COUPLED AND UNCOUPLED ANALYSIS OF Y-WIND SEMI WIND TURBINE FOUNDATION

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ABSTRACT

There are several numerical approaches to evaluate the dynamic performances of floating offshore wind foundations (FOWF). Most common practices are to implement a fully coupled modeling of the foundation hull, mooring, tower and rotors. However, this requires significant efforts in the modeling, especially tower and rotor, control effects, whereas the uncoupled (or semi-coupled) method can minimize those efforts resulting in quick turn-around time for the design spiral which is very beneficial to early design stage of an FOWF. The paper presents the comparisons between the coupled and uncoupled methods for the 5MW Y-wind semi-submersible FOWF moored at a water depth of 200m. In the coupled analysis, the wind turbine and platform interact dynamically exchanging loads and motions at each time step. Aerodynamic loadings on blade element with wind-inflow data, tower/blade elasticity, rotating blades, and blade-pitch control are also taken into account. For the uncoupled analysis, the tower and rotors are set as a rigid body on the foundation, but the rotor thrust is modeled with two different schemes such as applying a steady force at the tower top and a disk drag with the same rotor swept area, where the thrust or mean drag is equivalent mean thrust computed from a land based wind turbine. Numerical simulations for the coupled and uncoupled models are carried out and the results in motions, accelerations, offsets, and mooring tensions are compared. The present results indicate that the uncoupled approach gives acceptable range of design results compared with the fully coupled approach and that the uncoupled approach can be utilized effectively in the design phases of the floating wind platform and mooring system.

Keywords:* *Y-Wind, Semi-submersible, Floating Offshore Wind Foundation, FOWF, Coupled Analysis, Uncoupled Analysis, Dynamic Response

INTRODUCTION

Various floating offshore wind foundation have been developed, such as semi-submersible, spars, TLP and barge type floaters by implementing the mature technologies of the floating platform design in oil and gas. However, the design of the floating wind platform must consider other types of interactions from the wind turbine rotor and tower, which cause complex couplings between the platform, station-keeping and turbine systems. In order to take these effects into account, fully coupled methods have commonly been utilized in the FOWF design and analysis. This integrated approach accounts for the elastic model of the tower and turbine rotor nacelle assembly (RNA), turbine control systems, rigid body model of platform structure, mooring lines and power cables (ABS, 2014).

A new design of a FOWF with the fully coupled method requires significant amount of efforts to validate many design factors complying with requirements of ABS (2015) or DNV (2013). However, a semi-coupled (or uncoupled) approach may provide a level of validation of the platform and mooring system with minimum efforts resulting in a quick turn-around time for the design spiral, which is very beneficial to early design stage of the FOWF.

In the semi-coupled analysis, the coupling effect from the tower and rotor can be neglected and treated as part of the hull as a rigid body (ABS, 2014). But the rotor thrust needs to be incorporated at the tower top as wind load which is a function of wind speed for the turbine operating condition. In this approach, however, the hull, mooring system and cables are fully dynamically coupled.

DNV (2013) also recommends several methods depending on the design components with appropriate accuracy levels. Among those components, the floater (platform) and mooring system can be designed and modeled with Level I accuracy whereas the wind turbine with Level III accuracy. This approach is similar with the semi-coupled analysis (ABS, 2014), except for the modeling of tower, gyroscopic effect and few others recommended in DNV (2013).

Majorities of the analyses have been utilized either coupled model with dynamic mooring or coupled model with quasi-static mooring modeling scheme, for instance, Bae (2013), Huijs et al. (2014), Jonkman (2010), Robertson et al. (2014), Roddier (2010) and Allen (2015). Some of their coupled simulation tools have been validated through comparison between measurement data and simulation results (Nygaard et al. 2015, Kim and Kim, 2016; Kim et al., 2017). Boo et al. (2017a; 2017b) implements the semi-coupled methods for the design validation of Y-wind semi type wind platform.

The objective of the present study is to evaluate the differences between fully coupled and uncoupled model results in the floating wind platform responses and assess the feasibility of the uncoupled method in the FOWF early design phases. The uncoupled model used in the present study is similar to the semi-coupled model described above but it will be called "uncoupled" in this paper.

The present fully coupled analysis utilizes the interface tool provided by Ocaflex (Masciola et al., 2011) which integrates the wind turbine (Jonkman, 2010) with the platform and mooring in time domain. Y-wind semi platform supporting 5 MW turbine is considered and moored at a water depth of 200 m with chain catenary mooring. The uncoupled analysis is conducted with Orcaflex with consideration of the thrust as explained below.

The turbine thrust in the uncoupled analysis are presented at the top of the tower as two different ways: disk drag and steadily applied load. The disk area is identical to the rotor swept area and an appropriate drag coefficient is used to generate the drag equivalent to the mean thrust which is from a land-based wind turbine.

Y-WIND SEMI TYPE FOWF

Y-Wind semi type platform (foundation) is made up of one center column, three outer columns, three pontoons and motion dampening structures. The center column is connected to each outer column with rectangular pontoon. Figure 1 represents the Y-Wind bare platform with 5MW wind turbine, where the motion dampening structures are omitted. The NREL 5MW wind turbine is installed on the top of the center column of Y-Wind. Particulars of the platform and wind turbine are summarized in Table 1 and Table 2.

The Y-Wind platform is assumed to be installed in the US offshore at a water depth of 200 m and designed to produce a power of 5MW for a service life of 25 years. Details of the Y-Wind can be found in Boo et al. (2017a, 2017 b). The natural frequencies of 6 DOF motions were determined from numerical free decay test and are summarized in Table 3.

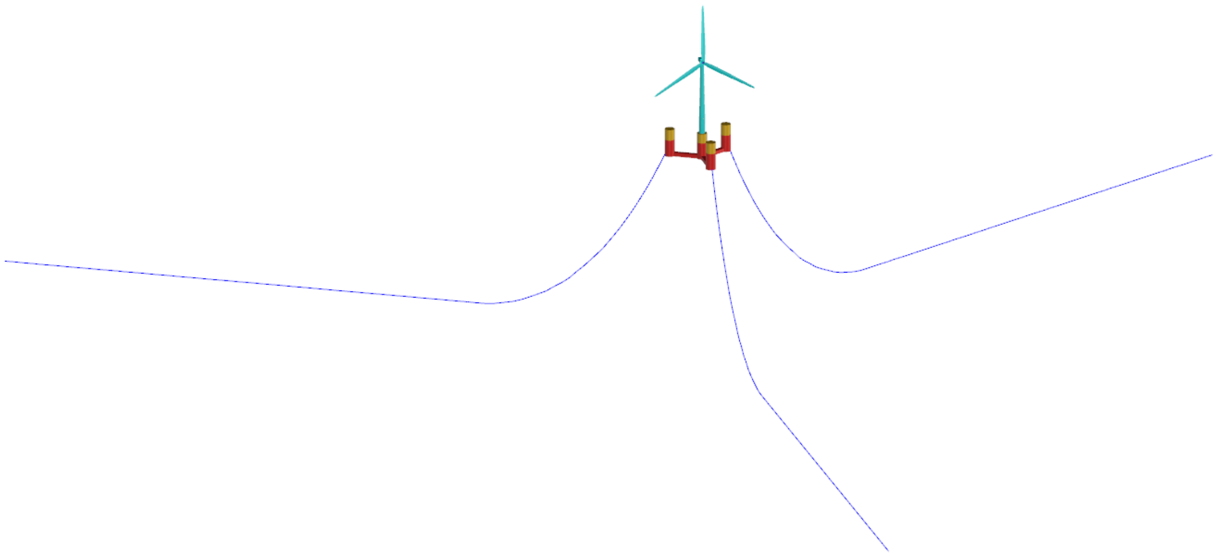

Figure 1 Y-Wind Semi Type FOWF with Mooring Lines

Table 1 Y-Wind 5MW FOWF Particulars

Items	Unit	Value
Displacement	tonnes	7,736
Draft	m	18
Outer Column Center Radius	m	35.0
Outer and Center Column OD	m	10.5
Outer Column Height	m	29.5
Center Column Height	m	28.0
Freeboard (Outer Column)	m	10
Pontoon Width × Height	m	4.5 × 4.0
Tower Base above MWL	m	10
Hub Height above MWL	m	90
COG (above keel)	m	14.01

Table 2 NREL 5MW Wind Turbine Dimensions

Items	Unit	Value
Power	MW	5
Rotor Diameter	m	126.0
Number of Blades	ea	3
Tower Height	m	77.6
Tower Diameter(Top/Base)	m	3.87/6.5
Cut-in / rated / cut-out wind at hub height	m/sec	3.0/11.4/25.0
Rotor and Nacelle Weight	tonnes	350
Tower Weight	tonnes	250

Table 3 Natural Frequencies of Y-Wind FOWF

Motions	Natural Period (sec)	Natural Frequency (Hz)
Surge	184.67	0.0054
Sway	184.67	0.0054
Heave	16.61	0.0602
Roll	19.72	0.0507
Pitch	19.61	0.0510
Yaw	104.29	0.0096

METOCEAN CONDITIONS

Metocean conditions for the Design Load Cases (DLCs) of operating conditions based on ABS (2015) are presented in Table 4. The irregular waves are presented with JONSWAP spectra, and 200 wave components are used. Wind speeds (10-minute average) considered are 11.4 m/sec (rated) and 13 m/sec at the hub. The wind speed of 1-hr average at 10 m elevation can estimated using the 10-minute average speed if necessary (ABS, 2013). The dynamic winds are generated using API wind spectrum. Figure 2 presents the API wind (rated wind) and JONSWAP wave spectra.

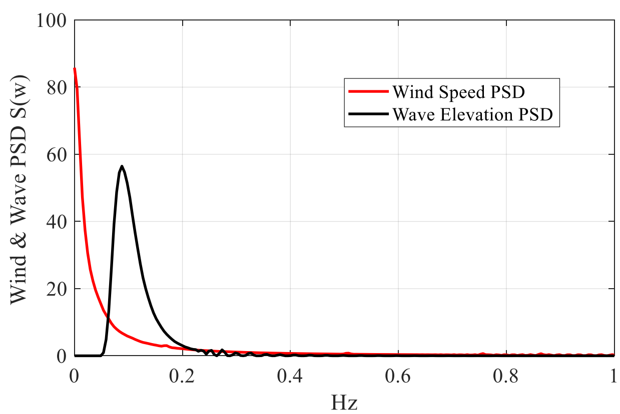

Figure 2 Rated Wind and Wave Spectra

Table 4 Metocean Conditions

Design Conditions (ABS)	Wave Hs (m)	Wave Tp (s)	Wave Gamma	Current (m/s)	Wind (m/sec)
DLC 1.3 Operating	7.5	11.5	1.0	0.40	11.4
DLC 1.3 Operating					13.0

NUMERICAL MODELING

Figure 3 presents the Y-Wind platform coordinate systems used for the present analysis. The reference center is located at the platform center on the mean water level (MWL). Wave direction (heading) is positive toward the x-direction and measured in counter-clock wise direction. Mooring line #1 to #3 with a 120 degree apart are also shown in Figure 2. The Y-Wind platform below the MWL was modelled with source panels for the radiation and diffraction analysis as shown in Figure 4 where the damping plate located at the keel is not shown. The platform is moored with a total of three catenary R4 studless chain lines with 120 mm diameter at a water depth of 200 m. The one end of the mooring line is connected to a fairlead located near the keel of the outer column and the other end is connected to an anchor foundation. The mooring line are designed to meet the requirements of the factor of safety for the case of no redundancy per corner, according to ABS (2015).

The radiation damping calculated from the radiation-diffraction analysis is added to the numerical model in time domain simulation. The viscous damping force is presented with Morison elements in Orcaflex numerical model. The viscous drag coefficients used for the simulation are tabulated in Table 5. The horizontal drag coefficients of pontoon and column are decided from the experimental data in reference (Venugopal et.al, 2009). A drag coefficient of 8.0of the damping plate is given to the vertical direction, which is based on the wave basin decay tests of Y-Wind platform. The vertical drag coefficients of the columns or pontoons are replaced with the coefficients of the damping plate if the column or pontoon has the damping plate.

In order to solve the interaction of the wind turbine with the floating platform, FAST was first considered (Jonkman and Buhl, 2004). Then it was linked to Orcaflex through a coupling module, so that both programs can simulate interactively the full coupled dynamics among the wind turbine, floating platform and mooring system. The coupling module is provided in OrcaFlex. In this interacting model, OrcaFlex calculates the mooring tension, hydrodynamic coefficients, and hydrodynamic forces and delivers to FAST. Then FAST calculates the displacements and velocities of platform and passes back into OrcaFlex at each time step. The detailed coupled process between OrcaFlex and FAST can be found in Masciola et al. (2011).

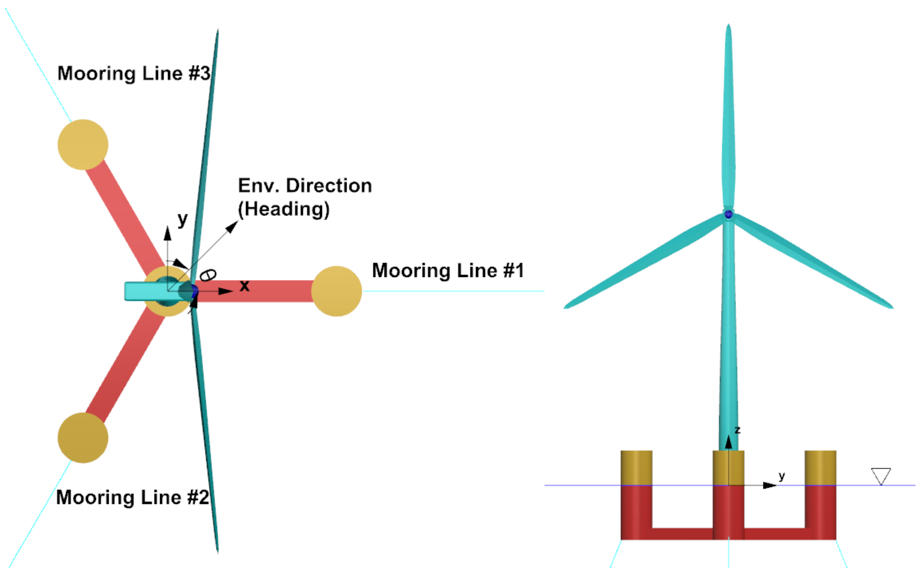

Figure 3 Coordinate System

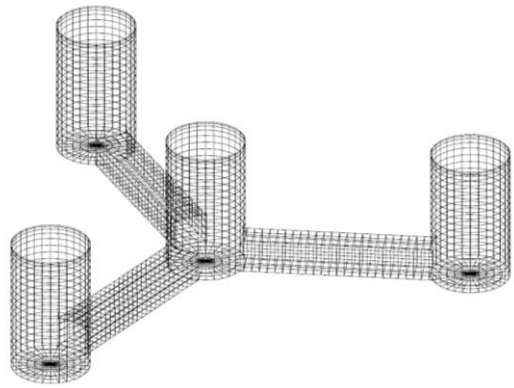

Figure 4 Mesh Panels of Y-Wind FOWF (Damping Plates Omitted)

Table 5 Morison Member Drag Coefficients

Structure		Value
Column	Horizontal	0.65
	Vertical	1.5
Pontoon	Horizontal	1.9
	Vertical	2.2
Damping Plate	Vertical	8

COUPLED AND UNCOUPLED MODELS

In this paper, three numerical models are considered to assess the coupled effects of the platform and wind turbine as below:

- Coupled (fully coupled) model
- Uncoupled – disk model
- Uncoupled - applied steady load model

The fully coupled analysis uses FAST and OrcaFlex together, where the time-varying aerodynamic loading, blade pitch control effect, blade rotation gyroscopic effect, and tower and blade flexibility effect are taken into account.

In the uncoupled-disk or applied steady load model, OrcaFlex only is used for the simulation. The RNA and tower are considered as a part of the hull as a rigid body but the turbine system weight and radii of gyrations are incorporated in the hull accordingly.

The uncoupled-disk model considers the rotor thrust as a wind drag force on the disk. The disk center is located at the top of the tower. The wind drag force used is determined from a mean thrust of a 5MW land-based wind turbine. At the rated wind speed of 11.4 m/s, the estimated thrust is 812 kN. This thrust is presented in the drag disk model as an equivalent wind load expressed with the rotor swept area of 12,445 m^2 and drag coefficients of 0.82. With this approach, the relative wind speed with respect to the platform motion is taken into account so that the instantaneous wind forces from the rotor generates motions of the platform.

The uncoupled-applied steady load model also applies the load of 812 kN steadily at the top of the tower in the global direction for the rated wind case. Thus, the force variations due to the relative wind speed are not considered in this uncoupled model but the horizontal loading and corresponding pitch moments are simulated.

When the natural frequency of Blade Pitch Control (BPC) is close to the natural frequency of the platform, the platform pitch motion can be affected as the BPC can change the damping of the platform pitch motion over the rated wind speed (Jonkman, 2008). Usually, a lower natural frequency of BPC than the natural frequency of platform pitch motion is suggested (Hansen et al., 2005). In the Y-Wind FOWF, the same BPC module as those used in DeepCWind semi-submersible platform are used since the pitch natural frequency of 0.051 Hz of Y-Wind FOWF is larger than

BPC natural frequency of 0.032 Hz. With the BPC in the simulation, it can be found that additional excitation exists near the platform pitch natural frequency. This is readily identified in the pitch power spectral density (Figure 12).

The gyroscopic effects of blade rotation induce non-zero transverse sway motion in the coupled simulation. However, the sway motion is almost zero in the uncoupled simulation due to the symmetry of all the external condition and the hull geometries in the xz-plane.

Lastly, when the tower and blade flexibilities are included in the simulation, the additional excitation can be occurred at the natural frequencies of the tower and blade modes. This effect is negligible in the platform responses because the lowest natural frequency of the tower and blade is relatively far from the natural frequencies of platform motions. However, the tower top acceleration is affected due to the flexibility. As shown in Figure 14, the tower top surge acceleration is excited in the natural frequency of 1st tower mode. The coupled and uncoupled effects in three models are summarized in Table 6.

Form the present study, it is observed that the uncoupled simulations are at least 25 times faster than the coupled simulations, which enables to shorten the design spiral duration in the early design stages of the FOWF.

Table 6 Comparison of Coupled and Uncoupled Models

	Coupled	Uncoupled- Drag Disk	Uncoupled – Applied Steady Load
Blade Pitch Control	O	X	X
Tower and Blade Flexibilities	O	X	X
Blade Rotation Gyroscopic Effect	O	X	X
Time-varying aerodynamic loading	O	O	X

RESULTS AND DISCUSSIONS

Three different wind conditions of 11.4 m/s (rated wind), 13.0 m/s and 21 m/sec were studied, but the results for 11. 4 m/sec and 13.0 m/sec cases are presented in this paper to focus on those wind effects as the floating wind platform designs are governed much around the rated wind. The same wave and currents associated with both wind cases were used, as presented in Table 4. Dynamic winds were simulated with API wind spectrum. Wind loads on the hull and tower were excluded to investigate the pure coupling effects of the tower and rotor on the hull. It was assumed a co-directional environment heading toward 180^o direction causing a negative excursion (offset) of the platform. Dynamic simulations were run for three hours excluding the ramp-up time.

Statistics of Platform and Turbine Responses

For comparison purposes, all the mean, standard deviation (SD) and maximum (MAX) values are normalized by the mean, standard variation, and maximum values from the coupled analysis with the dynamic winds, respectively. The maximum value was determined using Rayleigh extreme method with 1% risk factor. Dynamic run for the five different cases below were conducted; two for the coupled and three for uncoupled.

- Coupled (Dynamic Wind – Control on)
- Coupled (Steady Wind – Control on)
- Uncoupled – Disk (Dynamic Wind)
- Uncoupled – Disk (Steady Wind)
- Uncoupled – Applied Steady Wind

Surge, heave and pitch motion statistics are compared in Figure 5, Figure 6 and Figure 7. The trend of the statistical values of the five cases between 11.4 m/sec and 13 m/sec are very similar. However, the individual value of each case within the same wind (for instance, rated wind) differs from the other case values due to different interaction effects.

In general, the mean and max values of the surge and pitch motions from the uncoupled analysis are about 20 ~ 30% greater than the values from the coupled analysis. The higher platform excursions (offsets) and pitch responses of the uncoupled models affect the mooring line tensions, resulting in increasing the maximum top tension by about

30 ~ 48 % in the uncoupled cases compared to the coupled cases. Here the most loaded line #1 (ML#1) was selected. However, the heave responses between coupled and uncoupled show relatively good match. In the uncoupled simulations, the rapid mean thrust variations of the turbine around the rated wind speed is not modeled. Thus, the mean thrust from the uncoupled analysis at the rated wind (or near the rated wind of 13m/sec) becomes greater than the mean thrust from the coupled model. Overall, the surge, pitch, and mooring tensions from the uncoupled analysis are, therefore, relatively larger than the values from the coupled analysis, especially for the rated wind cases.

On the other hand, the surge acceleration on the tower top from the coupled dynamic wind case is about 10% larger than that of the uncoupled case (Figure 9). This phenomenon is mainly related to the tower elastic mode in the coupled analysis.

The present results indicate that the uncoupled models can predict the responses conservatively. Thus, the uncoupled models implemented at the early platform design phase can give benefits by providing acceptable ranges of values with quick design returns which enable to shorten the design validations and reduce the efforts, and to allow margins for potential design changes during the future detail phases.

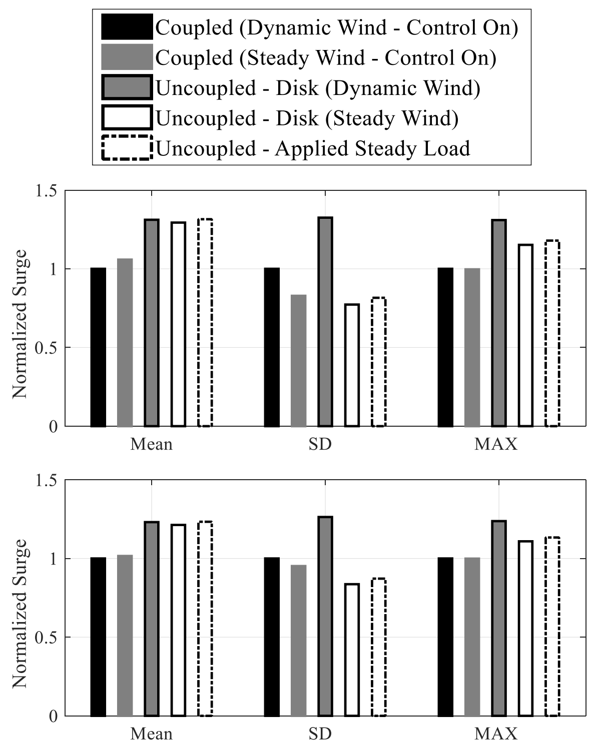

Figure 5 Normalized Surge Statistics for 11.4 m/sec (top) and 13 m/sec (bottom)

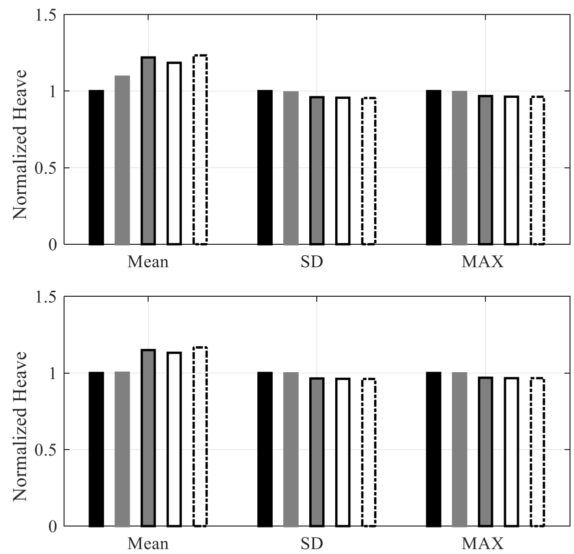

Figure 6 Normalized Heave Statistics for 11.4 m/sec (top) and 13 m/sec (bottom)

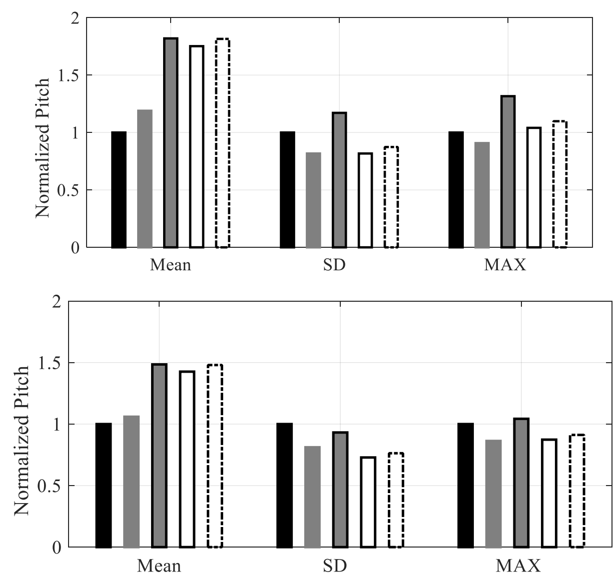

Figure 7 Normalized Pitch Statistics for 11.4 m/sec (top) and 13 m/sec (bottom)

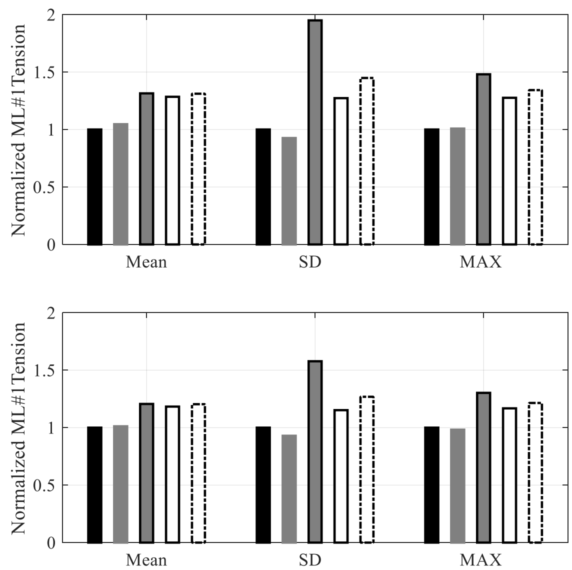

Figure 8 Normalized Mooring (ML #1) Top Tension Statistics for 11.4 m/sec (top) and 13 m/sec (bottom)

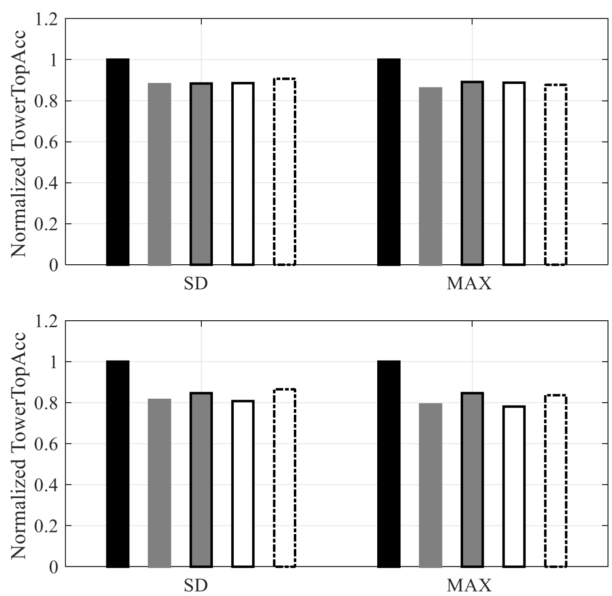

Figure 9 Normalized Tower Top Surge Acceleration Statistics for 11.4 m/sec (top) and 13 m/sec (bottom)

Power Spectral Densities of Platform and Turbine Responses

In the previous Section, the uncoupled-disk dynamic wind model was shown to lead to the most conservative results among uncoupled models. The model was, thus, selected to compare the spectral densities (PSDs) with the values from the coupled dynamic wind model. Figure 10 through Figure 14 present the time series of motions, mooring tension, and accelerations and PSDs from the coupled and uncoupled (disk dynamic wind) analyses. A part of the time histories out of 3-hour simulation is shown.

The surge motions of the uncoupled model resemble the coupled model except in the range of low frequencies (Figure 10). The surge dynamic motions from the coupled analysis decrease, compared to the uncoupled analysis due to the blade pitch control effects. The blade pitch angle varies according to the wind speed for the power regulation, which results in reducing the thrust force variation.

Figure 11 presents the heave PSDs showing the similar values to each other as also seen in Figure 6. It can be stated that the uncoupled models can produce the comparable results to the coupled model.

As presented in Figure 12, there are two distinct spectral peaks near the platform pitch natural frequency and incoming wave frequency in the coupled analysis results. The peak near the pitch natural period is induced by the blade pitch control resulting in reduction of the pitch damping and generation of the additional wind load near the frequency. However, in the uncoupled analysis, high pitch excitations in the very low frequency are generated due to the dynamic wind but this excitation is significantly decreased in the coupled model due to the blade pitch control.

Mooring dynamic tensions are strongly affected by the platform surge, heave, and pitch motions. The very large slowly-varying surge motions cause the significant increase of the mooring tensions as shown in Figure 13. The uncoupled PSDs reasonably agree well with the values from the coupled analysis except the low frequency regions. This is mainly related to the higher surge excitation of the uncoupled than the one of the coupled case at the low frequency.

Figure 14 compares the surge accelerations at the top of the tower. It is seen that there is not much difference between two methods in the wave frequency. However, the uncoupled method doesn't capture the excitation around the frequency of 0.5 Hz which is close to the 1st tower bending mode frequency. This results in the smaller uncoupled acceleration than the coupled one, which was also presented in Figure 9.

Due to the different behaviors of the excitations in the platform pitch and tower top acceleration between the coupled and uncoupled models, it may need a careful evaluation of the fatigue of the structural members and mooring lines in the uncoupled analysis.

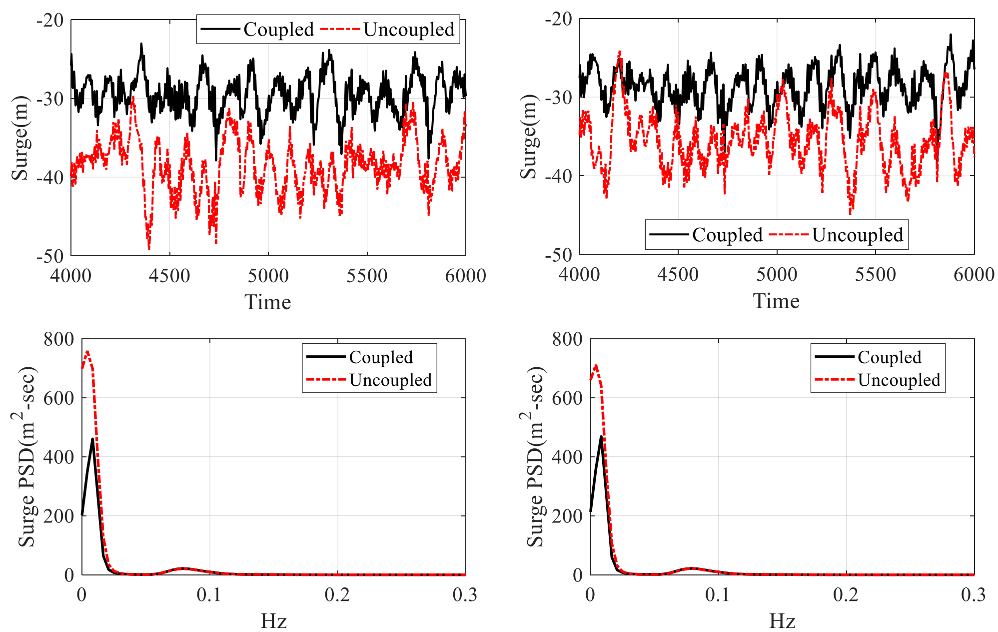

Figure 10 Surge Motions and PSDs of Coupled and Uncoupled (Disk) for 11.4 m/sec (left) and 13 m/sec (right)

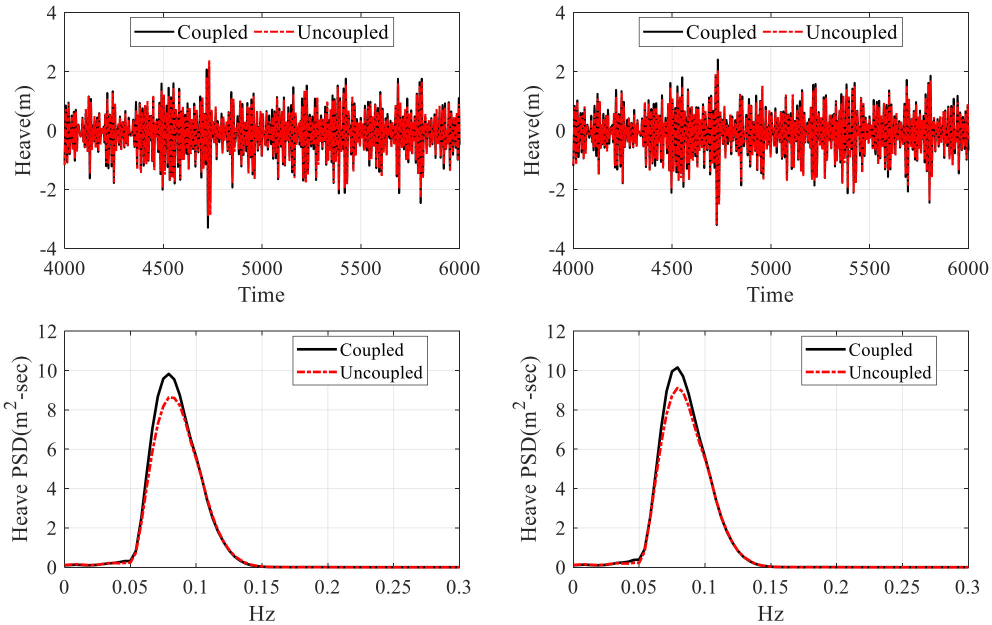

Figure 11 Heave Motions and PSDs of Coupled and Uncoupled (Disk) for 11.4 m/sec (left) and 13 m/sec (right)

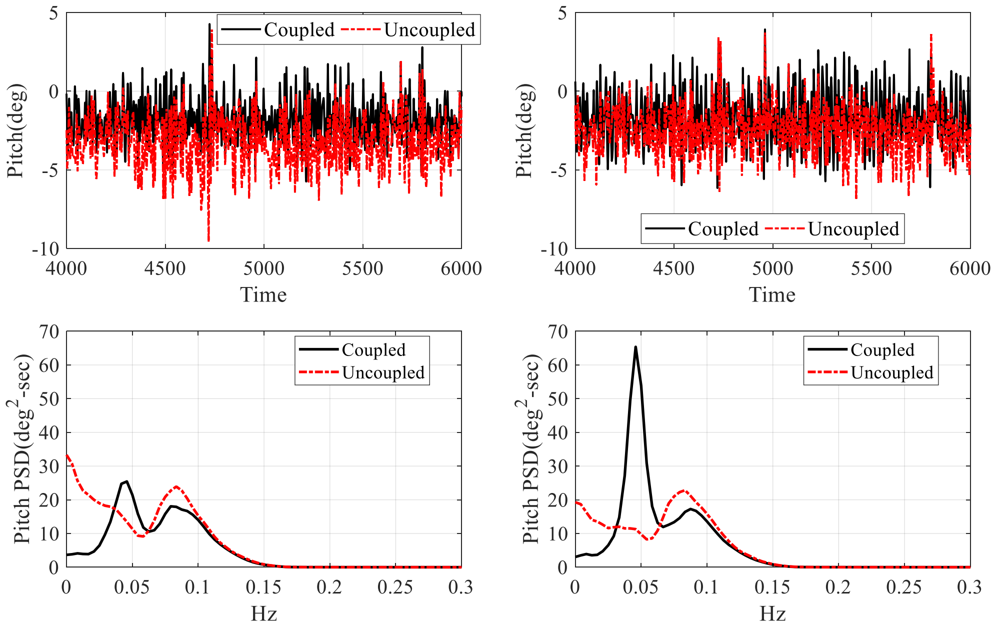

Figure 12 Pitch Motions and PSDs of Coupled and Uncoupled (Disk) for 11.4 m/sec (left) and 13 m/sec (right)

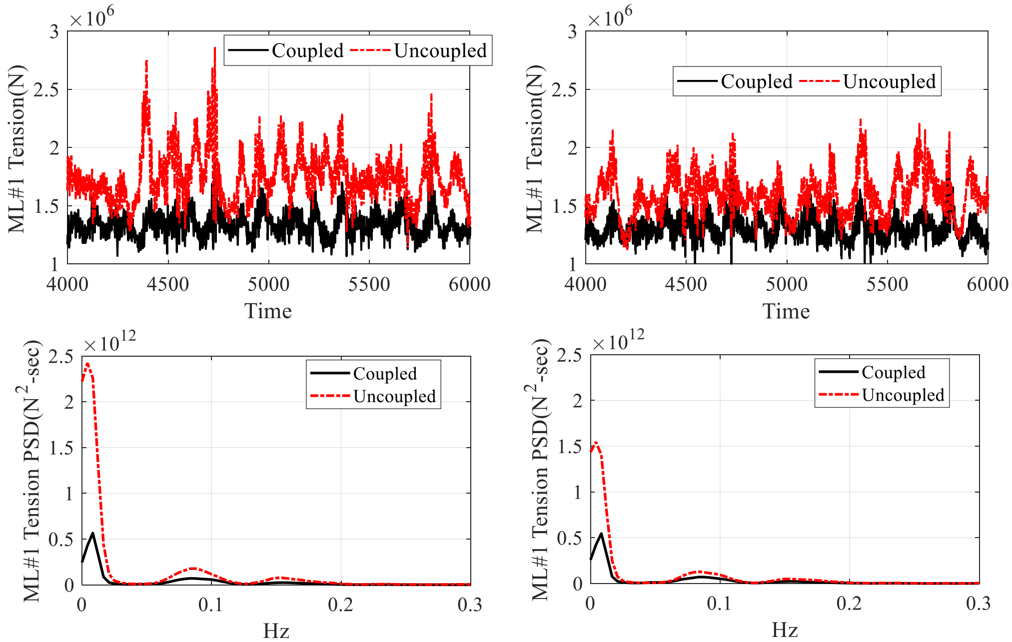

Figure 13 Mooring (ML #1) Tensions and PSDs of Coupled and Uncoupled (Disk) for 11.4 m/sec (left) and 13 m/sec (right)

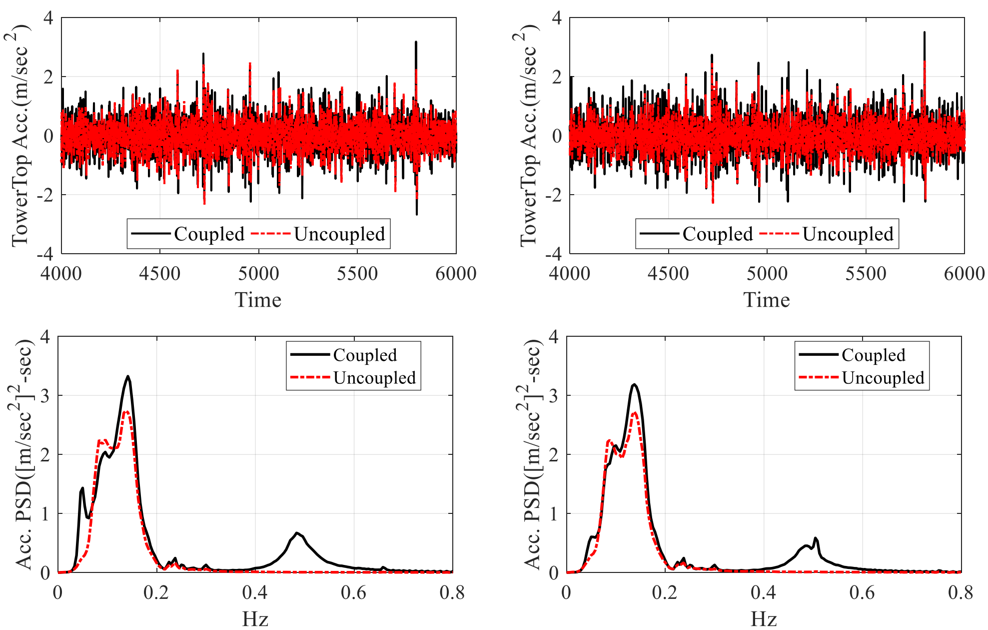

Figure 14 Tower Top Surge Accelerations and PSDs of Coupled and Uncoupled (Disk) for 11.4 m/sec (left) and 13 m/sec (right)

Figure 14 and Figure 15 shows additional comparisons of the platform pitch motion and tower top acceleration PSDs between the coupled BPC on, BPC off and uncoupled (disk) models for the dynamic winds of 11. 4 m/sec and 13 m/sec. Interestingly, the uncoupled pitch results are similar to the coupled control off case, although there are differences in the low frequencies. However, there are similar spectra of the accelerations between the coupled cases.

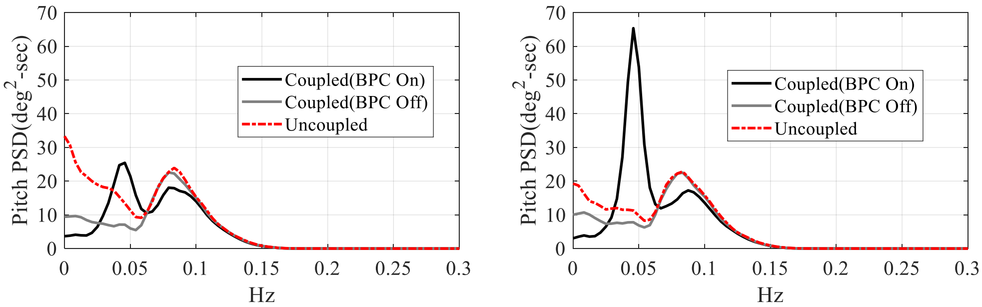

Figure 15 Pitch Motions PSDs of Coupled with BPC On and Off and Uncoupled (Disk) for 11.4 m/sec (left) and 13 m/sec (right)

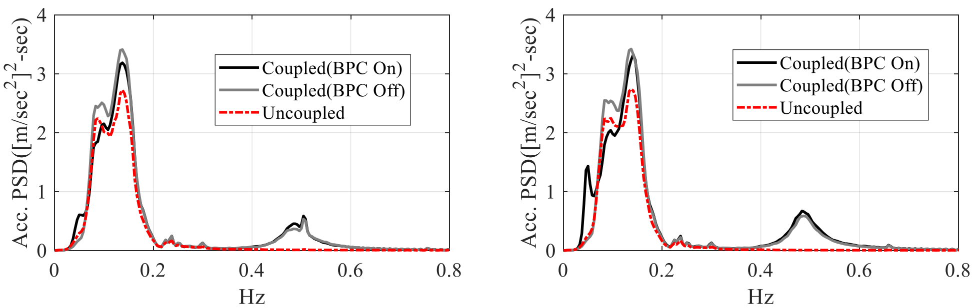

Figure 16 Tower Top Surge Accelerations and PSDs of Coupled with BPC On and Off and Uncoupled (Disk) for 11.4 m/sec (left) and 13 m/sec (right)

SUMMARY AND RECOMMENDATIONS

The dynamic responses of the Y-Wind FOWF was numerically simulated for the coupled and uncoupled models to identify the coupled effects on the platform and moorings. The coupled model considered the full couplings of the platform, mooring, tower, rotor and control. Whereas, the uncoupled model simplified the numerical modeling by considering the tower and rotor as a part of the rigid platform hull. The uncoupled modes, instead, took the rotor thrust into account as a disk drag or applied load at the tower top which is equivalent to the thrust. Both dynamic and steady wind conditions were considered in the coupled and uncoupled simulations. With these combinations, a total of two coupled and three uncoupled models were constructed and compared in terms of the platform surge, heave, pitch, tower top acceleration and mooring tension.

It is observed that the surge and pitch motions and mooring tensions were conservatively predicted in the uncoupled analysis, especially for the rated wind case, resulting from higher mean thrust than the value from the coupled simulation. The heave motions were, however, comparable between the coupled and uncoupled models.

Spectral behaviors of the platform pitch and tower top acceleration of the uncoupled model differ at certain frequencies from the coupled model. The pitch spectral peak induced by the blade pitch control and acceleration peak by the 1st bending mode of the tower were not captured in the uncoupled model results. Additional careful engineering considerations may be needed to evaluate the fatigue damages to the structural members and mooring systems with the uncoupled methods.

It has been confirmed that the uncoupled methods can predict the floating wind platform and mooring responses with acceptable ranges of accuracies overall. Thus, the uncoupled models can be implemented at the early floating wind platform design phases. The major benefit of this method is that it provides quick design returns which enable to shorten the design validations and reduce the analysis effort. The validation of the uncoupled method for the vertically tensioned wind platform shall be further investigated.

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