 100yr storm | 0 | 30 | 0 | 30 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Semi | EAST | 100yr storm | 0 | 90 | 0 | 90 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Semi | EAST | 100yr storm | 0 | 0 | 0 | 0 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Semi | EAST | 100yr storm | 30 | 30 | 30 | 0 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Semi | EAST | 100yr storm | 90 | 90 | 90 | 0 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Semi | EAST | 100yr storm | 0 | 30 | 0 | 30 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | Semi | EAST | 100yr storm | 0 | 90 | 0 | 90 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| Parked (Idling) | 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 wave | 0 | 0 | 0 | 0 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 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 wave | 30 | 30 | 30 | 0 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 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 wave | 90 | 90 | 90 | 0 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Semi | GOM | 50yr peak wind | 0 | 30 | 0 | 30 | 8 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Semi | GOM | 50yr peak wave | 0 | 30 | 0 | 30 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Semi | GOM | 50yr peak wind | 0 | 90 | 0 | 90 | 8 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Semi | GOM | 50yr peak wave | 0 | 90 | 0 | 90 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | 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 wave | 0 | 0 | 0 | 0 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |

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

| *Turbine Operational Mode* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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) | 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 wave | 30 | 30 | 30 | 0 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 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 wave | 90 | 90 | 90 | 0 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Semi | GOM | 50yr peak wind | 0 | 30 | 0 | 30 | 30 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Semi | GOM | 50yr peak wave | 0 | 30 | 0 | 30 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Semi | GOM | 50yr peak wind | 0 | 90 | 0 | 90 | 30 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | Semi | GOM | 50yr peak wave | 0 | 90 | 0 | 90 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | Semi | WEST | 50yr storm | 0 | 0 | 0 | 0 | 8 | 26.27 | 35.74 | 12.62 | 19.96 | 0.80 | MSL |
| | Semi | WEST | 50yr storm | 0 | 0 | 0 | 0 | 30 | 26.27 | 35.74 | 12.62 | 19.96 | 0.80 | MSL |
| | Semi | EAST | 50yr storm | 0 | 0 | 0 | 0 | 8 | 26.70 | 36.39 | 10.66 | 13.21 | 0.57 | MSL |
| | Semi | EAST | 50yr storm | 0 | 0 | 0 | 0 | 30 | 26.70 | 36.39 | 10.66 | 13.21 | 0.57 | MSL |
| Parked (Idling) | Semi | GOM | 10yr hurricane | 0 | 0 | 0 | 0 | 20 | 33.00 | 46.20 | 9.90 | 13.00 | 1.32 | MSL |
| | Semi | GOM | 10yr hurricane | 0 | 0 | 0 | 0 | 30 | 33.00 | 46.20 | 9.90 | 13.00 | 1.32 | MSL |
| | Semi | WEST | 10yr storm | 0 | 0 | 0 | 0 | 20 | 23.49 | 31.55 | 10.75 | 18.53 | 0.70 | MSL |
| | Semi | WEST | 10yr storm | 0 | 0 | 0 | 0 | 30 | 23.49 | 31.55 | 10.75 | 18.53 | 0.70 | MSL |
| | Semi | EAST | 10yr storm | 0 | 0 | 0 | 0 | 20 | 23.71 | 31.88 | 9.04 | 12.29 | 0.54 | MSL |
| | Semi | EAST | 10yr storm | 0 | 0 | 0 | 0 | 30 | 23.71 | 31.88 | 9.04 | 12.29 | 0.54 | MSL |

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

*Notes:*

1. API wind models are used for the 10-yr, 50-yr and 100-yr condition for turbine parked.
2. IEC wind models are used for power production, start-up and emergency shut down.
3. For Start-up, NWH (normal wave height) wave model is used.
4. GOM: GOM Central Region
5. WEST: US West Coast
6. EAST: US Northeast Coast
7. ETM: Extreme Turbulence Model
8. EOG: Extreme Operating Gust
9. NTM: Normal Turbulence Model
10. $V_{in}$ is the cut-in wind speed at hub height.
11. $V_r$ is the rated wind speed at hub height.
12. $V_{out}$ is the cut-out wind speed at hub height.
13. $H_s$ and $T_p$ are the significant wave height and the peak period of wave spectrum
14. Current Speed are given at water surface
15. MSL: Mean Sea Level (Mean Still Water Level)

### 3.6.2 Natural Periods and Motion RAOs

The natural periods for 6-DOF motions of Semi-submersible are listed in Table 3.21. The natural periods of heave, roll and pitch motions are derived from free decay simulations. Due to the coupling between sway and yaw motions, it is not possible to identify the natural period from the free decay analysis results. As an alternative, the natural periods of surge, sway and yaw motions are calculated using the equivalent mooring system stiffness and mass as well as the added mass.

The hull motion RAOs calculated by WAMIT for 0, 30 and 90 degree wave headings are shown in Figure 3.44.

**Table 3.21 Natural Periods of Semi-submersible Hull Motions**

| *Mode of Motion* | *Natural Periods (seconds)* |
|---|---|
| Surge | 58.64 |
| Sway | 57.81 |
| Heave | 20.27 |
| Roll | 43.61 |
| Pitch | 41.11 |
| Yaw | 43.15 |

### 3.6.3 Semi-submersible FOWT Case Study Results

Global responses, including the Semi-submersible hull motions, tower top acceleration, tower base shear and overturning moment, and maximum and minimum line top tensions at fairlead, are obtained for each load case specified in Section 3.5.1. In addition, for the power production load cases (DLC 1.3), the maximum generator power output, generator torque, rotor speed, generator speed, rotor thrust, rotor torque and blade pitch are also obtained. For start-up (DLC 3.2), the maximum generator power output and generator torque are derived.

All these Semi-submersible case study results are compiled for the parametric study presented in Section 3.8.

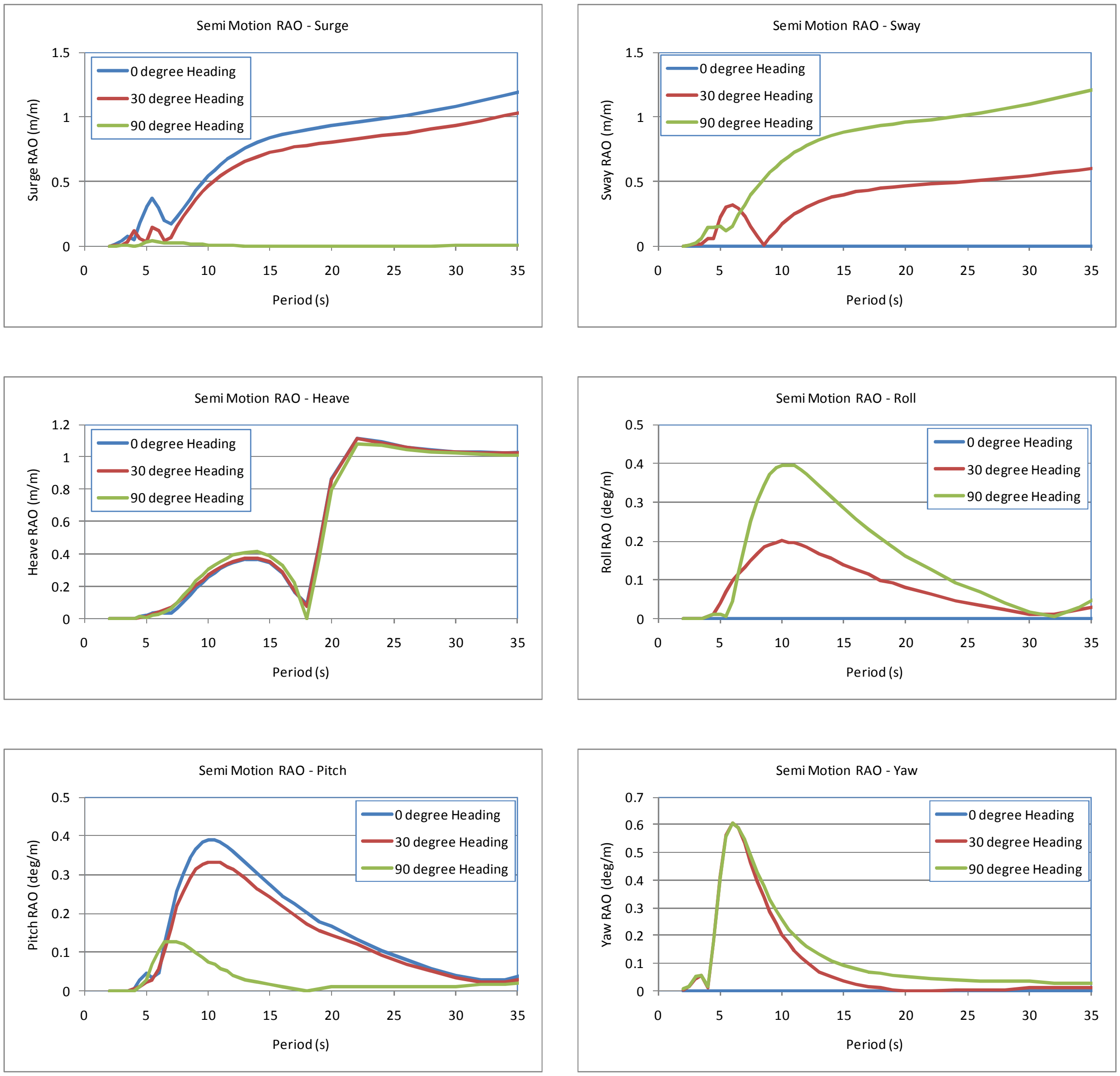



**Figure 3.44 Motion RAOs for the Semi-submersible Floating Support Structure**

## 3.7 TLP Floating Wind Turbine

### 3.7.1 Summary of Model Parameters

The TLP hull and mooring system are defined in Section 3.4.2.1. The site conditions are summarized in Section 3.4.2.3. 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 94 load cases are defined to evaluate the global responses of the TLP FOWT with the consideration of 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.

For the TLP FOWT with the parked turbine subjected to the 100-year or 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 and current heading is always 0 degree, while the wave heading is taken as 30 degrees and 90 degrees, respectively. The definitions of the headings are depicted in Figure 3.45.

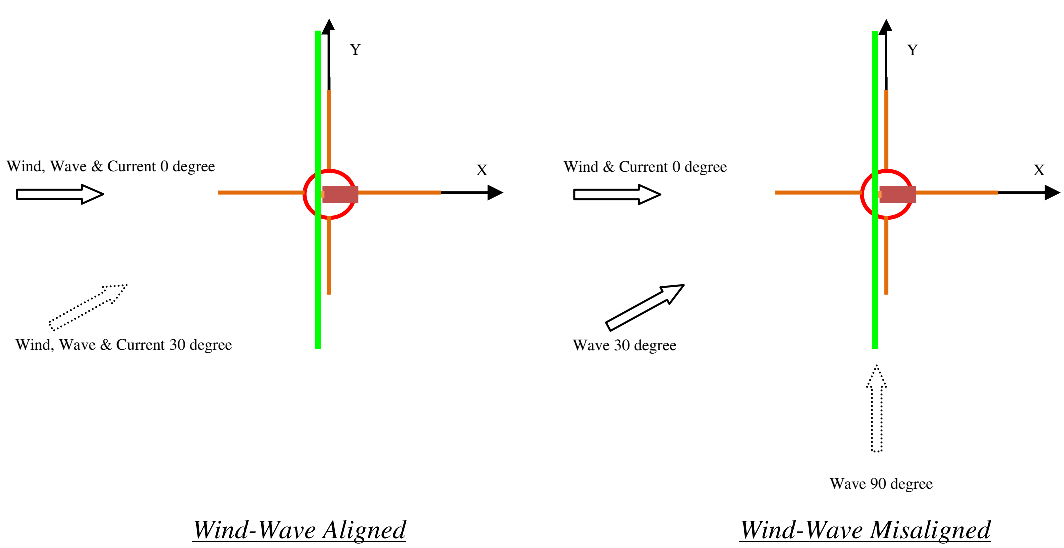



**Figure 3.45 Definition of Wind, Wave and Current Directionality – TLP FOWT**

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 3.46. 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 3.47 (wind turbine not shown). Each tendon is modeled by 20 high-order cable elements.

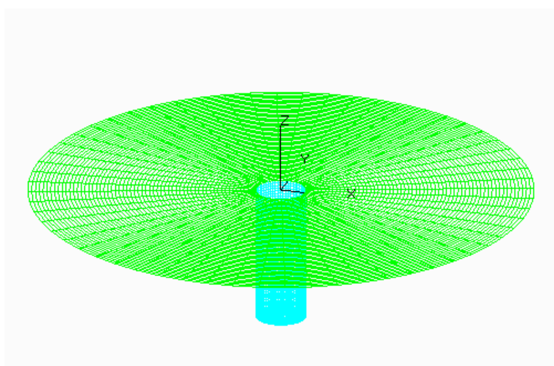



**Figure 3.46 Hydrodynamic Panel Model of the TLP Floating Support Structure**

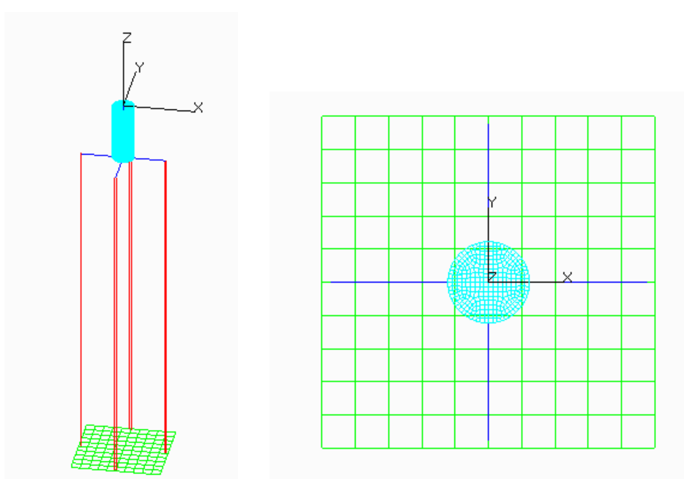



**Figure 3.47 Integrated TLP-Tendon Model**

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* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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 | TLP | GOM | ETM, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 0.13 | 1.61 | 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, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 7.35 | 12.12 | 0.40 | MSL |
| | TLP | WEST | ETM, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 2.01 | 11.52 | 0.60 | MSL |
| | TLP | WEST | ETM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 2.93 | 12.31 | 0.60 | MSL |
| | TLP | WEST | ETM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.16 | 14.13 | 0.60 | MSL |
| | TLP | EAST | ETM, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 0.95 | 6.90 | 0.50 | MSL |
| | TLP | EAST | ETM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.98 | 7.74 | 0.50 | MSL |
| | TLP | EAST | ETM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.79 | 10.33 | 0.50 | MSL |
| Start-up | TLP | GOM | EOG, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 0.13 | 1.61 | 0.40 | MSL |
| | 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 |
| | TLP | WEST | EOG, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 2.01 | 11.52 | 0.60 | MSL |
| | TLP | WEST | EOG, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 2.93 | 12.31 | 0.60 | MSL |
| | TLP | WEST | EOG, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.16 | 14.13 | 0.60 | MSL |
| | TLP | EAST | EOG, $V_{in}$ | 0 | 0 | 0 | 0 | 0 | 2.53 | 3.00 | 0.95 | 6.90 | 0.50 | MSL |
| | TLP | EAST | EOG, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.98 | 7.74 | 0.50 | MSL |
| | TLP | EAST | EOG, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.79 | 10.33 | 0.50 | MSL |

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

| *Turbine Operational Mode* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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) | |
| Emergency shut down | TLP | GOM | NTM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.71 | 5.84 | 0.50 | MSL |
| | TLP | GOM | NTM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 7.35 | 12.12 | 0.50 | MSL |
| | TLP | WEST | NTM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 2.93 | 12.31 | 0.40 | MSL |
| | TLP | WEST | NTM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.16 | 14.13 | 0.40 | MSL |
| | TLP | EAST | NTM, $V_r$ | 0 | 0 | 0 | 0 | 0 | 9.17 | 11.40 | 1.98 | 7.74 | 0.60 | MSL |
| | TLP | EAST | NTM, $V_{out}$ | 0 | 0 | 0 | 0 | 0 | 19.02 | 25.00 | 5.79 | 10.33 | 0.60 | MSL |
| Parked (Idling) | TLP | GOM | 100yr peak wind | 0 | 0 | 0 | 0 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wave | 0 | 0 | 0 | 0 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wind | 30 | 30 | 30 | 0 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wave | 30 | 30 | 30 | 0 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wind | 0 | 30 | 0 | 30 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wave | 0 | 30 | 0 | 30 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wind | 0 | 90 | 0 | 90 | 8 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wave | 0 | 90 | 0 | 90 | 8 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wind | 0 | 0 | 0 | 0 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wave | 0 | 0 | 0 | 0 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wind | 0 | 0 | 0 | 0 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | HSWL |
| | TLP | GOM | 100yr peak wave | 0 | 0 | 0 | 0 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | HSWL |
| | TLP | GOM | 100yr peak wind | 0 | 0 | 0 | 0 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | LSWL |
| | TLP | GOM | 100yr peak wave | 0 | 0 | 0 | 0 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | LSWL |

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

| *Turbine Operational Mode* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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) | TLP | GOM | 100yr peak wind | 30 | 30 | 30 | 0 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wave | 30 | 30 | 30 | 0 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wind | 0 | 30 | 0 | 30 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wave | 0 | 30 | 0 | 30 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wind | 0 | 90 | 0 | 90 | 30 | 48.00 | 71.14 | 14.73 | 15.01 | 1.80 | MSL |
| | TLP | GOM | 100yr peak wave | 0 | 90 | 0 | 90 | 30 | 45.60 | 67.01 | 15.50 | 15.40 | 1.80 | MSL |
| | TLP | WEST | 100yr storm | 0 | 0 | 0 | 0 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | TLP | WEST | 100yr storm | 30 | 30 | 30 | 0 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | TLP | WEST | 100yr storm | 0 | 30 | 0 | 30 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | TLP | WEST | 100yr storm | 0 | 90 | 0 | 90 | 8 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | TLP | WEST | 100yr storm | 0 | 0 | 0 | 0 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | TLP | WEST | 100yr storm | 30 | 30 | 30 | 0 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | TLP | WEST | 100yr storm | 0 | 0 | 0 | 0 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | HSWL |
| | TLP | WEST | 100yr storm | 0 | 0 | 0 | 0 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | LSWL |
| | TLP | WEST | 100yr storm | 0 | 30 | 0 | 30 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | TLP | WEST | 100yr storm | 0 | 90 | 0 | 90 | 30 | 27.48 | 37.58 | 13.43 | 20.58 | 0.80 | MSL |
| | TLP | EAST | 100yr storm | 0 | 0 | 0 | 0 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | TLP | EAST | 100yr storm | 30 | 30 | 30 | 0 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | TLP | EAST | 100yr storm | 0 | 30 | 0 | 30 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | TLP | EAST | 100yr storm | 0 | 90 | 0 | 90 | 8 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |

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

| *Turbine Operational Mode* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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) | TLP | EAST | 100yr storm | 0 | 0 | 0 | 0 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | TLP | EAST | 100yr storm | 30 | 30 | 30 | 0 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | TLP | EAST | 100yr storm | 0 | 0 | 0 | 0 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | HSWL |
| | TLP | EAST | 100yr storm | 0 | 0 | 0 | 0 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | LSWL |
| | TLP | EAST | 100yr storm | 0 | 30 | 0 | 30 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| | TLP | EAST | 100yr storm | 0 | 90 | 0 | 90 | 30 | 27.98 | 38.35 | 11.36 | 13.59 | 0.58 | MSL |
| Parked (Idling) | 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 wave | 0 | 0 | 0 | 0 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 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 wave | 30 | 30 | 30 | 0 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | TLP | GOM | 50yr peak wind | 0 | 30 | 0 | 30 | 8 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | TLP | GOM | 50yr peak wave | 0 | 30 | 0 | 30 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | TLP | GOM | 50yr peak wind | 0 | 90 | 0 | 90 | 8 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | TLP | GOM | 50yr peak wave | 0 | 90 | 0 | 90 | 8 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | 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 wave | 0 | 0 | 0 | 0 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 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 wave | 0 | 0 | 0 | 0 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 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 wave | 0 | 0 | 0 | 0 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | LSWL |

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

| *Turbine Operational Mode* | *Floater Type* | *Location* | *Wind Condition* | *Directions* | | | *Wave & Wind Misalignment* | *Yaw Error* | *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) | 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 wave | 30 | 30 | 30 | 0 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | TLP | GOM | 50yr peak wind | 0 | 30 | 0 | 30 | 30 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | TLP | GOM | 50yr peak wave | 0 | 30 | 0 | 30 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | TLP | GOM | 50yr peak wind | 0 | 90 | 0 | 90 | 30 | 44.40 | 64.96 | 13.87 | 14.62 | 1.67 | MSL |
| | TLP | GOM | 50yr peak wave | 0 | 90 | 0 | 90 | 30 | 42.18 | 61.21 | 14.60 | 15.00 | 1.67 | MSL |
| | TLP | WEST | 50yr storm | 0 | 0 | 0 | 0 | 8 | 26.27 | 35.74 | 12.62 | 19.96 | 0.80 | MSL |
| | TLP | WEST | 50yr storm | 0 | 0 | 0 | 0 | 30 | 26.27 | 35.74 | 12.62 | 19.96 | 0.80 | MSL |
| | TLP | EAST | 50yr storm | 0 | 0 | 0 | 0 | 8 | 26.70 | 36.39 | 10.66 | 13.21 | 0.57 | MSL |
| | TLP | EAST | 50yr storm | 0 | 0 | 0 | 0 | 30 | 26.70 | 36.39 | 10.66 | 13.21 | 0.57 | MSL |
| Parked (Idling) | TLP | GOM | 10yr hurricane | 0 | 0 | 0 | 0 | 20 | 33.00 | 46.20 | 9.90 | 13.00 | 1.32 | MSL |
| | TLP | GOM | 10yr hurricane | 0 | 0 | 0 | 0 | 30 | 33.00 | 46.20 | 9.90 | 13.00 | 1.32 | MSL |
| | TLP | WEST | 10yr storm | 0 | 0 | 0 | 0 | 20 | 23.49 | 31.55 | 10.75 | 18.53 | 0.70 | MSL |
| | TLP | WEST | 10yr storm | 0 | 0 | 0 | 0 | 30 | 23.49 | 31.55 | 10.75 | 18.53 | 0.70 | MSL |
| | TLP | EAST | 10yr storm | 0 | 0 | 0 | 0 | 20 | 23.71 | 31.88 | 9.04 | 12.29 | 0.54 | MSL |
| | TLP | EAST | 10yr storm | 0 | 0 | 0 | 0 | 30 | 23.71 | 31.88 | 9.04 | 12.29 | 0.54 | MSL |

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

*Notes:*

1. API wind models are used for the 10-yr, 50-yr and 100-yr condition for turbine parked.
2. IEC wind models are used for power production, start-up and emergency shut down.
3. For Start-up, NWH (normal wave height) wave model is used.
4. GOM: GOM Central Region
5. WEST: US West Coast
6. EAST: US Northeast Coast
7. ETM: Extreme Turbulence Model
8. EOG: Extreme Operating Gust
9. NTM: Normal Turbulence Model
10. $V_{in}$ is the cut-in wind speed at hub height.
11. $V_r$ is the rated wind speed at hub height.
12. $V_{out}$ is the cut-out wind speed at hub height.
13. $H_s$ and $T_p$ are the significant wave height and the peak period of wave spectrum
14. Current Speed are given at water surface
15. MSL: Mean Sea Level (Mean Still Water Level)
16. HSWL: Highest Still Water Level
17. 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 3.48.

**Table 3.23 Natural Periods 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 |

### 3.7.3 TLP Case Study Results

Global responses, including the TLP hull motions, tower top acceleration, tower base shear and overturning moment, and maximum and minimum line top tensions at fairlead, are obtained for each load case specified in Section 3.5.1. In addition, for the power production load cases (DLC 1.3), the maximum generator power output, generator torque, rotor speed, generator speed, rotor thrust, rotor torque and blade pitch are also obtained. For start-up (DLC 3.2), the maximum generator power output and generator torque are derived.

All these TLP case study results are compiled for the parametric study presented in Section 3.8.

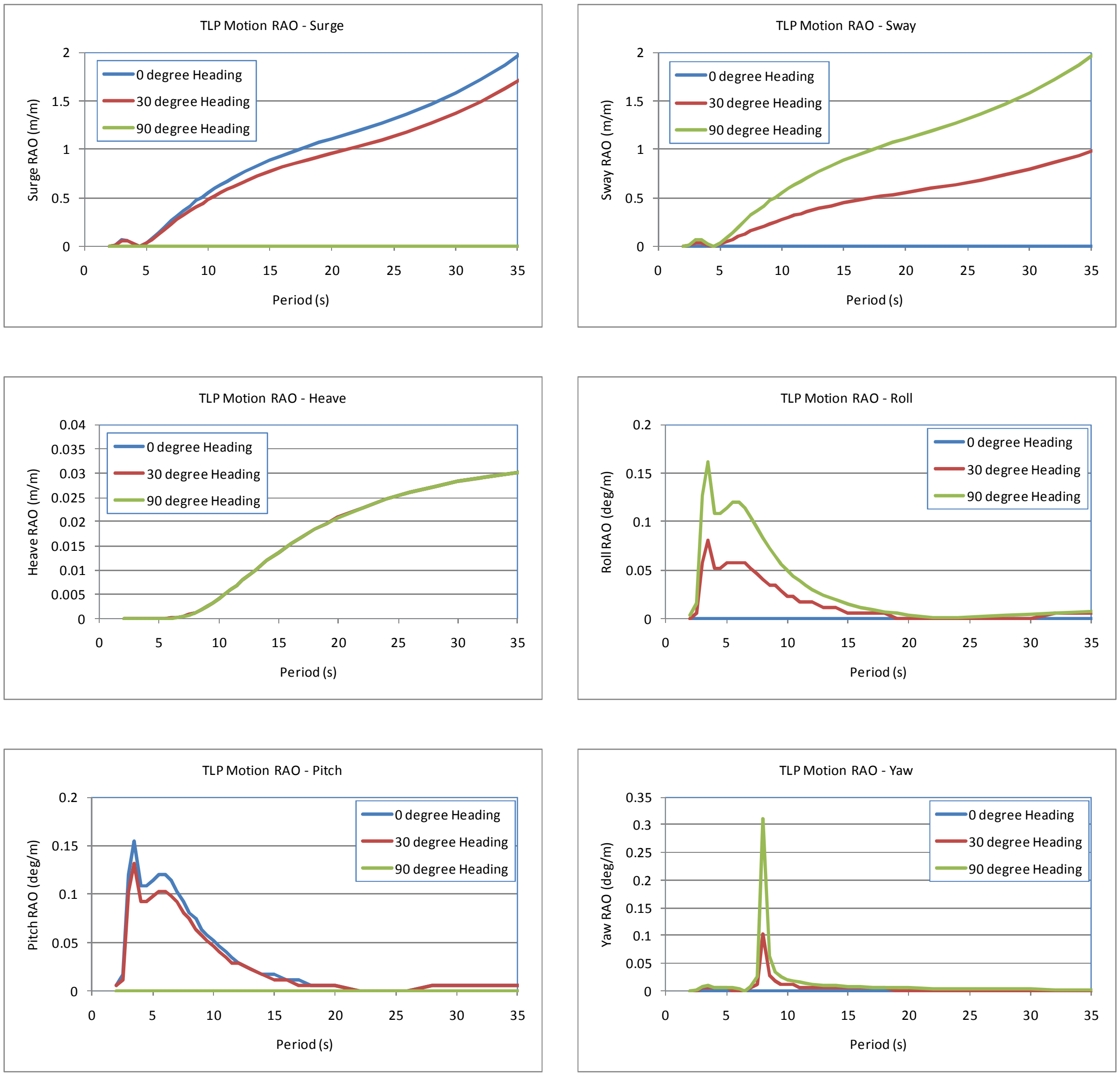



**Figure 3.48 Motion RAOs for the TLP Floating Support Structure**

## 3.8 Parametric Studies of Case Study Results

Parametric studies are carried out to assess the correlations between the global responses of the FOWTs and the main design parameters that are considered critical to the development of rational design criteria for FOWTs. The following parameters are included in the parametric study:

- Return period of extreme design environmental conditions
- Different turbine normal design conditions
- Nacelle yaw misalignment in extreme storms
- Misalignment between wind and wave directions
- Design water level for the TLP FOWT
- Type of floating support structures
- Site variations

### 3.8.1 Return Period of Environmental Conditions

The return period of design environmental conditions is often dependent upon the intended safety level, which is in turn determined by the anticipated exposure level of an offshore structure. Floating offshore oil and gas production installations are typically considered having the L1 exposure level (see ISO 19904-1 and API RP 2T) and 100-year return environmental conditions are required to be considered in the design. For bottom-founded offshore wind turbines, the industry consensus, as represented by IEC 61400-3 (2009), is that they can in general be designed to attain an exposure level equivalent to the medium (L2) exposure level of offshore oil and gas platforms. The design load cases specified in IEC 61400-3 (2009) for bottom-founded offshore wind turbines require the design environmental conditions with a return period of 50 years. Recent study by Yu et al. (2011a, 2011b) explored the applicability of IEC 61400-3 (2009) to the hurricane-prone regions on the US OCS and indicated that the return period of the design environmental conditions must be determined from the perspective of an overall design approach (i.e. “a design recipe”) rather than the return period of design environmental conditions alone. The present case studies are intended to provide a means of evaluating the effect of the return period of the design environmental conditions, in conjunction with other critical design parameters, on the global responses and the safety margin of the floating support structures and the stationkeeping systems of FOWTs.

Figure 3.49 depicts the ratio of each FOWT global response under the 100-year return environmental conditions to that calculated based on the 50-year return environmental conditions. The value of the ratio is calculated using the case study results for the Spar, Semi-submersible and TLP FOWT conceptual designs. The effect of normal and abnormal turbine operating conditions, which are represented by the yaw misalignment angle (Yaw Error) of 8 degrees and 30 degrees, respectively, is taken into account. The effect of site conditions in the US West Coast (WEST) and Northeast Coast (EAST) as well as the GOM Central Region (GOM) (see Section 3.3.2) are also considered.

The following observations are made from Figure 3.49:

- The ratios for the hull offset and heel are mostly between 1.05 and 1.2. The hull offset appears less affected by the yaw error than the hull heel motion. The effect of yaw error on the offset and heel is correlated to the severity of the storm condition. For the GoM Central Region where the storm condition is the strongest, the influence of yaw error is the most significant.

- The hull yaw motion is very sensitive to the increase of return period from 50 years to 100 years. The ratio of the 100-year to 50-year return yaw motion is mostly between 1.1 and 1.4, depending on the type of floating support structures. The hull yaw motion may be reduced with the increase of yaw error because of the additional aerodynamic damping introduced by the large yaw error. The Spar FOWT shows a high volatility in the ratio of the 100-year to 50-year return yaw motion, in part because its mooring system has relatively low yaw stiffness and damping.

- The ratios for the tower loads, including the top acceleration, base shear and overturning moment are approximately between 1.05 and 1.2, except for the "TLP-GOM" with the 30 degree yaw error where the ratio of the 100-year to 50-year return value is about 1.25. It appears the high frequency components (over 1 Hz) in the GoM 100-year return wind condition excite the large tower top acceleration in the "TLP-GOM" case. The higher variation in the tower top acceleration contributes to the relatively large ratio of the 100-year to 50-year return tower based loads.

- The ratio of the 100-year to 50-year return maximum line top tension appears insensitive to the variation of the yaw error. This observation is consistent with the one for the hull offset, as the maximum line top tension is mostly determined by the maximum hull offset. A similar observation can also be made to the minimum line top tensions, except for the "TLP-GOM" with the 30 degree yaw error.

- The ratios for the global responses in the GOM are mostly less favorable (i.e. lower for the minimum line top tension and higher for all the other global responses) than those in the WEST and EAST primarily due to the higher variation of environmental conditions in the GOM that corresponds to a steeper slope of the severity of environmental conditions versus the return period.

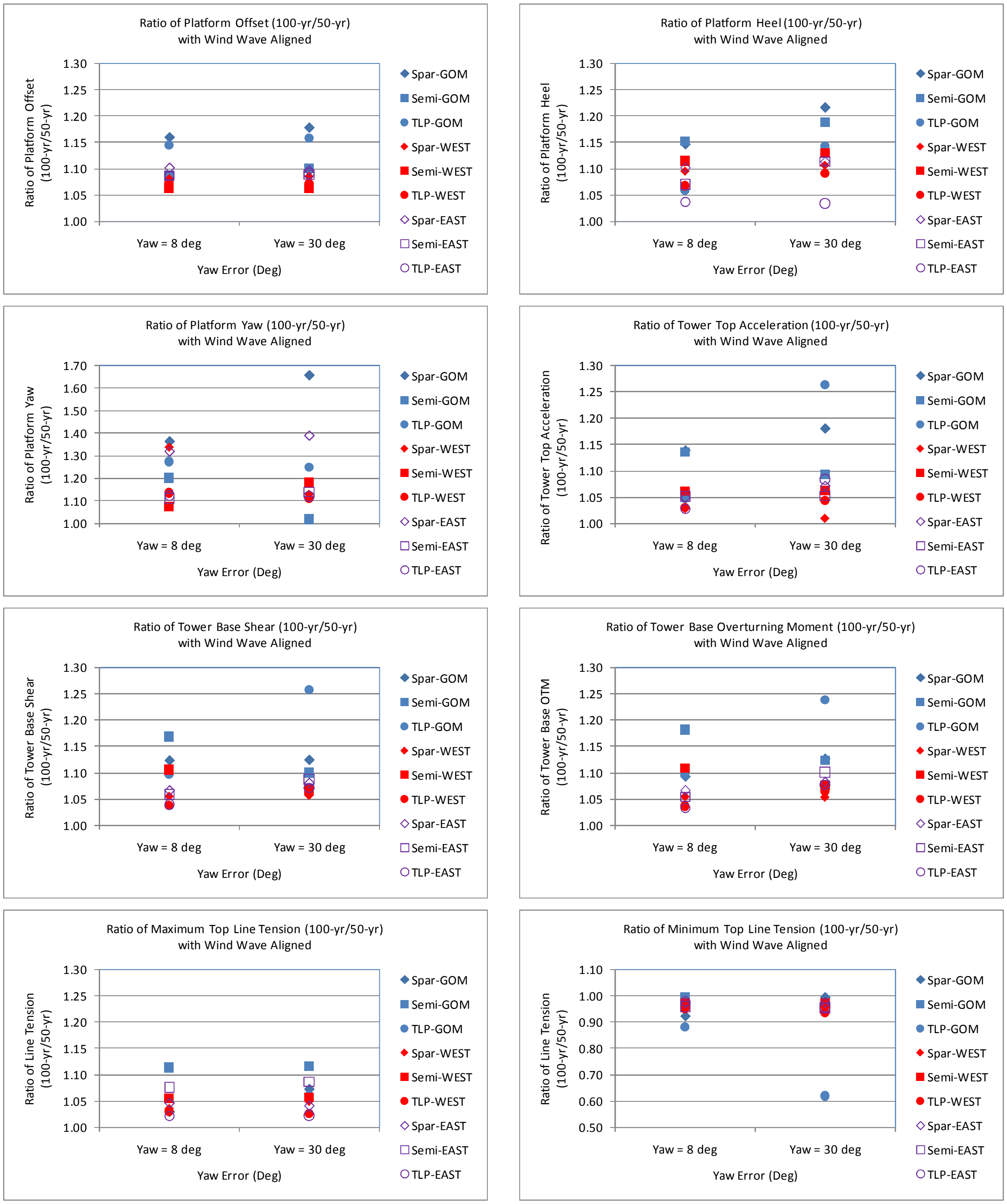



**Figure 3.49 Ratio of the 100-yr Return to 50-yr Return Global Responses**

### 3.8.2 Normal Design Conditions

The normal load cases considered in the case studies include the

- power production (DLC 1.3),
- start-up (DLC 3.2),
- emergency shut down (DLC 5.1),
- the parked condition subjected to 10-year return environmental conditions with a 20 degree yaw error, and
- the parked condition subjected to 50-year and 100-year return environmental conditions with an 8 degree yaw error.

The global responses under the power production (DLC 1.3), start-up (DLC 3.2), and emergency shut down (DLC 5.1) are compared in Figure 3.50 through Figure 3.52 for the three FOWT conceptual designs. The following observations can be made:

- The global responses under the power production (DLC 1.3) condition are mostly higher than those under the start-up (DLC 3.2) and emergency shut down (DLC 5.1) conditions.
- Due to transient effects, the start-up (DLC 3.2) and emergency shut down (DLC 5.1) conditions can sometimes induce higher motions and loads of the floating support structures than the power production (DLC 1.3). The differences, however, are not significant.
- In many cases, the rated wind speed, rather than the cut-out wind speed, is associated with the most significant global responses. Both of them should be considered in the global performance analysis.

In Figure 3.53 through Figure 3.55, the global responses under the power production (DLC 1.3) are further compared to those under the parked condition subjected to 10-year return environmental conditions with a 20 degree yaw error and 50-year and 100-year return environmental conditions with an 8 degree yaw error. It is found that

- Strong storm conditions in the GOM can significantly amplify the sensitivity of the global responses to the increase in wind speed.

- In the GOM, the global responses under the parked condition subjected to the 10-year, 50-year and 100-year return environmental conditions are more onerous that those under the power production.

- In WEST and EAST, the global responses under the parked condition subjected to 10-year, 50-yr and 100-yr return conditions are in general less favorable than those under the power production condition. However the differences are less significant than those observed in the GOM. On certain occasions, the power production condition can generate larger responses than the storm conditions, depending on the significance of aerodynamic loading.

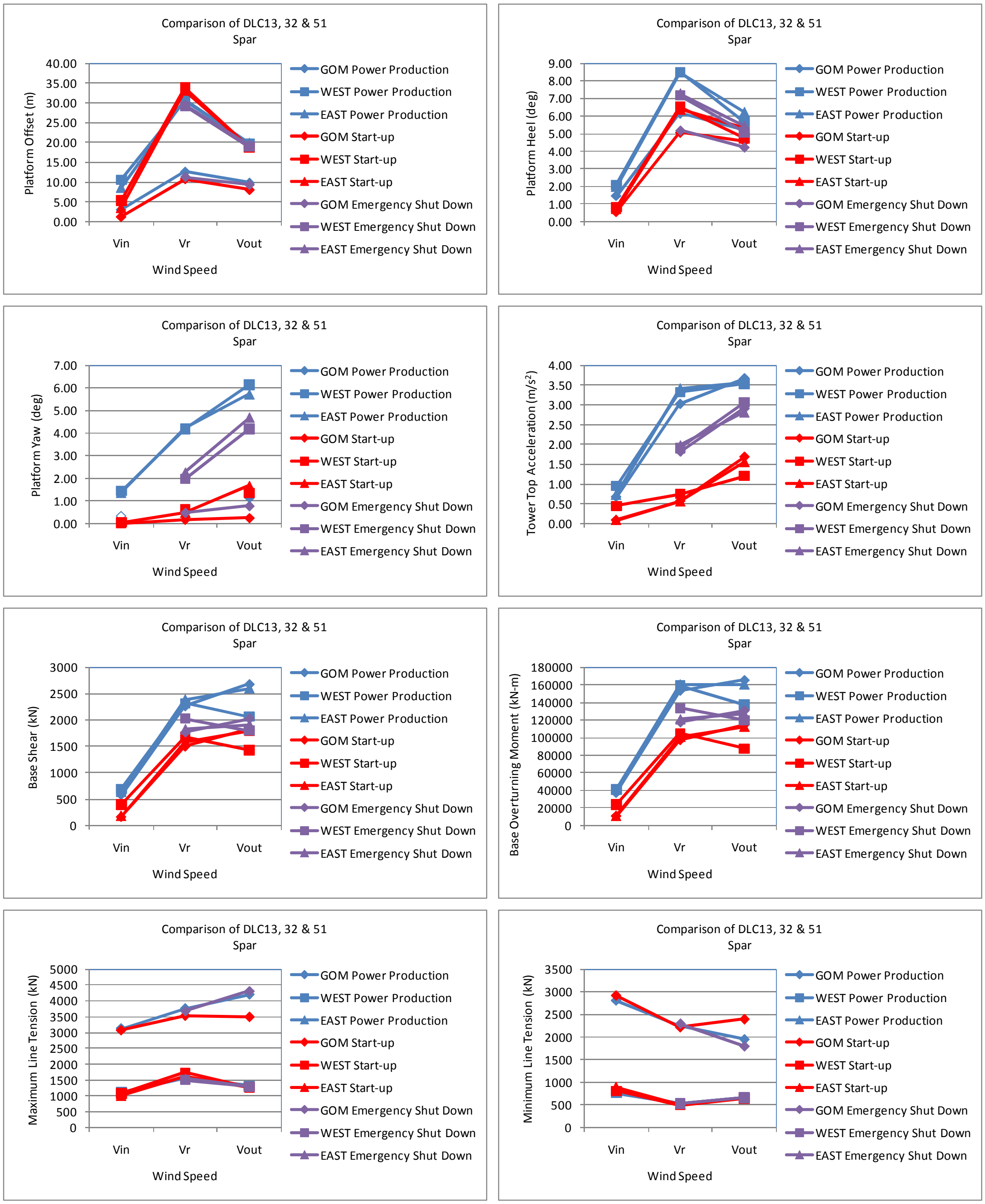



**Figure 3.50 Comparison of Power Production, Start-up and Emergency Shut Down of the Spar FOWT**

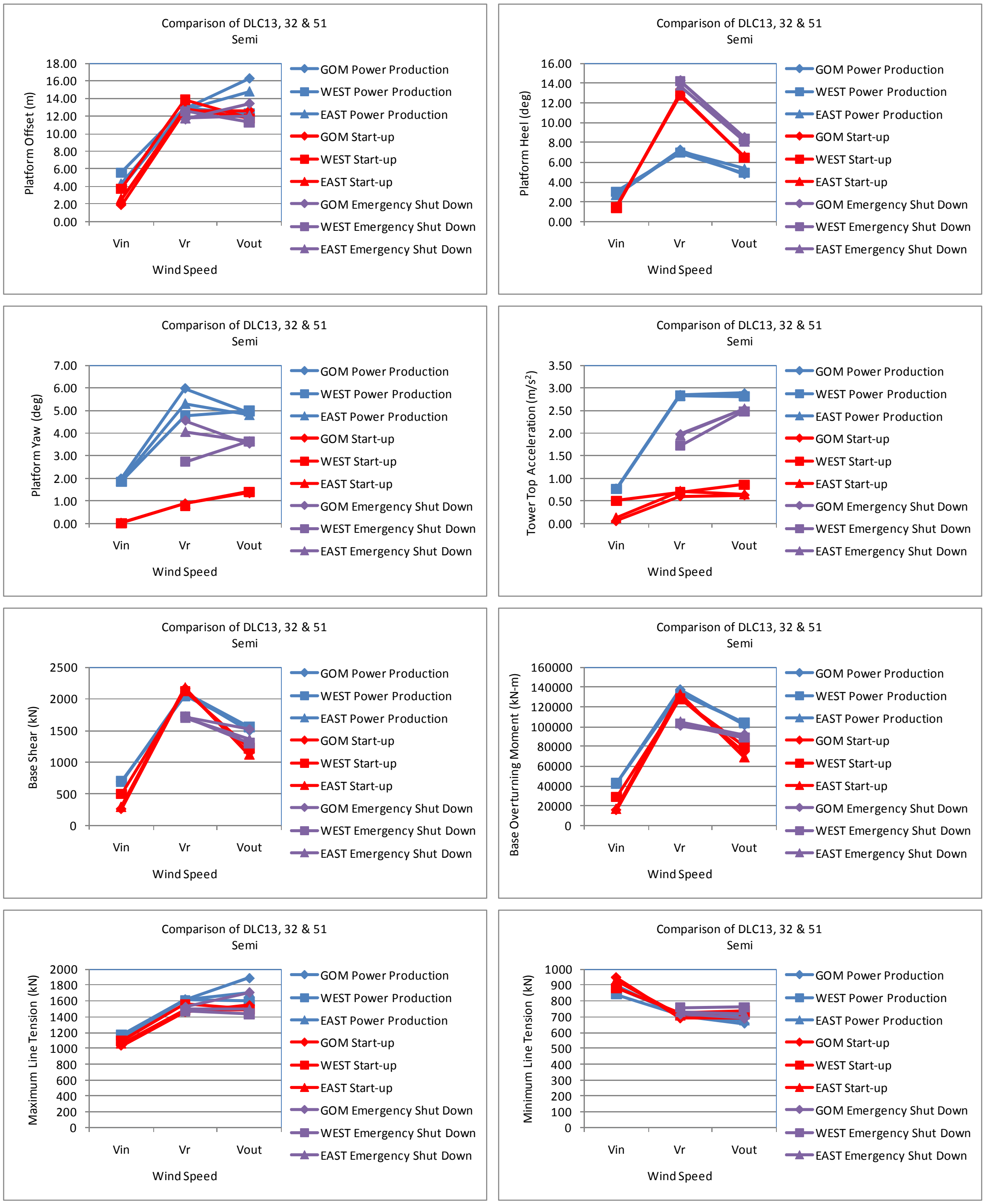



**Figure 3.51 Comparison of Power Production, Start-up and Emergency Shut Down of the Semi-submersible FOWT**

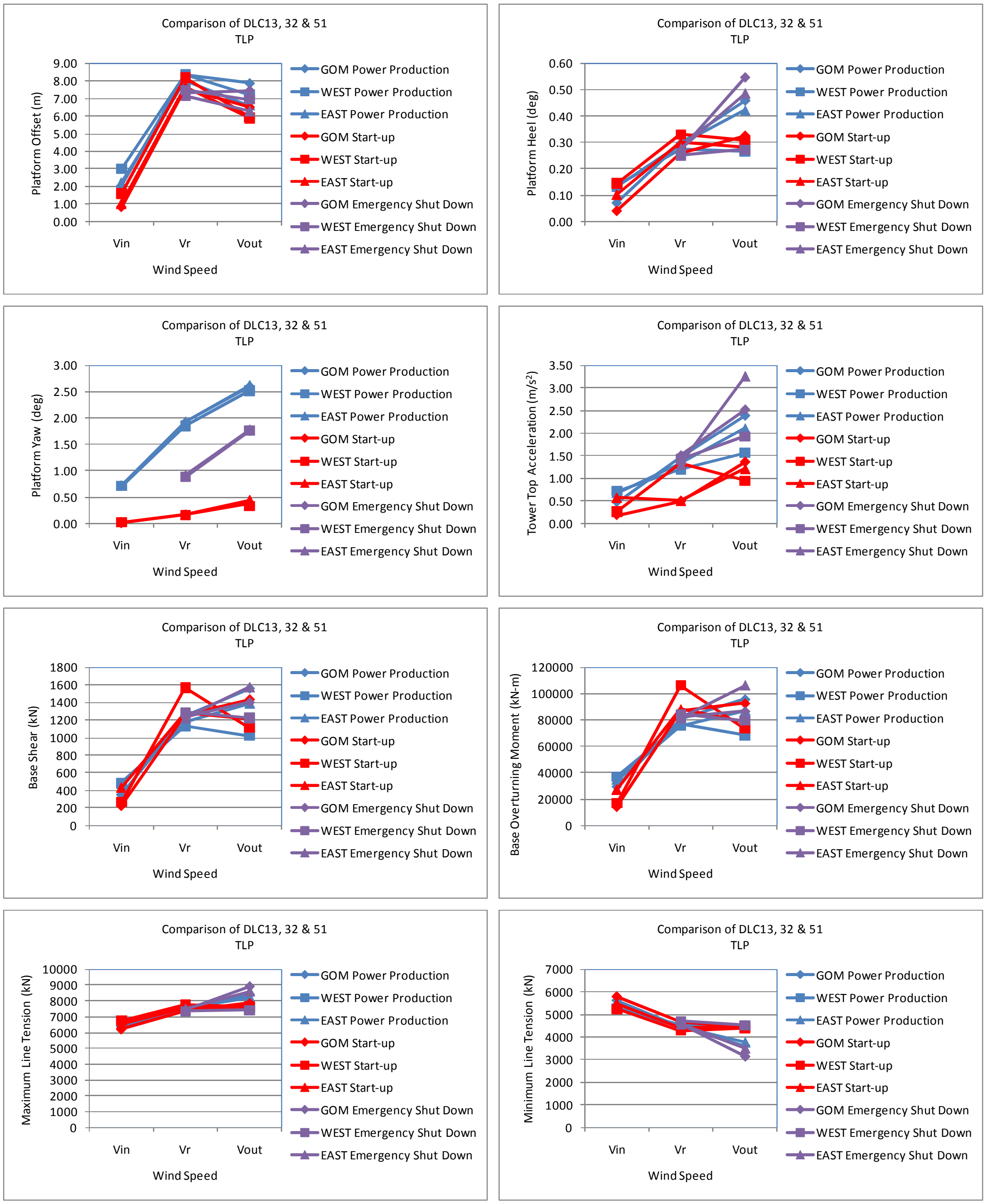



**Figure 3.52 Comparison of Power Production, Start-up and Emergency Shut Down of the TLP FOWT**

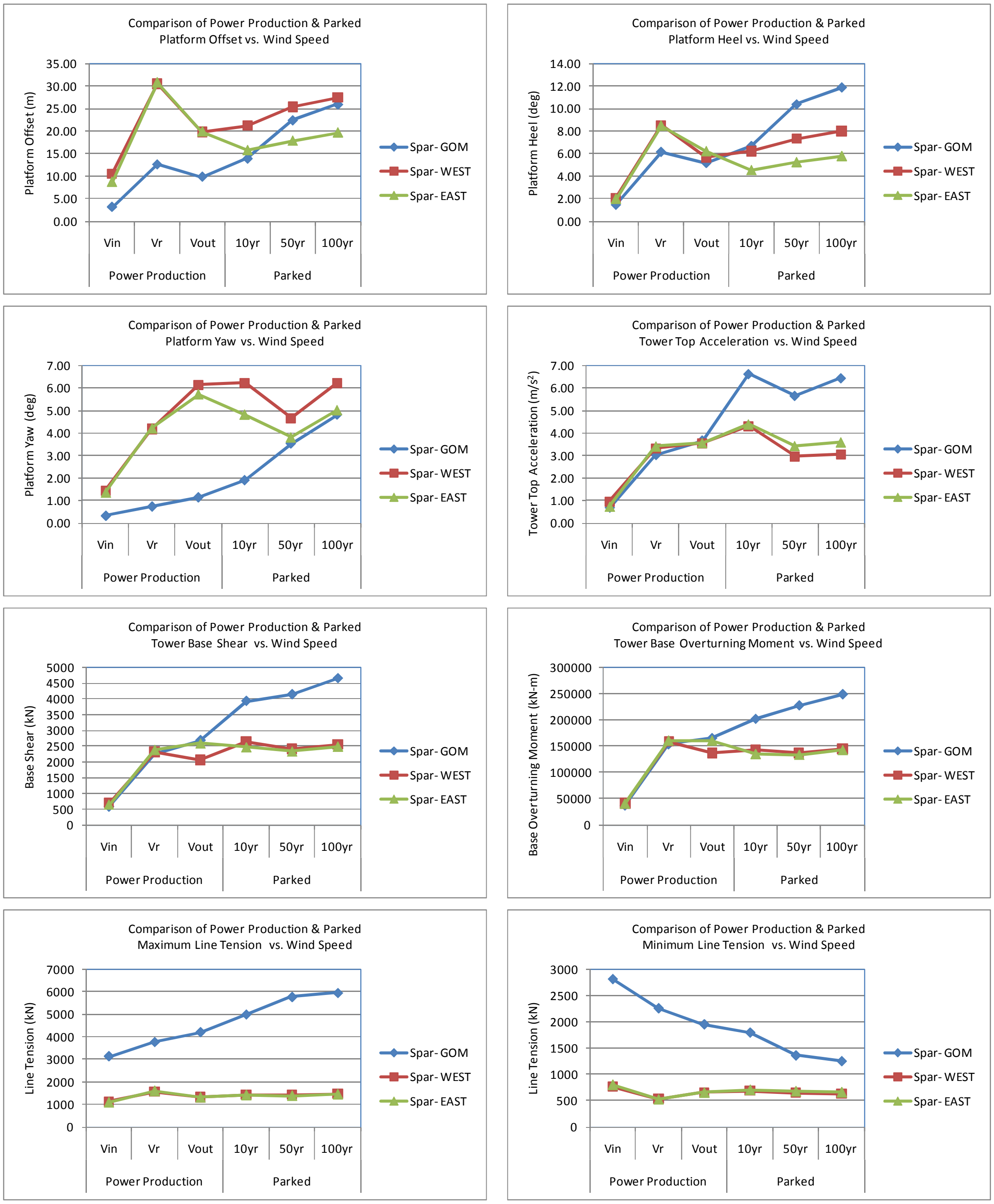



**Figure 3.53 Comparison of Power Production and Parked Condition of the Spar FOWT**

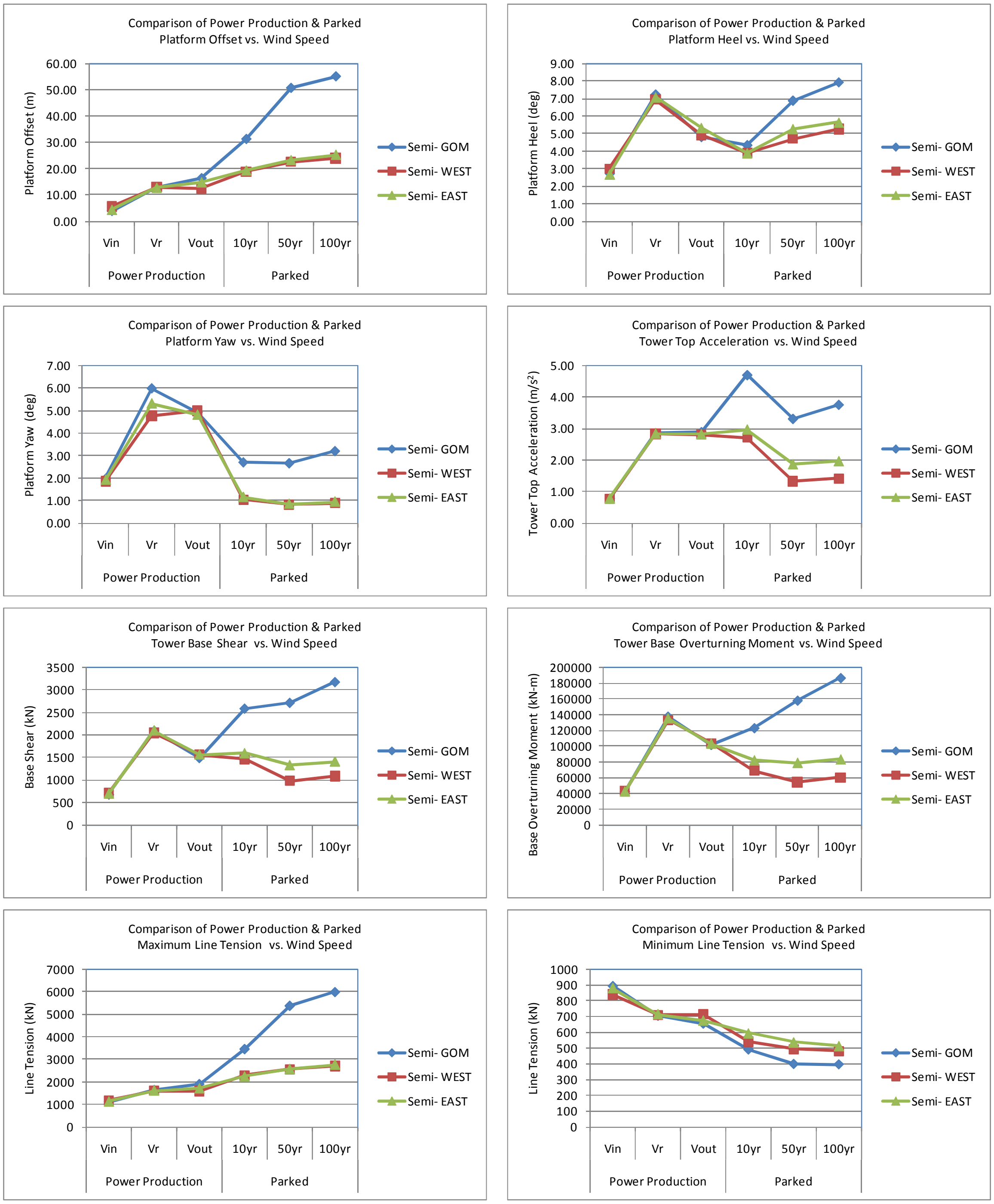



**Figure 3.54 Comparison of Power Production and Parked Condition of the Semi-submersible FOWT**

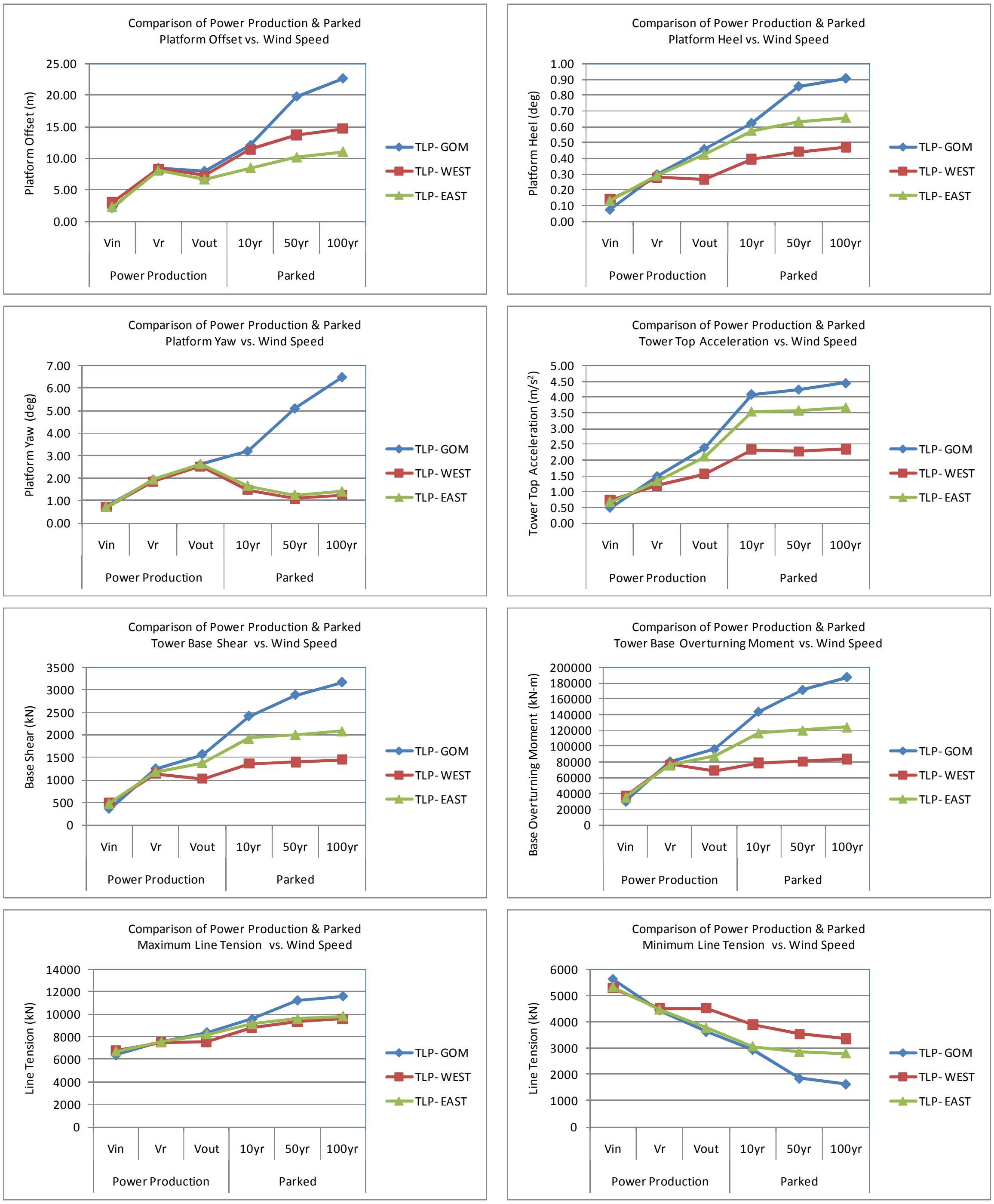



**Figure 3.55 Comparison of Power Production and Parked Condition of the TLP FOWT**

### 3.8.3 Nacelle Yaw Misalignment in Extreme Storms

The abnormal load cases considered in the case studies refer to the turbine in the parked condition with a 30 degree yaw error and the FOWT subjected to 50-year or 100-year environmental conditions. In this subsection, the global responses under the abnormal load cases with a yaw error of 30 degrees are compared to those under the normal load cases, where the yaw error is taken as 8 degrees in accordance with IEC 61400-3 (2009).

Figure 3.56 through Figure 3.63 illustrate the sensitivity of global response to the change of nacelle yaw misalignment angle when the FOWT is subjected to 50-year and 100-year return environmental conditions. It can be found that

- In general, the 30 degree yaw misalignment (i.e. the abnormal load case) results in higher responses than the 8 degree yaw misalignment (i.e. the normal load case).
- The hull offset and the maximum and minimum line top tensions are insensitive to the nacelle yaw misalignment. They are mostly governed by the hydrodynamic loads rather than the aerodynamic loads.
- Significant increase in the tower responses, including the tower top acceleration and the tower base shear and bending moment, are observed when changing the nacelle yaw misalignment angle from 8 degrees to 30 degrees.
- The yaw and heel motions of the Spar FOWT are also sensitive to the increase in the nacelle yaw misalignment angle, mainly because the Spar FOWT has relatively lower yaw stiffness and damping while the large nacelle yaw misalignment can generate very high yawing moment.

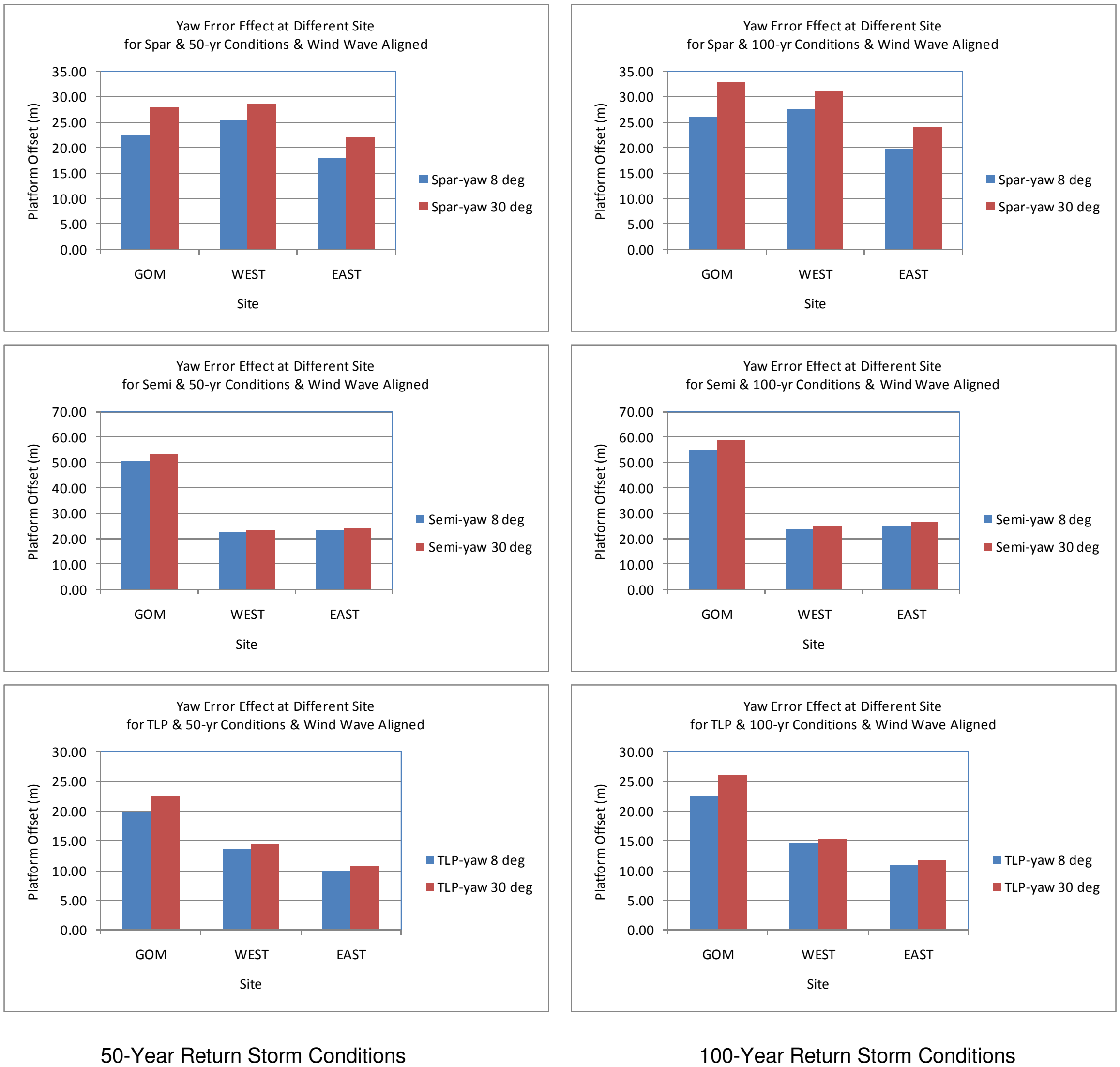
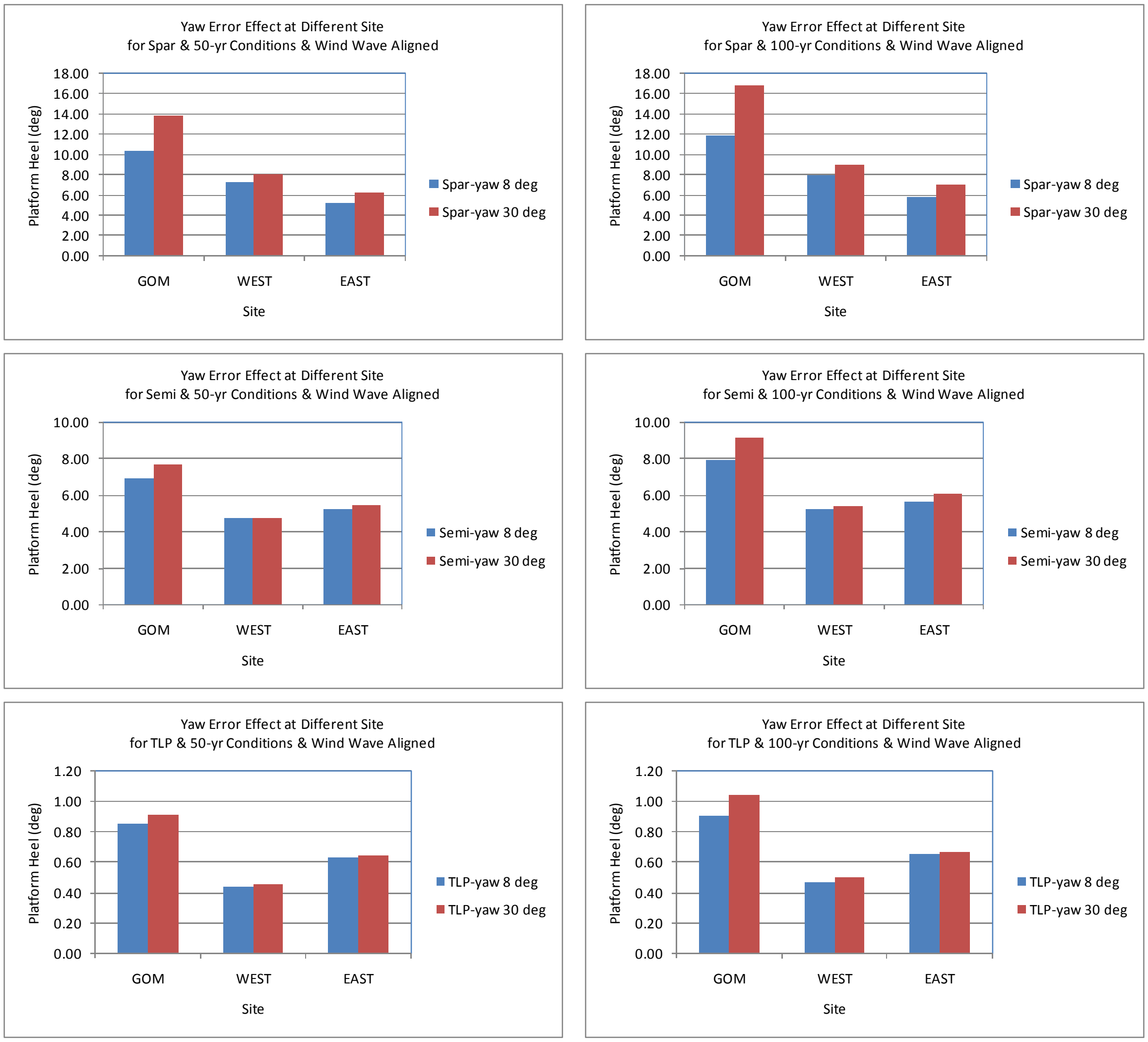
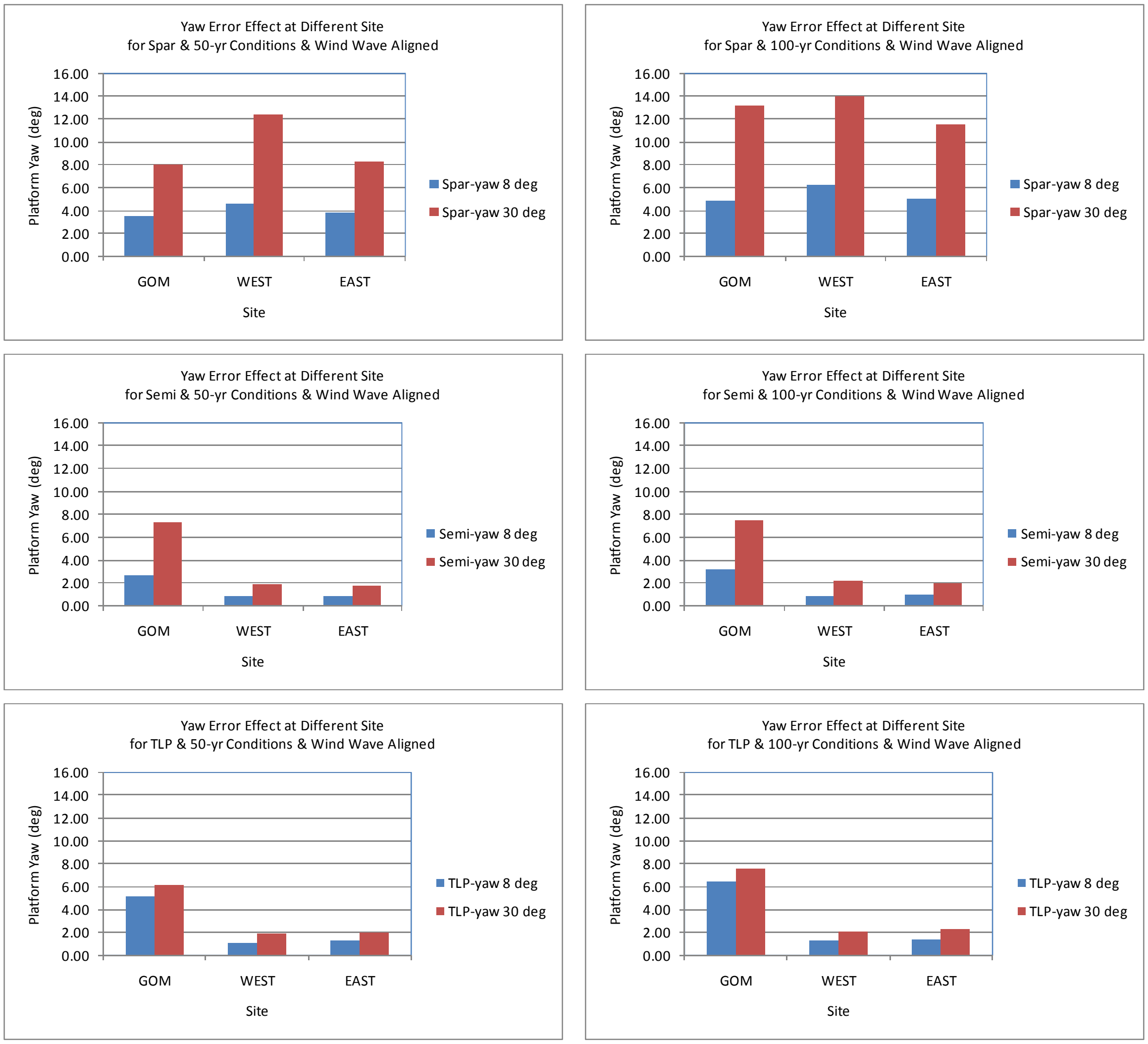



**Figure 3.56 Platform Offset (Normal vs. Abnormal) under the Storm Conditions**



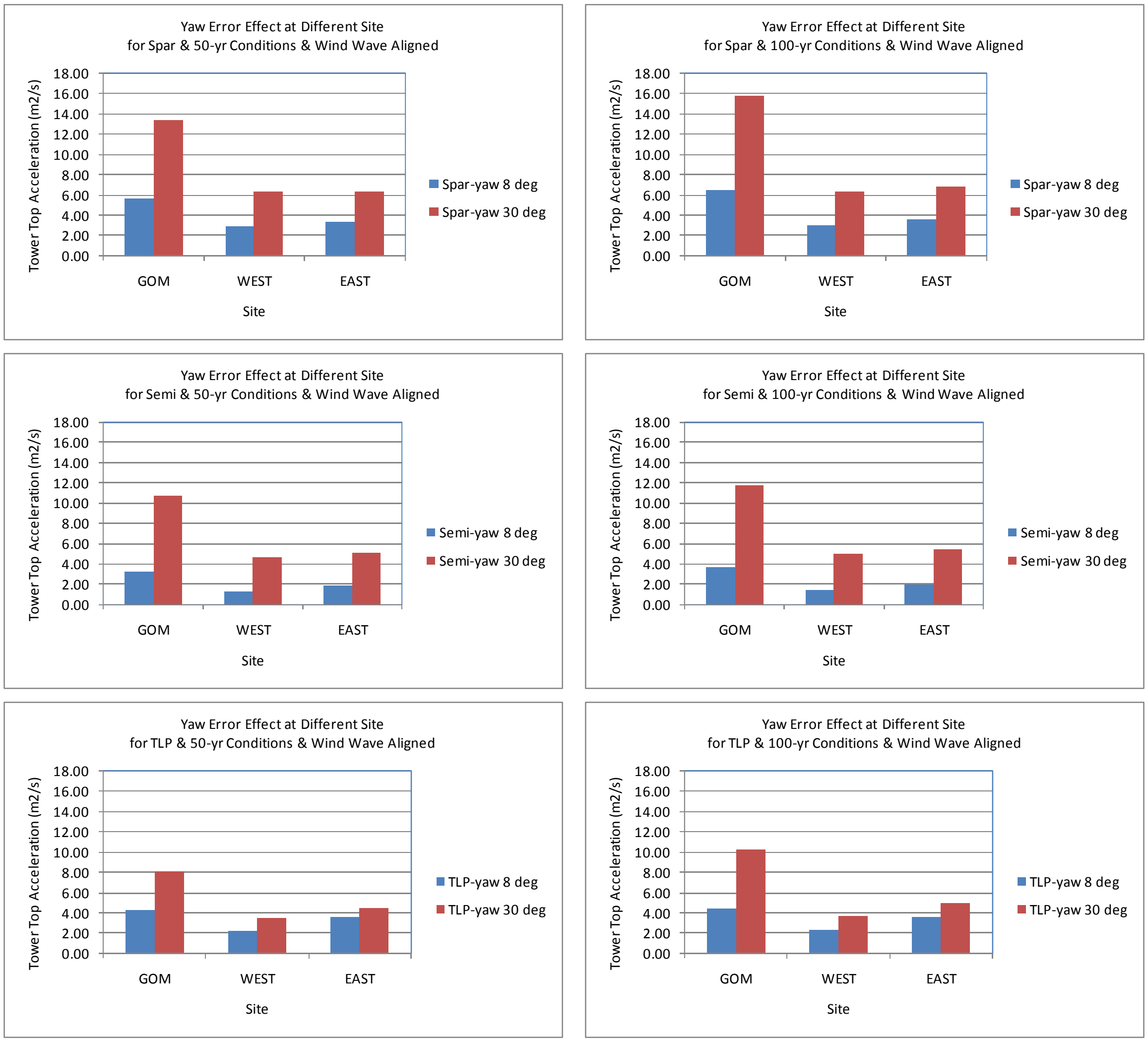

50-Year Return Storm Conditions 100-Year Return Storm Conditions

**Figure 3.57 Platform Heel (Normal vs. Abnormal) under the Storm Conditions**



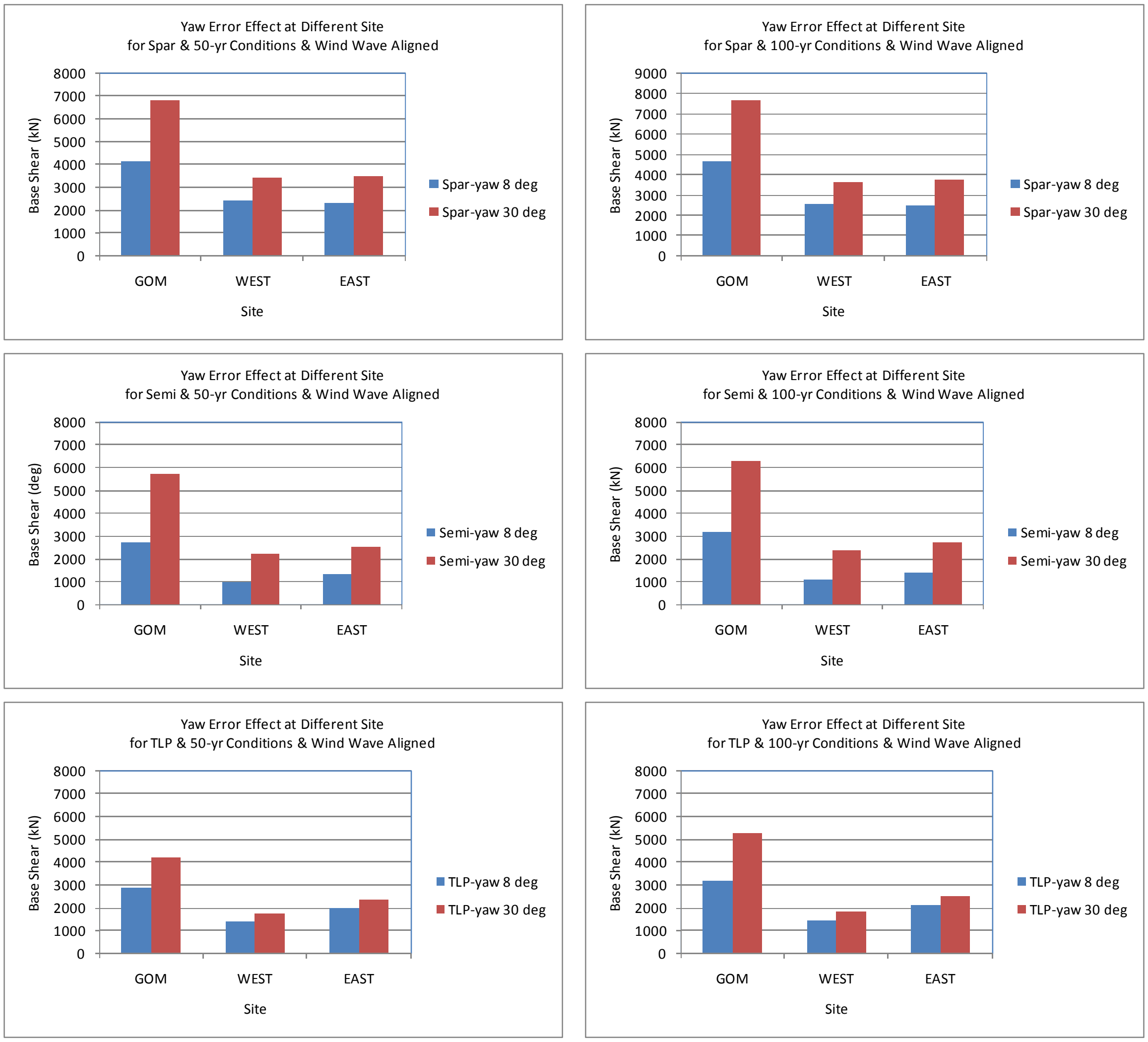

50-Year Return Storm Conditions 100-Year Return Storm Conditions

**Figure 3.58 Platform Yaw (Normal vs. Abnormal) under the Storm Conditions**



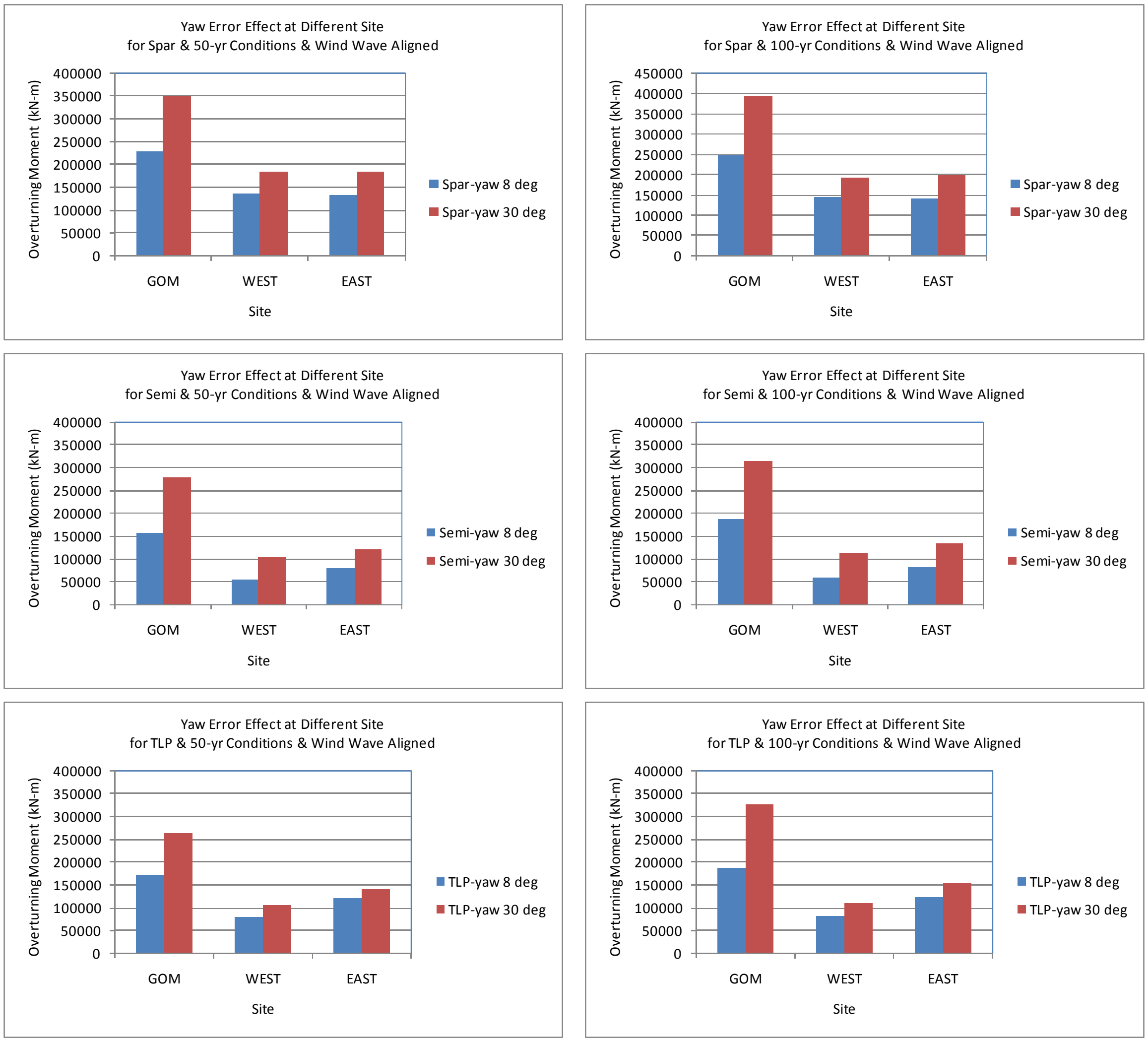

50-Year Return Storm Conditions 100-Year Return Storm Conditions

**Figure 3.59 Tower Top Acceleration (Normal vs. Abnormal) under the Storm Conditions**



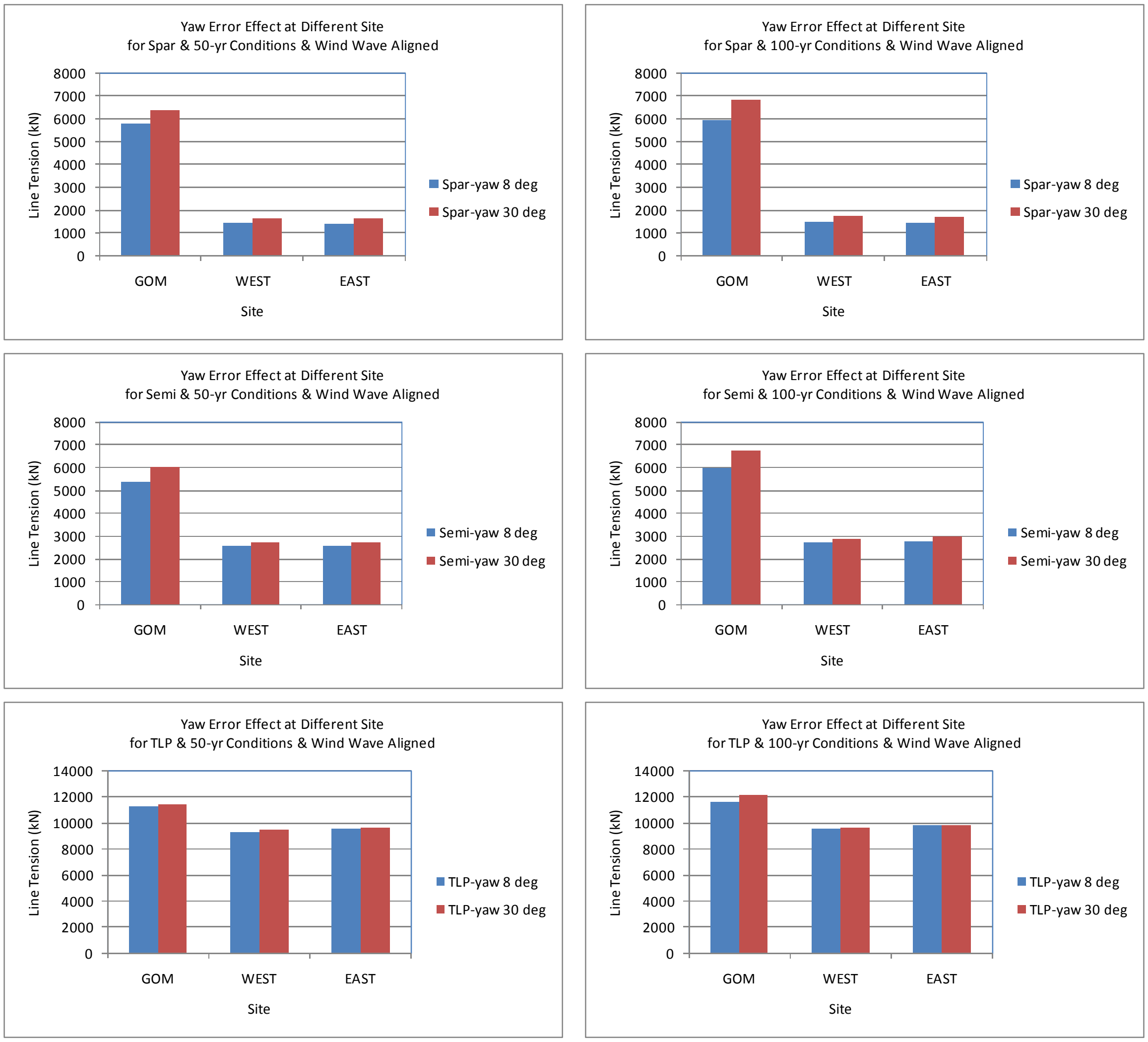

50-Year Return Storm Conditions 100-Year Return Storm Conditions

**Figure 3.60 Tower Base Shear (Normal vs. Abnormal) under the Storm Conditions**




50-Year Return Storm Conditions 100-Year Return Storm Conditions

**Figure 3.61 Tower Base Overturning Moment (Normal vs. Abnormal) under the Storm Conditions**




50-Year Return Storm Conditions 100-Year Return Storm Conditions

**Figure 3.62 Maximum Line Top Tension (Normal vs. Abnormal) under the Storm Conditions**

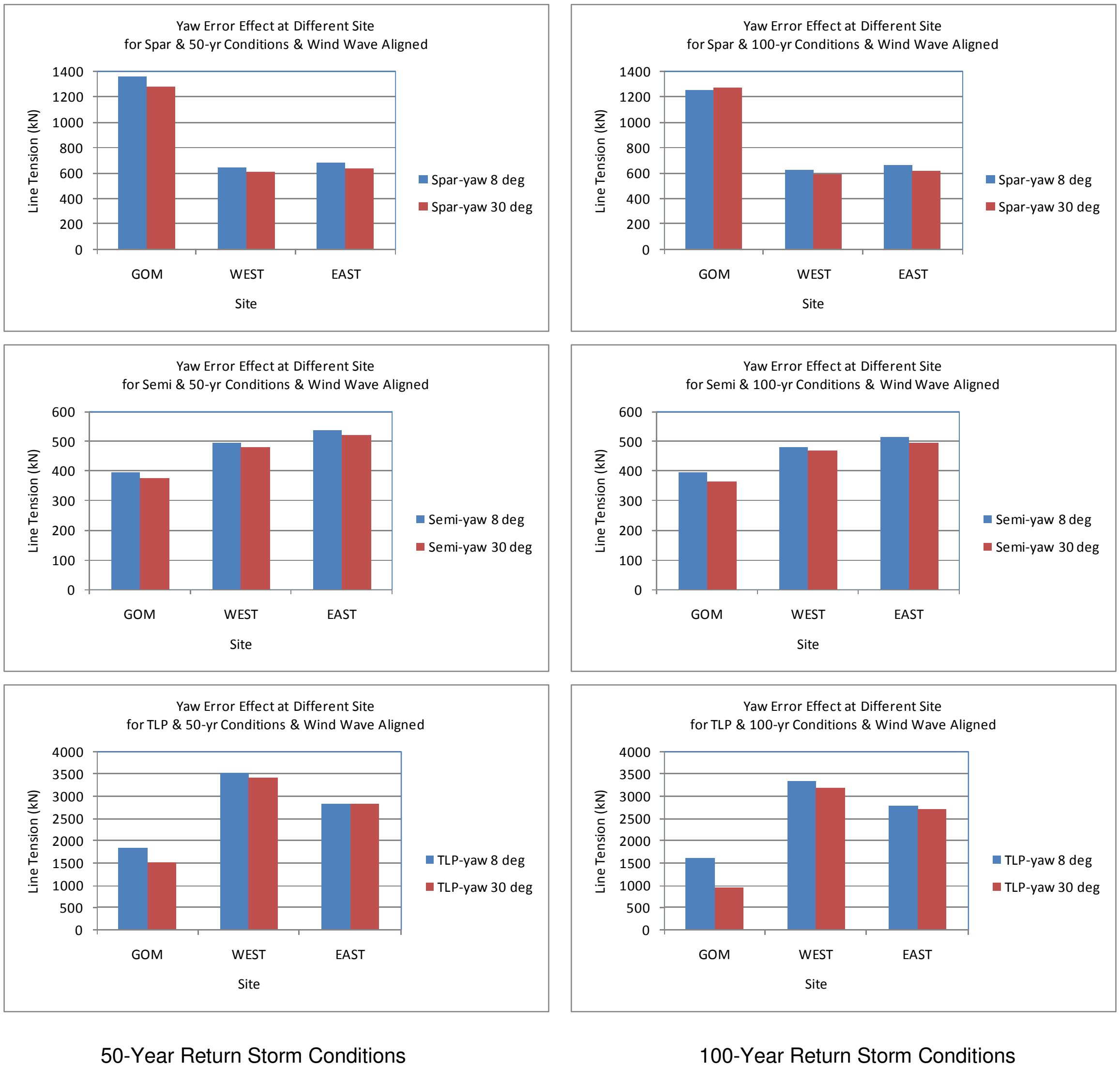



**Figure 3.63 Minimum Line Top Tension (Normal vs. Abnormal) under the Storm Conditions**

### 3.8.4 Wind and Wave Misalignment

The existing design guidelines for bottom-founded offshore wind turbines require considering the misalignment of wave and wind directions up to ±30 degrees. However, waves in the region in front of the hurricane eye could be roughly perpendicular to the local wind direction. The comparison made in this subsection is to assess the sensitivity of global responses to the misalignment between wind and wave directions.

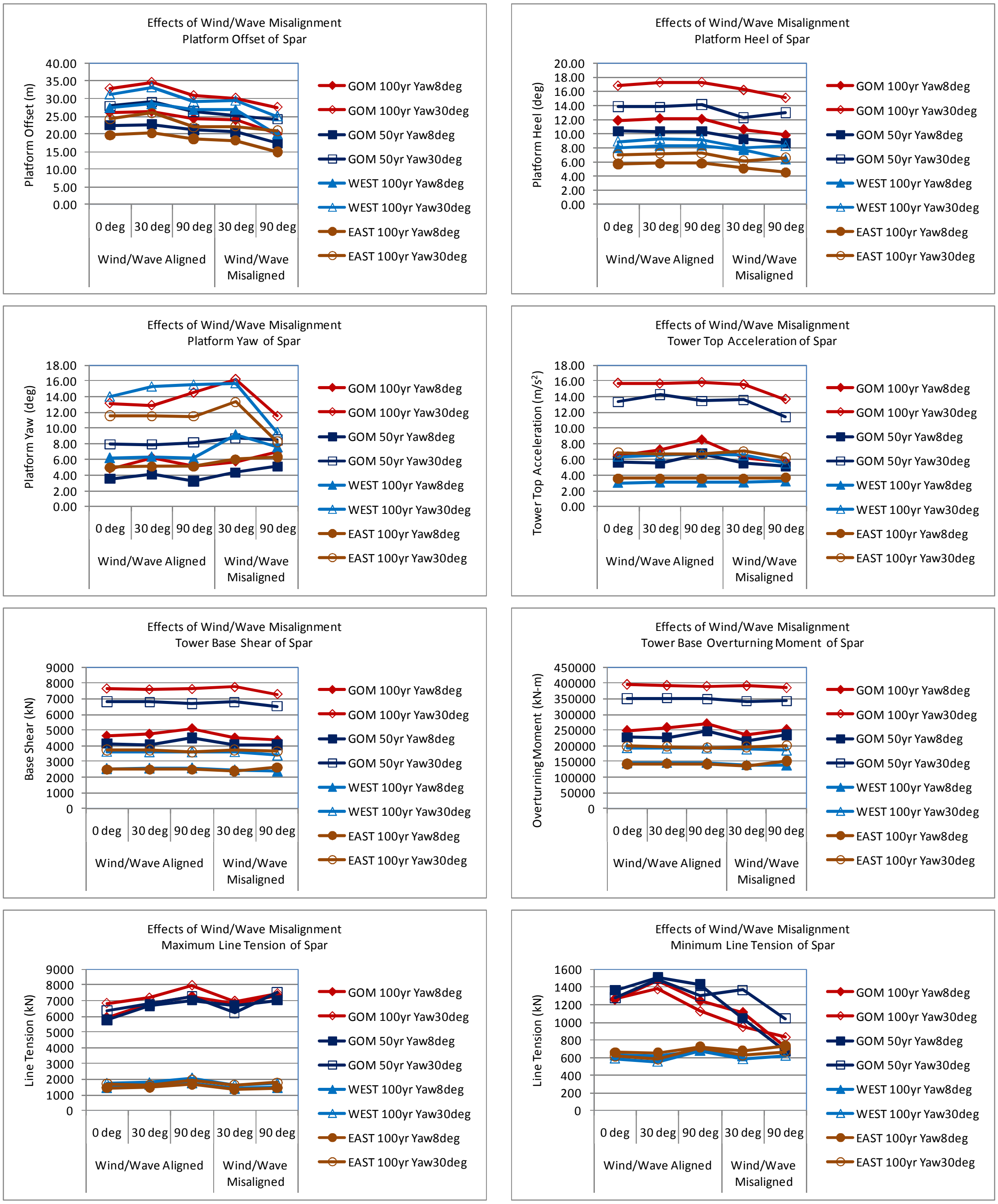
The definition of wind and wave directionality is plotted in Figure 3.36 for the Spar FOWT, Figure 3.41 for the Semi-submersible FOWT and Figure 3.45 for the TLP FOWT.

Figure 3.64 through Figure 3.66 depict the hull offset, hull heel, hull yaw, tower top acceleration, tower base loads, and line top tension for aligned (collinear) and misaligned (cross) wind and wave directions. All the three FOWT concepts are assumed to be in the parked conditions and subjected to 50-year and 100-year return storm conditions, respectively.

Figure 3.67 through Figure 3.69 present the comparisons of the hull motions, tower base loads and line top tensions of the three concepts subjected to the 50-year return hurricane conditions in the GoM Central Region.

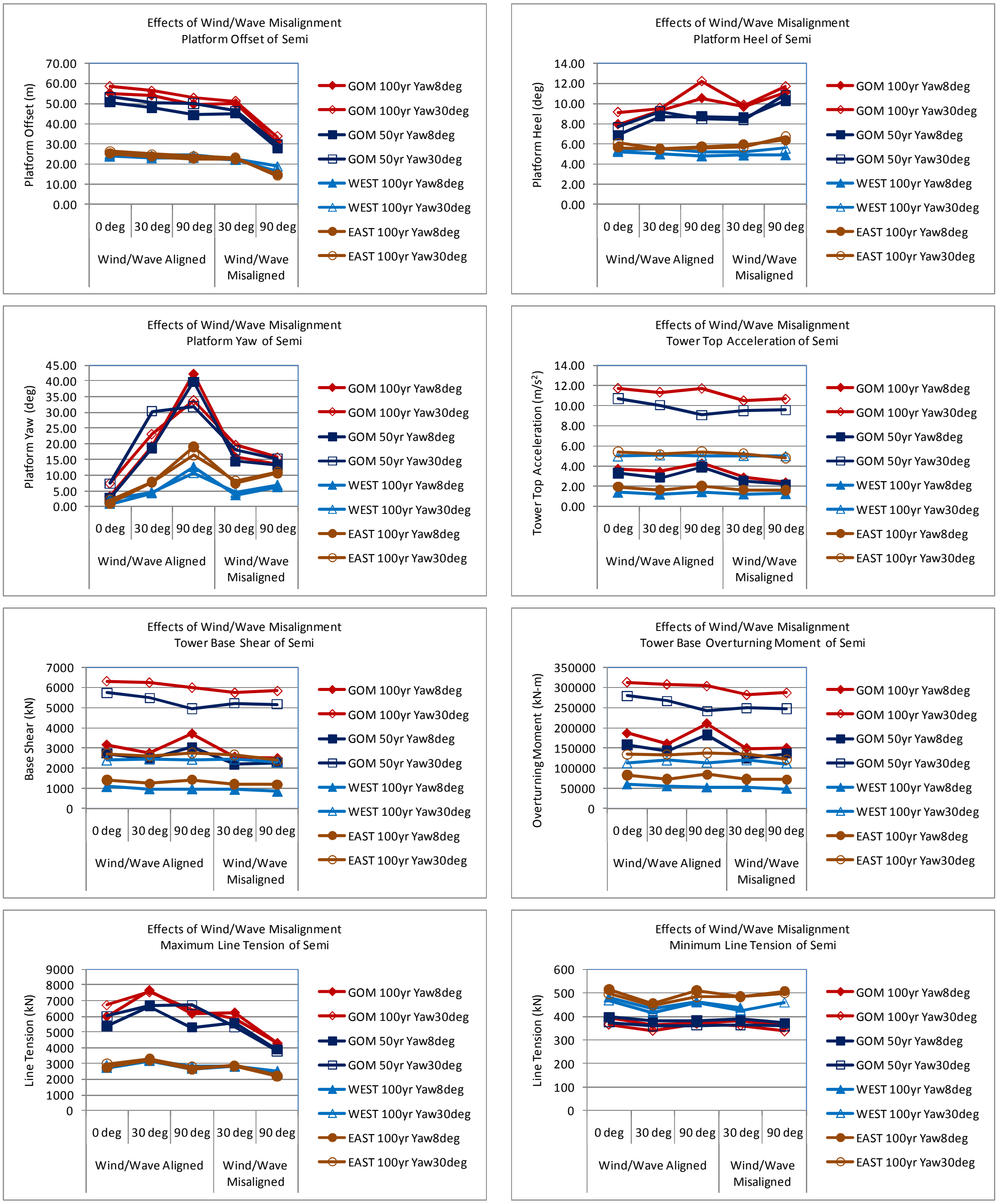
The following observations are made from these figures:

- In general, the collinear wind-wave results in the higher hull offset and higher maximum line top tension. The trend is consistent among all three FOWT conceptual designs.
- Misalignment of wind and wave may increase the platform heel, tower top acceleration and tower based loads.
- Misalignment of wind and wave may results in a much lower minimum line top tension.
- Hull yaw motions are very sensitive to the heading and the misalignment of wind and wave. The sensitivity and the trend of the hull yaw motions are greatly affected by the mooring arrangement and the hull form of the floating support structure.



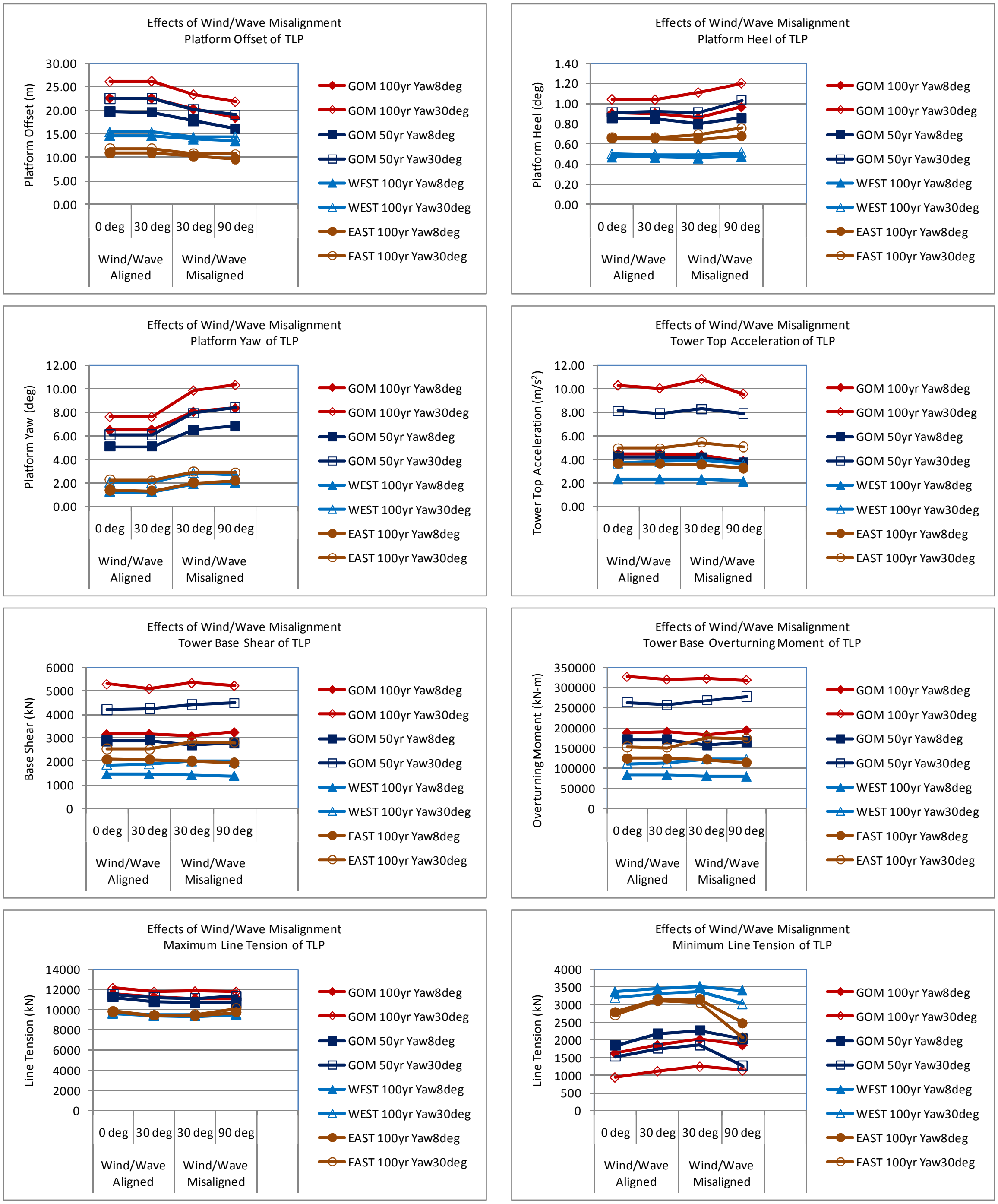

Notes:
1. The aligned cases include the wind, wave and current headings of 0, 30 and 90 degrees.
2. The misaligned cases assume that the wind and current heading is always 0 degree, while the wave heading is taken as 30 and 90 degrees, respectively.

**Figure 3.64 Effects of Wind/Wave Misalignment for the Spar FOWT**




Notes:
1. The aligned cases include the wind, wave and current headings of 0, 30 and 90 degrees.
2. The misaligned cases assume that the wind and current heading is always 0 degree, while the wave heading is taken as 30 and 90 degrees, respectively.

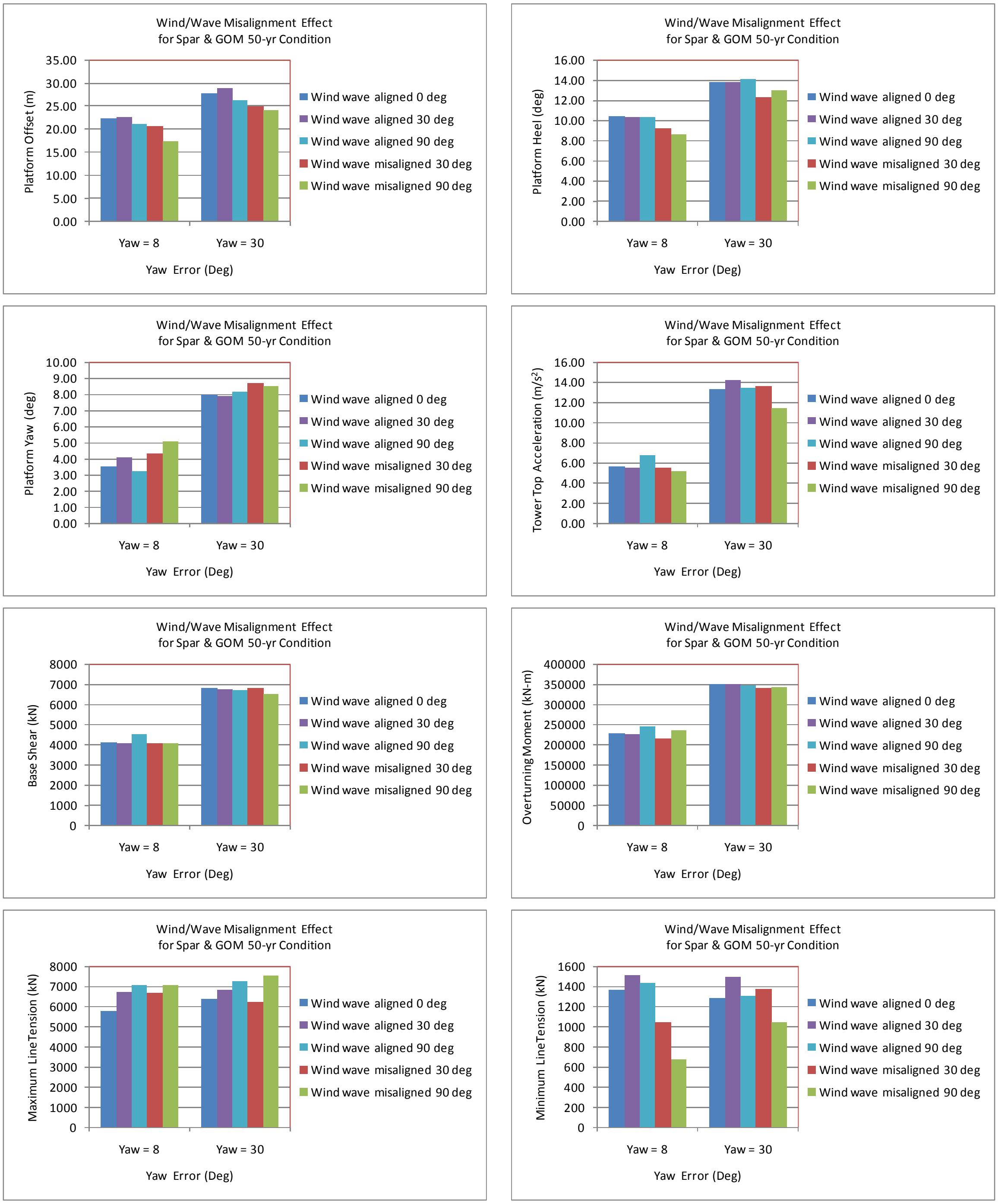
**Figure 3.65 Effects of Wind/Wave Misalignment for the Semi-submersible FOWT**




Notes:

1. The aligned cases include the wind, wave and current headings of 0 and 30 degrees.
2. The misaligned cases assume that the wind and current heading is always 0 degree, while the wave heading is taken as 30 and 90 degrees, respectively.

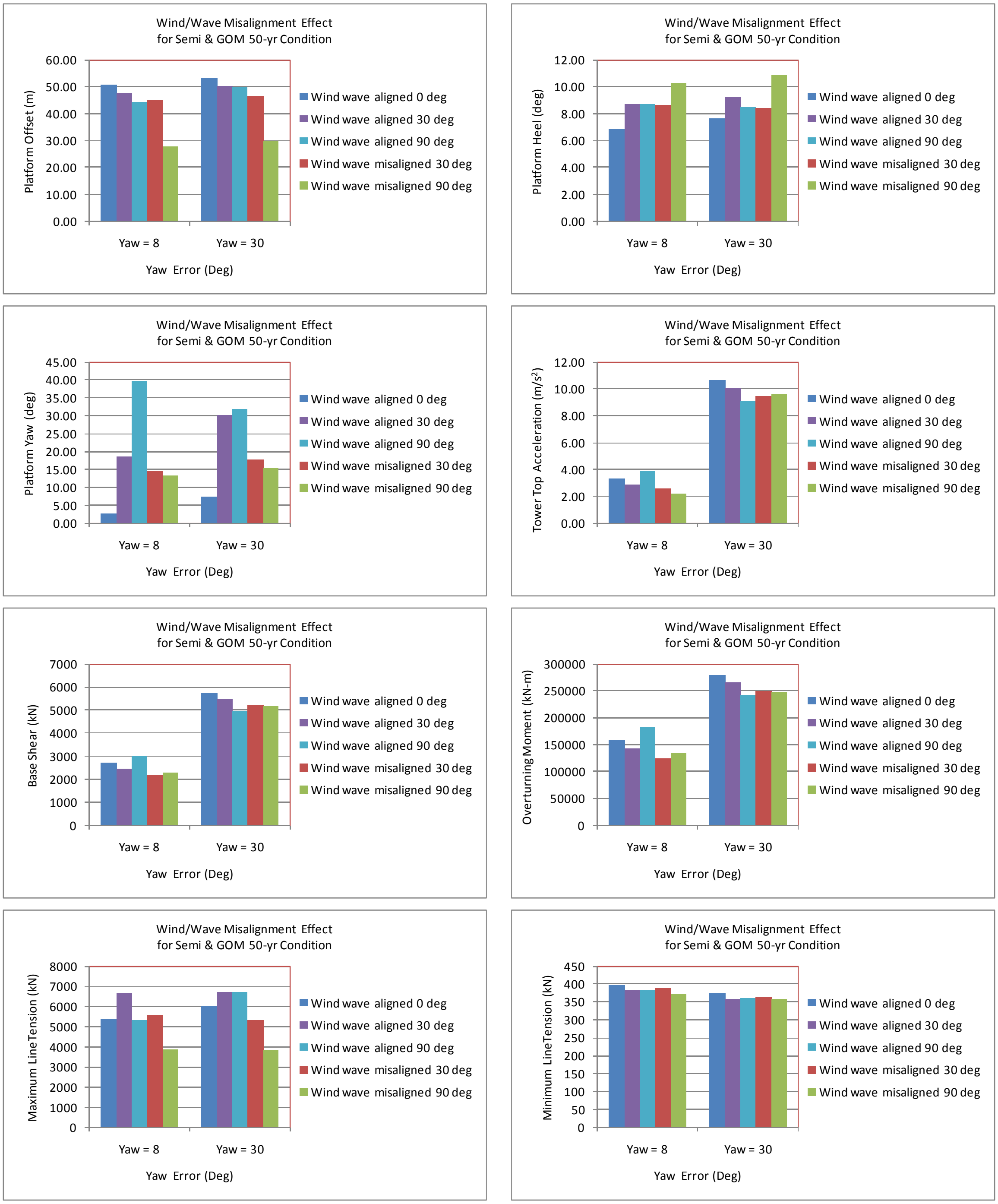
**Figure 3.66 Effects of Wind/Wave Misalignment for the TLP FOWT**




Notes:

1. The aligned cases include the wind, wave and current headings of 0, 30 and 90 degrees.
2. The misaligned cases assume that the wind and current heading is always 0 degree, while the wave heading is taken as 30 and 90 degrees, respectively.

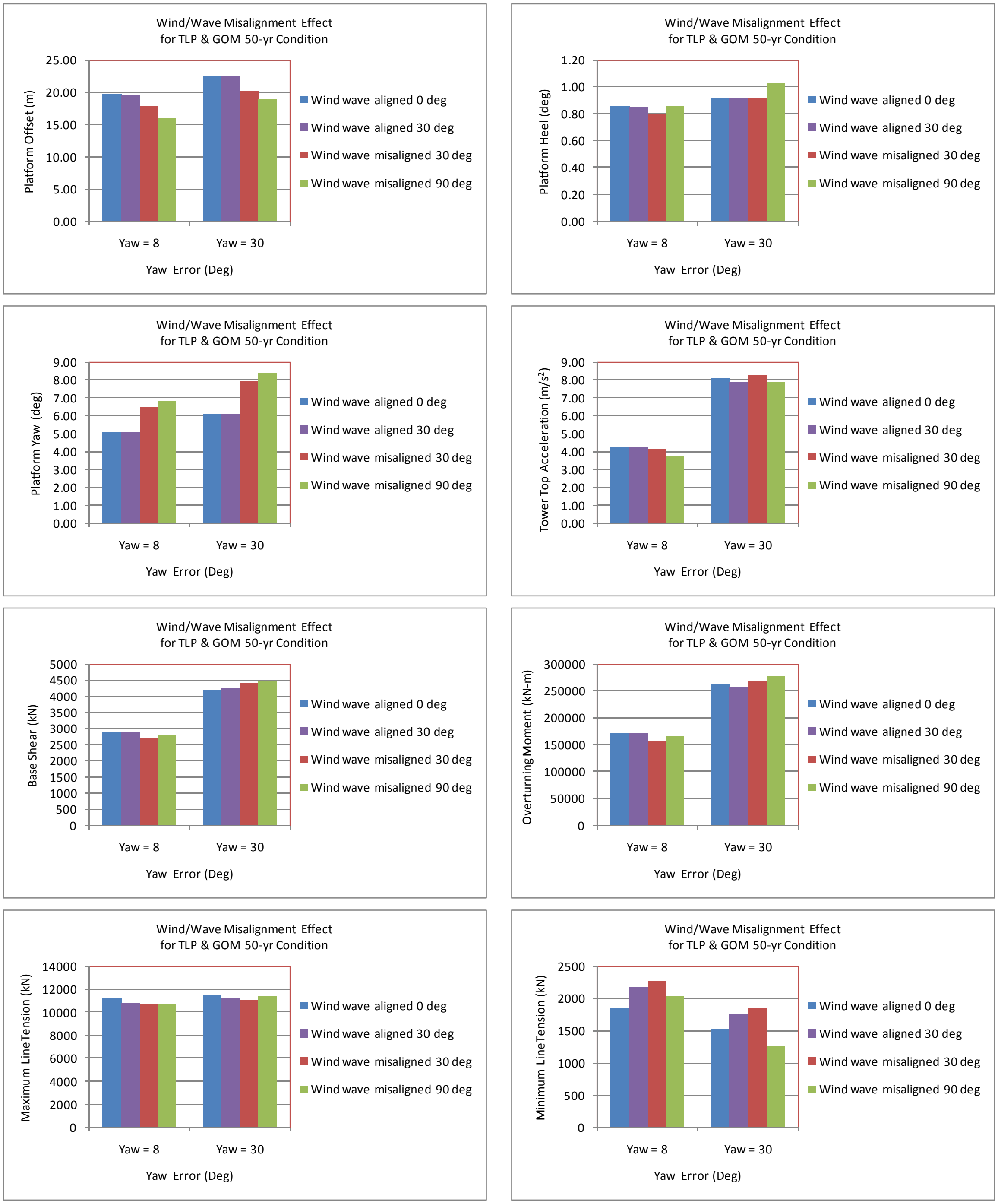
**Figure 3.67 Maximum Responses for the Spar FOWT vs. Wind-Wave Misalignment (under the 50-Year Return Conditions in the GOM Central Region)**




Notes:

1. The aligned cases include the wind, wave and current headings of 0, 30 and 90 degrees.
2. The misaligned cases assume that the wind and current heading is always 0 degree, while the wave heading is taken as 30 and 90 degrees, respectively.

**Figure 3.68 Maximum Responses for the Semi-submersible vs. Wind-Wave Misalignment (under the 50-Year Return Conditions in the GOM Central Region)**




Notes:
1. The aligned cases include the wind, wave and current headings of 0 and 30 degrees.
2. The misaligned cases assume that the wind and current heading is always 0 degree, while the wave heading is taken as 30 and 90 degrees, respectively.

**Figure 3.69 Maximum Responses for the TLP FOWT vs. Wind-Wave Misalignment (under the 50-Year Return Conditions in the GOM Central Region)**

### 3.8.5 Effect of Changing Water Level on the TLP FOWT

The effects of design water level on the global responses of TLP are assessed in this section. The abnormal load cases, which assumes the turbine is parked and the nacelle has a yaw error of 30 degrees, are analyzed. The 50-year and 100-year return hurricane conditions in the GOM, the 100-year return storms in the WEST and EAST are applied in the global performance analysis. It is assumed that the wind, wave and current are collinear and at 0 degree heading. The design water levels, including HSWL (Highest Still Water Level) and LSWL (Lowest Still Water Level) in addition to MSL (Mean Sea Level), are considered. The global performance analysis results are presented in Figure 3.70 and Figure 3.71. It is shown that

- A lower water level results in a higher TLP offset but lower maximum tendon top tensions and therefore smaller system stiffness for all site conditions considered in the study.
- The TLP yaw motions increases when the water level decreases. A lower water level increases the turbine hub height and thus increases the yaw moment generated by aerodynamic loading.
- The design water level has significant impact on the minimum tendon top tensions. For the TLP FOWT and the load cases considered in this study, the minimum tendon top tension associated with LSWL could be as low as 50% of the minimum tendon top tension associated with HSWL.
- The water level effects on the tower top accelerations and the tower based loads do not appear to have a consistent trend. However, the variations of these tower responses with respect to the water level are insignificant.

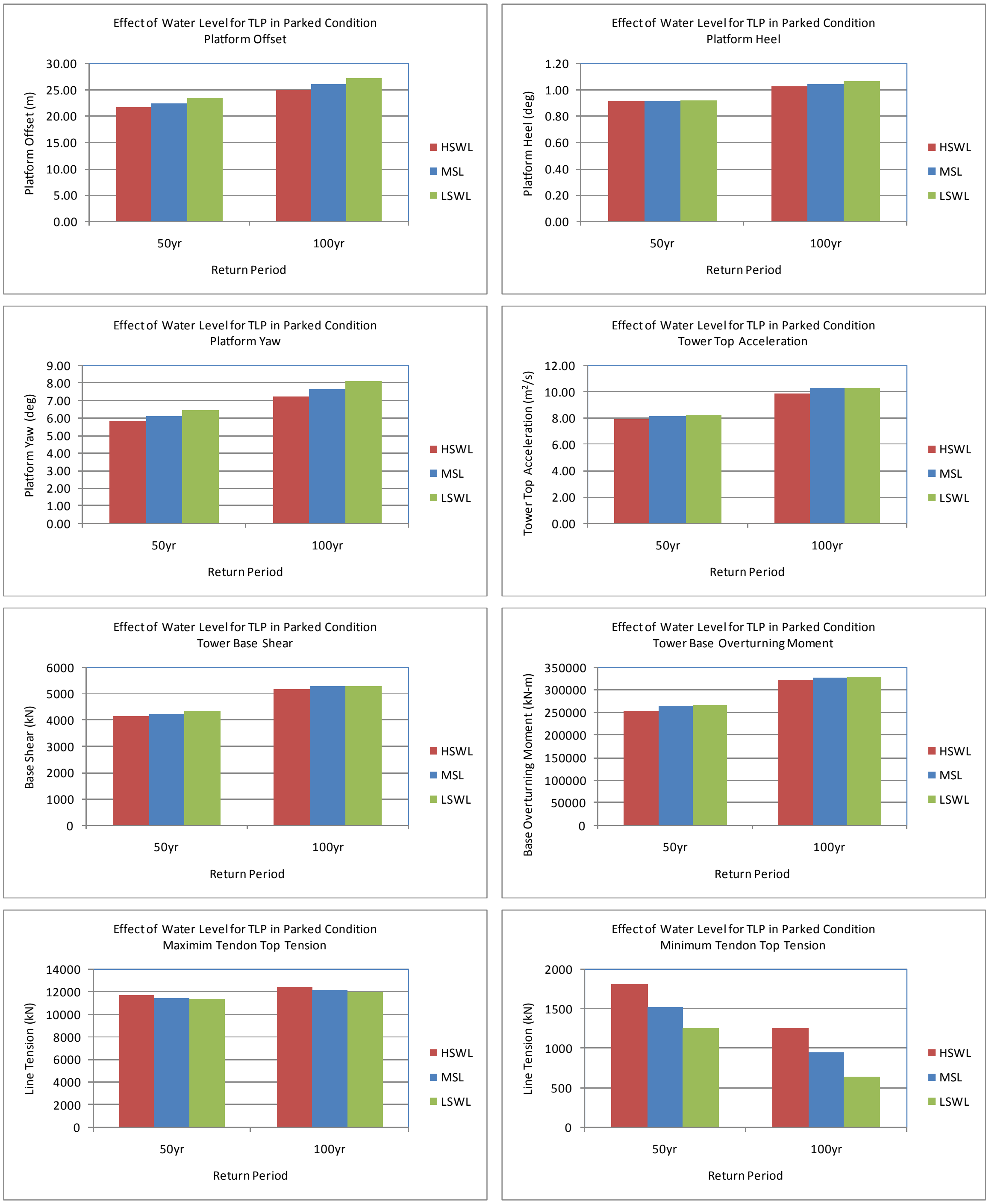



**Figure 3.70 Effects of Water Level on TLP in Parked Condition in 50-yr and 100-yr Hurricanes in GOM Central**

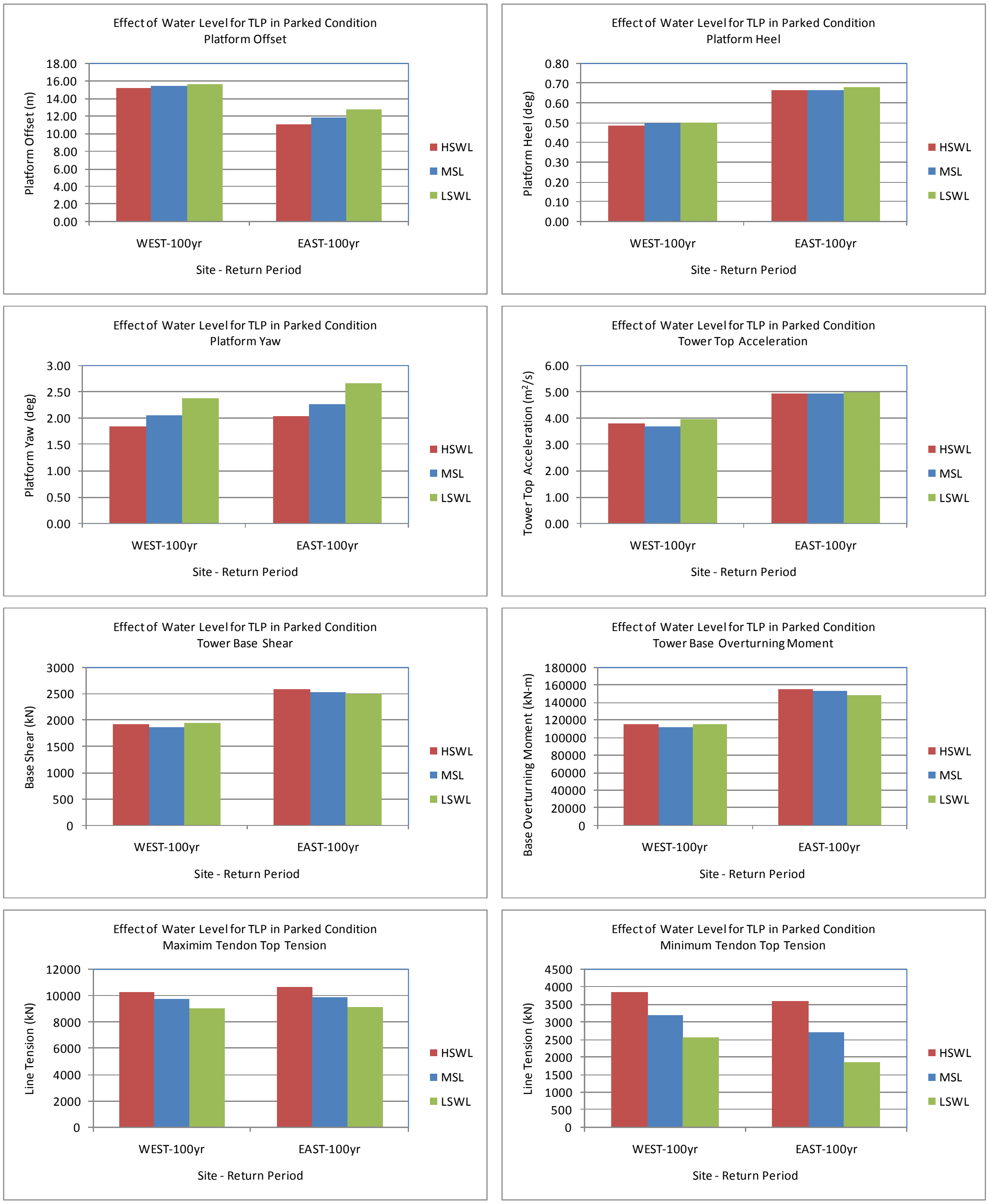



**Figure 3.71 Effects of Water Level on TLP in Parked Condition in 100-yr Storms in US West Coast and US Northeast Coast**

## 3.9 Robustness Check

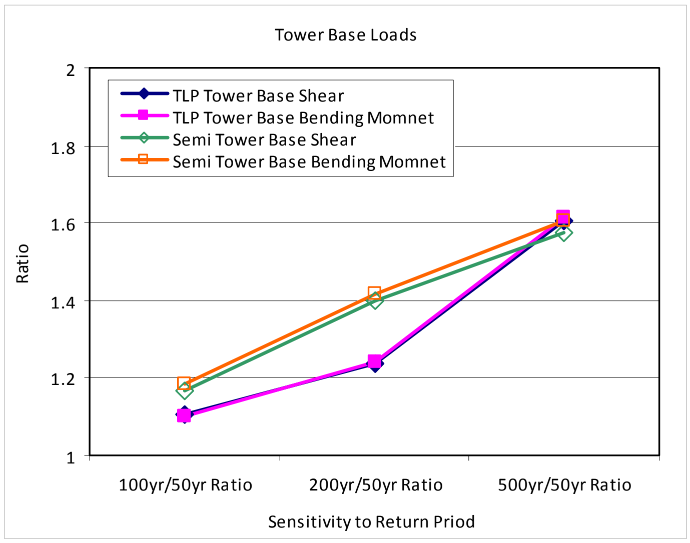
A robustness check is performed for the Semi-submersible and TLP FOWT conceptual designs. The 500-year return hurricane conditions in the GoM Central Region, including both the peak wind and the peak wave scenarios, are applied in the robustness check. The metocean conditions are derived based on API 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. The derived 500-year return peak wind and peak wave conditions in the GoM Central Region for a water depth of 320 m are given in Table 3.24.

**Table 3.24 500-Year Hurricane Conditions in GoM Central**

| Combination of Environmental Conditions | | Peak Wind | Peak Wave |
|---|---|---|---|
| Return Period (Years) | | 500 | 500 |
| Wind (10m Elevation) | 1-hour Mean Wind Speed (m/s) | 55.9 | 53.1 |
| | 10-min Mean Wind Speed (m/s) | 64.3 | 60.8 |
| | 1-min Mean Wind Speed (m/s) | 75.1 | 70.7 |
| | 3-sec Gust (m/s) | 89.1 | 83.5 |
| Wave | Significant Wave Height (m) | 17.21 | 18.11 |
| | Maximum Wave Height (m) | 30.38 | 31.98 |
| | Peak Spectral Period (s) | 16.17 | 16.59 |
| | Period of Maximum Wave (s) | 14.55 | 14.92 |
| Current Profile | Current Speed (m/s) at 0.0 m | 2.10 | 2.10 |
| | Current Speed (m/s) at 43.7m | 1.57 | 1.57 |
| | Current Speed (m/s) at 87.4 m | 0.0 | 0.0 |
| Water Level | Storm Surge (m) | 0.72 | 0.72 |
| | Tidal Amplitude (m) | 0.42 | 0.42 |
| | Surge and Tide (m) | 1.14 | 1.14 |

Global performance analyses are carried out with an 8-degree yaw error and collinear wind, wave and current at 0 degree heading. The turbine blades are assumed to be intact. Three design water levels (HSWL, MSL and LSWL) are also considered for the TLP FOWT. The robust check results are presented in Table 3.25 for the Semi-submersible FOWT and in Table 3.26 for the TLP FOWT. The ratios of the global responses under the 100, 200 and 500-year return hurricanes to those under the 50-year return hurricanes, are also provided in the two tables as well as in Figure 3.72.

It should be noted that the validity of these robustness check results is up to the limit imposed by the simulation software for aerodynamic load calculations. The extreme storm conditions in the GoM Central Region include very high wind speeds that may exceed the application limit of the FAST program.



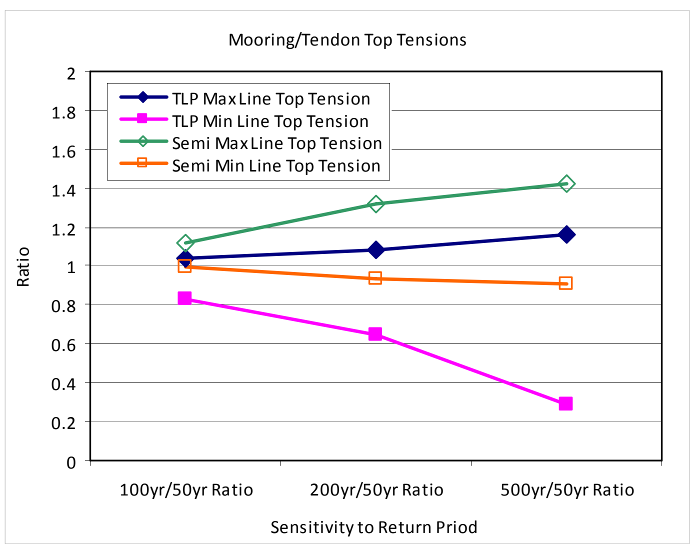




**Figure 3.72 Robustness Check Results for Tower Base Loads and Line Top Tensions**

**Table 3.25 Robustness Check for the Semi-submersible FOWT in the GoM Central Region**

| *Environmental Condition* | *Water Level* | *Wave & Wind Misalignment* | *Yaw Error* | *Platform Offset* | *Platform Heel* | *Platform Yaw* | *Tower Top Acceleration* | *Tower Base Loads* | | *Line Top Tension* | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | *Shear* | *Overturning Moment* | *Maximum* | *Minimum* |
| | | (deg) | (deg) | (m) | (deg) | (deg) | (m/s$^2$) | (kN) | (kN-m) | (kN) | (kN) |
| 500yr Hurricane | MSL | 0 | 8 | 70.07 | 9.66 | 4.44 | 4.86 | 4280 | 253382 | 7667 | 361 |
| 200yr Hurricane | MSL | 0 | 8 | 65.49 | 9.04 | 4.39 | 4.57 | 3800 | 223153 | 7108 | 372 |
| 100yr Hurricane | MSL | 0 | 8 | 55.07 | 7.93 | 3.19 | 3.75 | 3174 | 186415 | 5989 | 395 |
| 50yr Hurricane | MSL | 0 | 8 | 50.68 | 6.88 | 2.65 | 3.30 | 2715 | 157685 | 5378 | 397 |
| 100yr/50yr Ratio | | | | 1.09 | 1.15 | 1.20 | 1.14 | 1.17 | 1.18 | 1.11 | 0.99 |
| 200yr/50yr Ratio | | | | 1.29 | 1.31 | 1.65 | 1.38 | 1.40 | 1.42 | 1.32 | 0.94 |
| 500yr/50yr Ratio | | | | 1.38 | 1.40 | 1.67 | 1.47 | 1.58 | 1.61 | 1.43 | 0.91 |

Notes: The value of each global response under 50, 100, 200 and 500 year return hurricanes, respectively, is the maximum of those obtained under the corresponding peak wind and peak wave scenarios.

**Table 3.26 Robustness Check for TLP FOWT in the GoM Central Region**

| *Environmental Condition* | *Water Level* | *Wave & Wind Misalignment* | *Yaw Error* | *Platform Offset* | *Platform Heel* | *Platform Yaw* | *Tower Top Acceleration* | *Tower Base Loads* | | *Line Top Tension* | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | *Shear* | *Overturning Moment* | *Maximum* | *Minimum* |
| | | (deg) | (deg) | (m) | (deg) | (deg) | ($m/s^2$) | (kN) | (kN-m) | (kN) | (kN) |
| 500yr Hurricane | EWLR | 0 | 8 | 32.02 | 1.30 | 10.93 | 5.80 | 4637 | 277748 | 13278 | 466 |
| 200yr Hurricane | EWLR | 0 | 8 | 26.20 | 0.99 | 8.47 | 4.68 | 3570 | 213386 | 12338 | 1047 |
| 100yr Hurricane | EWLR | 0 | 8 | 23.52 | 0.91 | 7.03 | 4.45 | 3189 | 189448 | 11877 | 1339 |
| 50yr Hurricane | EWLR | 0 | 8 | 20.22 | 0.85 | 5.43 | 4.25 | 2886 | 171885 | 11417 | 1620 |
| 100yr/50yr Ratio | | | | 1.16 | 1.06 | 1.30 | 1.05 | 1.10 | 1.10 | 1.04 | 0.83 |
| 200yr/50yr Ratio | | | | 1.30 | 1.15 | 1.56 | 1.10 | 1.24 | 1.24 | 1.08 | 0.65 |
| 500yr/50yr Ratio | | | | 1.58 | 1.52 | 2.01 | 1.37 | 1.61 | 1.62 | 1.16 | 0.29 |

Notes: The value of each global response under 50, 100, 200 and 500 year return hurricanes, respectively, is the maximum of those obtained under the corresponding peak wind and peak wave scenarios in combination with the HSWL, MSL and LSWL.

# 4 Technical Challenges in the Design of Floating Offshore Wind Turbines

This section presents an overview of the technical challenges that need to be addressed in the development of design guidelines for FOWTs. The primary focus is placed on the floating support structure and the stationkeeping system, although due considerations are also given to the turbine RNA and other equipment and systems on FOWTs. In particular, discussions were made about the turbine RNA design requirements that are directly related to the performance of the floating support structure and the stationkeeping system of an FOWT.

## 4.1 Design Philosophy and Safety Level

Floating offshore wind turbines, similar to offshore oil and gas production installations, are considered site-specific installations. Because of the apparent similarities, many design practices of offshore oil and gas production installations can be adapted for the design of the floating support structures and the stationkeeping systems of FOWTs. There are, however, some major differences, as summarized as follows, which must be considered in the determination of the overall design philosophy and the intended safety level of FOWTs.

- FOWTs are normally un-crewed and therefore have a low risk to human life. The extent of environmental pollution due to the failure of an FOWT is many orders of magnitude lower than that of offshore oil and gas production installations.

- A recent report issued by Transportation Research Board (2011) introduces a new consequence regime termed as the “policy risk”, which is traditionally not considered in the design of offshore oil and gas production installations in the US, but considered crucial for the emerging offshore renewable energy industry.

- A common basis of design for FOWTs within an offshore wind farm could make the wind farm vulnerable to a “common-cause” failure due to, for example, an extreme or accidental loading event.

- The floating support structure of an FOWT tends to be highly optimized such that the strength capacities of the tower and hull structural members would simultaneously approach their acceptance limits, and could therefore lead to a less redundant design compared to a traditional offshore oil and gas production installation.

- Current design practice for FOWTs mostly use non-redundant stationkeeping systems, which are uncommon for offshore oil and gas production installations.

- Wind loads generated by aerodynamic responses of turbine rotor could contribute a major part of the loads on the global hull structure. This is in contrast to floating offshore oil and gas production installations where wind loads are normally due to the drag effect and affect mostly the design of topside structures and stationkeeping systems.

- Effects of turbine control and safety systems play a significant role in regulating the aerodynamic loads by adjusting the yawing angle between rotor rotating plane and wind direction and the blade pitch angle. The loads generated by a turbine in the power production mode can potentially be higher than those inflicted by design storm wind and wave conditions when the same wind turbine is in parked condition (standstill or idling). The definition of "Operational" and "Extreme" conditions commonly used in the design of floating offshore oil and gas production installations (see, for instance, API RP 2T and API RP 2FPS) is, therefore, not directly applicable to FOWTs.

- There is limited knowledge about the complex interaction among the turbine rotor, control system, floating support structure, mooring and cable. Experimental methods and computer simulation tools that can take into account these interactions are not fully developed and validated. Uncertainties embedded in the design and analysis methods, i.e. modeling errors, could be high.

- With the change to load modeling and the effect of wind turbines control and safety system, the sensitivity of global loads on the hull structure to the change of return period of extreme design environmental conditions could be different than those that can normally be anticipated in the design of floating offshore oil and gas production installations. Applying the same design approach valid for floating offshore oil and gas production installations to FOWTs may not result in the anticipated safety level.

The design criteria for the floating support structures and the stationkeeping systems of FOWTs should be established to enable resultant FOWTs to at least achieve the intended safety level, as determined by their exposure level. In the development of design criteria for those FOWTs to be deployed on the US OCS, the experience gained from the design and operation of offshore oil and gas production installations on the US OCS should be taken into account. Instead of overemphasizing the return period of environmental conditions, the overall design approach (i.e., "design recipe") should be considered in the process of developing rational design criteria for FOWTs. All aspects contributing to the safety level of an FOWT need to be considered collectively. They include, but are not limited to, the following items.

- Prescribed safety factors
- Return period of extreme design environmental conditions
- Load models of environmental and operational loading
- Strength and fatigue capacity models of materials, structural members and joints and foundation elements
- Statistical variation of environmental conditions at sites where FOWTs will be deployed
- Characteristics of responses of specific combinations of the floating support structure and the stationkeeping system subjected to aggregated environmental loading
- Regulatory requirements

Several studies indicated that the offshore wind energy industry had, in general, accepted that offshore wind turbines, both bottom-founded and floating, should be designed to have an exposure level equivalent to the medium (L2) exposure level as defined in ISO 19902 (2007) and ISO 19904-1 (2006). There are also arguments that a higher exposure level equivalent to the high (L1) exposure level as defined in ISO 19904-1 (2006) should be applied to the stationkeeping systems of FOWTs. Few discussions, however, have been made about how to incorporate the "policy risk", as recommended by the report by Transportation Research Board (2011), into the definition of exposure level of FOWTs on the US OCS. In view of this, a regulatory perspective, as well as input from the industry, becomes very important. It is hoped that the study presented in this report can serve as a starting point for such discussions.

## 4.2 Turbine RNA

The turbine RNA to be installed on an FOWT may need to be designed to tolerate potentially 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.

According to IEC 61400-1 (2005), the standard turbine class is categorize and certified based upon the mean hub height wind speed and turbulence intensity. For FOWTs, large motions may increase the wind speed relative to turbine blades and may also change the turbulence structure. The S-class turbines are supposed to be used for offshore applications as per IEC 61400-3 (2009). However, there appears no commercially available S-class turbine. The common practice is to select a standard class turbine that can meet or exceed the requirement of site conditions. This approach is acceptable for bottom-founded offshore wind turbines, which are, to some extend, similar to land-based turbines in terms of the stiffness of support structure. For FOWTs, large heeling angles or accelerations induced by motions of floating support structure (hull and tower) have to be considered in the selection of turbines, and these motions, in turn, are partially determined by the turbine selected. Therefore, the process of selecting a standard class turbine for an FOWT becomes part of an iterative process for the design of the floating support structure and the stationkeeping system.

Furthermore, as evidenced by the cases study and the literature review, the control system regulating blade pitch angles and nacelle yaw angles could also greatly affect global motion characteristics of FOWTs, potentially causing motion instabilities. The turbine's control system should therefore be designed along with the floating support structure and the stationkeeping system to preclude the unfavorable issues such as negative damping and motion instabilities.

## 4.3 Environmental Conditions

The definition of environmental conditions should be compatible with the load conditions for the design of FOWTs. The external conditions specified in IEC 61400-3 (2009) for the design of bottom-founded offshore wind turbines may be referred to when defining the environmental conditions for FOWTs.

Cautions should be taken when using the storm wind model recommended in IEC 61400-3 (2009) for hurricane-prone areas. Some studies indicate that the wind model, including the wind shear and the turbulent wind spectrum and the spatial coherence functions, recommended in API RP 2A-WSD (2007) may be more appropriate for modeling hurricane wind conditions at open ocean sites. However, it is believed that further validation is still needed to verify the applicability of the turbulent wind model recommended by API to modeling hurricane winds on the US OCS.

In addition, the deterministic wave conditions specified in IEC 61400-3 (2009) for the calculation of wave kinematics and wave loads on the slender members of bottom-founded wind turbines are not considered necessary for the design of large floating support structures, which are typically located in relatively deep water where wave nonlinearity is insignificant.

## 4.4 Load Conditions and Load Calculations

Similar to those of bottom-founded offshore wind turbines, the responses of the floating support structure are closely related to the operating conditions of the turbine RNA. Since turbine control and safety systems play a significant role in regulating the aerodynamic loads, the definition of load conditions for the design of floating support structures should take into account the effect of turbine's operating conditions. The design load case (DLCs) specified in IEC 61400-3 (2009) for bottom-founded offshore wind turbines can be used as a starting point for this purpose. However, unique features of loads and responses of floating support structure of FOWTs should be considered.

For the stationkeeping systems of FOWTs, the design load cases may be defined on the basis of common practices in the offshore oil and gas industry, with additional considerations of the effect of turbine operating conditions. It is noted that stationkeeping systems for offshore oil and gas production installations are designed to withstand extreme storm conditions with both intact and damaged mooring/tendon conditions. For FOWTs, the stationkeeping system may well be designed as non-redundant. Hence, the damaged mooring/tendon design conditions typical for oil and gas platforms may become irrelevant for an FOWT and additional criteria should be provided for such non-redundant stationkeeping systems (see Section 4.7).

Recent studies indicate that due to the higher variability of the wind and wave climate in hurricane-prone areas, bottom-founded offshore wind turbines in US waters would not achieve the same level of safety as those in European waters if the existing IEC 61400-3 Ultimate Limit State (ULS) design criteria were applied without any modification and the design of turbine support structure were governed by the strength design criteria (Yu et al., 2011a, 2011b). Based on the results of these studies, the ABS Guide for Building and Classing Offshore Wind Turbine Installations (2010) requires to consider the design load cases for the extreme storm conditions defined using environmental conditions with a return period of 100 years in place of 50 years as required by IEC 61400-3 (2009). The main reason of requiring a higher return period rather than a larger safety factor for bottom-founded offshore wind turbines is the large scattering of sensitivities of responses to the variation of metocean conditions. If 50-year return environmental criteria were retained, the increase in safety factor would be between 100% for the monopile support structure and 20% for the jacket support structure as shown in the case studies reported in Yu et al (2011a). The scattering of sensitivity is mostly due to the sensitivity of aerodynamic loads to return period of environmental criteria and the occurrence of breaking wave impact. For a jacket support structure installed in relatively deep water, hydrodynamic loads (drag & inertia) could prevail and thus the support structure could become more like a fixed oil/gas platform.

In contrast to bottom-founded offshore wind turbines, FOWTs show a very different pattern of sensitivity to the return period of environmental conditions. The case study results presented in Section 3.8.1 indicate that in most cases the sensitivity of global responses to the return period are falling into a rather narrow band (1.05-1.25). Higher sensitivity is only found for the yaw motions. Assuming that the structural responses are approximately proportional to these global responses, the 50-year return environmental criteria along with a nominal safety factor of 1.25 can approximately survive a hurricane with a return period higher than 100 years.

In addition to the design load cases, other load conditions should also be considered for the cases where

- the floating hull structure is damaged, or
- FOWTs are under the survival condition.

The damaged hull condition is defined to verify that the structural integrity and stability can be maintained when a prescribed damage scenario is applied.

The survival condition is intended to verify the adequacy of air gap and stationkeeping capacity, as well as structural integrity if considered relevant. The survival check for an FOWT subject to the environmental conditions that are more severe than the extreme design environmental conditions provides an explicit indicator of the robustness of the design.

Load calculations, often combined with global performance analyses, for FOWTs are one of the most challenging technical areas. Although significant progress has been made in recent years, further improvements are still needed to better address some unique issues with FOWTs, such as

- nonlinear interactions among the rotor, tower, hull structure and stationkeeping system,
- effects of large tower deflections and hull motions on surrounding wind flow conditions and aerodynamic loading,
- wake and array effects from neighboring FOWTs in a wind farm, and
- software validation.

## 4.5 Global Performance Analysis

Global performance analyses are carried out to determine the global effects of environmental and other loads on the hull structure and the stationkeeping system. The primary results expected from a global performance analysis include global motions of the floating support structure, loads on the stationkeeping system, accelerations at the locations of interest, air gaps, and the global load effects on the floating support structure. The separation of resonance peaks could also be checked through global performance analyses. Results of global performance analyses provide the input required for subsequent structural analyses and design for FOWTs.

In general, common practices of global performance analyses for offshore oil and gas production installations, as summarized in API RP 2SK, API RP 2SM, ISO 19901-7, API RP 2T, and relevant 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. The following summarizes some subjects that need special considerations.

- Metocean data that have sufficient coverage on joint occurrence of wind, wave and current conditions, with special attentions to wind conditions required by turbine load analyses
- Dynamic interactions among the RNA, the floating support structure and the stationkeeping system

- 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 the statistical convergence for FOWTs subjected to both turbulent wind and irregular wave loading

Several global performance analysis programs for FOWTs are currently available (see Section 2.2), although their modeling capabilities vary significantly. Some of these tools have sophisticate turbine aerodynamic load modeling capabilities, while others are featured by their ability to perform high-fidelity simulations of hydrodynamic responses of an integrated floating structure and stationkeeping system. A common issue with all these analysis tools is the software validation. Significant efforts have recently been made by the offshore wind energy industry to perform "code-to-code" comparisons. The most prominent one is organized through IEA Wind Task 23-2 (OC3) and currently on-going IEA Wind Task 30 (OC4). There are, however, very limited amount of experimental test data available in the public domain. Some full scale measurements do exist, but are all proprietary to the developers. Further validation of the global performance analysis software against experimental test results or field measurements are still dependent upon when and to what level of details the data will be made available.

Even with latest global performance analysis capabilities, model tests may still be required 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.

## 4.6 Hull Structural Analysis and Design

Due to complexity of structure configuration, time domain structural analyses, which are commonly used for the design of bottom-founded offshore wind turbines (mostly monopile supported), may not be a viable solution for FOWTs.

The design wave approach for global strength analyses of floating offshore oil and gas platforms may be adapted along with due considerations of the effect of aerodynamic loads. The spectral based structural analysis approach is another alternative which may be more appropriate for the fatigue assessment. It is noted that few studies have been performed to develop practical guidance on how these structural analysis methods should be implemented for the design of FOWTs. Most of the current research on FOWTs appears to focus more on load calculations and global performance analyses rather than structural design and analysis. Further studies are also required to establish the load mapping procedures and tools that can translate the load calculation results to the design loads for structural analyses, where detailed structural finite element models are normally used.

For the design of structural members and components of the stationkeeping system, the existing design practices provided in API RP 2T, API RP 2A, API RP 2SK and various classification society criteria for the offshore oil and gas production installations are mostly applicable. The safety factors, however, should be defined in such a way that the intended safety level of FOWTs and the turbine operating conditions can be taken into account. In this regard, the safety factors specified in IEC 61400-3 and other offshore wind turbine design guidelines may be used as a reference.

## 4.7 Stationkeeping System

As demonstrated by the case studies, the dynamic behavior of stationkeeping system of FOWTs is similar to that of floating offshore oil and gas production installations. The analysis and design of stationkeeping system can be based on experience from the offshore oil and gas industry, with the consideration of the following issues relevant to FOWTs:

- Quantities of mass and water plane area of FOWTs are typically an order of magnitude smaller than those of floating offshore oil and gas production installations. The coupling effect and nonlinear dynamic response of an FOWT could be so significant that the decoupled analysis, quasi-static analysis, or frequency domain analysis that is normally acceptable for floating offshore oil and gas production installations may potentially introduce large errors in the case of FOWTs.
- The characteristics of some motion components of an FOWT could be driven by the dynamic wind loads, which are associated with the turbine operating conditions. The unique load and response characteristics of FOWTs, in particular the effect of turbine control and safety systems should be considered.

- Non-redundant or unconventional stationkeeping systems may be used in FOWTs. Special considerations of the design requirement are needed for those stationkeeping systems that are not commonly used by floating offshore oil and gas production installations.
- Overall safety level of an FOWT may be lower than that of a floating offshore oil and gas production installation. Reduced design criteria could be applied to the design of the stationkeeping system of an FOWT. Nevertheless, there are arguments indicating that the consequence of failure of a single stationkeeping system in an offshore wind farm with closely spaced FOWTs could lead to catastrophic chain reactions and, therefore, the high safety level may be necessary for the stationkeeping systems of FOWTs.

## 4.8 Stability and Watertight Integrity

FOWTs are typically un-crewed and do no store hydrocarbons or hazardous chemicals in bulk. The requirements on stability and marine pollution based on IMO regulations, as for ocean-going vessels or floating offshore oil and gas platforms, may be overly restrictive for FOWTs.

In general, the stability, including the intact and damage stability, should meet the requirements of national authorities (or Administrations) having jurisdiction over the location where FOWTs will be installed. Sufficient stability and watertight integrity should be maintained during the pre-service (load-out, transportation, and installation) and in service (in place) phase. Appropriate account should be taken of various hull configurations of FOWTs, in particular for those innovative designs.

## 4.9 Cable System

The cable system is designed to transmit turbine generated electrical power to subsea cables and may also be used to convey control signals. The strength and fatigue design of the cable and its support structures should be considered for both installation and in-service conditions. Dynamic responses of the suspended cable should be determined through global performance analyses. The suspended cable may also affect the global performance of the floating support structure and the stationkeeping system. The design of cable may be referenced to the existing design practice for subsea umbilicals in accordance with API Spec 17 E, which is identical to ISO 13628-5.

## 4.10 Other Important Design Considerations

In addition to those discussed in Section 4.1 through 4.9, a number of design consideration listed below may also be deemed critical.

- Minimum requirements on analysis software

  As discussed in Section 4.4 and Section 4.5, the capability, robustness, and level of maturity vary significantly among the existing load calculation software and global performance analysis software for FOWTs. The design and analysis approach used in a specific project may have to be adjusted to accommodate the limitation of chosen software. The software application boundary should be clearly understood and observed, and the verification of results against reliable benchmark should be requested.

- Foundation design

  For the design of foundation elements for a tendon or taut leg mooring system, references can be made to the guidance provided by API RP 2T and API RP 2SK, which represent existing design practices in the offshore oil and gas industry.

- Model test requirements

  Model tests for the integrated floating wind turbine system subjected to combined wave and wind conditions could be very challenging. Special attentions should be paid to the model scaling, generation of turbulent wind fields, and simulation of turbine's control systems.

- Requirement for safety, fire protection, lightning protection, piping and ballast, electrical and mechanical systems

  Relevant experience from the design of bottom-founded offshore wind turbines and floating offshore oil and gas production installations may be adapted.

# 5 Draft Design Guideline for Floating Offshore Wind Turbines

## 5.1 Scope

The criteria proposed in Section 5 are intended to provide guidance for the design of floating support structures and stationkeeping systems of floating offshore wind turbines. The Rotor-Nacelle Assembly (RNA) should be designed according to IEC 61400-1 and demonstrated that the offshore site-specific external conditions do not compromise structural integrity and intended functions of the floating wind turbine.

A floating support structure is a buoyant hull structure that supports the wind turbine RNA as well as other systems and equipment. It is maintained on location by a suitable stationkeeping system. The stationkeeping system considered in Section 5 includes the mooring (or tendon) and anchoring systems.

The following types of floating support structure are explicitly considered in this section:

- Tension Leg Platform (TLP)
- Spar (Deep Draft Caisson Vessel – DDCV)
- Column-Stabilized Platform

In addition to the specifically mentioned types listed above, the design criteria proposed in Section 5 may also be applicable to other types of floating support structures consisting of partially submerged buoyant hulls, which are made up of the combination of plated and space frame components and are maintained on location by suitable stationkeeping systems. An example of such a floating support structure is a deep-draft column-stabilized floating structure, which has the features of both a Spar and a column-stabilized support structure.

Floating offshore wind turbine technology is a fast evolving new frontier, where innovative concepts of floating support structure and component designs are emerging rapidly. The design criteria proposed in Section 5 are developed on the basis of:

- the results of the study carried out in this project, as reported in the previous sections;
- industry experience of designing bottom-founded offshore wind turbines and, to a limited extent, floating offshore wind turbines; and

- common practices of designing floating offshore structures and stationkeeping systems for the offshore oil and gas industry.

An extensive literature review and case studies have been performed in order to provide a sound technical basis for the proposed design criteria; additional such work, along with input from regulators and industry experts will lead to consensus about the appropriate criteria.

## 5.2 Definitions

### 5.2.1 Types of Floating Support Structures

#### *5.2.1.1 TLP-Type Support Structures*

A TLP-type support structure consists of structural components of hull, tendon system and foundation system. It may also include column top frame and topside deck. The hull consists of buoyant pontoons and columns. The tops of the columns may be connected 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 tendon legs to the seafloor.

#### *5.2.1.2 Spar-Type Support Structures*

A Spar-type support structure consists of an upper hull, mid-section and lower hull. The upper hull serves to provide buoyancy to support the topside and provide 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. Normally, the cylindrical column mid-section is free flooded, while the truss space frame is buoyant. 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 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 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.

#### *5.2.1.3 Column-Stabilized Support Structures*

A column-stabilized floating support structure consists of a topside deck 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 deck structure can be of an enclosed hull type or an open space truss frame construction. The topside deck structure is interconnected with the stability columns of the hull to form the overall strength of the floating support structure.

### 5.2.2 Terms and Definitions

#### *5.2.2.1 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

#### *5.2.2.2 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

#### *5.2.2.3 Design life*

Assumed period for which a structure or a structural component should be used for its intended purpose with anticipated maintenance, but without substantial repair being necessary

#### *5.2.2.4 Emergency Shutdown*

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

#### *5.2.2.5 Floating Offshore Wind Turbine*

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

#### *5.2.2.6 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 Support Structure consists of the Tower and the Hull Structure.

#### *5.2.2.7 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

#### *5.2.2.8 Gust*

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

#### *5.2.2.9 Hull Structure*

Combination of connected buoyant structural components such as columns, pontoons and intermediate structural braces

#### *5.2.2.10 Hub Height*

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

#### *5.2.2.11 Idling*

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

#### *5.2.2.12 Mean Sea Level (Mean Still Water Level)*

Average level of the sea over a period long enough to remove variations due to waves, tides and storm surges.

#### *5.2.2.13 Mean Wind Speed*

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

#### *5.2.2.14 Normal Shutdown*

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

#### *5.2.2.15 Offshore Wind Farm*

A group of wind turbines installed at an offshore site

#### *5.2.2.16 Omni-directional (Wind, Waves or Currents)*

Acting in all directions

#### *5.2.2.17 Parked*

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

#### *5.2.2.18 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.

#### *5.2.2.19 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

#### *5.2.2.20 Return 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.

#### *5.2.2.21 Rotor-Nacelle Assembly (RNA)*

The Rotor-Nacelle Assembly 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.

#### *5.2.2.22 Standstill*

Condition of a wind turbine that is not rotating

#### *5.2.2.23 Stationkeeping System*

System capable of limiting the excursions of a Floating Support Structure within prescribed limits

##### *5.2.2.24 Still Water Level (SWL)*

Still Water Level (SWL) is taken as the sum of the highest astronomical level and the positive storm surge excluding variations due to waves.

##### *5.2.2.25 Tendon*

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

##### *5.2.2.26 Tower*

Structure component which connects the Hull Structure to the Rotor-Nacelle Assembly

##### *5.2.2.27 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

##### *5.2.2.28 Uni-directional (Wind, Waves or Currents)*

Acting in a single directions

##### *5.2.2.29 Water Depth*

Vertical distance between the sea floor and Still Water Level

##### *5.2.2.30 Wind Profile (Wind Shear Law)*

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

##### *5.2.2.31 Yawing*

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

##### *5.2.2.32 Yaw Misalignment*

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

## 5.3 General Design Requirements

### 5.3.1 General

The floating support structure and the stationkeeping system should be designed to allow the floating offshore wind turbine to fulfill its intended mission during its design life and meet specified minimum requirements for serviceability and operability for at least the specified time.

The Rotor-Nacelle Assembly carried by the floating support structure may be designed initially according to a standard wind turbine class as defined in IEC 61400-1 (2005), and further be demonstrated that it can fulfill the requirements imposed by offshore site-specific external conditions and a specific design of the floating support structure and the stationkeeping system. The demonstration should comprise a comparison of loads, deflections and accelerations calculated for the floating offshore wind turbine subjected to site-specific conditions with those calculated during initial design. Safety margins that reflect increased uncertainty of offshore site conditions and design methods should be applied. The influence of the environment on structural resistance as well as the appropriate material selection should also be taken into account.

The design of a floating offshore wind turbine should comply with the local regulations specified by national authorities (or Administrations) having jurisdiction over the location where the floating offshore wind turbine will be installed.

### 5.3.2 Exposure Level

The floating support structures and the stationkeeping systems can be categorized at various levels of exposure based on the consideration of life-safety and consequences of failure. Life-safety considers the maximum anticipated environmental event that would be expected to occur while personnel are on the floating offshore wind turbine. Consequences of failure should consider loss of life, environmental pollution, financial loss and potential negative impact to the industry. Lower consequences of failure and reduced exposure to life-safety may justify the use of environmental criteria with a shorter return period.

Since the floating offshore wind turbine is typically un-crewed and has moderate consequences of failure, the floating support structure and the stationkeeping system can in general be designed to have an exposure level equivalent to the medium (L2) exposure level as defined in ISO 19904-1

(2006). A higher exposure level equivalent to the high (L1) exposure level as defined in ISO 19904-1 (2006) may be warranted when considering the fact that

- FOWTs are still at the early stage of development. Potential large-scale failures at this stage could result in negative public perceptions and impose high risks on the viability of the offshore renewable energy industry and the development of supportive governmental policies.
- Due to the economic considerations, the floating support structure and stationkeeping system are likely to be non-redundant or have very low level of redundancy. It is also possible that the same design may be used for all FOWTs in an offshore wind farm, which becomes vulnerable to "common-cause" failures.

For an offshore wind farm having multiple floating offshore wind turbines located in a close proximity, failure of a single stationkeeping system could cause extensive damage to other floating offshore wind turbines and their stationkeeping systems in the offshore wind farm. A risk analysis should be conducted to evaluate the consequence of failure of the stationkeeping system. Such an analysis should examine various scenarios of failure of the stationkeeping system, probability of occurrence of each scenario, and their consequences. The risk analysis may be used to determine the exposure level of the stationkeeping system. However, the exposure level of the stationkeeping system should not be lower than that of the floating support structure.

The design criteria specified in Section 5 are intended for the floating support structure and the stationkeeping system having an exposure level equivalent to the medium (L2) exposure level as defined in ISO 19904-1 (2006).

### 5.3.3 Environmental Conditions

The floating support structure should be designed to withstand specified operational and environmental conditions at the site while the RNA is under various operating conditions. The environmental conditions are defined in Section 5.4.

The floating support structure should also be designed for all pre-service operations such as load-out, transportation, and installation. The environmental conditions for load-out, transportation, and installation should be specified by the designers or Operators.

Environmental conditions having a low probability of being exceeded when the hull structure is damaged or a mooring line or tendon is broken should be specified. For structural strength design, joint statistics may be used to determine a return period which, combined with the probability of damage, produces a risk level consistent with the intended exposure level.

Additionally, environmental conditions should be specified for verifying survivability 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 floating support structure and the stationkeeping system can endure such responses without loss their intended functions and structural integrity.

### 5.3.4 Design Load Cases and Load Calculations

The floating support structure's life cycle phase, including pre-service (load-out, transportation, and installation), in-service (in-place) and decommissioning operations, should be investigated using anticipated loads. Gravity loads together with relevant environmental loads due to the effects of wind, waves, currents, water level variations and, where deemed necessary by the designer, the effects of earthquake, temperature, fouling, ice, etc. 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 floating support structure and the stationkeeping systems, as determined by the requirements of the pre-service, in-service, and decommissioning operations, should be applied.

Structural dynamics models should be developed to predict design load effects for all relevant combinations of external conditions and turbine operating conditions. A minimum set of such combinations, which are termed as Design Load Cases (DLCs), are defined in Section 5.5.

### 5.3.5 Global Performance Analyses

Global performance analyses of the floating support structure and the stationkeeping system are aimed at determining the global effects of environmental loads on the RNA, the overall structure and components (e.g. mooring lines and anchors) of the stationkeeping system, as well as the export electrical cable system. The primary function of the analyses should establish that the floating support structure and the stationkeeping system meet all requirements of pre-service, in-service and decommissioning operations. It is suggested that global response analyses be performed for each of the most critical design phases. The following aspects should be included in the global performance analyses:

- Six degrees of freedom motions of the floating support structure
- Mooring line tensions, including maximum and minimum tensions and mooring line fatigue loads for mooring component design
- Aerodynamic and hydrodynamic loads for the global structural analysis
- Accelerations for the determination of inertia loads
- Air gap (also known as deck clearance or freeboard)

Global performance analyses using various design load cases are required because complex motion characteristics of the floating support structure and interactions of turbine's control system with the dynamic responses of the floating support structure may have distinct impacts on different structural components and the RNA. It is recommended to include the turbine, floating support structure, moorings and export electrical cables in an integrated (also termed as "coupled") simulation model for the global performance analyses. For those global loads and responses that are deemed having weak coupling effects with others, global performance analyses may also be performed using a non-integrated model.

Either frequency 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, a time-domain analysis should be performed. Methods and models employed in the analyses should account for the relevant nonlinear and dynamic coupling effects of the RNA, the floating support structure, and the stationkeeping system.

### 5.3.6 Structural Design

The design of the hull structure should be based on applicable API and ISO standards and classification society criteria together with the safety factors as defined in Section 5.7. In cases where the structure's configuration or loading condition is not specifically addressed in existing standards, other accepted codes of practice can be used as a design basis. Where alternative standards are followed, the designer should justify that the safety levels and design philosophy provided in these standards are consistent with the intended exposure level.

Fatigue damage due to cyclic loading should be considered in the design of structure. Fatigue analyses should be carried out using an appropriate loading spectrum or time series in accordance with the accepted theories in calculating accumulated damage. All significant stress cycles imposed on the structure during its entire life should be accounted for, including those induced during fabrication, load-out, transportation, installation and in-service phases. Increased safety factors should be considered for the areas that are not inspectable.

### 5.3.7 Stationkeeping System

The floating support structure should be restrained by the stationkeeping system, which may be either passive or active or a combination of both. Passive stationkeeping systems include catenary mooring, taut-line mooring, spring buoy, articulated leg and tension leg systems. Active systems include the dynamic positioning based on thrusters or the catenary mooring systems with the ability of changing mooring line tensions. In the current design of offshore floating offshore wind turbines, passive stationkeeping systems are the most commonly adopted solution.

The stationkeeping system should be designed to

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

### 5.3.8 Stability

Adequacy of stability of the floating support structure should be checked for all relevant pre-service, in-service and decommissioning phases. The assessment of stability should include the consideration of both intact and damaged conditions. When recognized standards are utilized in the assessment of damage stability, it should be verified that the criteria adopted in the standard are compatible with the accidental event being addressed.

For the stability checks, considerations should be given to relevant unfavorable effects, including those resulting from the following:

- Environmental actions, such as wind, wave (including green water effects), current, snow and ice accumulation, etc.
- Turbine operating conditions, such as power generation, fault, parked, etc.
- Applicable damage scenarios (including owner-specified requirements)
- Rigid body motions
- Free-surface effects in ballast tanks
- Boundary interactions, such as mooring and electric cables.

### 5.3.9 Structural Material Selection, Welding and Connection

Structural materials should be selected with the consideration of requirements for performance, welding and inspection. In general, the materials to be used for the construction of the floating support structure and the stationkeeping system should follow the requirements and criteria specified for floating offshore oil and gas platforms and their stationkeeping systems. The following lists some of relevant design standards:

- API Recommended Practices (RP 2T, RP 2A, RP 2FPS, RP 2SK, etc.)
- API Specifications (2H, 2W, 2Y, 2F, etc.)
- ASTM Specifications (A131, etc.)
- European Normatives (EN 10025, EN 10225, etc.).
- NORSOK standards
- Applicable classification society criteria

Where appropriate standards do not exist, a material specification should be developed, subject to reproduction qualification requirements, such as those specified in API RP 2Z (2005).

The welding of steel for the floating support structure should follow established industry practices such as those described in API RP 2A-WSD (2007), API RP 2T (2010), and AWS Structural Welding Code D1.1 (2010) as well as applicable classification society criteria. Special attention should be given to the weld details for fatigue sensitive areas, whenever relevant. Weld improvements by means of toe grinding and weld profiling should be used if required by fatigue analysis results.

For connections other than welded joints such as clamps, connectors and bolts, which are used to join diagonal braces to the column or the tower to the support structure, the strength and fatigue resistance should be assessed by analytical methods or testing following established industry practices such as those specified in AISC Steel Construction Manual (2011)

### 5.3.10 Corrosion Protection and Control

A corrosion protection and control system utilizing anodes and/or coating in accordance with the recognized industry standards such as API and NACE should be provided. The design life of the corrosion protection and control system should be in general the design life of the floating support structure unless a monitoring and repair plan is established. In the splash zone, corrosion allowance should be added to the external shell plating. Reference may be made to the guidance on corrosion allowance in the relevant industry standards for floating offshore structures.

### 5.3.11 Operating Manual

An Operating Manual of an FOWT 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 FOWT.

## 5.4 Environmental Conditions

### 5.4.1 Overview

The environmental conditions that influence pre-service, in-service and decommissioning operations of a floating offshore wind turbine 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. Hindcasting methods and models should be fully documented if they are used to derive the environmental data.

In general, the design of a floating offshore wind turbine requires investigations of the following environmental factors.

- Winds
- Waves
- Currents
- Tides, storm surges, and water levels
- Air and sea temperatures
- Air density
- Marine growth
- Seabed and soil conditions
- 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 are made to IEC 61400-3 (2009) and ISO 19901-1 (2005) for the requirements and recommended practices on the assessment of environmental conditions. API Bulletin 2INT-MET (2007) and API RP 2A-WSD (2007) provide more guidance for offshore sites on the US OCS.

### 5.4.2 Winds

#### *5.4.2.1 General*

Statistical wind data are normally to include information about frequency of occurrence and duration and direction of various wind speeds at the location where the floating offshore wind turbine should 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.

#### *5.4.2.2 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 variance of wind speed).

In the design criteria proposed in this section, 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 cases in Section 5.5.

The turbulence of wind over 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 speed, 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

### 5.4.2.3 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) |
| $\alpha$ | = | power law exponent, values of which are given in Section 5.4.2.7 and 5.4.2.8 |
| $z$ | = | height above the SWL, in m (ft) |
| $z_{hub}$ | = | hub height above the SWL, in m (ft) |

For extreme storm wind conditions at open ocean sites, the mean wind speed profile may also 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.

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

For strong wind conditions, such as a hurricane wind in the Gulf of Mexico with return period in excess of 10 years, API RP 2A-WSD (2007) recommends using the NPD wind spectrum (also known as Frøya model) in conjunction with the two-point coherence function and the logarithmic wind shear law to model hurricane wind conditions

#### *5.4.2.5 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 duration as are used for the determination of loads.

#### *5.4.2.6 Wind Conditions*

A wind condition for offshore wind turbine design is represented by a constant mean flow combined with either a varying deterministic gust profile or turbulence. Wind conditions referred to in Section 5 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 5.4.2.7 through 5.4.2.9. The load case descriptions in Section 5.5 indicate which wind condition should be applied.

#### *5.4.2.7 Normal Wind Conditions*

*i.)* Normal Wind Profile Model (NWP)

The NWP model (vertical wind shear) should be defined by the power law specified in Section 5.4.2.3, where the power law exponent $\alpha = 0.14$.

*ii.)* Normal Turbulence Model (NTM)

The NTM model should be applied together with the normal wind profile model (NWP) 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.

#### *5.4.2.8 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 5.4.2.3 and 5.4.2.4. 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 should be taken as $0.11 \times V_{hub}$.

The EWM model should be applied in combination with the Extreme Sea State (ESS) defined in Section 5.4.3.3 and the Extreme Current Model (ECM) defined in Section 5.4.4.3.

*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 several classification society criteria for bottom-founded offshore wind turbines, need to be considered in the design of floating support structures. 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)

#### *5.4.2.9 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 5.4.2.8, 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 5.4.2.3 and 5.4.2.4. 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 should be taken as $0.11 \times V_{hub}$.

### 5.4.3 Waves

#### *5.4.3.1 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 such exist. Hindcasting 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 floating support structure and the stationkeeping system
- Maximum responses of structures and stationkeeping system components
- Fatigue
- Provision for air gap
- Impact on local structures

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, considerations should be given to waves of less than the maximum height but with different period and/or direction. 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 the design of the floating support structure and the stationkeeping system of a floating offshore wind turbine are defined in Sections 5.4.3.2 through 5.4.3.5. The load case descriptions in Section 5.5 are specified using various wave conditions as described below in this section. The return period for the severe, extreme and survival wave conditions is defined in Section 5.5.

#### *5.4.3.2 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. The NSS model should be determined based on the site-specific long-term joint probability distribution of metocean parameters conditioned upon a number of given 10-minute mean wind speeds at hub height ($V_{hub}$).

The normal sea state is used in Section 5.5 to define several Design Load Cases (DLCs) required for either strength analysis or fatigue analysis. For fatigue calculations, the number and resolution of 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 load calculations. The resultant most unfavorable responses should be used in the design of floating support structure and stationkeeping system.

#### *5.4.3.3 Extreme Sea State (ESS)*

The ESS model should represent 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 the 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 the floating support structure and the stationkeeping system.

The ESS model should be applied in combination with the Extreme Wind Model (EWM) defined in Section 5.4.2.8 and the Extreme Current Model (ECM) defined in Section 5.4.4.3.

#### *5.4.3.4 Severe Sea State (SSS)*

The SSS model should be applied in combination with the normal wind conditions as specified in Section 5.4.2.7 for the strength analysis of the floating support structure and 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 described in Section 5.4.3.3. A series of $V_{hub}$ should be selected within the range of mean wind speed corresponding to 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 floating support structure and stationkeeping system

#### *5.4.3.5 Survival Sea State (SurSS)*

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

#### *5.4.3.6 Breaking Waves*

Where breaking waves are likely to occur at the installation site, the loads exerted by those breaking waves 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.

### 5.4.4 Currents

#### *5.4.4.1 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 should 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 extratropical 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 floating offshore wind turbines in U.S. offshore regions, the current profile should be determined in accordance with Sections 2.3.3 and 2.3.4 of API RP 2A-WSD (2007).

The current models for the design of the floating support structure and the stationkeeping system of a floating offshore wind turbine are specified in Sections 5.4.4.2 through 5.4.4.4. The load case descriptions in Section 5.5 indicate which current condition should be applied in each DLC.

#### *5.4.4.2 Normal Current Model (NCM)*

The Normal Current Model is defined to represent site-specific wind generated currents conditioned upon a given 10-minute mean wind speed at hub height. Tide and storm-generated sub-surface currents are not included. The normal current model is applied in combination with the normal or severe sea states (NSS or SSS) defined in Section 5.4.3.2 and 5.4.3.4, respectively.

#### *5.4.4.3 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 5.4.2.8 and the Extreme Sea State (ESS) defined in Section 5.4.3.3.

#### *5.4.4.4 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 as specified in Section 5.5.

### 5.4.5 Tides, Storm Surges, and Water Levels

#### *5.4.5.1 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 should be estimated from available statistics or by mathematical storm surge modeling. The still water level (SWL) referenced in the definition of environmental conditions for load calculation 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 the design criteria proposed in Section 5 are illustrated in Figure 5.1.

For the TLP-type floating offshore wind turbine, variations in the elevation of the daily tide may be used in determining the elevations of boat landings, barge fenders and the top of the splash zone for corrosion protection of structure. Water depths assumed for various types of analysis should be clearly stated.

The water level range for the design of the floating support structure and the stationkeeping system of a floating offshore wind turbine are specified in Section 5.4.4.2 to 5.4.4.4. The load cases descriptions in Table 5.1 indicate which current condition should be applied.

#### *5.4.5.2 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 load cases should be performed based on the water level within the NWLR that results in the most unfavorable responses in the floating support structure. The influence of water level variation in the fatigue load cases should also be considered where relevant.

#### *5.4.5.3 Extreme Water Level Range (EWLR)*

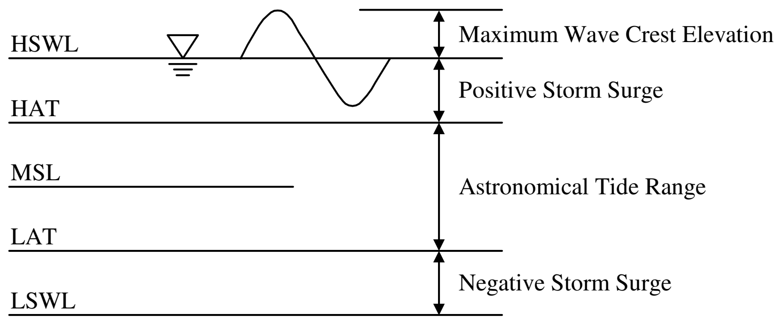
The extreme water level range with a given return period should be applied in the Design Load Cases where the extreme wave model (EWM) with the same return period is applied. Load calculations for strength load cases should be performed based on the water level within the EWLR in order to determine the most unfavorable responses in the floating support structure and 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 Still Water Level (MSL)
- The highest still water level (HSWL), defined as a combination of highest astronomical tide (HAT) and positive storm surge, with a given return period
- The lowest still water level (LSWL), defined as a combination of lowest astronomical tide (LAT) and negative storm surge, with a given return period
- The water level associated with the highest breaking wave load, if relevant

### *5.4.5.4 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**

## 5.4.6 Other Conditions

### *5.4.6.1 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, as relevant to the installation.

### *5.4.6.2 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.

#### *5.4.6.3 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.

#### *5.4.6.4 Marine Growth*

Marine growth should be considered in the design of the floating support structure and the stationkeeping system. 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.

#### *5.4.6.5 Soil Conditions*

Site investigation should be performed and soil data should be taken in the vicinity of the tendon foundation or anchoring site and export cable touchdown area. 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 probings 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 further guidance on soil and sea floor conditions, see API RP 2T (2010), ISO 19901-4 (2006) and API RP 2A-WSD (2007).

#### *5.4.6.6 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 a floating offshore wind turbine should be determined. Two levels of earthquake conditions should be considered as required 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 a floating offshore wind turbine.
- 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 including, as appropriate, the following:

- 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 a floating offshore wind turbine. 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

#### *5.4.6.7 Sea Ice or Lake Ice*

For a floating offshore wind turbine intended to be installed in areas where ice hazards may occur, the effects of sea ice or lake ice on the floating support structure and 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 moving ice and fast ice covering.

Statistical ice data for the site should be used as the basis for deriving 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 Coriolis Effect should be considered in the design.

The interaction between ice and the floating offshore wind turbine produces responses in the ice, the floating support structure and the stationkeeping system. Such 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.

#### *5.4.6.8 Lightning*

The lightning protection of a floating offshore wind turbine should be designed in accordance with IEC 61400-24. It is not necessary for protective measures to extend to all parts of the wind turbine, provided that safety is not compromised.

## 5.5 Loads

This section pertains to the identification, definition and determination of the loads to which a floating offshore wind turbine may be subjected in its pre-service (load-out, transportation and installation), in-service (operating, maintenance and repair), and decommissioning phases.

### 5.5.1 Types of Loads to be Considered

Loads applied to a floating offshore wind turbine are categorized as permanent loads, variable loads, environmental loads, and accidental loads.

#### *5.5.1.1 Permanent Loads*

Permanent loads are loads which do not change during the mode of operation under consideration. Permanent loads include, but are not limited to, the following.

- Weight of rotor components (blades, hub, shaft, etc.) and equipment inside the nacelle (control and protection components, gearbox, drive train components, electrical generation components, cables, etc.)
- Weight of nacelle housing structure, floating support substructure, stationkeeping systems, export cable system, fenders, ladders, corrosion protection system, and other permanent structures
- Permanent deformation and loads introduced during fabrication
- External hydrostatic pressure
- Pre-tension in mooring lines
- Static earth pressure

#### *5.5.1.2 Variable Loads*

Variable loads associated with the normal operation of a wind turbine are loads which may change during the mode of operation considered. Variable loads acting during in-service phase include, but are not limited to, the following.

- Weight of personnel and consumable supplies
- Forces exerted on the wind turbine by lifting equipment during maintenance and repair

- Forces exerted on the floating offshore wind turbine support structure by vessels moored to the structure or routine impact loads from a typical supply vessel that would normally service the installation
- Loads associated with helicopter operations, where relevant
- Actuation loads generated by wind turbine operations and controls including torque control from a generator or inverter, yaw and pitch actuator loads, and mechanical braking loads. The range of actuator forces should be considered as appropriate in the calculation of response and loading. In particular, the range of friction, spring force or pressure for mechanical brakes is influenced by temperature and aging, which should be taken into account when calculating the response and loading during any brake event.
- Deformation loads due to deformation imposed on the floating support structure and the stationkeeping system. The deformation loads include those due to temperature variations leading to thermal stress in the structure and, where necessary, loads due to soil displacements (e.g., differential settlement or lateral displacement) or due to deformations of adjacent structures.

Where applicable, the dynamic effects of the variable loads on the floating support structure and the stationkeeping system should be taken into account.

Variable loads encountered during pre-service and decommissioning phases should be determined for each specific operation involved and the dynamic effects of such loads should be accounted for as necessary.

#### *5.5.1.3 Environmental Loads*

Environmental loads are loads due to the action of wind, wave, current, ice, snow, earthquake, marine growth and other environmental phenomena as described in Section 5.4. The characteristic parameters defining environmental loads should be appropriate to the installation site of floating offshore wind turbines and in accordance with the requirements specified Section 5.4. The combination and severity of environmental conditions for the design of the floating support structure and the stationkeeping system are specified in Section 5.5.2. Calculations of environmental loads should be in accordance with Section 5.5.3.

Directionality should be taken into account in applying the environmental criteria. Unless site-specific studies provide evidence in support of a less stringent requirement, environmental loads should be applied from directions producing the most unfavorable effects on the floating support structure or the stationkeeping system.

#### *5.5.1.4 Accidental Loads*

The occurrence of accidental events and the resultant loads should be assessed in the design of the floating support structure and the stationkeeping system. The accidental event may include exceptional conditions, such as collisions, dropped objects, fire, explosion, or flooding.

### 5.5.2 Design Load Cases

#### *5.5.2.1 General*

Design load conditions should be represented by a set of Design Load Cases (DLCs), which are defined by the combinations of turbine operational modes, site-specific environmental conditions, electrical network conditions and other applicable design conditions, such as specific load-out, transportation, installation, maintenance, repair and decommissioning conditions. All relevant DLCs with a reasonable probability of occurrence and covering the most significant conditions that a floating offshore wind turbine may experience should be considered in the design.

As a minimum, the DLCs defined in Table 5.1 and described in Section 5.5.2.2 and 5.5.2.3 should be assessed in the design of a floating offshore wind turbine. The DLCs specified in Table 5.1 are adapted from “Table 1 – Design load cases” in IEC 61400-3 (2009) for bottom-founded offshore wind turbines, with various modifications to address unique load and response characteristics of the floating support structure and the stationkeeping system.

Other design load cases should be considered, whenever they are deemed relevant to the structural integrity of a specific floating offshore wind turbine design. In particular, if correlation exists between an extreme environmental condition and a fault condition of wind turbine, a realistic combination of the two should be considered as a design load case. Due considerations should also be given to the effect of Vortex-Induced-Vibration (VIV) on the floating support structure and the stationkeeping system. For those floating offshore wind turbines to be deployed at ice-infested offshore sites, design load cases should be specified to account for the effect of fast ice formation and moving ice on the floating support structure and the stationkeeping system.

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 permanent loads and variable loads. Combinations of the load effects that produce the most severe local and global effects on the floating support structure or the stationkeeping system, as determined by the requirements of pre-service, in-service and decommissioning phases as well as different nature of structures, should be used.

Extreme metocean conditions in a specific load case (e.g. DLC 6.1 in Table 5.1) 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, with the consideration of the peak wind, peak wave and 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.

#### *5.5.2.2 Design Load Cases (DLCs) for Floating Support Structures*

As a minimum, the DLCs defined in Table 5.1 should be assessed. For each DLC, the "Type of Analysis" is denoted as "S" for strength or "F" for fatigue analysis. The results of the strength analysis are used in the structural assessment with acceptance criteria for the yielding and buckling. The results of fatigue analysis are used in the structural assessment with criteria pertaining to fatigue performance.

Those DLCs indicated with "S", are further classified as normal (N), abnormal (A), or load-out, transportation, installation, maintenance, repair and decommissioning (T) of a floating offshore wind turbine. Normal design conditions are expected to occur frequently during the lifetime of a floating offshore wind turbine. The corresponding operational mode of the turbine is in a normal state or with minor faults or abnormalities. Abnormal design conditions are less likely to occur than normal design conditions. They usually correspond to design conditions with severe faults that result in activation of system protection functions. The type of design conditions, N, A, or T, determines the safety factor, as specified in Section 5.7, to be applied in the design of the floating support structure.

The descriptions and analysis requirements for DLCs defined in Table 5.1, as well as the amendment to the original DLCs specified in IEC 61400-3 (2009), are presented as follows. Further reference is made to Section 7.4 and Section 7.5.4 of IEC 61400-3 (2009).

*i.)* The DLC serial numbers are in accordance with those specified in IEC 61400-3 (2009).

*ii.)* DLC 1.1 required by IEC 61400-3 (2009) for calculation of the ultimate loads acting on the RNA is not included Table 5.1, which is specified for the design of the floating support structures and the stationkeeping systems of offshore wind turbines.

*iii.)* The DLCs associated with regular wave conditions as defined in IEC 61400-3 (2009) are not applicable to the design of floating offshore wind turbines 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.)* The safety factors referenced in Table 5.1 are specified in Section 5.7 for the design of the floating support structure.

*v.)* The design environmental conditions referred to in Table 5.1 for winds, waves, sea currents, and water level ranges are in accordance with the definitions specified in Section 5.4. Detailed references are listed in the table notes.

*vi.)* The Site-specific extreme wind speed with a specified return period 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 reference is made to the turbine'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 in DLC 6.1 and DLC 6.2 and for the severe wave conditions in DLC 1.6 should not be less than 50 years, unless appropriate justifications are provided and such reduction is acceptable to national authorities (or Administrations) having jurisdiction over the floating offshore wind turbine.

*ix.)* DLC 6.2 assumes a loss of connection to the electrical power network at an early stage of a storm containing the extreme wind conditions. A nacelle yaw misalignment ranging between -180° and +180° should be assumed for DLC 6.2. Load calculations should be based on the misalignment angle that results in the highest load acting on the floating support structure. The range of yaw misalignment assumed in the design of the floating support structure 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 floating offshore wind turbine.

*x.)* For those load cases, including DLC 6.1, 6.2, 6.3, 7.1, and 8.2, which require full time domain dynamic simulations for the combined extreme turbulent wind and extreme stochastic 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 10-minute mean wind speed and significant wave height 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 for bottom-founded offshore wind turbines. 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, provided 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 should be increased by 0.2 m/s (0.66 ft/s) relative to the value associated with 10-minute mean wind speed. For a floating support structure, a simulation time duration longer than one hour may be required in order to provide sufficient information for calculating the statistics of low frequency responses. An appropriate adjustment to the wind model should be applied such that the extreme responses can be adequately estimated.

*xi.)* Where a wind speed range is indicated in Table 5.1, wind speeds leading to the most unfavorable responses should be considered for the design of the floating support structure. When the range of wind speeds is represented by a set of discrete values, the interval between two adjacent discrete wind speeds should not be greater than 2 m/s

(6.6 ft/s), In addition, the turbine Rated Wind Speed ($V_r$), where applicable, should be included as one of the discrete wind speeds to be used in the load calculation.

*xii.)* The description for DLC 8.x is revised to “Load-out, transportation, installation, maintenance, repair and decommissioning”. The environmental condition for transportation should be a 10-year return event of the selected transit route, unless a weather routing plan is implemented for the voyage.

*xiii.)* 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 floating support structure. For DLC 6.x and DLC 7.x, the misalignment between wind and wave directions should be considered up to 90° for tropic cyclones.

*xiv.)* Section 5.5.2.1 should be consulted for the general requirements on DLCs.

#### *5.5.2.3 Design Load Cases (DLCs) for Stationkeeping Systems*

The DLCs in Table 5.1 should be applied, as a minimum, to the design of stationkeeping system. When site-specific directional data are not available, the direction of applied environmental loads should be determined to produce the most unfavorable effect on the stationkeeping system.

The safety factors for the stationkeeping system design are discussed in Section 5.8. The association between safety factors and designation “N”, “A” and “T” turbine operating conditions are not applicable to the stationkeeping system design.

Section 5.5.2.1 should be consulted for the general requirements on DLCs. 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, the consideration of the effect of following conditions, whenever applicable.

- Vortex Induced Vibration (VIV) fatigue due to the site current conditions established in accordance with Section 5.4.4
- Earthquake-induced foundation movements on the design of TLP tendon system for the TLP-type floating support structures located in seismically active areas (see Section 5.4.6.6)
- Loads due to fast ice formation and moving ice at offshore sites where sea ice or lake ice is expected to occur (see Section 5.4.6.7)

**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* | *Safety Factor* |
|---|---|---|---|---|---|---|---|---|---|
| 1) Power production | 1.2 | NTM, NWP<br>$V_{in} \le V_{hub} \le V_{out}$ | NSS Joint prob. distribution of $H_s$, $T_p$, $V_{hub}$ | COD, MUL | NCM | NWLR or $\ge$ MSL | | F | FDF |
| | 1.3 | ETM<br>$V_{in} \le V_{hub} \le V_{out}$ | NSS<br>$H_s = E[H_s \| V_{hub}]$ | COD, UNI | NCM | MSL | | S | N |
| | 1.4 | ECD<br>$V_{hub} = V_r - 2$ m/s (6.6 ft/s), $V_r$, $V_r$+ 2 m/s (6.6 ft/s) | NSS<br>$H_s = E[H_s \| V_{hub}]$ | MIS, wind direction change | NCM | MSL | | S | N |
| | 1.5 | EWS<br>$V_{in} \le V_{hub} \le V_{out}$ | NSS<br>$H_s = E[H_s \| V_{hub}]$ | COD, UNI | NCM | MSL | | S | N |
| | 1.6 | NTM, NWP<br>$V_{in} \le V_{hub} \le V_{out}$ | SSS<br>$H_s = H_{s,SSS}$ | COD, UNI | NCM | NWLR | | S | N |
| 2) Power production plus occurrence of fault | 2.1 | NTM<br>$V_{in} \le V_{hub} \le V_{out}$ | NSS<br>$H_s = E[H_s \| V_{hub}]$ | COD, UNI | NCM | MSL | Control system fault or loss of electrical network | S | N |
| | 2.2 | NTM<br>$V_{in} \le V_{hub} \le V_{out}$ | NSS<br>$H_s = E[H_s \| V_{hub}]$ | COD, UNI | NCM | MSL | Protection system or preceding internal electrical fault | S | A |
| | 2.3 | EOG<br>$V_{hub} = V_r \pm 2$ m/s (6.6 ft/s) and $V_{out}$ | NSS<br>$H_s = E[H_s \| V_{hub}]$ | COD, UNI | NCM | MSL | External or internal electrical fault including loss of electrical network | S | A |
| | 2.4 | NTM<br>$V_{in} \le V_{hub} \le V_{out}$ | NSS<br>$H_s = E[H_s \| V_{hub}]$ | COD, UNI | NCM | NWLR or $\ge$ MSL | Control, protection, or electrical system faults including loss of electrical network | F | FDF |

**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* | *Safety Factor* |
|---|---|---|---|---|---|---|---|---|---|
| 3) Start-up | 3.1 | NWPs<br>$V_{in} \le V_{hub} \le V_{out}$ | NSS<br>$H_s = E[H_s \vert V_{hub}]$ | COD, UNI | NCM | NWLR or $\ge$ MSL | | F | FDF |
| | 3.2 | EOG<br>$V_{hub} = V_{in}$, $V_r \pm 2$ m/s (6.6 ft/s) and $V_{out}$ | NSS<br>$H_s = E[H_s \vert V_{hub}]$ | COD, UNI | NCM | MSL | | S | N |
| | 3.3 | EDC<br>$V_{hub} = V_{in}$, $V_r \pm 2$ m/s (6.6 ft/s) and $V_{out}$ | NSS<br>$H_s = E[H_s \vert V_{hub}]$ | MIS, wind direction change | NCM | MSL | | S | N |
| 4) Normal shut down | 4.1 | NWP<br>$V_{in} \le V_{hub} \le V_{out}$ | NSS<br>$H_s = E[H_s \vert V_{hub}]$ | COD, UNI | NCM | NWLR or $\ge$ MSL | | F | FDF |
| | 4.2 | EOG<br>$V_{hub} = V_r \pm 2$ m/s (6.6 ft/s) and $V_{out}$ | NSS<br>$H_s = E[H_s \vert V_{hub}]$ | COD, UNI | NCM | MSL | | S | N |
| 5) Emergency shut down | 5.1 | NTM<br>$V_{hub} = V_r \pm 2$ m/s (6.6 ft/s) and $V_{out}$ | NSS<br>$H_s = E[H_s \vert V_{hub}]$ | COD, UNI | NCM | MSL | | S | N |

**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* | *Safety Factor* |
|---|---|---|---|---|---|---|---|---|---|
| 6) Parked (standing still or idling) | 6.1 | EWM<br>$V_{hub} = k_1 V_{10\text{min},50\text{-yr}}$ | ESS<br>$H_s = k_2 H_{s,50\text{-yr}}$ | MIS, MUL | ECM<br>50-yr Currents | EWLR<br>50-yr Water Level | | S | N |
| | 6.2 | EWM<br>$V_{hub} = k_1 V_{10\text{min},50\text{-yr}}$ | ESS<br>$H_s = k_2 H_{s,50\text{-yr}}$ | MIS, MUL | ECM<br>50-yr Currents | EWLR<br>50-yr Water Level | Loss of electrical network | S | A |
| | 6.3 | EWM<br>$V_{hub} = k_1 V_{10\text{min},1\text{-yr}}$ | ESS<br>$H_s = k_2 H_{s,1\text{-yr}}$ | MIS, MUL | ECM<br>1-yr Current | NWLR | Extreme yaw misalignment | S | N |
| | 6.4 | NTM<br>$V_{hub} \leq V_{10\text{min},1\text{-yr}}$ | NSS Joint prob. distribution of $H_s, T_p, V_{hub}$ | COD, MUL | NCM | NWLR or ≥ MSL | | F | FDF |
| 7) Parked and fault conditions | 7.1 | EWM<br>$V_{hub} = k_1 V_{10\text{min, }1\text{-yr}}$ | ESS<br>$H_s = k_2 H_{s,1\text{-yr}}$ | MIS, MUL | ECM<br>1-yr Current | NWLR | | S | A |
| | 7.2 | NTM<br>$V_{hub} \leq V_{10\text{min},1\text{-yr}}$ | NSS Joint prob. distribution of $H_s, T_p, V_{hub}$ | COD, MUL | ECM<br>1-yr Current | NWLR or ≥ MSL | | F | FDF |
| 8) Load-out, transportation, installation, maintenance, repair and decommissioning | 8.1 | To be defined by the manufacturer and/or operator | | | | | | S | T |
| | 8.2 | EWM<br>$V_{hub} = k_1 V_{10\text{min},1\text{-yr}}$ | ESS<br>$H_s = k_2 H_{s,1\text{-yr}}$ | COD, UNI | ECM<br>1-yr Current | NWLR | | S | A |
| | 8.3 | NTM<br>$V_{hub} \leq V_{10\text{min},1\text{-yr}}$ | NSS Joint prob. distribution of $H_s, T_p, V_{hub}$ | COD, MUL | NCM | NWLR or ≥ MSL | No grid during installation period | F | FDF |

**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.
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 (5.4.2.8) |
| ECM | extreme current model (5.4.4.2) |
| EDC | extreme direction change (5.4.2.8) |
| EOG | extreme operating gust (5.4.2.8) |
| ESS | extreme sea state (5.4.3.3) |
| EWLR | extreme water level range (5.4.5.3) |
| EWM | extreme wind speed model (5.4.2.8) |
| EWS | extreme wind shear (5.4.2.8) |
| ETM | extreme turbulence model (5.4.2.8) |
| MIS | misaligned wind and wave directions |
| MSL | mean sea level (Figure 1) |
| MUL | multi-directional wind and wave |
| NCM | normal current model (5.4.4.2) |
| NTM | normal turbulence model (5.4.2.7) |
| NWLR | normal water level range (5.4.5.2) |
| NWP | normal wind profile model (5.4.2.7) |
| NSS | normal sea state (5.4.3.2) |
| SSS | severe sea state (5.4.3.4) |
| UNI | uni-directional wind and wave directions |
| F | fatigue (5.7.4 and 5.8.4) |
| S | strength (5.7.3 and 5.8.4 ) |
| N | normal (5.5.2.1) |
| A | abnormal (5.5.2.1) |
| T | load-out, transportation, installation, maintenance, repair and decommissioning (5.5.2.2) |
| FDF | fatigue design factor (5.7.4 and 5.8.4) |
| $H_s$ | 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 (5.5.2.2) |
| $k_2$ | simulation time scaling factors for significant wave height (5.5.2.2) |
| $T_p$ | 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 (5.2.2.2) |
| $V_r \pm 2$ m/s (6.6 ft/s) | Sensitivity to the wind speeds in the range should be analyzed (5.5.2.2) |

### 5.5.3 Survival Load Cases

The survival load cases should be assessed for the robustness check of the integrity of the stationkeeping system and the air gap (also known as deck clearance or freeboard). Although such a survival check is not required for the structural strength of the floating support structure, the global loads and their effect on the structural integrity should be evaluated when an insufficient air gap resulting in submergence of the deck structure, transition piece or tower is observed.

As a minimum, the survival load cases specified in Table 5.2 should be assessed in the robustness check of a floating offshore wind turbine. The probability of joint occurrence of environmental parameters should be taken into account when establishing extreme metocean conditions, with the consideration of the peak wind, peak wave and peak current condition (see e.g. API Bulletin 2INT-MET, 2007). The effect of environmental loads should be combined with the effect of permanent loads and variable loads. Combinations of the load effects that produce the most unfavorable local and global effects on the stationkeeping system or the air gap should be used to assess the design adequacy.

The safety factors applicable for the survival load case are described in Section 5.8.4 and Section 5.8.6. The differentiation of “N”, “A” and “T” turbine operating conditions is not applicable to the survival load cases.

For the TLP-type floating support structures, the robustness check under survival load cases should also include the assessment of minimum tendon tension. When the “one-tendon removed” case is relevant, the robustness check for the tendon system with one-tendon removed and subjected to a 50-year return extreme environmental event should also be assessed. Additionally, fatigue damage in the tendon system caused by a single extreme environmental event with a return period of 50 years should be evaluated according to API RP 2T (2010).

**Table 5.2 Survival Load Cases**

| *Design Condition* | *Wind Condition* | *Waves* | *Wind and Wave Directionality* | *Sea Currents* | *Water Level* |
|---|---|---|---|---|---|
| Parked RNA<br>Intact Blades<br>Intact Hull | SurWM<br>$V_{hub} = k_1 V_{10min,n\text{-}yr}$ | SurSS<br>$H_s = k_2 H_{s,n\text{-}yr}$ | MIS, MUL | SurCM<br>n-yr<br>Currents | SurWLR<br>n-yr<br>Water Level |
| Parked RNA<br>Damaged Blade(s)<br>Intact Hull | SurWM<br>$V_{hub} = k_1 V_{10min,500\text{-}yr}$ | SurSS<br>$H_s = k_2 H_{s,500\text{-}yr}$ | MIS, MUL | SurCM<br>500-yr<br>Currents | SurWLR<br>500-yr<br>Water Level |

*Notes:*

1. "Parked RNA, Damaged Blades, Intact Hull" case should be considered when turbine blades can not 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 |
| $H_{s,n\text{-}yr}$ | significant wave height with a return period of $n$ years |
| $H_{s,500\text{-}yr}$ | significant wave height with a return period of 500 years |
| $V_{10min,n\text{-}yr}$ | 10 minute average wind speed at hub height with a return period of $n$ years |
| $V_{10min,500\text{-}yr}$ | 10 minute average wind speed at hub height with a return period of 500 years |
| SurWM | survival wind model (5.4.2.9) |
| SurSS | survival sea state (5.4.3.5) |
| SurCM | survival current model (5.4.4.4) |
| SurWLR | survival water level range (5.4.5.4) |

Other symbols and abbreviations used in the table are defined in the Notes of Table 5.1.

### 5.5.4 Accidental Load Cases

The structural design of the floating support structure should take into account the possibility of accidental events as described in Section 5.5.1.4. The design should consider the damaged condition with reduced structural capacity and higher hydrostatic pressure due to damaged waterline. Hydrostatic stability of the structure in the damaged condition should also be investigated in accordance with the requirement specified in Section 5.9 on the damage stability and compartmentation of the hull.

Two accidental load cases specified below should be assessed, whenever relevant. The safety factors applicable for the accidental load cases are described in Section 5.7.5. The association between safety factors and designation "N", "A" and "T" turbine operating conditions are not applicable to the accidental load cases.

*i.)* Accidental load case for the floating support structure at the time when an accidental event occurs

Loads induced by each accidental event should be combined with permanent loads and variable loads. Combinations of the loads that produce the most unfavorable local and global effects on the floating support structure should be applied.

*ii.)* Accidental load case for the floating support structure that has damages or flooded compartments after an accidental event has occurred

The probability of joint occurrence of environmental parameters should be taken into account when establishing extreme metocean conditions, with the consideration of the peak wind, peak wave and peak current condition. The environmental load conditions are specified in Table 5.3. The effect of environmental loads should be combined with the effect of permanent loads and variable loads. Combinations of the load effects that produce the most unfavorable local and global effects on the floating support structure should be used to assess the design adequacy.

**Table 5.3 Accidental Load Case for Post-Accident Assessment**

| *Design Condition* | *Wind Condition* | *Waves* | *Wind and Wave Directionality* | *Sea Currents* | *Water Level* |
|---|---|---|---|---|---|
| Parked RNA<br>Damaged and/or Flooded Hull | EWM<br>$V_{hub} = k_1 V_{10\text{min},1\text{-yr}}$ | ESS<br>$H_s = k_2 H_{s,1\text{-yr}}$ | MIS, MUL | ECM<br>1-yr Currents | NWLR |

*Notes:*

1. The symbols and abbreviations used in the table are defined in the Notes of Table 5.1.

## 5.5.5 Determination of Environmental Loads

### *5.5.5.1 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 characteristics of the floating wind turbine and site conditions.

#### 5.5.5.2 *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 a floating offshore wind turbine. Static and dynamic wind load effects generated directly by the inflowing wind and indirectly by the wind generated motions of the floating offshore wind turbine and the operations of the floating offshore wind turbine should be taken into account.

Aerodynamic loads induced by airflow 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.

For floating offshore wind turbines installed in a wind farm, the shadow effect and wake effect on the loads should be considered for both strength and fatigue analyses. For large wind farms, an increase in the turbulence intensity or surface roughness should be taken into account. The mutual influence of floating offshore wind turbines through the wake interaction behind the rotor should be considered up to a distance of 10 times of rotor diameter. Reference is made to IEC 61400-1 (2005) for the guidance on the wake effects from neighboring offshore wind turbines.

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 using 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, as applicable. Both drag and lift components of load 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 when applicable. This would especially apply to load-out or transportation phases.

#### *5.5.5.3 Wave Forces*

The wave forces acting on a floating offshore wind turbine consist of three primary components, i.e., first order forces at wave frequencies, second order forces at frequencies lower than the wave frequencies and steady components of the second order forces (also known as mean drift forces). For the TLP-type floating offshore wind turbine, high-frequency wave loads also need to be considered as they may excite the floating support structure at its natural periods in heave, roll and pitch with typical natural periods ranging from 1 to 5 seconds.

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 to a structure 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 a 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.

Wave slamming loads should be considered for members such as pontoons, columns, braces, and members forming the underside of the topside deck structure that are subjected to wave slamming during transportation and operation. Breaking wave slamming loads should also be considered, if applicable. Guidance on the breaking wave hydrodynamics and the slamming loads exerted by a breaking wave on a cylindrical member is given in IEC 61400-3 (2007), Annex C and D. The calculation of local slamming pressure and scantling design requirements may be found in applicable classification society criteria or equivalent.

Vortex Induced Vibration (VIV) is a resonant response incurred by vortex shedding at resonant frequencies of long slender bodies in current. Effects of VIV on fatigue and increased drag loads should be assessed for the slender hull structures and the mooring system.

Green water effects should be considered for the strength of affected structures on the top of the hull, as applicable.

#### *5.5.5.4 Wave-induced Motion Responses*

The wave-induced response of a floating offshore wind turbine 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) and are 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 load in the mooring lines could be a dominating design load 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

A floating offshore wind turbine 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 model tests.

*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).

#### *5.5.5.5 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.

#### *5.5.5.6 Ice and Snow Accumulation Induced Loads*

At locations where floating offshore wind turbines 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.

#### *5.5.5.7 Earthquake Loads*

For floating offshore wind turbines supported by the tendon system and located in seismically active areas, the Strength Level and Ductility Level earthquake induced ground motions (see Section 5.4.6.5) should be determined based on seismic data applicable to the installation site. Reference is 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 that such spectra reflect site-specific conditions affecting frequency content, energy distribution, and duration. These conditions include:

- type of active faults in the region
- proximity of the site to the potential source faults
- attenuation or amplification of ground motion between the faults and the site
- 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.

#### *5.5.5.8 Marine Growth*

The following effects of anticipated marine growth should be considered in the design.

- Increase in hydrodynamic diameter
- Increase in surface roughness used in the determination of hydrodynamic coefficients (e.g., lift, drag and inertia coefficients)
- Increase in 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.

#### *5.5.5.9 Ice Loads*

Ice loads acting on a floating offshore wind turbine are both static and dynamic loads. Static loads are normally generated by temperature fluctuations or changes in water level in a fast ice covering. Dynamic loads are caused by moving ice interactions with the floating support structure and the stationkeeping system. The global forces exerted by ice on the floating support structure as whole 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).

## 5.6 Global Performance Analysis

### 5.6.1 General

Global performance analyses should determine the global effects of environmental and other loads on a floating offshore wind turbine and its components, such as nacelle, floating support structure, mooring lines, anchors, export cable, etc. Global response analyses should be performed for each of the most critical design phases, represented by the load conditions specified in Section 5.5.

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) and cable 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

Because significant interactions could occur among the turbine, 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 stationkeeping systems 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 for the floating offshore wind turbine. The analysis procedures should reflect the application limit of the selected software. Both industry-recognized software and in-house software may be used for the analyses. However, in-house software has to be adequately validated against model tests or 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 applicable 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 applicable classification society criteria.

### 5.6.2 Frequency Domain Analyses

Frequency domain analyses solve the equations of motion using methods of harmonic analysis or methods of Laplace and Fourier transformations.

In order to evaluate the wave-frequency responses of the floating support structure and the stationkeeping system, the linear wave theory is usually employed in the wave frequency analysis. Alternative methods may be applied to evaluate the effects of finite amplitude waves. The low frequency analysis should be carried out to evaluate the effects caused by wind dynamics and wave drift forces. The damping levels used in the analyses should be properly determined and documented. For the TLP-type of floating support structure, where second-order sum-frequency effects are determined to be significant, the high frequency springing analyses should also be carried out to evaluate the springing responses of the floating support structure and tendons. Frequency domain analyses for aerodynamic responses of turbine RNA and effects of turbine control systems should be properly formulated. Combined aerodynamic, hydrodynamic and control system actions in the frequency domain should be used in the calculation of dynamic responses the Floating Offshore Wind Turbine Installation.

Frequency-domain analyses, by nature, cannot capture nonlinear dynamic interactions among the RNA, the floating support structure and the stationkeeping system. They are also not able to take into account transient responses, nonlinear aerodynamic and hydrodynamic load effects, and effects of turbine's control systems and operating conditions. Because of these limitations, currently available simulation software for floating offshore wind turbines are mostly based on the time domain analysis approach as described below in Section 5.6.3. Frequency domain analyses are usually performed to calculate the hydrodynamic coefficients which are used as input to time domain analyses.

### 5.6.3 Time Domain Analyses

The time domain analysis procedure consists of a numerical solution of the equations of motion for the floating support structure subjected to external forces exerted by actions of environmental conditions, the stationkeeping system, and the operations of wind turbine.

In time domain analyses, wind and wave spectra are transferred to time series for simulating turbulent wind conditions and stochastic wave elevations and kinematics. The most probable maximum responses should be predicted using appropriate distribution curves fitted to the simulation results or other recognized statistical techniques. Time domain analyses should be carried out for a sufficiently long time to achieve stationary statistics, particularly for low frequency responses. Multiple realizations of the same conditions may be necessary to generate adequate data for statistical analysis and to verify consistency of the simulation.

Time domain analyses are preferable approaches for global performance analysis of the floating offshore wind turbine, primarily because they can take into account the nonlinear and transient effects in global responses of a floating offshore wind turbine. These nonlinear effects include hydrodynamic drag forces, finite wave amplitude effects, nonlinear restoring forces from moorings, and motion suppression devices or components (e.g. heave plates). When an integrated (coupled) model is used for global performance analyses, coupling effects among the turbine RNA, the floating support structure and the stationkeeping system can be taken into account at each analysis time step. A more realistic simulation of the effects of turbine control system and turbine's operating conditions can be achieved using this approach.

For the TLP-type floating support structure, the ringing (the high frequency vertical vibration of a TLP excited by impulsive loading) and springing (the high frequency vertical vibration of the TLP excited by cyclic loading at or near the resonant periods) should be considered in global performance analyses.

The effect of Vortex Induced Motions (VIM) for the Spar or other deep-draft slender hull structures should also be determined.

### 5.6.4 Critical Global Loads and Responses

Stochastic methods for the global performance analysis of floating offshore wind turbines provide a rational approach to calculate the global responses to irregular waves and turbulent winds. The results of global performance analyses are either in the format of response spectra in the frequency domain or the response time series in the time domain.

From the structural design point of view, engineering judgment and knowledge of structural behavior are vital for a sound and optimal structure. For this purpose, spectral-based stochastic stress analyses are not considered well suited, as correlation between internal forces/moments and stress distributions can not be established, making it difficult to optimize the structural design. Furthermore, the complexity of structural configuration of the floating support structure makes either the spectral-based or the time domain stress analyses a very costly process.

To address these issues and provide an engineering viable design method, the "design wave approach" is commonly adopted by the offshore oil and gas industry for the strength analysis of floating offshore structures. The merits of stochastic methods can be retained when the design waves are derived using the extreme stochastic values of pre-determined critical response parameters, which are compatible with a specific structural configuration. The procedures of development of the stochastic equivalent design wave cases for structural analysis are described in API RP 2T (2010) as well as applicable classification society criteria.

### 5.6.5 Air Gap (Deck Clearance or Freeboard)

Unless topside deck structures, equipments on deck, turbine tower and transition piece, and tendon system, whenever relevant, are satisfactorily designed for passage of waves and wave impact, reasonable clearance between the lowest point where the structure is not designed to withstand the wave impact and the wave crests should be established for all afloat modes of operation.

The minimum deck elevation should maintain a 1.5 m (5 ft) air gap to the lowest point of the topside deck structures when the Floating Offshore Wind Turbine Installation is subjected to the extreme environmental conditions with 50-year return environmental conditions. Local wave crest increase should also be considered in accordance to API RP 2FPS. The design criterion on air gap should be check for the design load case DLC 6.1 and DLC 6.2 specified in Section 5.5.2. Under the survival load cases, as specified in Section 5.5.3, the air gap should not be smaller than zero. The air gap criterion should also be checked at various locations on the underside of topside deck.

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 offshore wind turbine 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
- Various environmental headings
- Draft of floating support structure

### 5.6.6 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 rather to complement each other. The primary objectives of model testing are listed below:

- To determine the responses of a particular design, such as to calibrate low-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.

Relevant environmental conditions should be covered in the model testing. Due considerations should be given to the model scaling for the floating offshore wind turbine where both hydrodynamic and aerodynamic load effects need to be taken into account.

Further guidance on hydrodynamic model tests can be founded in API RP 2T (2010) and ISO 19904-1 (2006).

## 5.7 Design of Floating Support Structures

### 5.7.1 General

This section outlines general concepts and considerations to be incorporated in the design of the floating support structure of an offshore wind turbine.

#### *5.7.1.1 Design Approach*

The design requirements are defined using either the Working Stress Design (WSD) approach or the Load and Resistance Factor Design (LRFD) approach for steel components of the floating support structure. Use of other design approach formats may also be acceptable. It is designer's responsibility to demonstrate that the adopted alternative approach can result in a design with a safety level equivalent to, or exceeding that of, the design using the approach described in this section.

#### *5.7.1.2 General Design Criteria*

The floating support structure of an offshore wind turbine should be designed and analyzed for the loads to which it is likely to be exposed during pre-service, in-service and decommissioning phases. The effects of a minimum set of loading conditions, as specified in Section 5.5, on the floating support structure should be determined. The resulting structural responses of the floating support structure are not to exceed the design criteria given in Section 5.7.3.

#### *5.7.1.3 Design life*

The design life of the floating support structure of an offshore wind turbine should be not less than 20 years. A shorter design life may be acceptable for the floating offshore wind turbine installed for the purpose of testing new design concepts or conducting pilot operations.

#### *5.7.1.4 Air Gap*

A minimum air gap requirement should be satisfied in compliance with Section 5.6.5. 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 are anticipated, local strengthening of these structures may be required. Structures and equipment subjected to wave run-up or green water should be designed for the associated forces.

### *5.7.1.5 Long-Term and Secondary Effects*

Consideration should be given to the following effects, as appropriate to the planned floating support structure:

- Local vibration due to machinery, equipment and vortex shedding
- Stress concentrations at critical joints
- Secondary stresses induced by large deflection
- Cumulative fatigue
- Corrosion
- Abrasion due to ice
- Freeze-thaw action on coatings

### *5.7.1.6 Access for Inspection*

In the design of the floating support structure, considerations should be given to providing access for inspection during construction and, to the extent practicable, for survey after construction. Any openings on the floating support structure for the purpose of providing access to an offshore wind turbine should be evaluated to verify there is no adverse effect on the integrity and floating of the structure.

### *5.7.1.7 Zones of Exposure*

Measures taken to mitigate the effects of corrosion should be specified and described by the following definitions for corrosion protection zones.

*i.)* Submerged Zone: That part of the floating support structure below the splash zone.

*ii.)* Splash Zone: That part of the floating support structure containing the areas above and below the Still Water Level (SWL) and regularly subjected to wetting due to wave and tide actions. Normally, the splash zone is not easily accessible for field painting, nor protected by cathodic protection.

*iii.)* Atmospheric Zone: That part of the floating support structure above the splash zone.

Additionally, for floating offshore wind turbines located in areas subjected to floating or submerged ice, the portion of the floating support structure expected to come into contact with floating or submerged ice should be designed with consideration for such contact.

### 5.7.2 Loading Conditions

Loading conditions that produce the most unfavorable effects on the structure during pre-service and in-service operations, as well as decommissioning operations if relevant, should be considered. Loading conditions to be investigated for in-service phases should include at least those relating to both the realistic operating and environmental conditions combined with permanent and variable loads (see Section 5.5.1) that are appropriate to the function and operations of floating offshore wind turbines. The influence of the less severe environmental loads in combination with various anticipated operational loads should be investigated for their potential to produce maximum peak stresses.

Load combinations should reflect the load conditions as specified in Section 5.5.

### 5.7.3 Strength Design Criteria

#### *5.7.3.1 General*

The design of the floating support structure of an offshore wind turbine can be based on either the Working Stress Design (WSD) approach or the Load and Resistance Factor Design (LRFD) approach as specified below in Section 5.7.3.2 and 5.7.3.3, respectively. However, it is not permitted to mix elements of these two approaches in the design of the same structural component in the floating support structure.

Reference is also made to Section 5.7.1 for the general design requirements.

#### *5.7.3.2 Working Stress Design (WSD) Approach*

When the strength design of the floating support structure is based on the WSD approach, the design acceptance criteria are expressed in terms of allowable stresses. Linear, elastic methods can be used in the analysis of the floating support structure provided proper measures are taken to prevent general and local buckling failure.

The load combination should be in accordance with Section 5.7.2.

The safety factors, structural member strength capacities, and the acceptance criteria should be determined in accordance with the strength design criteria specified in Chapter 5, Section 2 of the ABS Guide for Building and Classing Offshore Wind Turbine Installations (2010), where the safety factors are defined for the normal (N) and abnormal (A) design conditions as well as the design conditions (T) related to transportation, assembly on site, maintenance and repair of offshore wind turbines (see Section 5.5.2).

In conjunction with the safety factors described above, strength capacity of structural members may be determined in according with the following design standards or their equivalent.

- API RP 2A-WSD (2007) for tubular members and joints,
- AISC Steel Construction Manual (ASD part) for the structural members with non-tubular beam-columns members,
- API Bulletin 2V (2004) for flat plate structures with or without stiffeners, and
- API Bulletin 2U (2004) for cylindrical shell structures with or without stiffeners.

#### *5.7.3.3 Load and Resistance Factor Design (LRFD) Approach*

In lieu of the WSD approach described in Section 5.7.3.2, the design of the floating support structure can also be based on the LRFD approach.

The load combination should be in accordance with Section 5.7.2. The partial safety factors for loads should be in accordance with Clause 7.6.2 of IEC 61400-3 (2009).

Reference may be made to Clause 9.7.3.3 of ISO 19904-1 (2006) for the determination of resistance factor and to applicable classification society criteria or equivalent for the calculation of the ultimate strength capacity.

#### *5.7.3.4 Survival Conditions*

The survival load conditions as specified in Section 5.5.3 are expected to occur very rarely during the design life of a floating offshore wind turbine. The robustness check under the survival load conditions is not required for the structural strength design of the floating support structure. Although it is at the designer’s discretion to perform such robustness check, the floating support structure should be designed to survive under the survival load conditions without total loss of the structure. Depending on the nature of the design, the yielding or failure of components or local areas of structure may be acceptable, provided that no progressive failure is initiated.

When an insufficient air gap resulting in submergence of the deck structure, transition piece or tower is observed under the survival load conditions, the resultant global loads and their effect on the structural integrity should be evaluated.

### 5.7.4 Fatigue Design Criteria

For structural members and joints where fatigue is a probable mode of failure, or for which experience is insufficient to justify safety from possible cumulative fatigue damage, an assessment of fatigue life should be carried out. Emphasis should be given to structural members and joints that are difficult to inspect and repair once the floating support structure is in service and those susceptible to corrosion-accelerated fatigue.

For structural members and joints that require a detailed assessment of cumulative fatigue damage, the calculated fatigue life should be greater than the design life of the floating support structure multiplied by a safety factor for fatigue life [i.e., fatigue design factor (FDF)] as defined in Table 5.4 below.

The fatigue resistance of structural details may be determined according to applicable classification society criteria or equivalent industry standards. Suitable S-N curves should be selected, with special attentions being given to the application method and limitations of those curves.

The load combination for fatigue assessment should be in accordance with Section 5.7.2. A minimum set of Design Load Cases (DLCs) for fatigue assessment is specified in Table 5.1, where “F” in the column titled as “Type of Analysis” designates the fatigue assessment.

Where the design is based on the LRFD approach, the load factors for all load categories and material/resistance factors should be taken as 1.0 in the fatigue assessment.

**Table 5.4 Safety Factors (Fatigue Design Factors) for Fatigue Life of the Floating Support Structure**

| *Importance* | *Inspectable and Repairable* | |
|---|---|---|
| | *Yes* | *No* |
| Non-Critical | 1 | 3 |
| Critical | 3 | 5 |

*Notes:*

1 "Critical" indicates that failure of these structural items would result in the rapid loss of structural integrity and produce an event of unacceptable consequence.

2 A Fatigue Design Factor of 1.0 is applicable to

- inspectable and repairable non-critical structural members above the splash zone
- diver or ROV inspectable and repairable redundant framing and plating

3 For the turbine tower structure installed above the splash zone, a Fatigue Design Factor of 2.0 may be applied provided that the tower structure is inspected at times of anticipated scheduled survey or when structural damage is suspected such that critical crack development can be detected and repaired.

### 5.7.5 Design Criteria for Accidental Load Cases

The purpose of assessing accidental load cases is to verify that the floating support structure is capable to withstand specified accidental events and maintain overall structural integrity, stability and watertightness.

The load combination for accidental load cases should be in accordance with Section 5.5.4. The safety factor should be taken as 1.0.

Where the design is based on the LRFD approach, the load factors for all load categories and the material/resistance factors should be taken as 1.0.

The damage stability criteria and watertight requirements are described in Section 5.9.

### 5.7.6 Scantling Design of the Hull Structures

The initial scantling design of hull structural members, including plating, stiffeners, girders, brackets, etc., should be based on applicable classification society criteria. The aspects that are not covered by these criteria should be based on recognized standards.

Pontoons, columns, tanks and braces may be considered either as framed or unframed shells. Ring girders, bulkheads, or other suitable diaphragms should be adequate to maintain shape and stiffness under all anticipated loadings in association with established analysis methods.

### 5.7.7 Analysis and Design of Primary Structures

#### *5.7.7.1 General*

Structural analyses should be performed to assess yielding, buckling and fatigue of the hull, the topside deck structure and main intersections of primary structural components of the hull to the topside deck structure. The purpose of these analyses is to verify the scantlings established in the basic design as described in Section 5.7.6, but should not be used to reduce these scantlings. Reference is made to API RP 2T (2010), ISO 19904-1 (2006), and applicable classification society criteria for general procedures and methodologies of structural analysis and design for the floating support structure.

#### *5.7.7.2 Global Strength Analysis*

The primary structural components of the hull, topside deck structure and turbine tower structure should be analyzed using the loading conditions specified in Section 5.7.2. The analyses should be performed using recognized calculation methods and fully documented and referenced.

The global strength of the floating support structure should be designed for withstanding the maximum global effects induced by the critical global loads/responses described in Section 5.6.4. The type of critical global loads/responses depends on the specific configuration of the floating support structure.

#### *5.7.7.3 Major Joint Analysis – Analysis for Main Intersections of Primary Structures*

When the details of main intersections are not adequately captured in the global strength model, local FEM analyses should be used to design these areas.

For Column-Stabilized or TLP-type floating support structures, the main intersections include connections of pontoon to pontoon, column to pontoon, column to topside deck structure, the tower (or the transition piece) to hull structure, and the tower to the RNA. For twin-pontoon Column-Stabilized support structures, special attention should be given to brace connections to braces, columns, pontoons, and topside deck structure.

For Spar-type floating support structures with truss connections, the main intersections include connections of top section to topside deck structure, truss to hull structure, the tower (or the transition piece) to hull structure, and the tower to the RNA. For the truss space frame of the mid-section, the design of unstiffened tubular joints, stiffened tubular joints and transition joints should comply with API RP 2A-WSD (2007). Connections of tubular structural members should be designed to provide effective load transmission between joined members, to minimize stress concentration, and to prevent excessive punching shear. Connection details should also be designed to minimize undue constraints against overall ductile behavior and to minimize the effects of post-weld shrinkage. Undue concentration of welding should be avoided.

#### *5.7.7.4 Fatigue Analysis*

The fatigue analysis should be performed to verify adequate capacity against fatigue failure within the design life. The fatigue analysis should consider the loading history of the floating support structure including both pre-service and in-service phases.

Special attention should be given to the major joints described above in Section 5.7.7.3. Attention should also be given to the designs of structural notches, cutouts, brackets, toes, and abrupt changes of structural sections where they are prone to fatigue damages.

#### *5.7.7.5 Acceptance Criteria*

The structural analysis should be performed using the design loading conditions specified in Section 5.7.2 and verified against the design criteria specified in Sections 5.7.3 through 5.7.5.

### 5.7.8 Analysis and Design of Other Major Structures

#### *5.7.8.1 General*

Depending on the specific features of the floating support structure, additional analyses may be required to verify the design of other structural components, such as

- Hull structural interface with the stationkeeping system (fairlead, chain stopper, and winch foundations)
- Equipment/machinery support structures and their interface to the topside deck structure or the hull structure

- Topside deck structural interface with deck modules, if relevant

The analysis and design criteria to be applied to the other pertinent structural design should conform to recognized industry practices.

#### *5.7.8.2 Hull Structural Interface with the Stationkeeping System*

Each individual foundation and back-up structure of the fairlead, chain jack, and winch should be designed for the breaking strength of the mooring line with a safety factor of 1.25.

The foundation and back-up structure for multiple fairleads, chain jacks, or winches should be designed for the maximum anticipated mooring loads and verified against the design criteria specified in Section 5.7.3 and Section 5.7.5.

Fatigue strength should be designed to meet the requirements in Section 5.7.4, taking into account the effects of both local drag and inertia loads on the moorings and the global motions of the floating support structure.

#### *5.7.8.3 Topside Deck Structural Interface with Equipment/Machinery Foundations or Deck Modules*

The topside deck structure may require reinforcements to resist the reaction forces from equipment/machinery foundations or deck modules. The reinforcements of the topside deck structure are referred to as backup structures. The forces to be resisted by the backup structures of the topside deck structure should be designed for the maximum anticipated gravity, functional, and environmental loads together with the inertia loads induced by the motions of the floating support structure and verified against the design criteria specified in Section 5.7.3 and Section 5.7.5. If deemed necessary, the fatigue strength should meet the requirements of Section 5.7.4.

### 5.7.9 Local Structures

Structures that do not directly contribute to the overall strength of the floating support structure, i.e., their loss or damage does not impair the structural integrity of the floating support structure, are considered to be local structures.

Local structures should be adequate for the nature and magnitude of applied loads. The criteria of Section 5.7.3 are applicable to the design of local structural components, except for those structural parts whose primary function is to absorb energy, in which case sufficient ductility should be demonstrated.

## 5.8 Design of Stationkeeping Systems

### 5.8.1 General

The stationkeeping system, also known as the position mooring system, is designed to maintain the floating offshore wind turbine at a specified location within acceptable offset limits.

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 offshore floating offshore wind turbines, spread mooring systems and tendon systems, or the combination of both, have mostly 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 a floating offshore wind turbine. The main focus is placed on spread mooring systems, single point mooring systems, and tendon systems.

General guidance on the design and analysis of the stationkeeping system is referred to API RP 2SK (2008), ISO 19901-7 (2005) and API RP 2T (2010). Reference is also made to applicable classification society criteria. For the stationkeeping system using synthetic ropes, additional design considerations should be in accordance with API RP 2SM (2007) and applicable classification society criteria.

Innovative designs of the stationkeeping system (configuration, material, components and equipment) that are not covered by existing industry standards will be subject to special considerations.

### 5.8.2 Loading Conditions

#### *5.8.2.1 Design Load Cases*

The design load cases for the strength and fatigue analysis of the stationkeeping system should be in accordance with Section 5.5.2.1 and Section 5.5.2.3.

#### *5.8.2.2 Survival Load Cases*

The stationkeeping system should be designed to withstand the survival load cases, as specified in Section 5.5.3, without compromising its intended functions.

### 5.8.3 Design Conditions for the Stationkeeping System

#### *5.8.3.1 Intact Condition*

Intact Condition is the design condition of the stationkeeping system, where all components of the system are intact while the floating offshore wind turbine is exposed to the design load cases (see Section 5.8.2.1).

#### *5.8.3.2 Damaged Condition (with One Broken Line)*

Damaged Condition is the design condition of the stationkeeping system, where any one of mooring lines or tendons is assumed to have been broken or removed while the floating offshore wind turbine is subjected to the design load cases (see Section 5.8.2.1). The floating support structure is assumed to oscillate around a new equilibrium position determined after taking into account the effect of a broken line.

Breakage of the mooring line or tendon that sustains the maximum load in the intact condition might not lead to the worst broken line case. The designer should determine the worst case by analyzing several cases of broken line, including lead line broken and adjacent line broken cases.

Damaged Condition does not apply to a non-redundant stationkeeping system, for which an increased safety factor is required (see Table 5.5).

#### *5.8.3.3 Transient Condition (with One Broken Line)*

Transient Condition is the design condition of the stationkeeping system, where breakage of a mooring line or tendon (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 could be an important design consideration when proper clearance between the moored floating support structure and nearby structures is required. Where deemed necessary, global performance analyses for this transient condition subjected to the design load cases (see Section 5.8.2.1) should be performed.

Transient Condition does not apply to the non-redundant stationkeeping system.

### 5.8.4 Design Criteria for Mooring Lines or Tendons

The steel mooring lines should be designed with the safety factors no less than those specified in Table 5.5 and Table 5.6, with respect to the minimum breaking strength and fatigue characteristics, respectively, of the mooring line or tendon. These safety factors are dependent on the loading conditions as well as the design conditions and the redundancy of the stationkeeping system.

For the TLP tendon system, additional design considerations should be in accordance with API RP 2T (2010) or applicable classification society criteria.

For the stationkeeping system using synthetic ropes, design requirements should comply with API RP 2SM (2007) or applicable classification society criteria.

Fatigue damage due to a single extreme event, as described in Section 5.5.3, should not be combined with the fatigue damage accumulation incurred by long-term environmental and other loading. Reference is made to API RP 2T (2010) for further guidance.

Allowances for corrosion and abrasion of a mooring line should also be taken into consideration in accordance with the recommendations in Section 3.1 of API RP 2SK (2008).

**Table 5.5 Safety Factors for Mooring Lines or Tendons in Tension**

| *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 line | 1.25 |
| | | Transient condition with one broken line | 1.05 |
| | Non-redundant | Intact | 2.0 |
| Survival Load Cases | Redundant or Non-redundant | Intact | 1.0 |

*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.

**Table 5.6 Safety Factors (Fatigue Design Factors) for Fatigue Life of the Mooring Lines or Tendons**

| *Redundancy of the Stationkeeping System* | *Inspectable and Repairable* | *Fatigue Design Factors* |
|---|---|---|
| Redundant | Yes | 3 |
| | No | 5 |
| Non-redundant | Yes | 5 |
| | No | 10 |

### 5.8.5 Analysis Methods

Global performance analyses for the purpose of designing the stationkeeping system of a floating offshore wind turbine should be in compliance with Section 5.6. The dynamic analysis method should be employed to account for characteristics of dynamic responses of the floating offshore wind turbine. The stationkeeping system should be considered intact in the global performance analysis for the fatigue design load cases.

Fatigue analyses should in general follow the procedure outlined in API RP 2T (2010) for tendon mooring and API RP 2SK (2008) for other types of mooring system. The fatigue life of each mooring 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 applicable classification society criteria.

### 5.8.6 Design of Components and Equipment of the Stationkeeping System

Typical mooring equipment for the floating offshore wind turbine may include winches, windlasses, chain, wire and synthetic fiber rope, in-line buoys, fairleads and chain stoppers. The foundation components for 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 2T (2010), ISO 19901-7 (2005) or applicable 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 5.5.2.1 and Section 5.5.2.3. For the non-redundant stationkeeping system, a 20% increase should be applied to those safety factors defined for the redundant stationkeeping system.

For the robustness check of strength using the survival load cases as specified in Section 5.5.3, the safety factor should be at least 1.0.

Hull structural interface with the stationkeeping system should be designed in accordance to Section 5.7.8.2.

## 5.9 Stability and Watertight/Weathertight Integrity

### 5.9.1 General

Stability of floating support structure in both intact and damaged conditions during its pre-service and in-service phases should satisfy the regulations of national authorities (or Administrations) having jurisdiction over the location where the floating offshore wind turbine will be installed. When such regulations are not available, the applicable classification society criteria or equivalent should be applied.

### 5.9.2 Stability

For the stability analysis, consideration should be given to relevant unfavorable effects, including, but not limiting to, those resulting from the following:

- Environmental conditions, such as wind, wave (including green water effects, if applicable), snow and ice accumulation, and current,
- Applicable damage scenarios (including owner-specified requirements),
- Motions of floating support structure in six degrees of freedom
- Effects of various turbine RNA operation conditions
- Unfavorable effects of the stationkeeping system
- Free-surface effects in ballast tanks

The extent of damage from penetration or flooding to be considered in the stability analysis is dependent upon the type of floating support structure. Damage stability should incorporate a one-compartment flooding criteria as a minimum. Reference is also made to the national regulations, applicable classification society criteria and equivalent for the definition of damage scenarios, stability analysis procedures, and the acceptance criteria, along with the considerations of unfavorable effects of turbine operating conditions.

Stability of a TLP-type floating support structure for the in-place condition is typically provided by the pretension and stiffness of the tendon system, rather than by the waterplane area and restoring moments. The stability requirement should be satisfied through the minimum and maximum tension criteria based on dynamic global performance analysis, and by serviceability limits on pitch and roll motions as well as tower top accelerations.

Special consideration should be given to any unconventional stability issues that may be specific to an innovative configuration of the floating offshore wind turbine. The concept of requirements for righting/heeling moment curve area ratio may be considered for application to a floating support structure having unconventional stability issues that are not covered by existing industry standards. The dynamic response based intact stability analysis may also be acceptable, provided that model tests are performed to validate the analysis results.

### 5.9.3 Compartmentation

The hull of the floating support structure should be subdivided into a number of compartments to meet strength and stability requirements and to minimize consequences of damage, pollution risks if any, and risks of loss of the floating offshore wind turbine in the event of damage. As a minimum, one-compartment damage stability should be considered in determination of compartmentation.

### 5.9.4 Watertight and Weathertight Integrity

All external openings whose lower edges are below the levels to which weathertight integrity should be maintained in both intact and damaged conditions should have weathertight closing appliances. Openings fitted with closing appliances to ensure weathertight integrity should effectively resist the ingress of water due to intermittent immersion of the closure.

Suitable closing appliances should be fitted to achieve watertight integrity for all internal and external openings whose lower edges are below the levels to which watertight integrity should be maintained in both intact and damaged conditions.

Closing appliances and their controls, indicators, actuators, power sources, etc., should be arranged so that they remain functioning effectively in both intact and damaged condition. A plan should be incorporated into the Operating Manual to identify the disposition (open or closed) of all non-automatic closing devices and locations of all watertight and weathertight closures as well as unprotected openings.

Where watertight bulkheads and flats are necessary for damage stability, they should be made watertight throughout. Where individual lines, ducts or piping systems serve more than one compartment or are within the extent of damage resulting from a relevant accidental event, satisfactory arrangements should be provided to preclude the possibility of progressive flooding through the floating support structure.

## 5.10 Systems and Equipment

### 5.10.1 Hull Systems

#### *5.10.1.1 Marine Piping Systems*

Marine piping systems (such as bilge, ballast and tank venting) are those systems that may be required to conduct marine operations. Marine piping systems should comply with the applicable requirements specified in API RP 2T (2010), ISO 19904-1 (2006), or classification society criteria.

#### *5.10.1.2 Electrical Systems*

The electrical system referred to in Section 5 comprises all electrical equipment installed on the floating support structure.

The design considerations and requirements for the electrical system that is considered as a part of the RNA should be in compliance with IEC 61400-3 (2009). For those electrical systems that are not part of the RNA, reference is made to API Spec 4F (2008) and applicable classification society criteria or equivalent.

### 5.10.2 Fire Protecting Systems and Equipment

Fire protection measures on a floating support structure may consist of structural fire protection, fire detection systems, and fire-extinguishing systems. Requirements on fire protection systems and equipment should comply with national regulations. Reference is also made to applicable guidance in API RP 2T (2010), ISO 13702 (1999) and classification society criteria, with the consideration of the exposure level of floating wind turbines.

### 5.10.3 Export Cable System

The export cable system serves as the interface between the turbine RNA (or the electric power collection system) and the subsea electrical cable on the sea floor. It consists of the electrical/umbilical cable that transmits turbine generated electrical power to the subsea cable and conveys controls signals.

The export cable system is usually connected to a certain location on the hull structure or the topside deck. Local support structures should be designed for the maximum static and dynamic loading. Dynamic responses of the suspended segment of an export cable should be determined in accordance with the guidance described in Section 5.6 for global performance analyses and with the consideration of the Design Load Cases specified in Section 5.5.2.3. The strength and fatigue design criteria for the export cable should follow Section 5.8.4. Reference is made to applicable part of API Spec 17 E (2009), which is identical to ISO 13628-5 (2009), for additional guidance on subsea electrical cables.

# 6 Summary and Recommendations

Four major tasks are accomplished in this project. They include:

- Conducting a state-of-the-art review of the technologies related to floating offshore wind turbines
- Performing the case studies to explore the global load and response characteristics of the typical designs of floating wind turbines
- Identifying critical design considerations for the floating support structures and the stationkeeping systems of floating wind turbines
- Proposing a design guideline to provide recommended design practices for the floating support structures and the stationkeeping systems of floating wind turbines

The design guideline is proposed based on the knowledge garnered through this project and the 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 such work and particularly the input from regulators as well as domain experts from the industry are required to establish consensus and to finalize the design guideline. The proposed design guideline in this report should be treated as "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**

As discussed in Section 4, the existing load analysis and global performance analysis software for FOWTs lacks essential calibrations using experimental model test data or, preferably, full-scale field measurements. Although extensive code-to-code comparisons have been made, the validity of the software is still not fully confirmed partially because most analysis tools used in the comparative study are based on somewhat similar theoretical models and assumptions for the aerodynamic load calculation that were originally developed for land-based wind turbines. Perhaps, the case studies conducted in this project may have already stretched the application limit of the simulation software, in particular for those cases associated with the survival load cases where 500-year return environmental conditions are applied. 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.

- **Structural Analysis Procedures and Design Methodology for the Floating Support Structures of FOWTs**

Current research on the design of FOWTs appears to focus mostly on load calculations and global performance analyses. It is understandable that there are un-resolved technical challenges in these areas, which are considered crucial to achieving a robust design of an FOWT and certainly deserve their priority. However, it is believed that due attentions should also be paid to the development of a practical analysis procedure and design methodology for the floating support structures. Due to complexity of the typical configuration of the floating support structure, time domain structural analyses, which are commonly used for the design of bottom-founded wind turbine support structures, may not be a viable solution for the design of FOWTs. The recognized design practices for floating offshore oil and gas platforms, including the design wave method and the spectral analysis method, may be adapted with further considerations of the effect of aerodynamic loads and possible unconventional hull forms. However, more studies are needed to justify the application of these methods to the floating support structures of FOWTs and develop a recommended design practice. Research is also needed to develop a practical load mapping method that translates the load calculation results into the input of design loads for structural analyses, where high fidelity structural models are often employed.

- **Analysis Procedures and Design Methodology for Stationkeeping Systems of FOWTs**

Innovative designs of the stationkeeping system are often adopted by FOWTs in order to achieve cost savings and at the same time cope with unique motion responses of FOWTs. In addition to studies conducted in this project, further research is needed to evaluate the impact of using these new designs, which are typically non-redundant systems and may not be able to find directly applicable experience in the offshore oil and gas industry, to the overall safety level of the stationkeeping system. Special considerations should be given to the effect of aerodynamic and rotor control actions, the large yaw motion that could lead to unusual failure modes, the effect of high frequency excitations on the tendon system, and new materials for the mooring or tendon systems, as well as further refined global performance analysis methodology.

Developing a recommended design practices for the stationkeeping systems of FOWTs will also be valuable to the offshore wind energy industry. The existing design practices specified in the guidelines of API, ISO and classification societies for the offshore oil and gas production installations can be used as a starting point. Regulatory perspectives and industrial consensus will be required to establish the intended consequence level and the design acceptance criteria for the stationkeeping systems of FOWTs. It is recommended that the future research on the stationkeeping systems of FOWTs should leverage the latest development of global performance analysis capabilities.

- **Hurricane Wind Model and Requirement in the Design Standards**

The case study results for the hurricane wind conditions reveal that the mooring responses of the conceptual designs evaluated in this project appear to be insensitive to applying either the turbulent wind model recommended in API RP 2A-WSD (2007) or the wind models recommended in IEC 61400-3 (2009), which makes a further reference to IEC 61400-1 (2005). However, there are noticeable differences observed in the tower top accelerations, yaw motions and tower base loads, although the effect of wave and current actions tend to smooth out these differences. Similar observations were also made in another study for the mud line shear and bending moment of bottom-founded turbine support structures, where relatively higher sensitivities was found because wave loads was comparably smaller than aerodynamic loads.

The wind model recommended in API RP 2A-WSD (2007), as well as in API Bulletin 2INT MET (2007) and ISO 19902 (2007), is based on the measurement of offshore storm wind conditions near Norwegian coast. It has been used extensively by the offshore oil and gas industry for the design of topside structures and stationkeeping systems subjected to hurricane or extratropical storm wind conditions. On the other hand, IEC 61400-3 (2009) refers to IEC 61400-1 (2005) for the turbulent wind models that are developed mostly considering on-land wind measurements for terrains with small surface roughness. Some studies have been performed to compare various turbulent wind models, but no clear recommendation has been made. More research is needed to gain further understanding of the hurricane wind modeling as well as its applicability to the design of FOWTs.

- **Coordination with the IEC Workgroup on Developing Design Guidelines for FOWTs**

IEC Technical Committee TC-88 recently formed a workgroup to develop a Technical Specification for floating offshore wind turbines. It is believed to be valuable to coordinate with this workgroup to address some of the technical issues raised in this project, such as the intended exposure levels, the potential revision of the definition of standard class and S-class turbines, possible revision to the design load cases for turbine operating conditions, the hurricane wind models, and the overall design criteria. The research findings obtained from this project and future studies sponsored under BSEE TA&R program could contribute greatly to the development of the new IEC guidelines for FOWTs.

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