DESIGN CHALLENGES OF A HYBRID PLATFORM WITH MULTIPLE WIND TURBINES AND WAVE ENERGY CONVERTERS

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Proceedings of the 21st Offshore Symposium, February 2016, Houston, Texas
Texas Section of the Society of Naval Architects and Marine Engineers

ABSTRACT

The present paper describes the design challenges of a wind wave hybrid power generation floating platform. The platform is a semi-type which consists of multi columns, pontoons, decks and brace members. The platform with a column span 150m is moored with chain catenary mooring lines at a water depth of 80m to produce power generated from wind and waves. The hybrid system is designed to produce a total of 10MW power from four wind turbines and twenty four wave energy converters (WECs). The platform design is based on industry standards and rules. The wind turbines are installed on four columns located at each corner of the platform while the WECs are placed at the peripheral locations between semi pontoon and deck. The WECs are vertically supported by frames and the vertical linear WEC generators are integrated inside the deck.

Design of the unconventional size of platform faces many design challenges in configuration of the system, structural design, wind turbine wake effects, constructability, loadout, WEC structures, multi-turbine and platform coupled response, mooring system design and power cable and such design challenges are discussed. Brief results of the motion responses, mooring analysis, structural analysis and power cable analysis are also described.

Keywords: Offshore Floating Wind Turbine, Wave Energy Converter, Semi-sub, Floating Structure, Mooring, Hybrid Wind Wave Power Generation, Wind Turbine Wake, Power Cable

INTRODUCTION

There have been considerable attempts to extend the shallow water wind turbine technologies of the bottom mounted structures to the deep water turbines supported by a floating structure. The majority of the floating offshore structure types for the wind application are originated from the oil and gas platforms, for instance, spar, semi-sub and TLP as they are well-proven platforms complying with very strict functioning requirements in harsh environments. Representative prototype floating wind platforms installed are Hywind and Windfloat.

However, the floating wind turbine platform also has numerous deign concerns, for instance, dynamic coupled effects of turbine with platform responses, which is called aero-servo-elasto-hydro couplings. The coupled effects can affect the rotor, structure near the mounting location and mooring system in various aspects.

Most studies on floating offshore turbine have been aimed at wind turbine sitting on a single floater which may enable a designer to apply the existing design tool based on FAST (Jonkman, 2007). More recently, multiple turbine floating systems have drawn interest as they provide a large amount of power in a single platform. Recently, the South Korean government funded a project to develop a wind wave hybrid platform which can facilitate four wind turbines and multiple wave energy converters (WECs) to produce a combined power rate of 10MW (Kim et al., 2015). For this purpose, a semi type floater moored at a water depth of 80m was selected but numerous design challenges were faced upfront along with the conventional design issues. Due to wake effects, consideration of a proper turbine distance is the most critical element in determining the semi dimensions which can raise a series of associated design difficulties. As a result, decided column span of the multi turbine semi is very long compared to the conventional semi, which can then cause construction and loadout difficulties. Additional engineering issues on this structure include design tool to deal with the multi turbine coupling with the semi, the structural design, mooring system, WEC installation and others. In this paper, such design challenges and drivers are discussed.

The present design of the 10MW hybrid platform was evaluated through the analyses in the global strength, motion response, mooring system and power cable, and the results are described briefly.

SITE LOCATION AND METOCEAN DATA

The platform will be installed at the west coast of Jeju island of South Korea depicted in Figure 1. The site water depth is 80m. The location is exposed to persistent winds and waves thoughout the year but strong typhoon passes the site often during the summer and early fall, and typhoon conditions can drive the hybrid system design. As shown in the wind rose based on the winds at 10m above the sea level (Figure 2), wind directionality is well presented. Metocean conditions for various return periods are summarized in Table 1.

Figure 1 Platform Installation Site

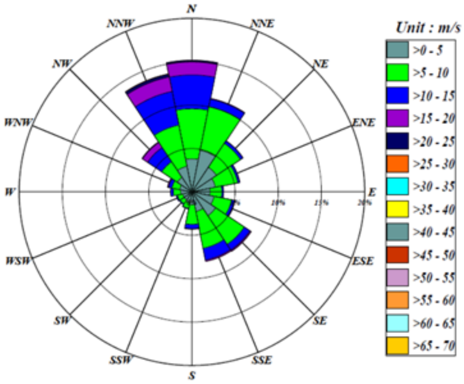

Figure 2 Wind Rose Plot

Table 1 Metocean Data

Items	Unit	1-yr	50-yr	100-yr	500-yr
Hs	m	5.74	9.72	11.32	16.02
Tp	s	10.81	13.98	15.10	17.57
Current	m/s	1.31	1.47	1.57	1.7
Wind	m/s	20.40	43.41	48.41	59.21
Tide	m	4.44	5.59	6.16	N/A

Current: Surface current
Wind:1-hr average at 10m
Tide: Tidal variation

FUNCTIONAL REQUIREMENTS

The wind-wave hybrid power platform produces a combined power rate of 10MW which is 8MW by wind turbines and 2MW by WECs. The WEC systems include a means to park the system during storm events. All the required electrical and marine systems are facilitated in the platform. A single power cable runs toward the coast and is connected to an existing grid. The mooring system is designed to limit the platform offset such that the power cable is in function with no damage. The platform provides facilities to monitor, support and repair the wind turbines and WECs. The wind turbines and WECs are integrated prior to wet-tow to site. Platform will have 25 years of design life.

DESIGN STANRDS AND GUIDELINES

The hybrid power floating platform system design is governed by various design standards, codes and guidelines in hull structure, station keeping, wind turbine, WEC and power cable. The documents for the design are summarized below.

Hull, Mooring and Stability

ABS Rules for Building and Classing Mobile Offshore Drilling Units, 2008
ABS FPI Guide for Building and Classing Floating Production Installations, 2013
API RP 2A Recommended Practice for Planning, Designing and Construction Fixed Offshore Platform – Working Stress Design, 2007
DNV-OS-C201 Structural Design of Offshore Units (WSD method), 2008
DNV-RP-C201 Buckling Strength of Plated Structures, 2010
DNV-RP-C202 Buckling Strength of Shells, 2010
DNV RP C203 Fatigue Design of Offshore Steel Structures, 2010
DNV-RP-F205 Global Performance Analysis of Deepwater Floating Structures, 2010
API RP 2SK Recommended Practice for Design and Analysis of Stationkeeping Systems for Floating Structures, 2nd edition, 2005

Floating Offshore Wind Turbine

ABS Guide for Building and Classing Floating Offshore Wind Turbine Installations, 2013
ABS Global Performance Analysis for Floating Offshore Wind Turbine Installations, 2014
DNV-OS-J101 Design of Offshore Wind Turbine Structures, 2010
IEC 61400-3 Requirements for Offshore Wind Turbines, 2009
IEC 61400-3-2 Technical Specifications for Floating Offshore Wind Turbines (draft)

Wave Energy Converter

IEC 62600-2 Design Requirement for Marine Energy System (draft), 2014
DNV Guidelines on Design and Operation of Wave Energy Converters, 2005
EMEC Guideline for Design Basis of Marine Energy Conversion System, 2009

Power Cable

API SPEC 17E Specification for Subsea Umbilicals
ISO-13628-5 Petroleum Natural Gas Industries – Design and Operation of Subsea Petroleum Production Systems – Part 5: Subsea Umbilicals
DNV RP F401 Electrical Power Cables in Subsea Applications, February, 2014
DNV RP J301 Subsea Power Cables in Shallow Water Renewable Energy Applications, February, 2014

DESIGN CHALLEGES

There are many challenging design drivers for the hybrid floating platform to support the multiple wind turbines and WECs. Key design drivers are discussed in this Section.

Turbine Distance and Wake Effects

The most notable design challenge in the present platform configuration and sizing is to determine the distance between turbines in order to minimize the wake effects to the downstream turbines. An example photo of the wake clouds behind the turbine in the wind farm is presented in Figure 3. The wake can cause a significant loss of the downstream wind turbine power output and also be a source of fatigue damage to the rotor and structures. The wake effects vary depending on the prevailing wind direction and turbine separation distance. Many empirical and analytical models have been developed and utilized for wind farm layouts although they are not satisfactory in predicting the wake.

Figure 3 Wakes Clouds behind Wind Turbine (Photo courtesy of Vattenfall)

For the present design, the wind turbine distance was decided to be 150m. The distance of 150m will not provide an ideal separation between tandem turbines. However, it may be the maximum distance when incorporating other design drivers discussed in subsequent sections. Wind velocity deficit can be estimated using Jensen model (Jensen, 1983);

$$u_0 - u = u_0\left(1-\sqrt{1-c_t}\right)\left(\frac{D_0}{D_0+2kX_0}\right)^2$$

$$c_t = \frac{2F_t}{\rho\frac{\pi}{4}D_0^2u_0^2}$$

Here u_o and u are speed of free stream wind and wake on the downstream turbine with a sweep diameter of D_o. F_t, X_o, and c_t and k are thrust force, separation distance, thrust coefficients and turbulence decay factor. The decay factor determines how quickly the wake expands with distance. It varies between 0.075 for onshore and 0.038 according to Pena et al. (2015)

Figure 4 and Figure 5 present the wind velocities at various downstream locations and power output ratio between downstream (P) and upstream (P_o) turbines aligned in tandem direction, for a 3MW turbine, where a decay factor of 0.04 was assumed. Also CFD results for the case of an upstream speed 10 m/s are shown in Figure 5. It can be observed that power output of the downstream turbine located at 150m behind can be reduced to about 28%. It is seen that the wind velocities from Jensen model are greater than the CFD results but the model reasonably predicts the wake velocities. According to this estimation, the wind turbines may produce approximately a total of 8MW in tandem alignment. However, the wake direction varies with wind direction, which can cause partial or full wake effects on three turbines on downstream, thus total power generated may decrease considerably. This complex phenomenon is under investigation with CFD.

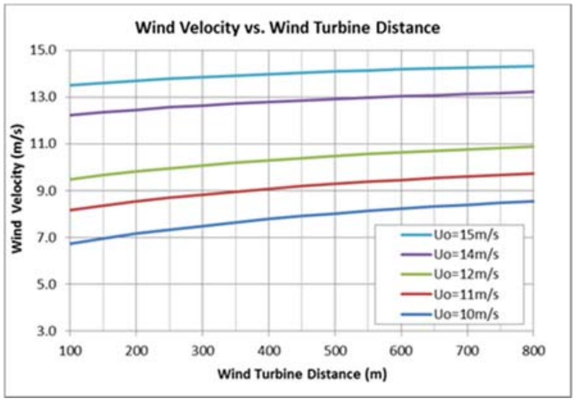

Figure 4 Wind Velocities at Locations behind Turbine by Jensen Model

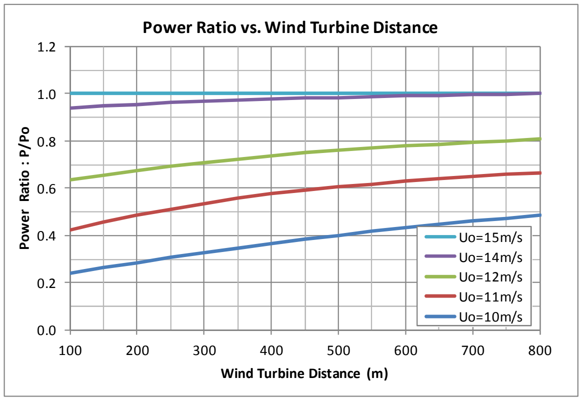

Figure 5 Power Ratio of Upstream to Downstream Turbines

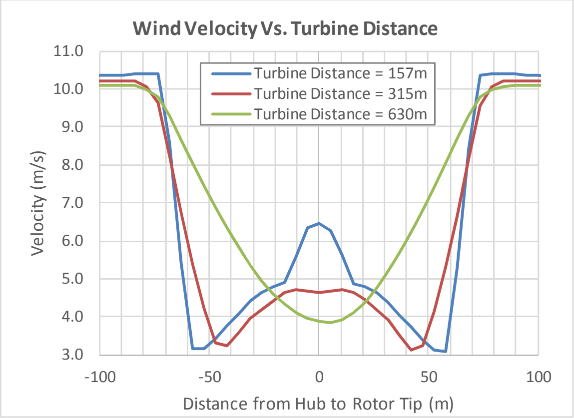

Figure 6 Wind Velocities at Locations behind Turbine from CFD

Floating Platform Type

Among all possible floating types, semi and TLP type of floaters are feasible options for installation in the water depth of 80m. The semi and TLP floaters have pros and cons in several aspects. As presented in Table 1, tidal variation at site is pretty large so that it will affect the floater draft change. The TLP buoyancy and tether tensions are very sensitive to tidal elevation compared to the semi. Thus, the semi type floater was selected for the present application.

The platform consists of multi columns, pontoons, decks and bracing members. The pontoons and decks connect the columns while the bracing members provide the structural support for the columns, pontoons and other structures. Center-to-center column span of the semi is 150m. A wind turbine tower is installed on the top of each column. The WECs are installed between pontoon and deck structure. The deck structure accommodates the WEC generator system.

Constructability and Loadout

Considering the column width, the semi dimensions are now a little greater than 150m in length and breadth which is unconventionally large and also very slender compared to semi rigs used in oil and gas. This size of semi is very problematic in various areas such as yard facility and space availability, construction method, loadout scheme, wind turbine tower and WEC integrations. A dry dock typically provides relatively better construction and easy loadout (or float-out). No dry dock is, however, available to deal with such an unconventional size semi so the following other options can be considered;

- Modular construction on land and welding in water
- Modular construction on land and welding on floating dock or submersible barge
- Entire semi construction on floating dock or submersible barge

- Entire semi construction on land and skid loadout to submersible barge
- Construction of entire lower hull and upper hull (deck) separately, loadout each using heavy lifting crane and integration of both at quayside

The maximum size of floating dock in Korea or commercially available submersible barge has insufficient width to support the whole hybrid semi. A huge overhang of the structure is anticipated during construction or loadout which will cause high bending loads to the semi structure. Thus a new build submersible barge could be optioned for both construction and float-off purposes. Any of the options above affects the structural design, construction, interface, cost and execution.

WEC System Installation

These WECs are installed in the sides of the platform between pontoon and deck. A point absorbing type WEC with 100kW capacity was utilized. The WEC consists of buoy, shaft, permanent magnet system, coil system and support frames as depicted in Figure 7. Details of the WEC system and linear generator are presented in Figure 8. Electricity is produced by the vertical oscillation of the magnet system through the linear generator with coil inside the deck. Due to this functional configuration required, penetrations of deck are inevitable. This requires larger size of deck with sufficient strength. Also proper water tight is to be provided to protect the generator system. Many trade-off studies have been carried out to determine the vertical and lateral support frame layout and sizes.

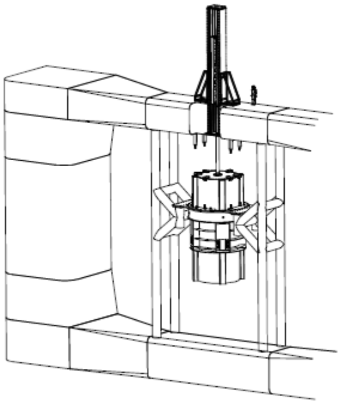

Figure 7 WEC System Installed and Support Frames

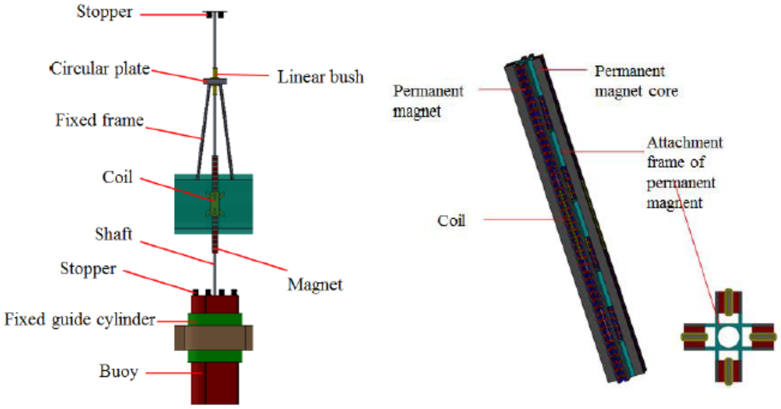

Figure 8 WEC System and Linear Generator

Design Tool for Multiple Wind Turbine and Platform Coupled Analysis

Time domain analysis of aero-elasto-hydro coupling with floating structure has been undertaken by many researchers, for instance, Rodier et al. (2000) and Shim et al. (2008). These studies were performed for a single wind turbine mounting on a moored floater, based on FAST (Jonkman, 2007).

Fully coupled analysis of the multiple wind turbines with the floating platform is a very complex and extremely challenging subject. Recently a program to deal with the multiple wind turbine effects was developed (Bae, 2013) and is being extended for the present study.

PLATFORM CONFIGURATION

The wave and wind hybrid power generation platform has four 3MW turbines on the semi columns and twenty four WECs distributed along the four platform sides. The platform is configured by considering several cases of loadout, wet-tow, operating and storm conditions. The total weights of the platform for the in-place operating and storm conditions were estimated considering hull structure, appurtenance, marine growth, ballast, turbines, WECs, marine system, electrical system and reserve, where an appropriate contingency was applied based on the past experiences of the oil and gas rig design. The platform weight differs for each case.

The platform key figures for the storm condition are summarized in Table 2. Also schematics of the platformis illustrated in Figure 9, where the wind turbine rotors are omitted.

Table 2 Key Figures of 10MW Hybrid Semi Platform – Storm Condition

Items	Unit	Value
Displacement	ton	26,848
Draft (design)	m	15.0
Column Span (center to center)	m	150.0
Column Height	m	27.0
Tower + Rotor	ton	1,800
WEC System	ton	2,344
CoG above Keel	m	13.68
Roll / Pitch Radius of Gyration	m	58.56
Yaw Radius of Gyration	m	78.41
Heave Natural Period	s	16.5
Surge / Sway Natural Period	s	103.7
Roll / Pitch Natural Period	s	15.3
Yaw Natural Period	s	115.4

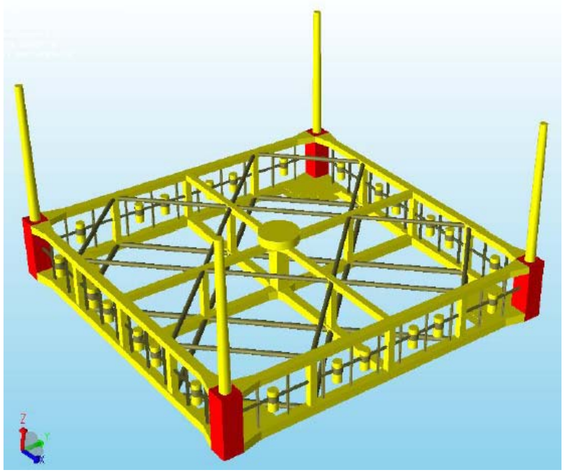

Figure 9 Hybrid Semi Platform Structure Schematics

STRUCTURAL DESIGN

Scantling analysis was conducted on the hull primary structures, deck structures and vertical square members for the initially configured structures presented in Figure 9. It was assumed that the tubular bracings are unstiffened.

The scantling design was verified by a global structure strength analysis using a SACS model. A couple of iterations were carried out by adding bracings and adjusting the structural member sizes to comply with the structural design criteria. One of the modifications is presented in Figure 10 where the added braces to the initial configuration are highlighted in red.

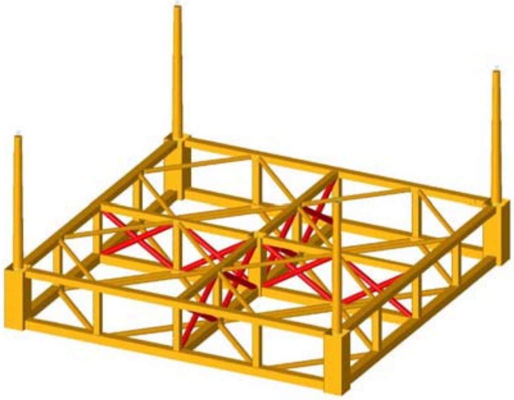

Figure 10 Structure after Modification in SACS Model

MOTION RESPONSE ANALYSIS

One quarter of platform was modeled with panels for analysis. The entire platform panel model is presented in Figure 11. WEC frames were excluded in the present model but their weights and displaced volumes were distributed to adjacent structures modeled.

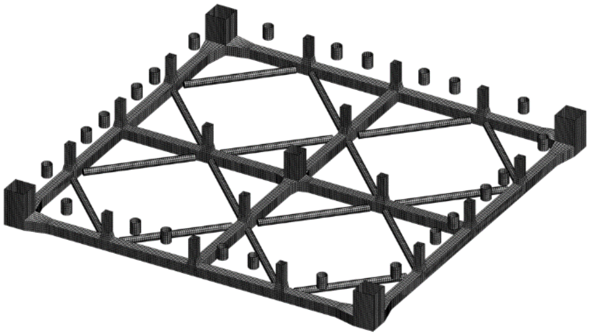

Figure 11 Simplified 3D Panel Model used in Hydrodynamic Analysis

Instead of including hull viscous damping in the WAMIT model, the damping were taken into account by Morison elements with drag coefficient on each element (columns, pontoons, braces, WECs, etc.). The input drag coefficient of the element was assumed initially based on its shapes (DNV-RP-C205, 2007) and then tuned with iterations until the overall current force and moment predicted by OrcaFlex are within acceptable range compared to the values predicted by WINDOS software. The mooring line size and configurations used for the analysis are described in the following section.

Wave tank tests with a 1/50 scale ratio were performed in the KRISO facility. The measured motion RAOs due to white noise and regular wave tank tests are compared with the numerical values by WAMIT (potential damping only) and numerical white noise values (potential plus viscous damping). Also based on the measured decay test results, the damping in the numerical model was correlated and then the simulation was re-run with the adjusted damping. These results are presented as “White Noise: with Correlation” in Figures 11, 12 and 13.

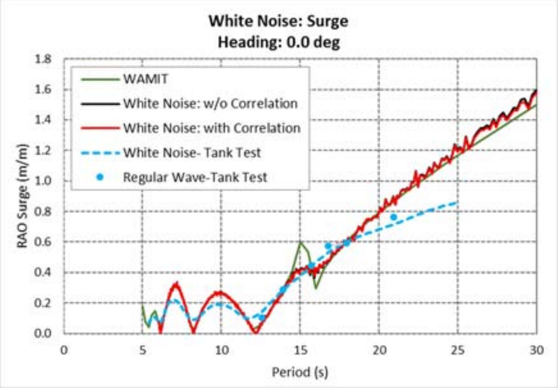

Figure 12 Surge Motion RAO Comparisons

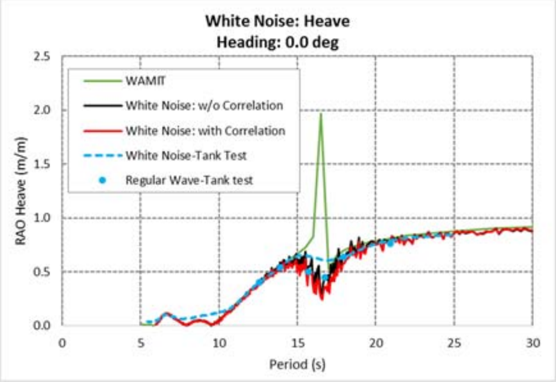

Figure 13 Heave Motion RAO Comparisons

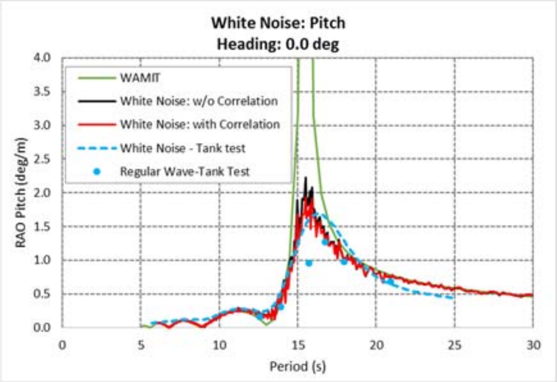

Figure 14 Pitch Motion RAO Comparisons

MOORING ANALYSIS

Several options of mooring layouts along with mooring line length variation have been studied. It is identified that a minimum of 500 ~ 600m long each line with 5 3/8 ~ 6 inch chain is required to limit the offset of the platform for the power cable performance and also to comply with the mooring strength criteria.

Several cases have been studied by changing and combining the number of lines, line length, chain sizes, clump locations and line separation angles. One of these cases was twelve mooring lines with 600m length, where three clumps were utilized. They are in four groups of three and consist of single chain system of R4 studless. Fairleads were assumed located near the keel. Chain diameter for the numerical strength analysis was adjusted accordingly due to the corrosion during the service life of 25 years. The mooring system layout with twelve lines used for the analysis is shown in Figure 15. Analysis was run by OrcaFlex software.

Load cases were selected for DLC 1.6 (operating), DLC 6.1 (50-yr extreme, parked), DLC 9.1 (100-yr survival, parked), based on ABS Guidelines.

Two environmental conditions of COD (codirectional) and MIS (misalignment) were also investigated. Using both Weibull and Rayleigh extreme approaches, the tensions at fairleads and anchors were calculated. It is found that the DLC 6.1 MIS condition for the wave heading 45 degrees governs the mooring strength design. Also the similar trend was observed in platform offset. Additional observation is on the ground chains suspended. The weatherside chains are most likely suspended entirely during the survival event which may require more mooring clumps, longer mooring line length or suction (or pile) anchor rather than a drag anchor. These are now being evaluated to minimize the cost impact.

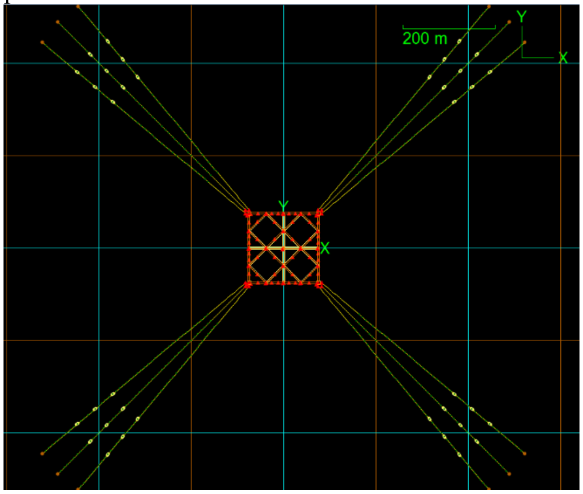

Figure 15 Modeled Twelve Mooring Line Layout

POWER CABLE ANALYSIS

Among numerous options for the power cable installation, a lazy wave configuration was chosen due to water depth at site. A single power cable running toward the platform east was considered. The cable top end was assumed to be connected to the center of the east pontoon keel. Cable diameter used is 105mm.

A screen capture of the numerical model by Orcaflex is shown in Figure 16. By considering the near, far and cross conditions of the platform offset, the lazy wave shape of the cable was determined iteratively by complying with the requirement of tension and minimum bend radius (MBR). The optimized length between the hang-off and first buoy location is identified to be about 62 ~78m with a buoy distribution length of 22m. The buoy OD, length and separation between buoys were 0.4m, 0.4m and 0.5m respectively.

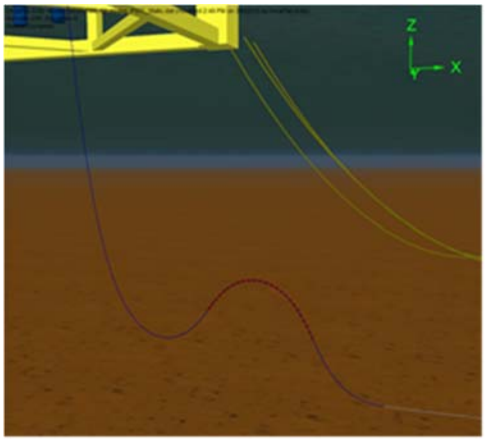

Figure 16 Power Cable Modeling for Lazy Wave Configuration

Figure 6 presents the effective tension distribution along the cable arc length for mooring intact, far condition under the extreme environment. The tensions are well below the allowable maximum. MBR for the extreme condition was estimated to be about 4.7m for mooring line intact and 4.2m for one mooring line damage which are greater the allowable MBR. The values were computed with Weibull extreme statistics. Time histories of the bend radius causing the MBR in extreme conditions (mooring intact, one line damage and near case) are plotted in Figure 18.

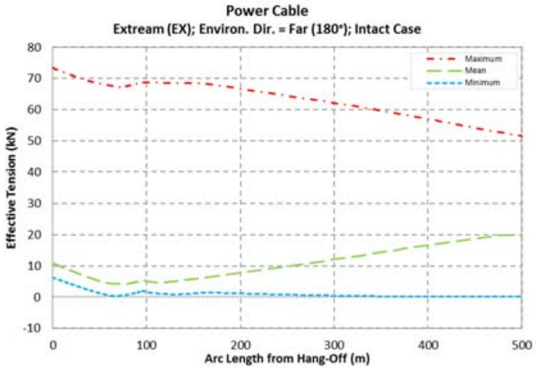

Figure 17 Effective Tensions on Power Cable: Far, Intact, Extreme

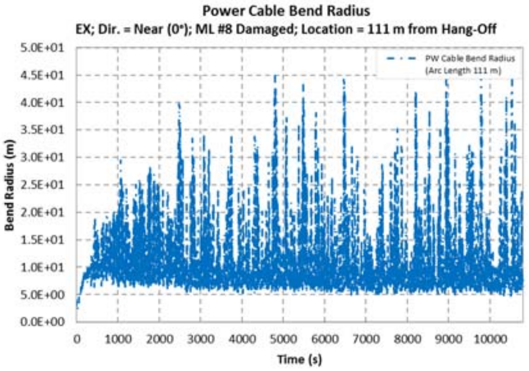

Figure 18 Bend Radius Time Histories: Near, Mooring Line Damage, 111 m from Hang-Off, Extreme

CONCLUSIONS

A wind-wave hybrid power platform has been designed to produce a power rate of 10MW which is a combined power output of 8MW by four wind turbines and 2MW by twenty four WECs. The platform is a four column semi but unconventionally long in length and breadth to provide a minimal turbine separation distance to create less wake effects to the downstream turbines. The wind turbines are mounted on the top of each column while the WECs are installed between pontoon and deck around the perimeter of the platform. WEC power generation systems are integrated inside the deck.

Design challenges of the long slender semi platform were discussed, which encompasses the wake effects, structural design, constructability, loadout, WEC system, and multi-turbine and platform coupled analysis.

The semi structure, mooring and power cable were designed to comply with the industry standards and codes applicable to floating wind turbine along with offshore floating installations. Numerical motion responses were compared with model test data to verify the numerical model. Numerical results on structure, mooring and power cable demonstrate that the current design meets the corresponding design requirements.

ACKNOWLEDGEMENTS

The present work is a result of the project "Development of the design technologies for a 10MW class wave-offshore wind hybrid power generation system" granted by the Ministry of Oceans and Fisheries, Korea. All support is gratefully acknowledged.

REFERENCES

Bae, Y.H., "Coupled Dynamic Analysis of Multiple Unit Floating Offshore Wind Turbine", PhD Thesis, Texas A&M Univ., 2013.

DNV-RP-C205 Environmental Conditions and Environmental Loads, 2007

Jensen, N.O., "A note on wind generator interaction", RISO, 1983

Jonkman, J.M., "Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine", November 2007.

Kim, K.-H., Lee, K., Sohn, J.M., Park, S.-W., Choi, J.-S., Hong, K., "Conceptual Design of 10MW Class Floating Wave-Offshore Wind Hybrid Power Generation System", Proceedings of the Twenty-fifth (2015) International Ocean and Polar Engineering Conference, 2015

Peña, A., Réthoré, P.-E. Paul van der Laan, M., "On the application of the Jensen wake model using a turbulence-dependent wake decay coefficient: the Sexbierum case", Wind Energy, 2015

Roddier, D., Cermelli, C., Aubault, A., "WindFloat: A Floating Foundation for Offshore Wind Turbines Part II Hydrodynamics Analysis", June 2009.

Shim, S., Kim, M.H., "Rotor-Floater-Tether Coupled Dynamic Analysis of Offshore Floating Wind Turbines", ISOPE 2008.