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PYRAWIND^{TM}: AN INNOVATIVE FLOATING OFFSHORE WIND TURBINE (FOWT) GLOBAL PERFORMANCE ANALYSIS

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ABSTRACT

In the near future, the offshore wind industry will experience a significant increase of turbine size and of floating wind development activities. A floating offshore wind turbine foundation offers many advantages, such as flexibility in site selection, access to better offshore wind resources, and quayside integration to avoid a costly heavy lift vessel offshore campaign. PyraWind^{TM} is a patented three canted column semisubmersible floating foundation for ultra large offshore wind turbines. It is designed to accommodate a wind turbine, 14 MW or larger, in the center of the interconnected columns of the hull with minimal modifications to the tower, nacelle and turbine. The pyramid-shaped hull provides a stable, solid foundation for the large wind turbine under development. This paper summarizes the feasibility study conducted for the PyraWind^{TM} concept. The design basis for wind turbine floating foundations is described and the regulatory requirements are discussed. Also included are the hydrodynamic analysis of the hull and ongoing work consisting of coupling hull hydrodynamics with wind-turbine aerodynamic loads. The fully coupled system was analyzed using OpenFAST, an aerodynamic software package for wind turbine analysis with the ability to be coupled with the hydrodynamic model. Due to the canted columns, a nonlinear analysis was performed using the coupled numerical hydrodynamic model of the platform with mooring system in extreme sea states.

Keywords: PyraWind, FOWT, Global Performance, Mooring, OpenFAST

NOMENCLATURE

FOWT	Floating Offshore Wind Turbine
DLC	Design Load Cases
RPM	Revolutions per minute
CFD	Computational Fluid Dynamics
QTF	Quadratic Transfer Function
RAO	Response Amplitude Operator
MW	Mega Watts
NREL	National Renewable Energy Laboratory
CAPEX	Capital Expenditure

1. INTRODUCTION

Wind energy, in particular offshore wind, is a fast growing renewable energy sector aiming at resolving climate change by reducing carbon footprint. There are abundant offshore wind resources all over the world, especially deep water floating wind energy. Currently, floating wind turbines have been used in two commercially operating offshore wind farms: 6 MW Hywind Scotland and 8.4 MW WindFloat Atlantic. Both wind farms are located off the coast of Europe. A number of new FOWT concepts have been proposed, such as Ideol's damping pool barge and SBM's TLP floating wind concept, mainly targeting the European region. While significant progress has been made in the FOWT industry, none of the existing technologies have proven to be competitive against fix-based wind farms in terms of cost at the moment. The National Renewable Energy Laboratory (NREL) has projected a significant cost reduction in the next few years, possibly matching the costs of floating wind to fixed foundation wind.

Contrary to the North Sea and European Coast, the U.S. East Coast and Gulf of Mexico are frequently affected by hurricanes. To survive in severe tropical cyclones, the air gap of turbine blades may have to be increased to avoid possible wave impact. At the same time, extreme wind and wave loading would make the stability and station keeping system of the FOWT more critical. These factors would inevitably increase the FOWT CAPEX. Therefore, the development of hurricane resilient FOWTs poses a unique challenge to US wind developers.

There are many challenges to an FOWT design: wind turbine interactions with floater motions; stability reduction due to large thrust loads at a very high elevation; tower structure design requiring avoidance of certain frequency range.

Interaction between the influence of the turbine on the floater, and the influence of the floater motions on the turbine performance had been extensively discussed by Jonkman [1]. A comprehensive overview of the hydrodynamics of floating platforms is given in Faltinsen [2]. In the case of a floating offshore wind turbine, wind load components generated by the turbine and their effects on platform motion are significant. The coupling effects cannot be ignored [3, 4, 5].

Large aerodynamic loads above the water surface and a raised center of gravity induce a large overturning moment in the floating substructure. A trade-off must be made between the required floating substructure size, to resist an overturning moment and the minimum substructure CAPEX.

For an FOWT design, a global sizing of the floater is dependent on the wind turbine system. The tower properties have a significant impact on the overall weight and CG of the wind turbine system according to Pegalajar-Jurado et al. [6]. In the wind turbine tower design, natural frequency considerations were the most important constraints. For an IEA 15MW wind turbine, the higher rotor speed variability increased instances of rotor under and over speeding beyond the design operating range. To avoid potential tower resonance issues, the NREL designed the tower with the first fore-aft and side-side natural frequencies outside modified rotation speed (1P) and blade passing (3P) ranges. Due to a very narrow soft-stiff range between 1P and 3P when additional safety factors were applied, a stiff-stiff tower with 1st natural frequencies above 3P, was required.

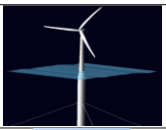
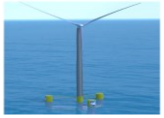
While a tower design relies on its vibration performance, the accuracy of the modeling tower is key. Substructure flexibility needs to be considered because it provides direct support to the tower. In many floating substructures, the tower is an extension of the column in the substructures. When the tower in OpenFAST is defined down to the tower interface of substructure, or even to the still water level, it is not necessarily capturing the equivalent floating substructure flexibility.

In many cases, the design of the tower is governed by the stiffness required to avoid resonance with the operational frequencies of the turbine. The substructure supporting condition is important. Table 1 shows tower supporting features among current floating offshore wind platforms. All are supported by a single column or barge, inevitably increasing the effective length of the tower and its support. It reduces the stiffness and thus the natural frequency of the tower system.

A general description of the design procedure is as following. At an initial design stage, the FOWT was sized without considering aerodynamics to simplify the process. After initial sizing was done, the coupled aerodynamics and hydrodynamics analysis had been performed to include the effects of turbine and floater interactions.

Coupling between the turbine and floater was accounted for using the following approximation: the wind thrust was determined by assuming that the base of the turbine was fixed and it was applied as force and an overturning moment at the base of the tower. ANSYS AQWA was used to perform time-domain simulations of the platform hydrodynamic response. Wind turbine loads were estimated on an equivalent drag model, which provided suitable wind thrust at the hub, and also generated aerodynamic damping. Gyroscopic effects due to the gyration of the rotor coupled with platform rotations were not included. This model was easy to implement numerically, and was computationally more efficient compared to a fully coupled aero-hydro-servo-elastic analysis. It could be used for screening purposes. However, this model did not account for the various control systems integrated on large wind turbines.

Table 1 Tower Supporting Features Among Current Platforms

Platform	Type	Image	Tower Support Feature
Hywind	Spar		Directly support by single column
WindFloat	Semisubmersible		Support at a single column top with bracing to connect between columns
Damping Pool	Barge		Support at top of barge deck
OO Star	Semisubmersible		Directly support by a center single column
Umaine VolturnUS	Semisubmersible		Directly support by a center single column

The aerodynamic calculation software OpenFAST developed by NREL was used to compute the platform motion and wind turbine loads, including the effects of blade pitch control, and the effect of platform motion on the resulting aerodynamic forces. The basic methodology for the OpenFAST predecessor FAST was described by Jonkman [1].

OpenFAST offered the ability to couple the effects of the mooring system, wave loading, and all the wind-induced loads on the turbine. The mooring lines were implemented in the OpenFAST module MoorDyn, a dynamic lumped-mass mooring line model that allows the user to define multi-segmented mooring lines. Hydrodynamics properties (hydrostatic stiffness matrix, frequency-dependent added mass and radiation damping matrices, and frequency-dependent vector of wave excitation forces) were precomputed in the radiation-diffraction solver ANSYS AQWA LINE for floating substructure and transformed to time domain by convolution. Viscous effects, not captured by radiation-diffraction theory, were captured internally in HydroDyn by inclusion of the Morison drag term for the PyraWind^{TM} floating substructure. A first set of simulations for system identification purposes was carried out to assess system properties such as static offset, natural frequencies and response to regular waves. A set of simulations in stochastic wind and waves was carried out to characterize the global response of the floating substructure, showing that the models behaved as expected.

2. PYRAWIND TECHNOLOGY

2.1 PyraWind^{TM} Description

The PyraWind^{TM} technology consists of a column-stabilized offshore platform with canted columns converging at center, and a spread mooring system. A wind turbine tower is positioned directly above the center of the platform. Figure 1 shows PyraWind^{TM}, a floating substructure supporting a reference offshore wind turbine, comprised of the following main elements:

- Three canted columns converging at center, which provide buoyancy and support the wind turbine.
- Three pontoons form an enclosed ring.
- Permanent water ballast, inside the pontoons.
- Permanent heavy ballast, inside the bottom of the node.
- Six mooring lines, made of conventional components (drag-embedded anchors, chains, and fairleads).
- An IEA 15MW Offshore Wind Turbine.
- Boat access to the platform is positioned at the vertical side surface of the canted column. The access stair leads to the canted surface of column and provide a natural slope to maintenance crew.

The advantage of using canted columns converging to a central location over other concepts with vertical columns is that it provides a better support to the tower and eliminates the deck structure by using the columns to directly support turbines and its foundation. The overall structure weight is reduced due to more efficient structure configuration, and the platform is hydrostatically stable with wind turbines installed at quayside. This design avoids the need for offshore integration of wind turbines and hulls at offshore sites.

The convergence of canted columns providing strong support to the center tower has additional advantage in keeping the tower natural frequency within desired range, outside of 1P and 3P. The unique feature of the PyraWind^{TM} reduces the effective length of tower and gives a higher stiffness to the tower. Therefore, it allows the use of a lightweight tower.

The turbine is located at the center of the platform, which gives the best turbine performance in an offshore structure. It also avoids an offset of a turbine induced permanent ballast. The structure load transfer from the turbine tower to 3 columns is natural and effectively utilizes the whole structure capacity.

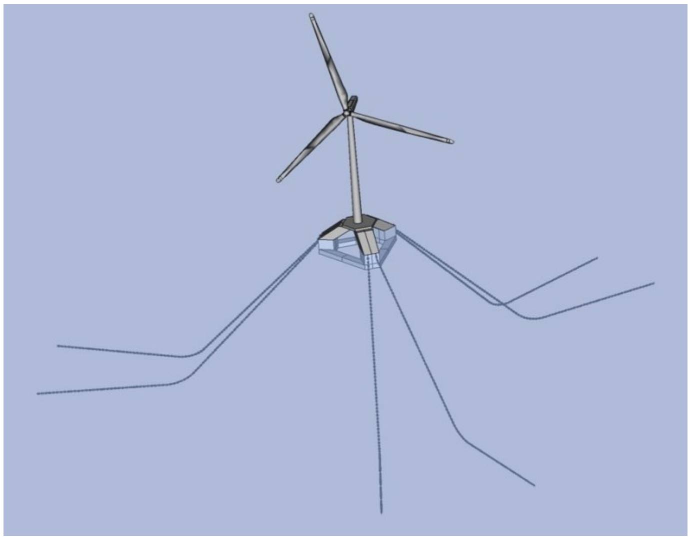


Figure 1 PyraWind^{TM} FOWT Concept

In the paper, the hull uses the metric unit system, and the coordinates are defined as follows in Figure 2:

X - Longitudinal Axis positive forward (towards platform East)
Y - Transverse Axis positive toward port (towards platform North)
Z – Vertical Axis positive upward

Origin – in the geometric center of pontoons, at the base line

Wind and wave heading is defined as following: 0 deg is along positive X axis, and 90 deg is along positive Y axis.

The principal dimensions of PyraWind^{TM} structure are given in Table 2.

Table 2 PyraWind^{TM} Floater Principal Dimensions

Principal Dimensions	Unit	PyraWind™
Draft	[m]	16.0
Displacement	[mT]	18,991
Hull Footprint	[m*m]	82 x 71
Column Freeboard	[m]	16.0
No. of columns	-	3
Column span c/c (EW)	[m]	60.0
Total column Height	[m]	32.0
Column Length (Radial)	[m]	*16.0*
Column Width	[m]	*16.0*
Pontoon Middle Width	[m]	8.0
Pontoon Height	[m]	5.0

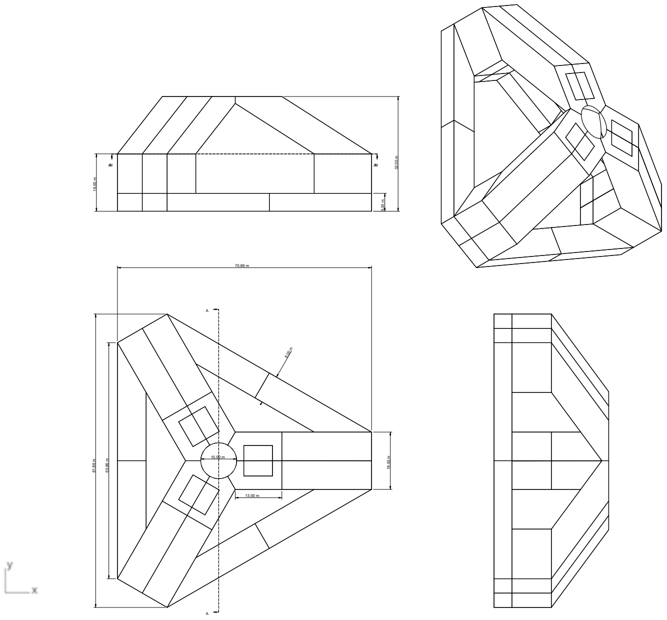


Figure 2 PyraWind^{TM} Elevation, Plan, Side and Isometric Views

2.2 Wind Turbine

Wind turbines have grown much larger in recent years and are expected to grow even larger soon. NREL published the IEA 15MW wind turbine (2020) [7, 8]. Floating offshore wind turbine towers have higher stiffness requirements than fixed-bottom configurations because of the increased inertial and gravity loads resulting from platform motion. The tower for this semisubmersible configuration was designed separately from the monopile configuration previously described [8].

2.3 Environmental Data

The environmental data used for PyraWind^{TM} design are a generic set of load cases based on [7] and combined with hurricane environmental conditions as shown in Table 3.

Table 3 Design Load Cases

DLC	Wind Condi-tion	Hub Height Wind Speed	Wind Headings (˚)	Significant Wave Height (m)	Peak Period (s)	Gamma Shape Factor	Wave Headings	Settings	# of Seeds	Total # of Sims.
		(m/s)					(˚)			
1.1	NTM	4	0/30	1.1	8.52	1	0/30		6	6
		6	0/30	1.18	8.31	1	0/30		6	6
		8	0/30	1.32	8.01	1	0/30		6	6
		10	0/30	1.54	7.65	1	0/30		6	6
		12	0/30	1.84	7.44	1	0/30		6	6
		14	0/30	2.19	7.46	1	0/30		6	6
		16	0/30	2.6	7.64	1.35	0/30		6	6
		18	0/30	3.06	8.05	1.59	0/30		6	6
		20	0/30	3.62	8.52	1.82	0/30		6	6
		22	0/30	4.03	8.99	1.82	0/30		6	6
		24	0/30	4.52	9.45	1.89	0/30		6	6
1.3	ETM	4	0/30	1.1	8.52	1	0/30		6	6
		6	0/30	1.18	8.31	1	0/30		6	6
		8	0/30	1.32	8.01	1	0/30		6	6
		10	0/30	1.54	7.65	1	0/30		6	6
		12	0/30	1.84	7.44	1	0/30		6	6
		14	0/30	2.19	7.46	1	0/30		6	6
		16	0/30	2.6	7.64	1.35	0/30		6	6
		18	0/30	3.06	8.05	1.59	0/30		6	6
		20	0/30	3.62	8.52	1.82	0/30		6	6
		22	0/30	4.03	8.99	1.82	0/30		6	6
		24	0/30	4.52	9.45	1.89	0/30		6	6
1.4	ECD+/-R-2.0	8	0/30	1.32	8.01	1	0/30	+/- Dir. Change	1	2
	ECD+/-R	10	0/30	1.54	7.65	1	0/30	+/- Dir. Change	1	2
	ECD+/-R+2.0	12	0/30	1.84	7.44	1	0/30	+/- Dir. Change	1	2
1.6	NTM	4	0/30	6.3	11.5	2.75	0/30		6	6
		6	0/30	8	12.7	2.75	0/30		6	6
		8	0/30	8	12.7	2.75	0/30		6	6
		10	0/30	8.1	12.8	2.75	0/30		6	6
		12	0/30	8.5	13.1	2.75	0/30		6	6
		14	0/30	8.5	13.1	2.75	0/30		6	6
		16	0/30	9.8	14.1	2.75	0/30		6	6
		18	0/30	9.8	14.1	2.75	0/30		6	6
		20	0/30	9.8	14.1	2.75	0/30		6	6
		22	0/30	9.8	14.1	2.75	0/30		6	6
		24	0/30	9.8	14.1	2.75	0/30		6	6
6.1	EWM 50 yr	47.5	0/30	10.7	14.2	2.75	0/30	Yaw +/- 8˚	6	12
6.3	EWM 1 yr	38	0/30	6.98	11.7	2.75	0/30	Yaw +/- 20˚	6	12

3. PRELIMINARY STABILITY

Extremely high wind turbine presented a challenge to the stability requirement of the floating wind turbine substructure. The restoring moment and wind overturning moment were computed for intact and damaged conditions at different wind headings. Wind generated thrust loads made the wind moment curve in power production mode completely different from conventional floaters [3].

Due to the unique shape of PyraWind^{TM}, the downflooding angle for which the vents above the top of columns were underwater was much larger than that of a typical semisubmersible. The restoring moment curves obtained were compared to the curves of wind overturning moment, to determine the heeling angle at equilibrium. Combined with a factor of safety, the comparison provided an estimation of the stability of the platform. A preliminary assessment of the wind overturning moment under steady wind was carried out in this analysis, based on a range of thrust coefficients for a 15MW wind turbine.

Wind headings every 30 degrees were considered for this analysis. It was determined that wind with Heading 0 deg was the most critical case. Damage cases with a column tank flooded were also taken into account. The angle of static equilibrium was much smaller than the downflooding angle and the platform remained stable in damaged conditions. The figures below show the representative stability curves of in-place intact and damage cases.

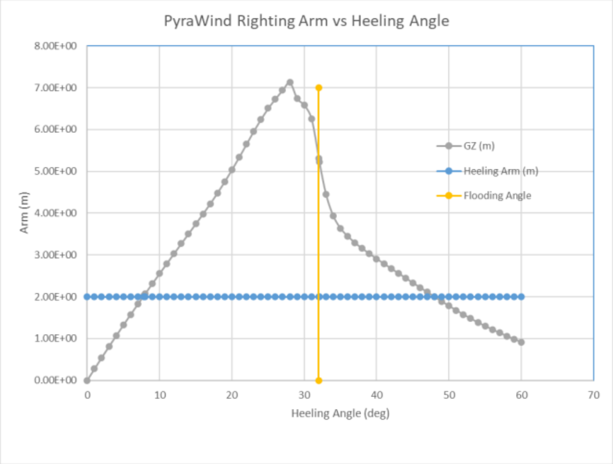


Figure 3 Intact Stability Curve with Wind Heading 0 Deg

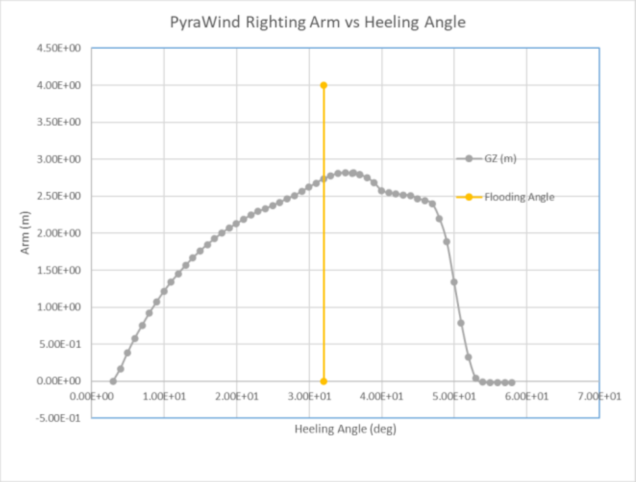


Figure 4 Damage Stability Curve (East Column Tunnel Flooded)

4. CONVERGED COLUMN SUPPORTS TO TOWER

One of the main benefits was that the canted columns provide strong support to the center tower. This design shortened the effective tower length, and provided higher supporting structure stiffness, leading to an increased tower natural frequency compared to other floating substructure concepts. The tower base loads and moment were shared by adjacent columns through the integrated column top structure. This led to more efficient structure design due to less loads in each column and pontoon.

Two simplified beam models (Figure 5) were built in ANSYS to simulate the PyraWind^{TM} and a hypothetical semisubmersible similar to VolturnUS for a 15MW wind turbine. The model is free floating.

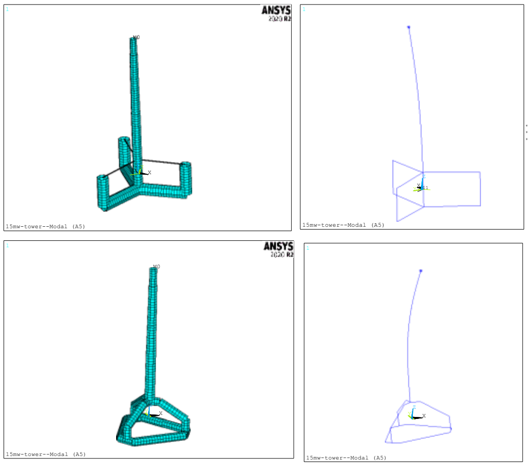


Figure 5 Tower 1st Natural Mode in 2 Semisubmersibles

A comparison of the system natural frequencies with the same tower structure revealed significant differences. The following Table 4 shows the results. It can cause significant differences in structure design of the tower, as tower design is controlled by the frequency requirement.

Table 4: 1st Natural Frequencies of Two Semisubmersibles

Design	Natural Frequency (Hz)
PyraWind^{TM}	0.54
VolturnUS-like	0.43

As from the above comparison, if similar natural frequency of tower was targeted, PyraWind^{TM} allowed the use of a light weighted tower. The reduced tower weight also led to reduced size requirements for the floating substructure. Therefore, the overall cost reduction comes from the contribution of saving tower weight and floating substructure.

5. HYDRODYNAMICS

The hydrodynamic panel model is given in Figure 6. The 3D diffraction model includes linear diffraction/radiation and 2nd order difference frequency forces in the form of QTF. The linear RAOs for 6-DOF motions are presented in Figure 7. The hydrodynamic coefficients from diffraction analysis were formatted to be the input for the fully coupled wind turbine analysis tool OpenFAST.

The canted columns caused a nonlinear effect in the wave response analysis. The linear wave theory based diffraction analysis was not sufficient to capture the effect of the inclined column above the water line, particularly on larger waves. For survival sea states when the relative motions were high and platform wet surface changes were significant, AQWA suite software was used to capture the instantaneous hydrostatic pressure and Froude-Krylov force updated in time domain analysis.

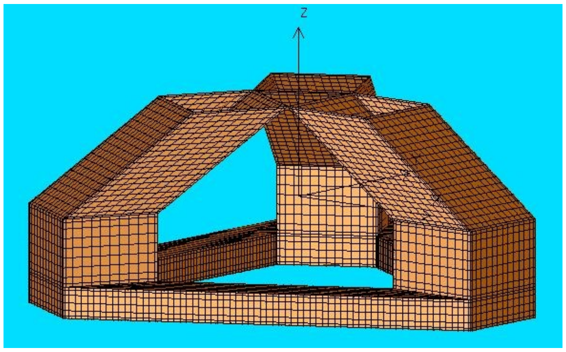


Figure 6 3D diffraction/radiation panel model

CFD techniques were used to assess the viscous damping, particularly at the frequencies where resonances were expected according to linear analysis. The equivalent damping level was modeled in the time domain analysis by a combination of Morison elements and external damping.

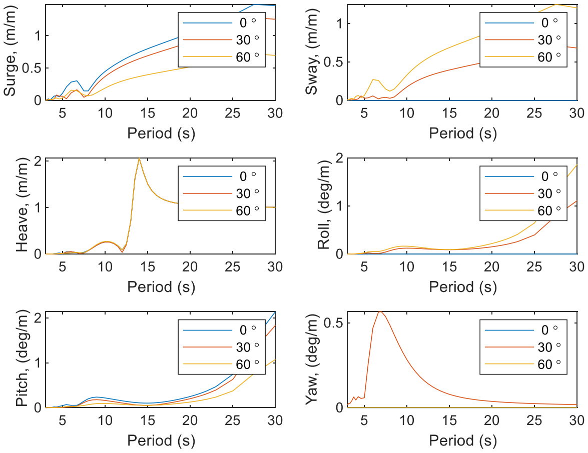


Figure 7 Floater linear RAO from 3D diffraction

Compared with similar floaters with vertical columns, the major dynamic difference of a canted column semi was the pitch responses in extreme environment conditions. As shown in Figure 8, the pitch peak distributions and spectrum from nonlinear analysis was compared with simulations with linear hydrostatic stiffness, which represented the vertical column case. In order to capture the canted column effect above mean water line, the instantaneous wet surface was updated during time domain simulations. The mean pitch angle was larger for canted column case as the hydrostatic stiffness was smaller due to columns incline inward; in the meantime, the low frequency resonance energy was reduced. The combined extreme pitch angle was almost the same at about 8 degree. The lower stiffness moved the pitch natural period further away from dominant wave energy and the natural period may also have varied with respect to pitch angle and allowing less resonance build up.

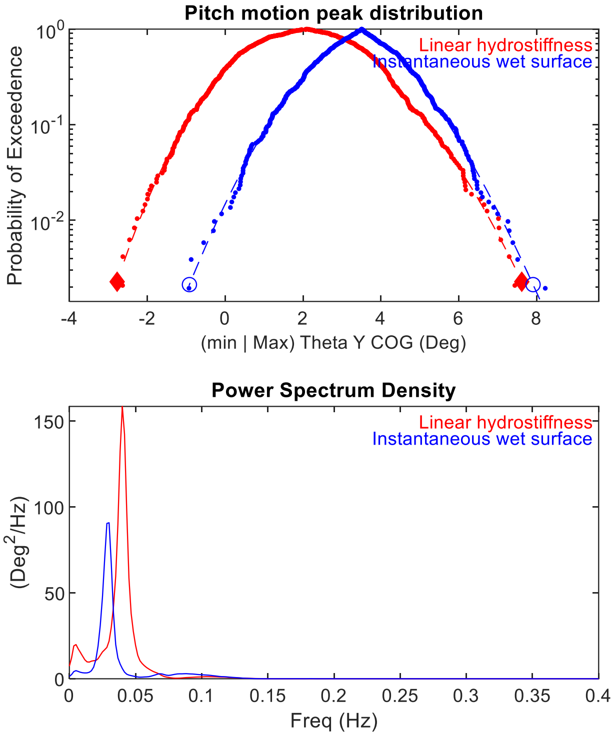


Figure 8 Extreme platform pitch peak distribution (upper) and spectrum (lower) comparison between linear hydrostatic stiffness and instantaneous wet surface analysis in time domain.

The linear heave natural period was determined by balancing the performances between operating and extreme conditions. Current configuration suggested a heave natural period at about 15 seconds which was usually not preferred for extreme conditions. However the cancellation period and lower first RAO peak was greatly beneficial to the daily operating of turbines. After assessing the damping at higher sea states with CFD, it was found that the heave resonance has a limiting peak only slightly over 1.0, which allowed the maximum heave acceleration at the nacelle to be at an acceptable level of 1.5m/s^2. In addition, the column pontoon ratio could be adjusted to fit a specific site environment. Therefore the overall performance was optimized.

6. MOORING

This section presents the design of the spread chain mooring system for 15 MW PyraWind^{TM} FOWT. The design basis of the mooring system includes the following:

- The design environment condition is given in Table 3.
- The design water depth is 100 m.
- The mooring system service life is 20 years.
- The chain corrosion allowance is 0.4 mm/year.

The primary objective of the mooring system design was the sizing and configuration design of the chain mooring system. The system will satisfy rules and regulations of ABS, which will be the certification authority.

The safety factors of the anchor leg chain segments are as per ABS rules [3] and are presented in the following Table 5:

Table 5 Extreme Mooring Chain Tension Safety Factors

Loading Condition	Redundancy	Safety Factor
Design Load Case	Redundant	1.67
Survival Load Case	Redundant	1.05

The mooring designs for PyraWind^{TM} FOWT followed the practices established by the oil & gas industry. The catenary mooring system adopted the “all chain” design commonly used in the shallow water. The catenary shape and the weight of ground chain will provide the station-keeping function and keep the FOWT at its location.

An FOWT mooring system should limit the vessel excursion and accommodate motion within certain allowable limits. In shallow waters, the allowances were usually governed by the bending restriction of the export electrical cable. A lazy wave shape export cable configuration is recommended to the PyraWind^{TM} system. The lazy wave configuration was achieved by introducing buoyancy modules into a cable with substantial bending stiffness. The buoyancy modules acted as a damper and isolated the floater motions from the critical touchdown area.

In the initial design stage, considering cost reduction, a three-line mooring system was proposed. However, based on the previous experience in the oil and gas industry, the three-line mooring system required corresponding large-diameter chain, large size anchors, massive bearing capacity of soil, a heavy installation vessel, and local structural reinforcement, which led to an exponential increase in costs. Considering the overall cost and engineering feasibility, a more practical six-line mooring system was proposed.

The mooring system properties and layout are provided in Table 6 and Figure 9, respectively. The anchoring system was spread moored with 6 anchoring legs divided into 3 bundles with 2 lines each bundle. The lines spanned radially to anchors spaced equally at 120 degrees. Each bundle was connected at the fairlead to one of the platform’s three outer columns at the level of the SWL. All mooring lines used a studless R4S chain with a nominal (bar) diameter of 121 millimeters (mm). After sensitivity testing, instead of at the bottom of the column, the fairleads were located at a higher level (SWL). The extreme dynamic mooring line tension and pitch angle was reduced due to this configuration.

Table 6 Mooring Chain Properties

Parameter	Units	Value
Line Type	-	R4S Studless Mooring Chain
Line Breaking Strength (corroded)	kN	13571
Number of Lines	-	6
Anchor Depth	m	100
Fairlead Depth	m	0
Anchor Radius	m	570
Fairlead Radius	m	43.4
Nominal Chain Diameter	mm	121
Dry Weigh of Mooring Chain	kg/m	293
Elastic Modulus	MN	1184
Line Unstretched Length	m	562
Fairlead Pretension	kN	352

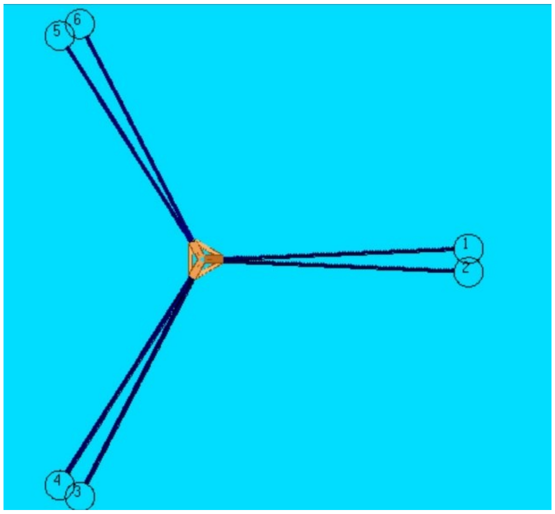


Figure 9 Mooring System Layout

The methodology used in the mooring design was based on the fully coupled dynamic analyses program ANSYS AQWA Suite and OpenFAST. ANSYS AQWA is a suite of integrated modules which addresses the vast majority of analysis requirements associated with the hydrodynamic assessment of all types of floating structures. AQWA-Line was used to perform diffraction-radiation calculations in order to derive the floater’s hydrodynamic database including RAOs and QTFs. AQWA-Drift is used to perform time domain coupled mooring analysis including mooring line dynamics and second order low frequency motions. In this method, the mooring lines and riser dynamics were fully modelled. Using the wind, current and hydrodynamic coefficients, the FOWT responses were solved in the time domain taking into account the mooring line and subsea cable responses. The six degree-of-freedom motion equations were solved utilizing the structural mass, the radiation matrices, the hydrostatic stiffness matrix, first order wave load RAO's, the wind and current loads, the second order wave drift loads, and a finite element (or finite difference) model of the anchoring and riser system. The maximum mooring line tension was obtained from the time domain analysis results. The AQWA-Drift model is given in Figure 10.

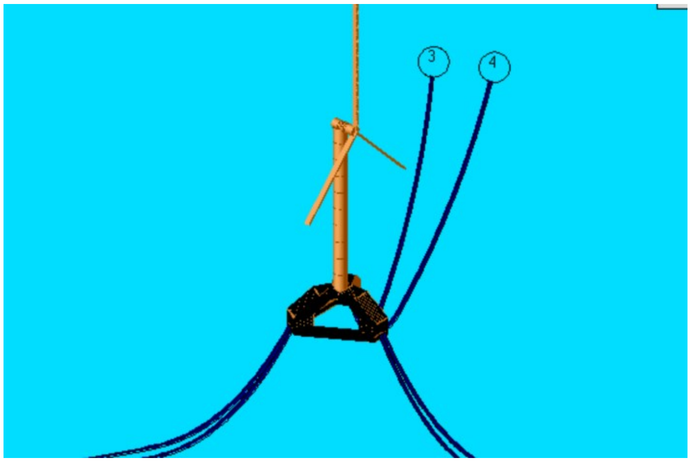


Figure 10 ANSYS AQWA Mooring Analysis Model

The mooring line tensions obtained from time domain simulations were used to calculated chain safety factors. The analysis results are given in Table 7. A 10% margin was included in the mooring line tension calculation to account for the aerodynamic effects of the wind turbine.

Table 7 Mooring Chain Tension Safety Factors

Loading Condition	Safety Factor
Design Load Case	2.02
Survival Load Case	1.07

The mooring configuration obtained from AQWA was input to OpenFAST to include wind turbine aerodynamic effects and verify the overall performance of the PyraWind^{TM} FOWT system.

7. OPENFAST COUPLED ANALYSIS

The forces generated by the wind turbine were reasonably well computed by AQWA, especially for extreme conditions while the turbine was idle. However, wind turbines are equipped with sophisticated control systems which affect the loads generated during operations. A wind turbine's control system adjusts the blade pitch to keep the rotor speed within operating limits as the wind speed changes. Blade pitch control changes the angle of attack of the blades by rotating them around their local axis, which adjusts the rotation speed and the generated power. Feathering the blades stops the rotor during emergency shutdowns, or whenever the wind speed exceeds the maximum rated speed. Blade pitching can have significant effects on floating platforms.

In order to assess the effects of blade pitching on the floater, and provide accurate computation of all loads induced by the wind turbine on a moving foundation, OpenFAST, was used to provide a fully coupled aero-hydrodynamic time-domain numerical model of the PyraWind^{TM} platform with a 15MW wind turbine.

OpenFAST is a fully coupled analysis with loads and responses transferred between its modules including HydroDyn, BeamDyn, ElastoDyn, ServoDyn, and AeroDyn via the FAST driver program to enable aero-elasto-servo interaction at each coupling time step. BeamDyn is a time-domain structural-dynamics module for slender structures. There is a separate instance of BeamDyn for each blade. At the root node, the inputs to BeamDyn are the six displacements, six velocities, and six accelerations; the root node outputs from BeamDyn are the six reaction loads including three translational forces and three moments. BeamDyn also outputs the blade displacements, velocities, and accelerations along the beam length, which are used by AeroDyn to calculate the local aerodynamic loads (distributed along the length) that are used as inputs for BeamDyn.

OpenFAST models the wind turbine as a combination of rigid and flexible bodies. There were 24 degrees of freedom (DOF) that could be accounted for in the program: 6 in platform translation and rotation, 4 in tower flexibility, 1 in nacelle yaw, 2 in variable rotor speed and generator flexibility; 9 in blade flexibility, 1 in rotor-furl, 1 in tail-furl. The model connected these bodies with several DOFs, including tower bending, blade bending, nacelle yaw, rotor teeter, rotor speed, and drive shaft torsional flexibility. Hydrodynamic forces, including wave-exciting forces, viscous forces, and mooring forces were computed by HydroDyn and passed to OpenFAST, which solved the coupled turbine-tower problem, and passed platform motions back.

The 15MW IEA wind turbine OpenFAST model was developed by NREL, DTU, and UMaine [8]. This wind turbine is a conventional three-bladed upwind variable-speed variable blade-pitch-to-feather-controlled turbine. Active proportional integral (PI) controllers were implemented for the generator torque and blade pitch angles. Desired shaft revolutions per minute (RPM) could be reached using the controllers. The OpenFAST model was run using the validated PyraWind^{TM} hydrodynamic model described in previous sections.

Sample results were provided for a 9.8 m significant sea-state with a 14.1 seconds peak period and a 24m/s steady wind. This was a severe sea state while power production was still on. Waves and wind were colinear at 0 degree heading, along the symmetry axis of the PyraWind^{TM}. Heading of 30 degree results were not significantly different. A Jonswap wave spectrum was assumed with a peakness factor of 2.75.

Figure 11 shows a 3 hour simulation for an extreme power production load case DLC1.6 as defined in Table 3. The maximum platform pitch angle was less than 7 degrees. The mean pitch angle of the OpenFAST time series was smaller than constant thrust loads caused platform tilting angle. With turbine pitch control in place, the extreme dynamic pitch angle in the OpenFAST time series was also small.

Figure 12 shows a 3 hour simulation for a parked turbine load case DLC6.1 as defined in Table 3. While the turbine was parked, the maximum pitch angle could reach 9 degrees in the extreme condition.

The pitch performance is the most important factor to an FOWT. **Figure 13** shows the spectral analysis of the pitch motions in DLC 1.6 and DLC 6.1. It was observed that the extreme pitch angle was suppressed in operating condition (DLC1.6), partly due to pitch control.

Figure 14 shows the platform surge and heave motion time-series over a 3 hour duration after the initial transients generated at the beginning of the numerical simulation have disappeared. Wave-induced surge was clearly visible in this irregular wave sea-state.

Figure 15 shows tower base loads, and **Figure 16** shows the accelerations components at nacelle over a 3 hour duration after the initial transients disappeared. All accelerations were sufficiently small in the severe sea states.

8. CONCLUSION

This paper discussed the design basis and global performance analysis of the PyraWind^{TM}, a floating platform for support of extra large offshore wind turbines such as an IEA 15MW turbine. A hydrodynamic model along with a simplified wind turbine loads was used for initial screening to account for diffraction-radiation effects, as well as viscous forces and the influence of the mooring. Although the mean pitch angle was larger than the case with vertical columns as the hydrostatic stiffness is smaller due to columns incline inward, the low frequency resonance energy was reduced due to lower pitch frequency. The lower stiffness moves the pitch natural period further away from dominant wave energy and the varying pitch natural period allows less resonance build up.

A coupled aeroelastic-hydrodynamic OpenFAST model was implemented to provide a better resolution of the wind turbine loads and take into account the effects of the turbine control system. It was shown that interactions between the wind turbine control system and the platform affect the pitch performance. The coupled global performance analysis showed the PyraWind^{TM} design behaved well within the turbine performance requirement, as expected. Further work will be carried out to assess the effects of coupled aeroelastic-hydrodynamic loads on the PyraWind^{TM} structure components.

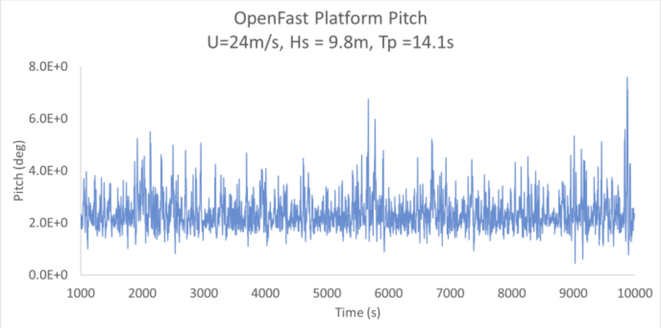


Figure 11 DLC1.6 Pitch Performance

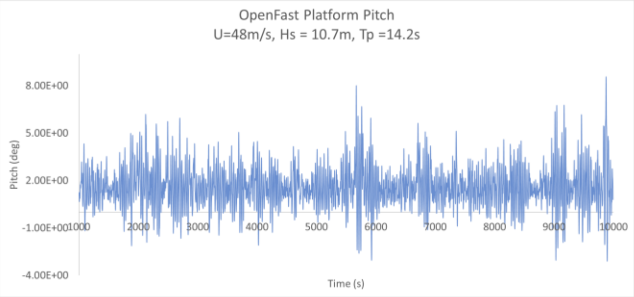


Figure 12 DLC6.1 Pitch Performance

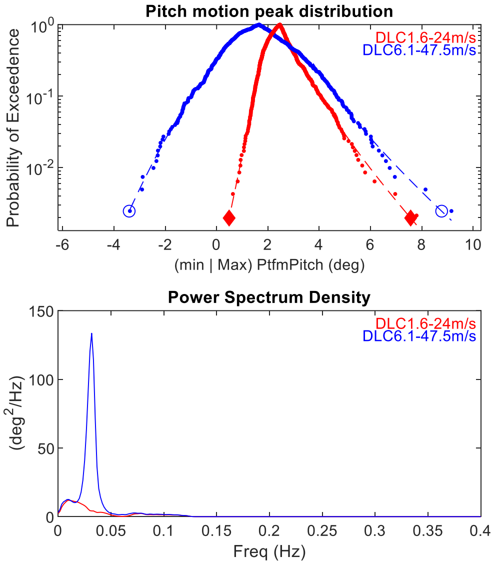


Figure 13 Extreme Platform Pitch Peak Distribution (upper) and Spectrum (lower) of DLC 1.6 and DLC 6.1

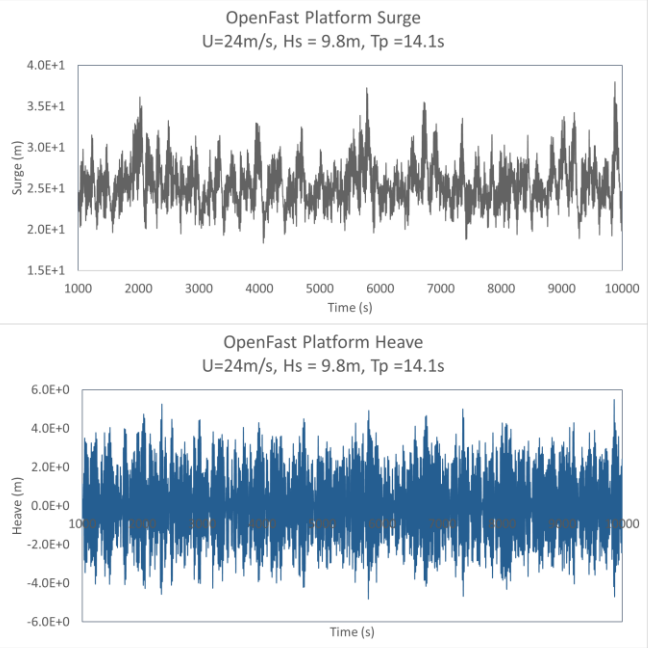


Figure 14 Platform Surge and Heave Motion in 9.8m Seas with 24 m/s Wind

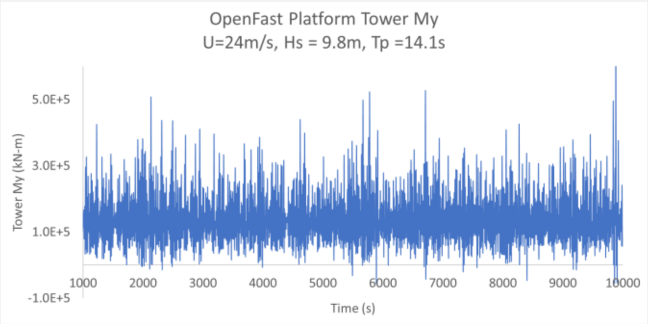


Figure 15 Tower Base Moment Loads in 9.8m Seas with 24m/s Wind

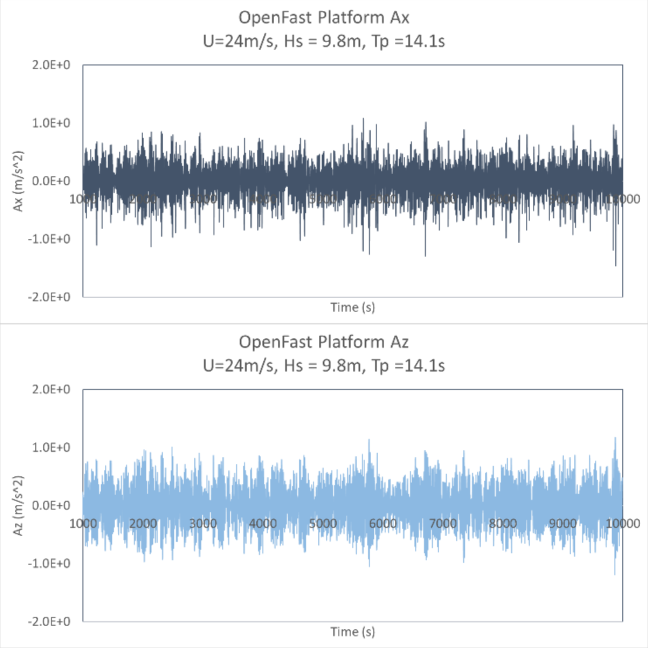


Figure 16 Nacelle Accelerations Ax and Az in 9.8m Seas with 24m/s Wind

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REFERENCES

[1] Jason M. Jonkman, Marshall L. Buhl Jr., FAST User's Guide, NREL, 2005

[2] O. Faltinsen, Sea Loads on Ships and Offshore Structures, Cambridge University Press, 1994

[3] American Bureau of Shipping, Guide for Building and Classing Floating Offshore Wind Turbines, July 2020

[4] Christian Cermelli, Dominique Roddier, Alexia Aubault, WindFloat: A Floating Foundation for Offshore Wind Turbine Part II: Hydrodynamics Analysis, OMAE 2009

[5] American Bureau of Shipping, Guidance Notes on Global Performance Analysis for Floating Offshore Wind Turbines, July 2020

[6] Pegalajar-Jurado, A., Madsen, F.J., Borg, M., Bredmose, H., Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m, 2018.

[7] Allen, Christopher, Anthony Viselli, Habib Dagher, Andrew Goupee, Evan Gaertner, Nikhar Abbas, Matthew Hall, and Garrett Barter. Definition of the UMaine VolturnUS-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-76773.

[8] Gaertner, Evan, Jennifer Rinker, Latha Sethuraman, Frederik Zahle, Benjamin Anderson, Garrett Barter, Nikhar Abbas, Fanzhong Meng, Pietro Bortolotti, Witold Skrzypinski, George Scott, Roland Feil, Henrik Bredmose, Katherine Dykes, Matt Shields, Christopher, Allen, and Anthony Viselli. 2020. Definition of the IEA 15-Megawatt Offshore Reference, Wind. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75698.