

# **Floating Offshore Wind Turbines: Responses in a Seastate Pareto Optimal Designs and Economic Assessment**

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## **Abstract**

Wind is the fastest growing renewable energy source, increasing at an annual rate of 25% with a worldwide installed capacity of 74 GW in 2007. The vast majority of wind power is generated from onshore wind farms. Their growth is however limited by the lack of inexpensive land near major population centers and the visual pollution caused by large wind turbines.

Wind energy generated from offshore wind farms is the next frontier. Large sea areas with stronger and steadier winds are available for wind farm development and 5MW wind turbine towers located 20 miles from the coastline are invisible. Current offshore wind turbines are supported by monopoles driven into the seafloor at coastal sites a few miles from shore and in water depths of 10-15m. The primary impediment to their growth is visual pollution and the prohibitive cost of seafloor mounted monopoles in larger water depths.

This paper presents a fully coupled dynamic analysis of floating wind turbines that enables a parametric design study of floating wind turbine concepts and mooring systems. Pareto optimal designs are presented that possess a favorable combination of nacelle acceleration, mooring system tension and displacement of the floating structure supporting a five megawatt wind turbine. All concepts are selected so that they float stably while in tow to the offshore wind farm site and prior to their connection to the mooring system. A fully coupled dynamic analysis is carried out of the wind turbine, floater and mooring system in wind and a sea state based on standard computer programs used by the offshore and wind industries. The results of the parametric study are designs that show Pareto fronts for mean square acceleration of the turbine versus key cost drivers for the offshore structure that include the weight of the floating structure and the static plus dynamic mooring line tension.

Pareto optimal structures are generally either a narrow deep drafted spar, or a shallow drafted barge ballasted with concrete. The mooring systems include both tension leg and catenary mooring systems. In some of the designs, the RMS acceleration of the wind turbine nacelle can be as low as 0.03 g in a sea state with a significant wave height of ten meters and water depths of up to 200 meters. These structures meet design requirements while possessing a favorable combination of nacelle acceleration, total mooring system tension and weight of the floating structure. Their economic assessment is also discussed drawing upon a recent financial analysis of a proposed offshore wind farm.

# 1 Introduction and Background

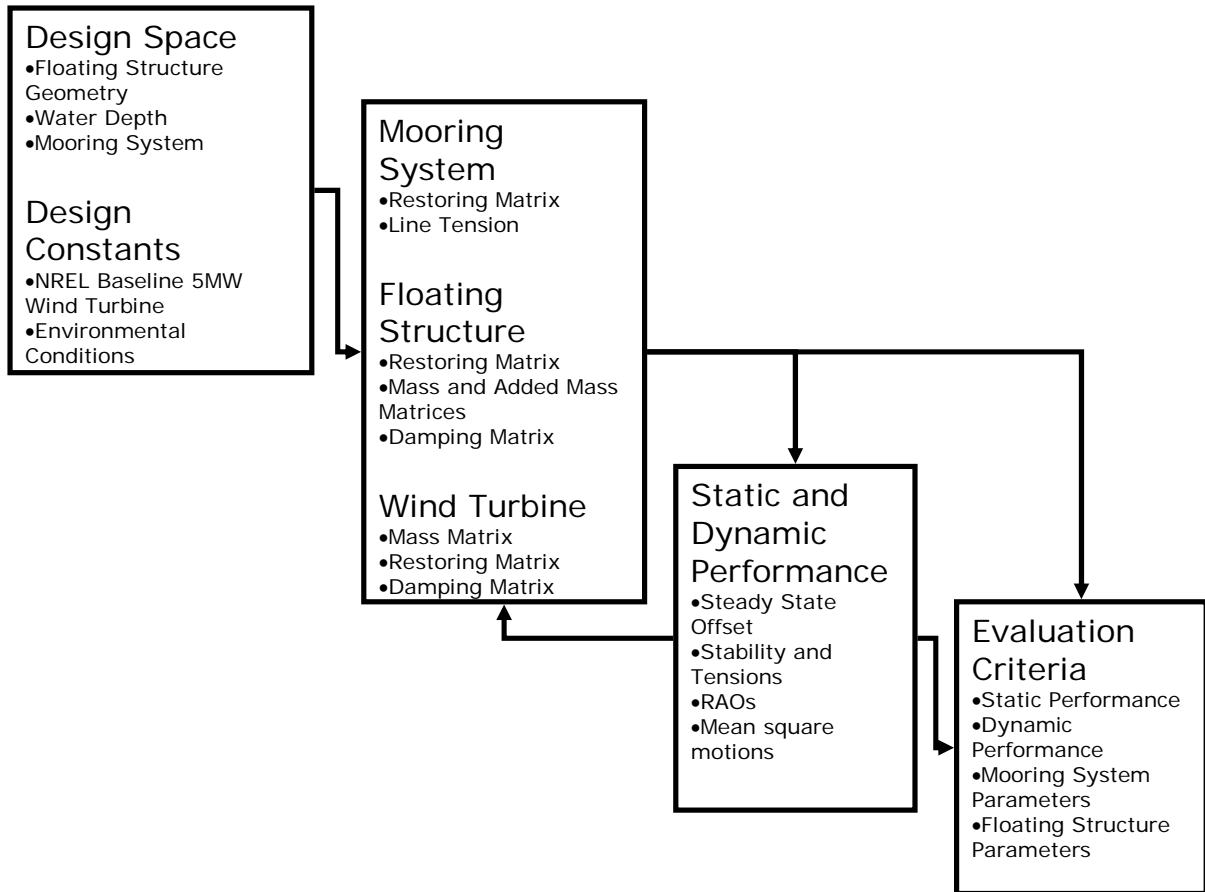
This paper presents a parametric study of the design space for a floating wind turbine system. Large floating structures were first developed by the offshore oil and gas industry. This technology offers the wind industry the ability to move large wind turbines offshore where the wind is stronger and more consistent. Aesthetic concerns of coastal residents are an additional motivation for moving the offshore wind turbines into deep water beyond the view of land.

Mooring systems for these floating structures have matured to allow installation in depths well over 1000 meters. While this is deeper than any currently planned projects, the mooring technology will permit development of offshore wind turbines in vast stretches of ocean. Applicable mooring systems for the floating wind turbines fall into two main categories. Tension leg mooring systems have vertical tethers under tension providing large restoring moments in pitch and roll. Catenary mooring systems provide station keeping for an offshore structure yet provide little stiffness at low tensions. Higher tensions and ballasted catenaries increase the stiffness of the mooring system considerably. A key task of the wind turbine floater design process is the selection of the optimal combination of floater shape and size, amount of ballast and mooring system attributes in order to keep the floater responses and nacelle acceleration within acceptable bounds and construction & installation costs low.

## 2 Parametric Design Process

In order to efficiently evaluate a large number of designs, the floating wind turbine system is parameterized to automate the design evaluation process. The parametric design architecture chosen for the floater can be described as a concrete ballasted circular cylinder. The concrete ballasted cylinder is a flexible yet simple design that would be easy to produce for an offshore wind farm. It consists of a steel cylinder which provides buoyancy for the wind turbine. Concrete ballast is added at the bottom of the cylinder to achieve static floatation stability in pitch and roll with the wind turbine installed and prior to its connection to the tether or catenary mooring system offshore.

The design space for a concrete ballasted cylinder is quite large. It ranges from a shallow draft barge with stability provided only by the waterplane area, to a slender spar buoy with stability provided by ballast, to a tension leg platform (TLP) with restoring provided primarily by the tether system. The design space consists of these configurations and all intermediate ones. The intent of this article is to provide a common analysis method and common constraints in order to compare the performance of these different designs against each other. An overview of the design and analysis is presented as a flow chart in Figure 1.



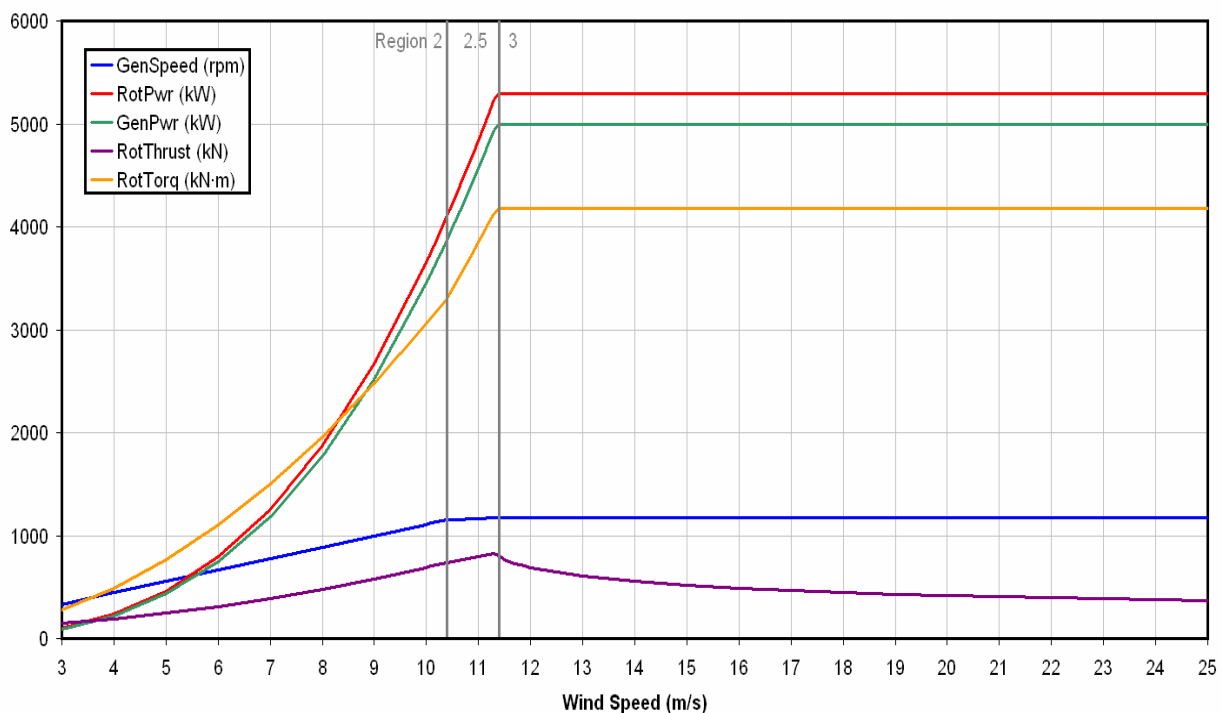
**Figure 1. Parametric Design Process**

Each distinct floating wind turbine configuration is defined by the design space shown in figure 1. The platform geometry is defined by the barge radius and draft. The mooring system is defined by the water depth, line tension and angle between the free surface and the anchor line segment. Each mooring system consists of eight identical tethers, grouped in two and spaced at 90 degrees apart. The structure includes four mooring line groups instead of three, so that the system does not become inherently unstable if one of the mooring sections fails.

Design constants in the analysis are the NREL baseline 5MW wind turbine and the wind conditions at which it operates. The wind turbine is assumed to be operating at a wind speed 11 m/s which produces the maximum thrust and torque on the wind turbine system and its attributes are presented in Figure 2.

Rotor Orientation	Upwind
Control	Variable Speed, Collective Pitch
Rotor Diameter/Hub Diameter	126 m/3 m
Hub Height	90 m
Max Rotor/Generator Speed	12.1 rpm/1,173.7 rpm
Maximum Tip Speed	80 m/s
Overhang/Shaft Tilt/Precone	5 m / 5° / -2.5°
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg

Overall c.g. location:  
(x,y,z)<sub>t</sub> = (-.2,0,64)m



**Figure 2: NREL 5MW Wind Turbine**

The dynamic performance analysis of each floating wind turbine configuration is decomposed into three major segments. These are the mooring system, the floating structure and the wind turbine. The program LINES<sup>1</sup> is used to calculate line tensions and restoring matrices for the mooring system, given the wind turbine load and the static offset. WAMIT<sup>TM</sup> is used to generate the linear hydrodynamic coefficients and exciting forces of the cylindrical floater while standard expressions give the hydrostatic coefficients. FAST<sup>2</sup> generates the linearized dynamic quantities for the NREL baseline 5MW wind turbine. A fully coupled linear dynamic analysis of the floating wind turbine system was carried out in the frequency domain by coupling the LINES,

<sup>1</sup> Selvaounos, P. D. *Swim\_Motion\_Lines Papers*. Report, Massachusetts Institute of Technology, 2002.

<sup>2</sup> Jonkman, J. M., Buhl, M.L., *FAST User Guide*, Golden, CO: National Renewable Energy Laboratory, 2005.

WAMIT™ and FAST codes. The system Gaussian response statistics in steady wind and a seastate were evaluated using standard linear system theory.

## 2.1 Derived Quantities

### 2.1.1 Subsystem Designs

The combination of input variables and constants are used to further define the configuration of the floating structure. The mooring line tension and angle are used with LINES to determine the zero offset heave force on the structure. Input variables define the configuration of the underwater structure. Concrete ballast is added to the bottom of the structure to equalize the buoyancy force with the total weight of the system at the design water line. The platform hydrostatic properties can also be calculated from the platform design. Because of symmetry in the system, the only non-zero entries in the hydrostatic restoring matrix are the diagonal entries for heave, pitch and roll. WAMIT™ is used to solve the potential flow problem for the wave, floating body interaction. It generates frequency dependent linear coefficients for the equations of motion. For each wave period, added mass and damping matrices are generated. WAMIT™ also generates a vector of complex exciting forces for each wave period.

FAST is used to generate the mass matrix, damping matrix and restoring matrix for the 5MW wind turbine at the given operating point.

LINES is used to generate the properties of the mooring system. While the performance of the mooring system may be approximated to be linear about the range of dynamic displacements, it may act non-linearly over larger displacements. Therefore the steady state offset must be solved for iteratively, and the restoring matrix determined about the steady state offset, not the zero offset point. The stiffening of the mooring system may be pronounced for slack catenaries and must be taken into account. For taut catenaries the evaluation of the restoring coefficient matrix about the zero offset point may be sufficient.

### 2.1.2 Equations of Motion and Response Amplitude Operators

Once all the linear terms are collected, they are assembled into equations of motion as shown in the expression below.<sup>3</sup> It is important to note that the added mass, damping, and exciting force are functions of frequency.

$$[M_{added}(\omega) + M_{WT} + M_{structure}] \ddot{\zeta} + [B_{structure}(\omega) + B_{WT}] \dot{\zeta} + [C_{WT} + C_{structure} + C_{mooring}] \zeta = X(\omega) e^{i\omega t}$$

$$M_{total}(\omega) \ddot{\zeta} + B_{total}(\omega) \dot{\zeta} + C_{total} \zeta = X(\omega) e^{i\omega t}$$

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<sup>3</sup> Selavounos, P.D., 2.24 Ocean Waves and Their Interaction with Ships and Offshore Energy Systems, Lecture Notes, OpenCourseWare, MIT.

Response amplitude operators (RAOs) can be calculated by solving the complex matrix equations of motion in the frequency domain in a standard manner:

$$\begin{aligned}\zeta(t) &= Z(\omega)e^{i\omega t} \\ -\omega^2 M_{total}(\omega)Z(\omega) + i\omega B_{total}(\omega)Z(\omega) + C_{total}Z(\omega) &= X(\omega) \\ Z(\omega) &= \left[ -\omega^2 M_{total}(\omega) + i\omega B_{total}(\omega) + C_{total} \right]^{-1} X(\omega)\end{aligned}$$

### 2.1.3 Performance Metrics

A critical quantity for the evaluation of the wind turbine performance is the motion of the wind turbine nacelle. Large motions of the nacelle could cause a degradation of turbine performance and damage to the equipment in extreme wave conditions. It is therefore necessary to understand the motion of the wind turbine nacelle and keep its acceleration to a minimum. The expressions for the nacelle displacement RAO and acceleration RAO are given below.

$$\begin{aligned}RAO_{\zeta_{nacelle}}(\omega) &= RAO_1 + h_{nacelle} \cdot RAO_5 \\ RAO_{\ddot{\zeta}_{nacelle}}(\omega) &= -\omega^2 (RAO_1 + h_{nacelle} \cdot RAO_5)\end{aligned}$$

When calculating the dynamic line tension, it is also important to know the variance of the line tension about its mean value. Given that the windward and leeward lines are the limiting cases for this analysis, the windward and leeward line tension RAOs are shown below.

$$\begin{aligned}RAO_{T_{windward}}(\omega) &= \sum_{i=1}^6 k_{windward_i} RAO_i(\omega) \\ RAO_{T_{leeward}}(\omega) &= \sum_{i=1}^6 k_{leeward_i} RAO_i(\omega)\end{aligned}$$

The restoring mooring line coefficients  $k$  are provided by the LINES program. Another important quantity is the difference between the floating structure's windward draft and the local free surface wave elevation to prevent bottom slamming of the structure. The corresponding RAO is given below, ignoring radiation and diffraction effects in the evaluation of the local wave elevation:

$$RAO_{fsh} = RAO_3 + R_{platform} RAO_5 - e^{i\omega^2 R_{platform}/g}$$

Using the RAOs for the previously mentioned quantities, root mean square (RMS) deviations from the mean value may be calculated using the standard expression.

$S(\omega)$  = Sea State Power Spectral Density

$$\sigma_{\zeta}^2 = \int_0^{\infty} |RAO_{\zeta}(\omega)|^2 S(\omega) d\omega$$

The spectral density of the sea states used in the present study is given by the following parametric expression.<sup>4</sup>

$$S(\omega) = H_s^2 T_1 \frac{0.11}{2\pi} \left( \frac{\omega}{2\pi} \right)^{-5} e^{-0.44 \left( \frac{\omega}{2\pi} \right)^4}$$

$H_s$  is the significant wave height and  $T_1$  is the modal period of the ambient seastate.

## 2.1.4 Constraints

It is advantageous to mount the tower, turbine and blades at a coastal facility and then tow the entire unit to sea. This eliminates the expensive and time consuming step of installing the wind turbine at sea. This analysis assumes a restoring coefficient of no less than 7E+07[N-m/rad] about the water plane in order to provide adequate restoring under towing conditions. This will provide enough stability to counteract a wind load on the turbine and tower without pitching more than 10 degrees. During operation, the stability of the system needs to be greater than during tow because of the increased load of the operating wind turbine. For a heel angle of less than 10 degrees in this condition, the total restoring coefficient in pitch must be at least 4.2 E+08 [N-m/rad].

It is also important that the dynamic displacements of the structure do not exceed the operating limits of the wind turbine in all but the most severe sea states. For pitch, it is desired that in the most severe sea state, the wind turbine stays close to vertical. The constraint limits the steady state pitch plus the RMS pitch to less than 10 degrees.

The static plus the dynamic line tension should not exceed the breaking load of the mooring lines within a factor of safety of two. For tension leg structures, it is also necessary that the lines do not lose tension since this could cause them to fail via a buckling load.

It is desired that the level of the free surface never falls below the bottom of the structure during operating conditions. To achieve this, the three sigma variation of free surface elevation at the waterline shall not exceed the cylinder draft when heeled at its steady state offset.

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<sup>4</sup> Wayman, E., Sclavounos, P. D., Butterfield, S., Jonkman, J. and Musial, W. Coupled Dynamic Modeling of Floating Wind Turbine Systems. Offshore Technology Conference, Houston, 2006.

### **3 Design Analysis**

Two types of mooring systems are analyzed. Tension leg platforms (TLPs) have vertical tethers which provide large amounts of stability in pitch and roll. Slack catenaries have low static tension mooring lines at roughly 45 degrees that provide little restoring in surge, pitch and roll. As part of ongoing research ballasted catenaries are being investigated. When properly tuned to the dynamics of the floating wind turbine system they may provide a blend of the benefits of TLP tethers and slack catenaries.

For the dimensions of the floating structure, all drafts are considered between two meters and fifty meters. Cylinder radii range between four and twenty two meters. The volume of the structure is constrained between 2000 and 15000 cubic meters. In total 777 configurations of cylinders were analyzed for each type of mooring system.

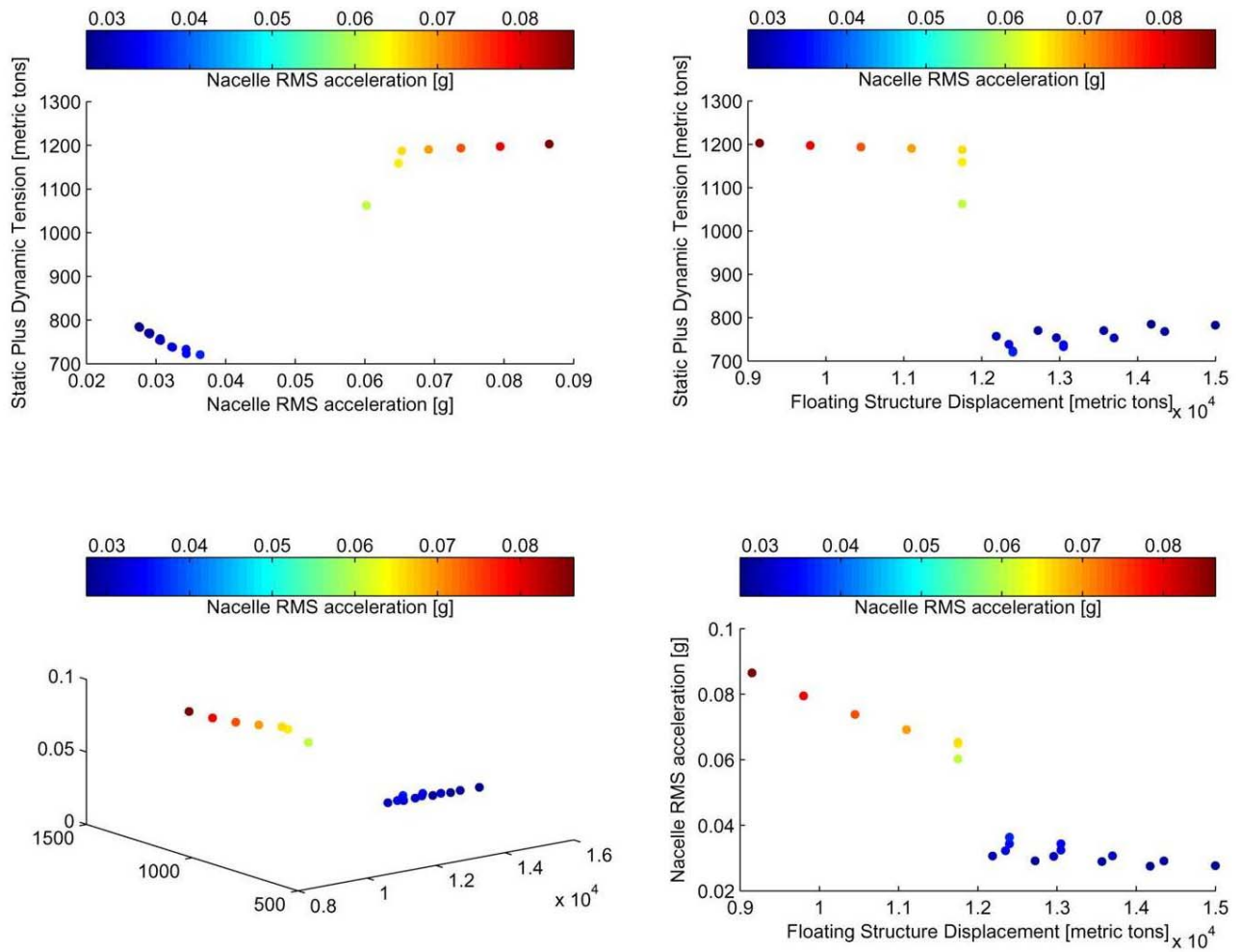
### **4 Results**

To perform the design comparison, a few key metrics are considered. The nacelle RMS acceleration is a key performance metric for the wind turbine and the objective of the analysis is to minimize that value for all sea states. One cost driver for the system is the mass of water displaced by the structure since this accounts for both the mooring system static tension and structure mass. The other cost driver is the static plus three sigma dynamic tension, since this covers the worst case load for which the mooring system must be designed.

#### **Pareto Optimal TLP Designs: 200 Meter Water Depth**

A total of 5436 different TLP designs are evaluated at a water depth of 200 meters and 120 meet the design criteria. In Figure 3, only the designs that are on the Pareto front of acceleration versus tension and displacement are shown. Designs are discarded if there is another design in the set that has lower value of tension, displacement and acceleration. That design is clearly superior to the discarded design. This step reduces the number of available designs from 120 to 20. There is a general trend that increasing total displacement of the structure decreases nacelle acceleration. This is somewhat expected as a more massive structure would have a lower natural frequency. In surge, the natural frequency of the TLP is generally at a lower value than the peak of sea state's power spectral density. Therefore reducing the TLP surge natural frequency would further reduce the overlap of the two frequency peaks, thus reducing the mean square accelerations of the nacelle. This occurs as the water depth increases. The relationship between the total tension and nacelle accelerations is such that the highest acceleration values occur at the highest tensions.

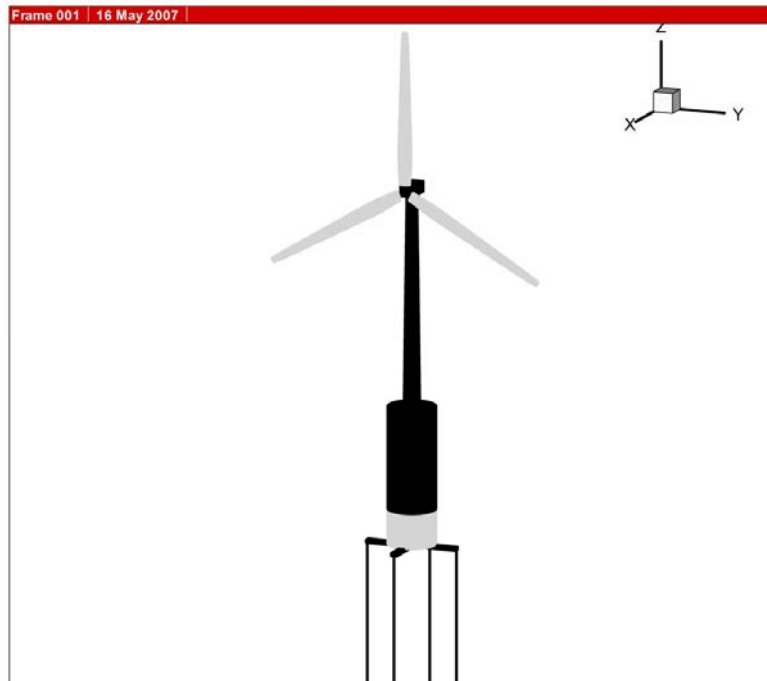




**Figure 3: TLP Designs, Pareto Front**

There are two main clusters of designs on the Pareto front. To more thoroughly understand each design class, an example of from each cluster is examined in more detail below.

## TLP-1

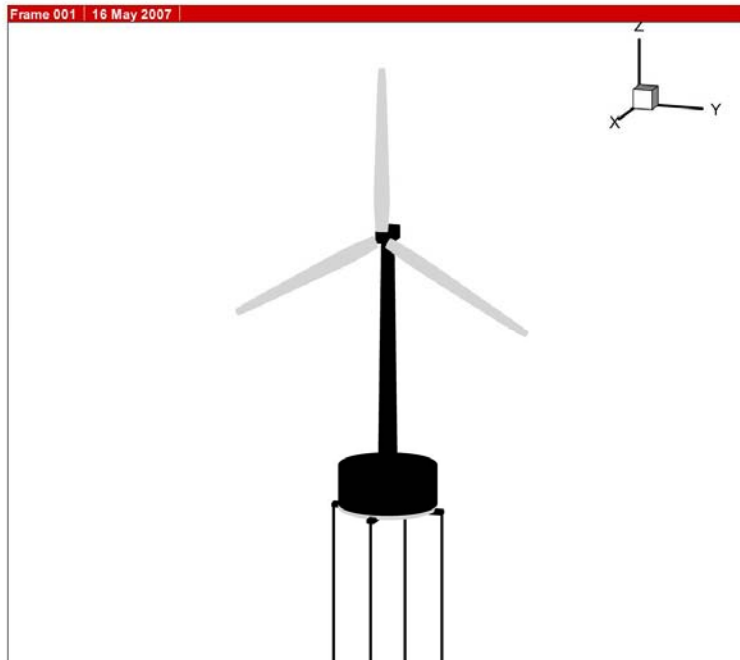


Platform Diameter [m]	18
Platform Draft [m]	47.89
Concrete Mass [metric tons]	8216
Concrete Height [m]	12.6
Total Displacement [metric tons]	12187
Windward Static Tension [metric tons]	539.3
Leeward Static Tension [metric tons]	262
Steady State Surge Offset [m]	4.394
Steady State Pitch Offset [deg]	0.438
Nacelle RMS Acceleration [g]	0.031
RMS Surge Displacement [m]	2.095
RMS Heave Displacement [m]	0.067
RMS Pitch Displacement [deg]	0.224
RMS Yaw Displacement [deg]	0.0
Windward RMS Tension [metric tons]	79.36
Static plus $3\sigma$ Dynamic Windward Tension [metric tons]	777.4
Static minus $3\sigma$ Dynamic Leeward Tension [metric tons]	27.4

**Table 1: Static and Dynamic Properties of TLP-1**

The first TLP-1 on the ten meter sea state Pareto front, shown above, is a deep slender structure. Small RMS motions in surge and pitch result in a low RMS acceleration of 3.1% of gravity in a ten meter sea state. The complete static and dynamic properties are listed in Table 1.

## TLP-2



Platform Diameter [m]	34
Platform Draft [m]	10.79
Concrete Mass [metric tons]	3886
Concrete Height [m]	1.67
Total Displacement [metric tons]	9800
Windward Static Tension [metric tons]	734
Leeward Static Tension [metric tons]	538
Steady State Surge Offset [m]	3.19
Steady State Pitch Offset [deg]	0.345
Nacelle RMS Acceleration [g]	0.079
RMS Surge Displacement [m]	4.017
RMS Heave Displacement [m]	0.217
RMS Pitch Displacement [deg]	0.053
RMS Yaw Displacement [deg]	0.0
Windward RMS Tension [metric tons]	165
Static plus $3\sigma$ Dynamic Windward Tension [metric tons]	1229
Static minus $3\sigma$ Dynamic Leeward Tension [metric tons]	11.34

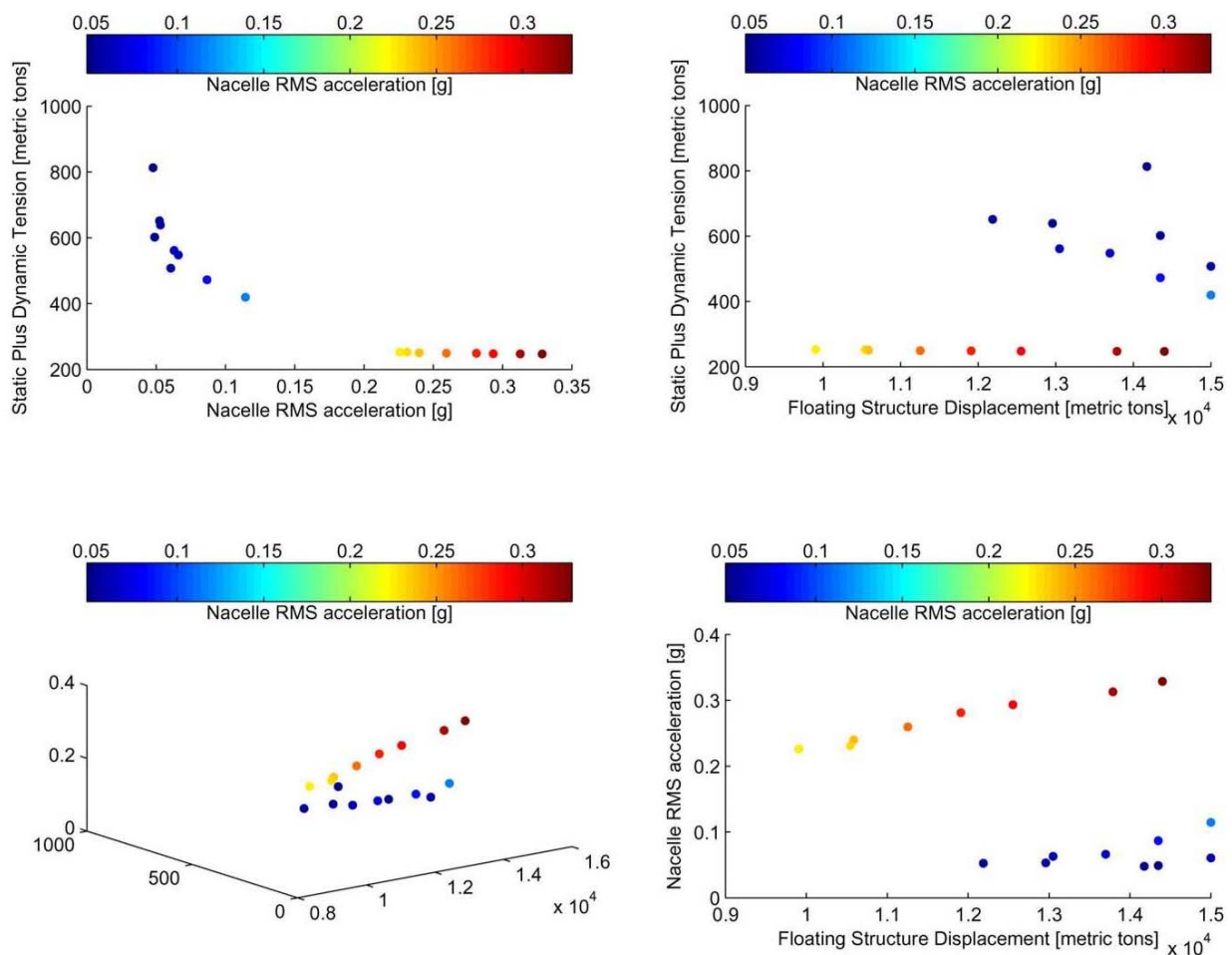
**Table 2: Static and Dynamic Properties**

The TLP-2 concept in the ten meter sea state is a shallow draft barge, pictured above. A large mooring preload is necessary to keep the leeward mooring line from going slack in the ten meter sea state. The large water plane area of the structure contributes to large exciting forces in heave compared to spar like structures. Because the tension leg mooring systems are stiff in heave, these heave exciting forces are directly absorbed by the mooring system. Therefore, the RMS values for tension are higher for the shallow draft barge than a spar, when secured with a tension leg mooring system. Static and dynamic properties of this structure are shown in Table 2.

## Pareto Optimal Catenary Designs: 200 Meter Water Depth

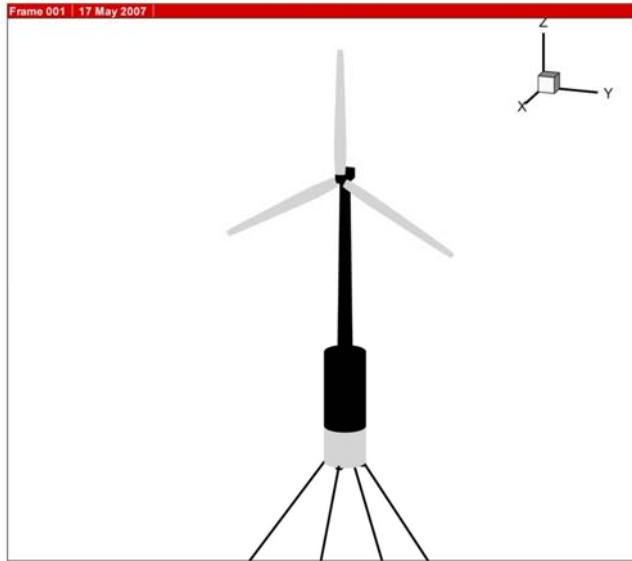
A total of 777 different designs of slack catenary moored floating wind turbines are evaluated. For all configurations, the angle between the fairlead and anchor is 45 degrees. At zero offset, the mooring systems provide minimal restoring in all modes of motion. However the windward catenaries stiffen during operation due to the operating wind loads.

Of the 777 configurations, 66 meet the requirements for the ten meter sea state. Examining just the 17 Pareto optimal designs in Figure 4, two clusters of designs are present. The first cluster of designs contains lower accelerations with higher displacements and total tensions. The second cluster contains designs with higher RMS acceleration, but lower displacement and higher total tensions. In the cluster of designs with higher accelerations, all the total tensions are very similar. Therefore the design with the lowest acceleration and displacement is clearly the best. An example design from each cluster is also examined in more detail below.



**Figure 4: Catenary Designs. Pareto Front**

## Slack Catenary - 1



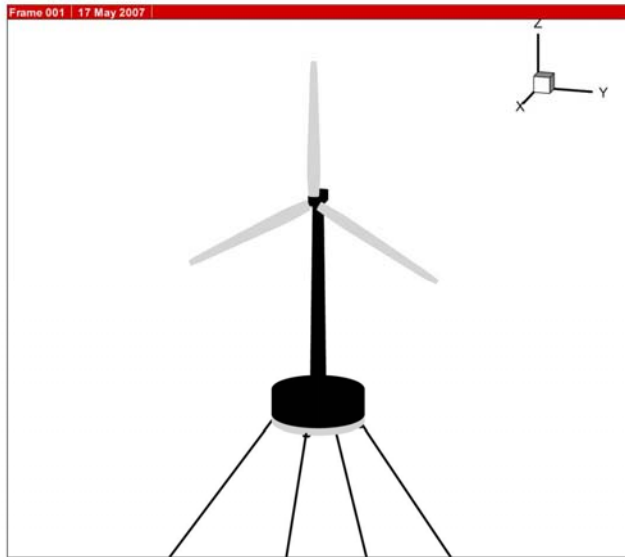
Similar to the other design cases, the highest displacement structure of interest is a slender spar with low accelerations, shown here. Relative to the corresponding TLP designs in a ten meter sea state, this slack catenary design requires an additional 3000 metric tons of concrete. This concrete adds static stability and brings the structure to the desired waterline as the slack catenaries do not have a significant preload. The steady state offset of the structure in pitch is almost five degrees, the limit imposed for this structure.

Dynamic tensions for the spar structure moored with a slack catenary system are higher than for a shallow draft barge moored with a similar system. These spars have much larger heave displacements than the shallow draft barge, which is the primary reason for the increase in the dynamic mooring loads. While the wind turbine tower and structure can absorb dynamic loads in heave, these loads have the disadvantage of causing larger dynamic tensions in the mooring system. Complete static and dynamic properties of this structure are given in Table 3.

Platform Diameter [m]	18
Platform Draft [m]	47.89
Concrete Mass [metric tons]	11209
Concrete Height [m]	17.19
Total Displacement [metric tons]	12187
Windward Static Tension [metric tons]	72.4
Leeward Static Tension [metric tons]	22.82
Steady State Surge Offset [m]	14.79
Steady State Pitch Offset [deg]	4.939
Nacelle RMS Acceleration [g]	0.052
RMS Surge Displacement [m]	2.015
RMS Heave Displacement [m]	7.732
RMS Pitch Displacement [deg]	0.929
RMS Yaw Displacement [deg]	0.0
Windward RMS Tension [metric tons]	198.8
Static plus $3\sigma$ Dynamic Windward Tension [metric tons]	668.7

**Table 3: Static and Dynamic Properties**

## Slack Catenary - 2



The second structure of interest along the Pareto front is a shallow draft barge, pictured here. This structure displaces 2000 metric tons less than the spar on the Pareto front but has a large RMS acceleration of 22.6% of gravity at the 10 meter sea state. Although the structure has lower static and dynamic tension than the spar, the mooring system is highly loaded so the small decreases in mass and tension probably do not outweigh the large difference in RMS acceleration of the nacelle. An environment where this structure may be attractive would be a situation where the draft at the port is limited and installing a wind turbine on a

deep draft structure and towing it to sea would be impossible. Complete static and dynamic properties of this structure are given in Table 4.

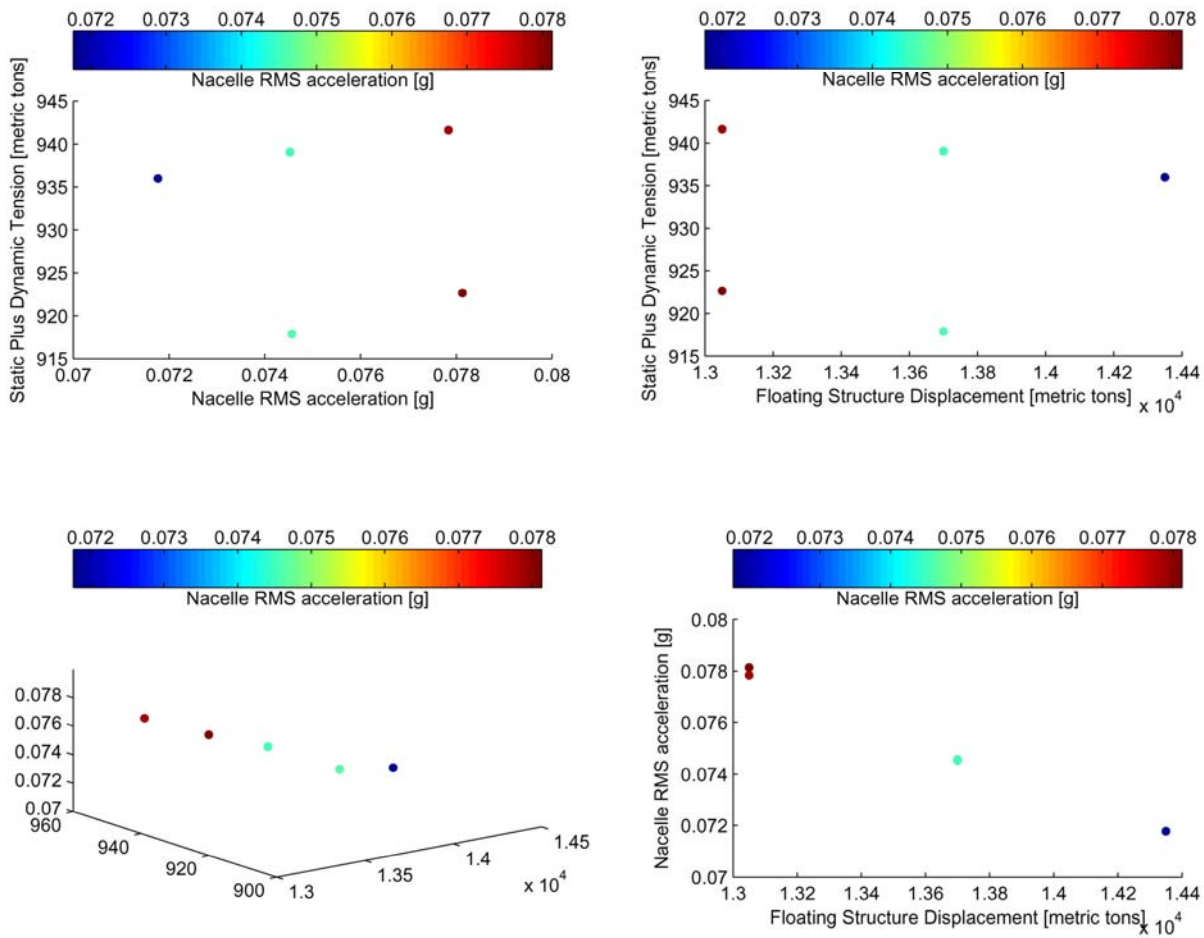
Platform Diameter [m]	38
Platform Draft [m]	8.736
Sea State Significant Wave Height [m]	10
Concrete Mass [metric tons]	8768
Concrete Height [m]	3.017
Total Displacement [metric tons]	9907
Windward Static Tension [metric tons]	77.83
Leeward Static Tension [metric tons]	28.94
Steady State Surge Offset [m]	12.92
Steady State Pitch Offset	4.561
Nacelle RMS Acceleration [g]	0.226
RMS Surge Displacement [m]	2.526
RMS Heave Displacement [m]	2.622
RMS Pitch Displacement [deg]	5.36
RMS Yaw Displacement [deg]	0.0
Windward RMS Tension [metric tons]	60.56
Static plus $3\sigma$ Dynamic Windward Tension [metric tons]	259.5

**Table 4: Static and Dynamic Properties**

## Pareto Optimal TLP Results: 60 Meter Water Depth

Each of structures examined in the previous section can also be analyzed at 60 meters water depth. Sixty meters is just beyond the reach of rigid structures to the ocean floor. Therefore, it represents a likely first step towards the installation of floating wind turbines.

When the 5439 TLP designs are subjected to the ten meter sea state, only six of them meet the requirements. Of these six designs, five are Pareto optimal. These five designs are shown in Figure 5. All of structures are quite massive, with displacements of at least 13,000 metric tons.

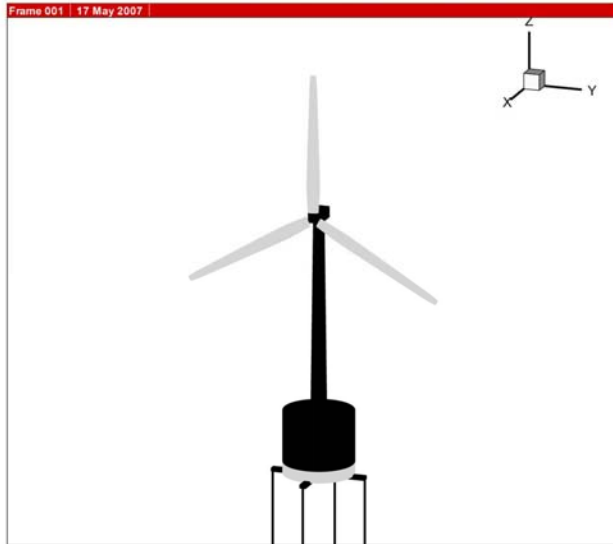


**Figure 5: TLP Designs, Pareto Front**

Along the Pareto front, there is again a trend of decreasing nacelle acceleration with increasing displacement. The total mooring line tensions are between 915 and 945 metric tons, a small range of values. Therefore, picking the best structure is simply a decision of trading additional displacement for lower acceleration.

The nacelle accelerations at the ten meter significant wave height is larger at 60 meters than at 200 meters water depth. The design presented below has the lowest acceleration and highest displacement of all the TLP designs along the Pareto front.

### TLP - 3



This TLP structure, shown here, is designed for a 10 meter sea state and 60 meters of water depth. It looks very different from TLPs optimized for the 200 meter water depth. The main reason is that deep draft structures significantly decrease the length of the mooring lines, leading to a higher natural frequency in surge and larger motions of the nacelle. Therefore the optimal design for low nacelle acceleration is a smaller draft structure than would normally occur in deep water. Complete static and dynamic properties of the structure are presented in Table 5.

Platform Diameter [m]	29
Platform Draft [m]	21.73
Concrete Mass [metric tons]	9885
Concrete Height [m]	5.84
Total Displacement [metric tons]	14350
Windward Static Tension [metric tons]	577.1
Leeward Static Tension [metric tons]	352.8
Steady State Surge Offset [m]	0.877
Steady State Pitch Offset	0.08
Nacelle RMS Acceleration [g]	0.072
RMS Surge Displacement [m]	5.224
RMS Heave Displacement [m]	0.118
RMS Pitch Displacement [deg]	0.036
RMS Yaw Displacement [deg]	0.0
Windward RMS Tension [metric tons]	128.1
Static plus $3\sigma$ Dynamic Windward Tension [metric tons]	961.2
Static minus $3\sigma$ Dynamic Leeward Tension [metric tons]	2.339

**Table 5: Static and Dynamic Properties**



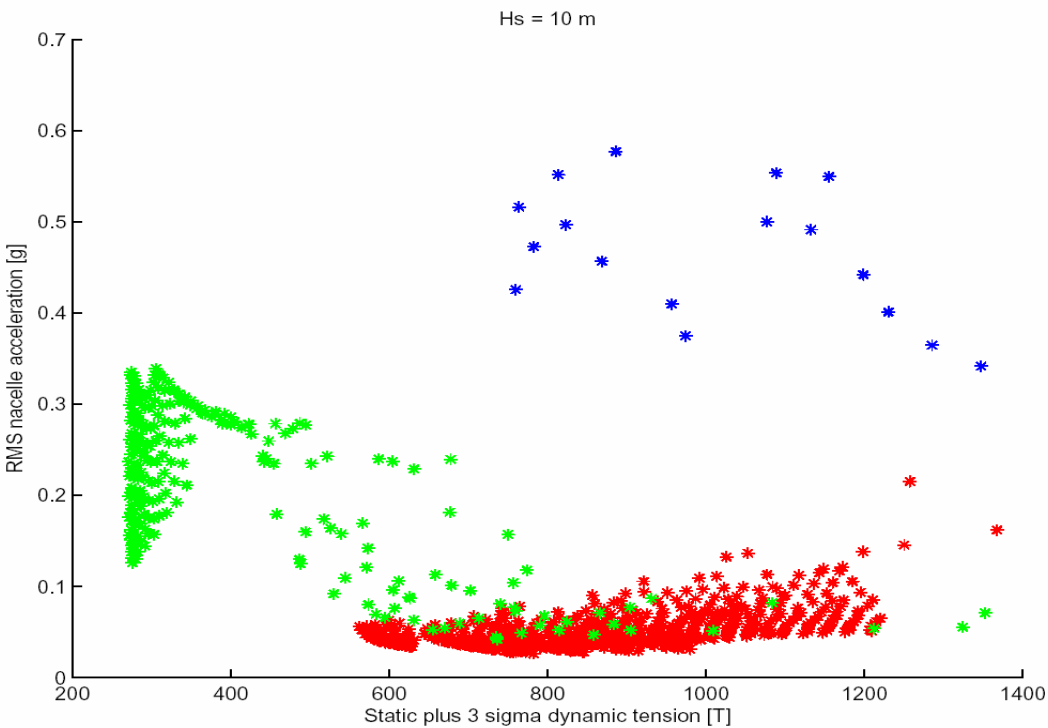
## 5 Overview

The designs that are Pareto optimal with respect to all other designs in their class in the ten meter sea state are presented in Table 6. The TLPs represent attractive choices because of their low RMS accelerations and negligible heave and pitch motions. Compared to the designs for the six meter sea state all the designs displace considerably more volume and have higher accelerations and total mooring tensions. Moreover, the TLP nacelle accelerations decrease with increasing water depth for the same tether tension.

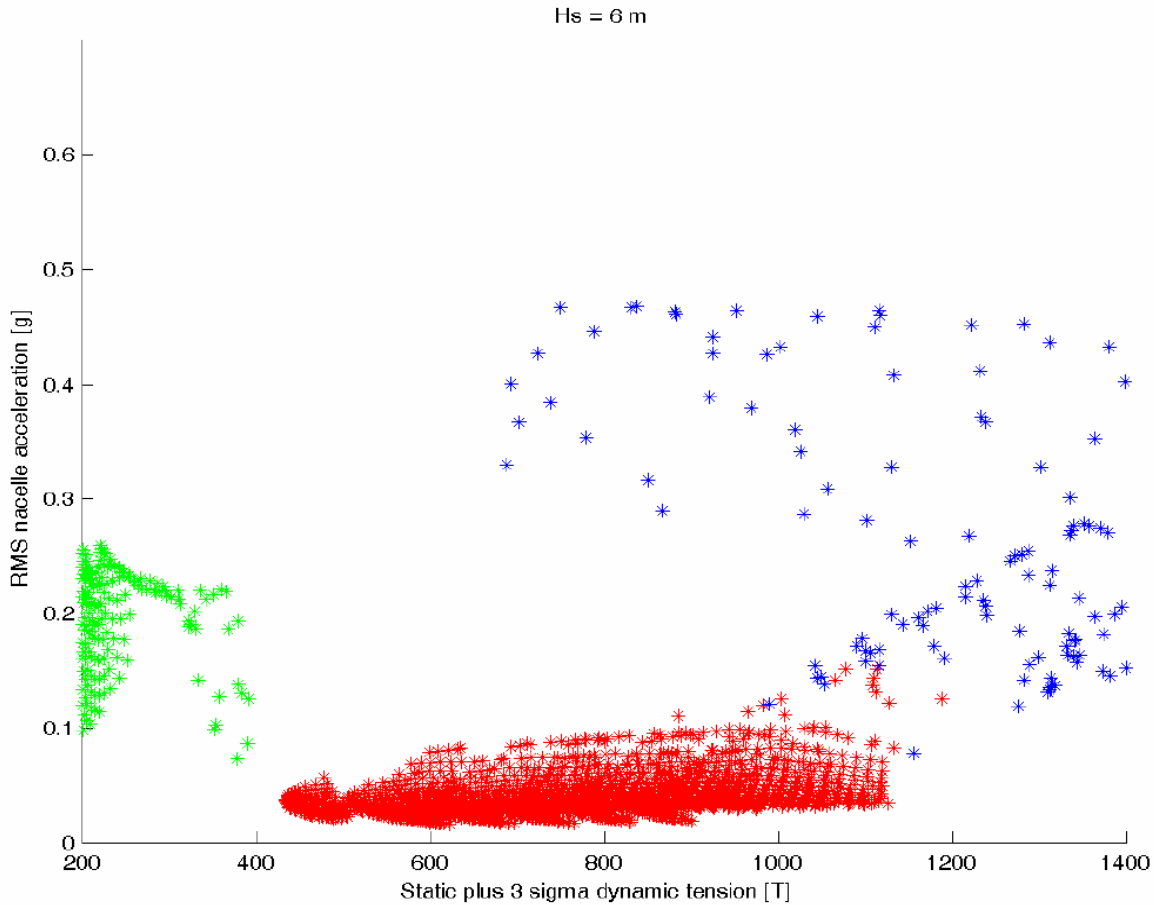
At 60 meters water depth, the TLP design is a fine performing structure, although with a displacement of 14350 metric tons, it is quite massive. The shorter mooring lines contribute to a higher natural frequency than an equivalent structure at 200 meters water depth, increasing the RMS accelerations of the nacelle.

**Table 6: Design Comparison, Ten Meter Sea State**

	Water Depth [m]	Static plus Dynamic Tension [metric tons]	Displacement [metric tons]	Nacelle RMS Acceleration [% g]
TLP - 1	200	777	12190	3.1%
TLP - 2	200	1229	9800	7.9%
Slack - 1	200	668	12187	5.2%
Slack - 2	200	259	9900	22.6%
TLP - 3	60	703	14350	7.2%



**Figure 6: Pareto Front. Red: TLP; Green: Slack Catenaries; Blue: Taught Catenaries**



**Figure 7: Pareto Front. Red: TLP; Green: Slack Catenaries; Blue: Taught Catenaries**

A summary of all designs tested in the present study is presented in the Pareto plots of Figures 6 for the 10m seastate and Figure 7 for the 6m seastate, respectively. The horizontal axis plots the static + 3\*sigma tension of the weather lines and the vertical axis plots the standard deviation of the surge acceleration at the nacelle as a percentage of g. In all cases the water depth is 200 meters.

It is seen from Figures 6 and 7 that the TLP designs generally lead to low nacelle accelerations since their surge natural frequencies are lower than the modal frequency of the ambient seastates. The TLP tether total tensions display a wide variation which is a function of the selection of the floater dimensions and weight of the concrete ballast. Two of the most promising designs, TLP-1, TLP-2 and TLP-3 were discussed in more detail in Section 4.

A number of slack catenary designs display both low nacelle accelerations and low mooring line tensions. These floaters generate most of their stability from the large waterplane area and ballast. Little stiffness is contributed from the mooring system. It is noteworthy that in the ten meter seastate there exists overlap between the TLP and some slack catenary designs suggesting

that the choice of the most attractive design may suggested by other considerations, for example construction cost. A promising slack catenary design was discussed in detail in Section 4.

In general, taught catenary designs with high mooring line tension and stiffness do not seem attractive because their response natural frequencies overlap with the peak frequency of the seastate spectrum leading to high nacelle accelerations.

It follows from the Pareto plots presented in Figures 6 and 7 that the optimal floater wind turbine design may reside between the TLP and the Slack Catenary families. An alternative design concept not considered in the present study is the Ballasted Catenary Concept. This involves catenary lines each supporting a ballast load -- a block of concrete or steel – floating in the fluid domain. The optimal selection of the mooring line/ballast configuration may permit to tune the stiffness and inertia of the mooring system to the floating wind turbine dynamics, leading to a minimum nacelle acceleration RMS and low mooring system tension at the anchors. This is the subject of ongoing research.

## **6 Economic Assessment**

Cost is an essential consideration for the successful commercial deployment of the present floating wind turbine concepts into large scale offshore wind farms. The full assembly of the wind turbine floater system at a coastal facility offers essential cost benefits relative to offshore assembly. Other important cost drivers include the floater weight – consisting of steel and concrete – and the tension of the tethers and mooring lines at their anchors. The latter drive the cost of the foundation structure. In the case of the TLP this may be a gravity caisson while for the catenaries it will consist of anchors widely used by the offshore industry. Therefore an important objective of the present study is the selection of floater and mooring system designs with acceptable dynamic response properties and low construction and installation costs.

The 5MW wind turbine used in the present study is assumed to be a marinized version of an onshore system. The same would be the case if a smaller or larger wind turbine system were to be used. The weight of larger wind turbines may be easily supported by a floater of larger displacement. Otherwise, buoyancy is free.

Guidance on the economic attributes of offshore wind farms is offered by the recent economic analysis carried out by Pace Global Energy Services LLC carried out for a proposed 144 MW offshore wind farm off the Long Island coastline consisting of 40 3.6 MW General Electric wind turbines supported by bottom mounted truss towers. As part of this analysis Pace Global evaluated the economics of the proposed wind farm against the 20-year costs of an standard Combined Cycle Gas-Fired Turbine (CCGT) consistent with the Long Island Power Authority's resource planning in the non-renewable domain. The conclusion of the Pace Global analysis is that the breakeven cost for an offshore wind farm to be competitive with the CCGT is approximately \$3,000 per installed Kilowatt including interconnection costs. The estimated cost of the proposed 144 MW offshore wind farm alone was estimated at \$5,231 per KW of nameplate capacity. The underwater cable and substation upgrade costs were estimated at \$400 per KW. The offshore wind farm was assumed to be operating at an annual average capacity factor of 36% and the projected cost of natural gas would range from \$9.21-\$15.68/MMBtu over

the 2010-2027 period. Further details of the economic analysis are provided in the Pace Global report<sup>5</sup>.

An analogous economic analysis applies to an offshore wind farm with turbines supported by floaters. The breakeven cost would be \$3M per installed MW or \$15M per floater supporting a 5MW wind turbine, including interconnection costs. For a hypothetical 10MW wind turbine the breakeven costs range from \$30M per floating unit. Floaters may be deployed in shallow and deeper waters and their economic advantages versus bottom mounted support structures become evident as the water depth increases. Moreover, the rate of increase of the costs of the floater as the wind turbine size increases and the cost of the mooring system with increasing water depth is likely to be moderate.

## 7 Conclusions

A fully coupled dynamic analysis was carried out of a floating wind turbine system supporting a 5 MW wind turbine moored to the seafloor with pre-tensioned tethers in TLP designs and by catenaries. The floater was selected to be a surface piercing vertical circular cylinder ballasted with concrete so that the floating wind turbine floats stably prior its connection to the tether or mooring system offshore. This configuration allows for the full assembly of the system at a coastal facility and its stable tow out at the offshore wind farm site.

The fully coupled dynamic response analysis was carried out in the frequency domain assuming small floater responses and using standard codes used by the wind and offshore industries. Gaussian response statistics in realistic seastates were evaluated using linear system theory as is the standard practice for the design of offshore structures. The use of linear theory and the assumption that the wind turbine tower and rotating blades are rigid are reasonable since the responses of optimized floaters are expected to be small. A nonlinear elastic response analysis of the wind turbine tower, nacelle and blades in the time domain may be carried out a posteriori using the response records generated from the present study at the tower base as input to standard elastic response codes used by the wind industry.

The optimized TLP and Slack Catenary designs lead to low nacelle acceleration RMS values in a ten meter seastate. In milder wave environments the nacelle accelerations are expected to be a lot lower. Other than cost, the water depth presents no restrictions, and for a number of the TLP designs considered in the present study the larger the water depth the lower the nacelle acceleration. The ballasted catenary mooring system under study may lead to even more economical designs. The weights supported by the eight catenaries may be comparable to the weight of a 5MW turbine leading to a lower system center of gravity and to a significant reduction of the concrete stored in the floater as ballast. Moreover, a ballasted catenary mooring system properly tuned to the floating wind turbine system dynamics and with a high tension at the fairlead and a low tension at the anchors, may lead to even more motion resistant and economical wind turbine floater and mooring system designs.

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<sup>5</sup> [http://www.lipower.org/newscenter/pr/2007/pace\\_wind.pdf](http://www.lipower.org/newscenter/pr/2007/pace_wind.pdf)