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Numerical Simulation of the Influence of Platform Pitch Motion on Power Generation Steadiness in Floating Offshore Wind Turbines

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Abstract

Offshore wind energy is a valuable renewable resource that is inexhaustible, strong, and consistent. To reduce cost and improve energy production efficiency, future trends are moving towards wind turbines in deep water, which use floating platforms such as tension leg platforms, barges, and semi-submersible designs. Compared to fixed based substructures, these floating platforms are in a state of constant motion which affects the power generation steadiness. The resulting complex dynamic behavior might compromise their efficiency and reduce their nominal life. The complex analysis of floating wind turbines requires computer tools that couple all the different components to represent the complete dynamic response. One such tool, developed by the National Renewable Energy Laboratory, is the aero-hydro-servo-elastic tool FAST. In this work, simplified models are used for three platform types, and the results are compared with FAST as a way of understanding the essential dynamics. Secondly, using FAST, the influence of platform pitch motion on the steadiness of power generation is examined. This analysis is done for all three platforms for a constant above rated wind speed and above average wave load. Results demonstrate that the power output fluctuation depends on the platform type and blade pitch motion. The effect of platform pitch on the steadiness of power output is only apparent under large oscillating pitch motion, where recurring power drops are observed. The semi-submersible design performs well with relatively steady power output, while the barge design has the most unsteady output, as a result of its susceptibility to typical wave loads.

Keywords

FAST; Floating Platform; Platform Pitch; Wind Turbine; Power Output

1. Introduction

Renewable resources such as wind energy have shown great potential to address increasing energy demands. It reduces dependency on fossil fuel, produces no harmful emission and is also inexhaustible. Wind turbines have been predominantly land-based. However, development has been impeded by several difficulties such as limited unused land area, relatively low wind velocities, and significant environmental and noise impact. To solve these problems, wind turbines might be installed offshore. The key component of an offshore wind turbine (OWT) is the support structure or substructure, which are classified by water depth: shallow ($<$ 30m), transitional (30 – 60 m), and deep water ($>$ 60m), see Figure 1.

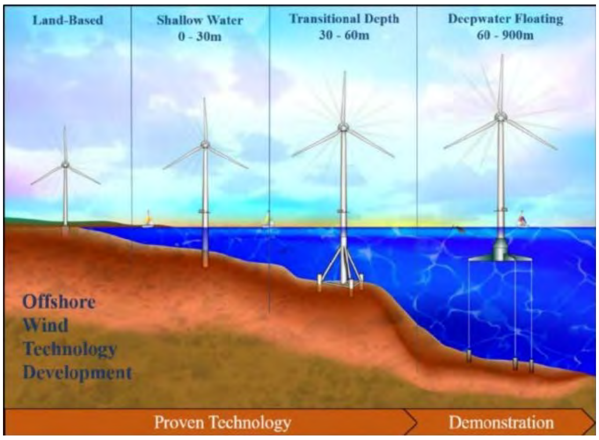

Figure 1. Figure 1 OWT water depth classification (Jonkman, & Buhl, 2005)

For shallow and transitional depth, the turbine tower is fixed rigidly to the seafloor using fixed-bottom foundations. For deep water case, this type of substructure is economically impractical, due to the large amount of material, added complexity of design, fabrication and installation costs. Floating platforms are then used as an alternative wind turbine substructure, drawing from related experience from the offshore oil and gas industry, in the associated tank, ballast, and mooring systems. Based on the method to achieve stability, floating platforms are categorized into three types: spar-buoy that utilizes a ballast weight to provide a restoring moment for motion resistance, tension leg platform (TLP) that relies on the tension in its taut mooring lines, and barge that stabilizes the motion through a distributed buoyancy platform with large water-plane area (Figure 2).

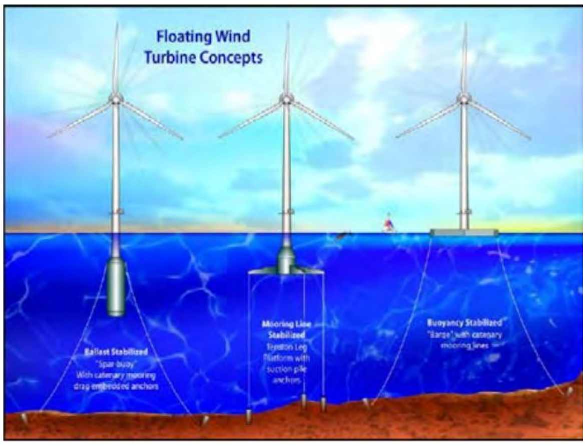

Figure 2. Floating platform concepts for OWT (Jonkman, & Buhl, 2005).

Spar-buoy and semi-submersible platforms have reached full-scale operational stage in Europe. In September 2009, the first floating offshore wind turbine (FOWT), Statoil's Hywind, was deployed in the North Sea of Norway. Hywind has a rated power of 2.3MW and utilizes a single spar-buoy platform moored with three catenary lines (Hywind - The World's First Full-Scale Floating Wind, 2014). In October 2011, the second full scale FOWT, Principle Power's WindFloat with 2MW rated power, was installed in Portugal. WindFloat utilizes a semisubmersible floating platform that is moored with four catenary lines (Roddier, Cermelli, Aubault, & Weinstein, 2010). In United States, UMaine developed a prototype semi-submersible floating wind turbine called VolturnUS 1:8, based on the OC4 DeepCWind (Robertson, Jonkman, Musial, Vorpahl, & Popko, 2013).

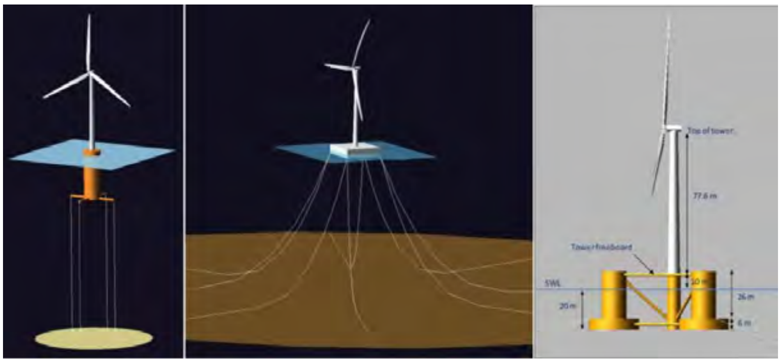

Figure 3. NREL 5 MW wind turbine on (left to right) theMIT/NREL TLP, ITI Energy Barge (MATLAB and Statistics Toolbox Release, 2014), and OC4 DeepCWind Semi-submersible (Tumewu, 2016).

Another FOWT prototype is the 80kW TLP developed by Blue-H Technology with an ongoing scaled testing (Arapogianni, Genachte, Manzanas, Vergara, Castell, Tsouroukdissian, Korbijn, Bolleman, Huera-Huarte, Schuon, Ugart, Sandberg, Laleu, Maciel, Tunbjer, Roth, Gueriviere, Coulombeau, Jedrec, Philippe, Voutsinas, Vita, Byklum, Hurley, & Grubel, 2013). Hybrid platforms that combine these stabilization methods also exist, for example, the semi-submersible platform. However, compared to fixed based substructures, the floating platforms are in a state of constant motion which affects the power generation steadiness. Dynamic analysis must be performed to determine the extent of the platform motion effect on the FOWT performance.

The complex nature of FOWT, i.e. combined environmental excitations, system coupling, and dynamic response, requires the system to be designed and analyzed with a computer-aided engineering (CAE) tool. The tool used in this research is FAST (Fatigue, Aerodynamic, Structures, and Turbulence), developed by NREL (National Renewable Energy Laboratory), (Jonkman, & Buhl, 2005). The latest version, FASTv8, is built as a modular framework to analyze the wind turbine system with aero-hydro-servo-elastic coupling. The goals of this work are, firstly, to understand the essential FOWT dynamics by comparing results from a simplified (limited degree-of-freedom) model with FAST simulations, and secondly, to examine the influence of platform motion on the steadiness of wind turbine power output. Specifically, the TLP, barge, and semi-submersible platforms are analyzed under wind and wave excitation.

2. Floating Offshore Wind Turbine System Characteristics

In order to obtain useful information and realistic results, standardized FOWT designs and load characteristics provided by NREL are used. The input data includes the NREL 5MW baseline wind turbine mounted on three different platforms: MIT/NREL TLP, ITI Energy Barge, and OC4 DeepCWind Semi-submersible platform. The three platforms (Figure 3) are compared herein as being alternative solutions to accommodate the same wind turbine. Gross properties of the NREL 5MW wind turbine and the floating platforms are provided in Table 1 and 2 respectively.

Table 1. NREL 5MW baseline wind turbine gross properties

Wind Turbine Properties	
Rating	5 MW
Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Blade Pitch
Rotor, hub diameter	126 m, 3 m
Hub height	90 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Rotor mass	Rotor mass

Continued on next page

Table 1 continued

Nacelle mass	240,000 kg
Tower mass	374,500 kg
Tower diameter bottom, top	6.5 m, 3.87 m
Tower COG coordinate	(-0.2 m, 0.0 m , 64.0 m)

Table 2. NREL TLP, barge (Jonkman, Butterfield, Musial, & Scott, 2009), and semi-submersible platform properties (MATLAB and Statistics Toolbox Release, 2014).

Floating Platform Properties	Floating Platform Properties	ITI Energy Barge	OC4 DeepCWind Semi-submersible
Platform dimension	18 m	40 m x 40 m x 10 m	6.5 m, 3x12 m, 3x24 m
Platform draft	-47.89 m	-4 m	-20 m
Water displacement	12,180 m^3	6,000 m3	13,917 m^3
Platform mass, including ballast	8,600,041 kg	5,452,000 kg	13,473,000 kg
Platform CM	-40.61 m	-0.2818 m	-13.46 m
Pitch inertia about CM	571,600,000 kg m^2	726,900,000 kg m^2	6,827,000,000 kg m^2
Number of mooring lines	8 (4 pairs)	8	3
Depth to fairleads, anchors	-47.89 m, -200 m	-4 m, -150 m	-14 m, -200 m
Radius to fairleads, anchors	27 m, 27 m	28.28 m, 423.4 m	40.868 m, 837.6 m
Un-stretched line length	151.7 m	473.3 m	835.5 m
Line diameter	0.127 m	0.0809 m	0.0766 m
Line mass density	116 kg m^{-1}	130.4 kg m^{-1}	108.63 kg m^{-1}
Line extensional stiffness	1,500,000,000 N	589,000,000 N	753,600,000 N

3. Limited Degree-of-Freedom Model and Comparison with FAST

To understand the main features of FOWT dynamics, a representative simplified limited degree-of-freedom model of the floating wind turbine is developed. The simplifications include: representing the combined wind turbine and floating platform as a rigid body, neglecting structural deflection, and considering only the three planar degrees of freedom (DOF): Horizontal displacement or Surge (u1), Vertical displacement or Heave (u2), and Rotation or Pitch (u3).

The simplified model follows the same coordinate representation as FAST. The global coordinate system is located at the intersection of the structure centerline and seawater level (SWL). Positive X-axis is defined as a horizontal line from origin point in the direction of wave propagation, while positive Z-axis is defined as a vertical line from origin point in upwards direction. Positive u1 is along positive X-axis, positive u2 is along positive Z-axis, and positive u3 is a clockwise rotation. A clear description of the DOF and sign convention can be seen in Figure 4.

From the gross properties of each FOWT, both the stiffness and mass components are calculated. The stiffness matrix comprises two parts: linear mooring lines stiffness and floater hydrostatic stiffness. The linear mooring lines stiffness is obtained from the tension force for taut mooring lines, and utilizing a MATLAB code based on previous work in (Petrone, Oliveto, & Sivaselvan, 2016) for catenary mooring lines. The floater hydrostatic stiffness on the other hand is obtained from the volume of displaced water due to the submerged platform.

The mass matrix also has two contributions: structural mass and hydrodynamic added mass. The former is calculated utilizing a lumped mass model and parallel axis theorem to obtain the structural mass and moment of inertia, while the latter is obtained from Wave Analysis of MIT (WAMIT) that takes into account the oscillating motion of the submerged platform. From the stiffness and mass matrices, eigenvalue analyses are performed using MATLAB and Statistics Toolbox Release (2014) code for all three floating platforms to acquire the natural frequency for surge, heave, and pitch DOFs. Results from the simplified model are compared with FAST as presented in Table 3. Details of the computation may be found in Tumewu (2016).

Table 3. Eigenvalue result comparison of three platforms

Wind Turbine Platforms	Surge frequency (Hz)		Heave frequency (Hz)		Pitch frequency (Hz)	
	LDOF	FAST	LDOF	FAST	LDOF	FAST
MIT/NREL TLP	0.017	0.016	0.438	0.439	0.273	0.239
ITI Energy Barge	0.008	0.008	0.128	0.132	0.09	0.08
OC4 DeepCWind Semi-submersible	0.009	0.010	0.053	0.054	0.047	0.039

From Table 3, it is observed that the results from FAST and MATLAB limited DOF model exhibit a good agreement, with differences in the order of 3% – 15%. The discrepancies are tolerable since the simplified model assumes the wind turbine tower and platform are a rigid body. It is concluded that the simplified model captures the main features of FOWT dynamics. From this verification process, it can also be concluded that low frequency range will govern the dynamics of FOWT, which is a typical wave loads characteristic with natural frequencies between 0.06 – 0.21 Hz (Robertson, Jonkman, Masciola, Song, Goupee, Coulling, & Luan, 2014).

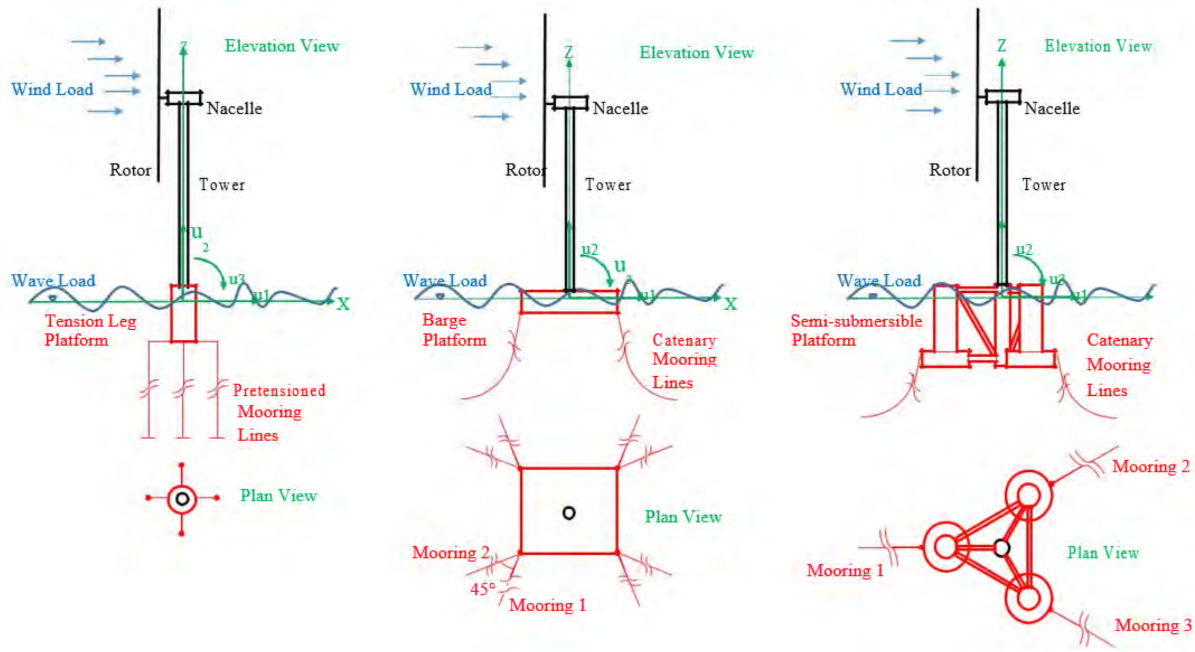

Figure 4. Limited DOF Model of NREL 5MW wind turbine on (from left to right) the MIT/NREL TLP, ITI Energy Barge, and OC4 DeepCWind Semi-submersible.

4. Influence of Platform Motion on FOWT Performance

Wind and wave loads out in the water excite the floating wind turbine, resulting in a constantly oscillating platform motion, in particular pitch rotation (u3 in Figure 4). Such pitching motion clearly distinguishes a FOWT from a wind turbine with fixed base. In this section of the paper, the influence of platform pitch motion on wind turbine performance is examined.

Based on previous work in (Grogg, 2005), the wind turbine generated power can be expressed as:

$$P = \frac{1}{2}\rho A U^3 C_p \tag{1}$$

Where:

U = wind speed (m/s);

Cp = performance power coefficient

P= power output (W);

p= air density (kg/m3);

A= πr2 = rotor swept area (m2);

For a lift-based wind turbine such as the NREL 5MW baseline wind turbine, the rotor blades have airfoil shapes. The airfoil experiences lift and drag force from the incoming wind. The two airfoil forces are highly dependent on the angle of attack (α). Increasing the angle of attack will consequently result in increased lift but also drag. Therefore, an optimized angle of attack that would result in large lift with small drag is desirable.

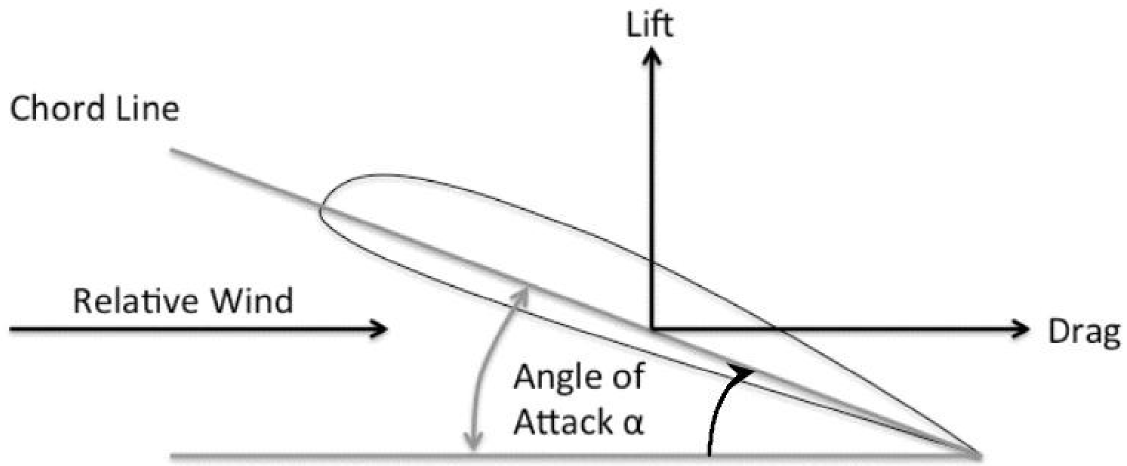

Figure 5. Lift and dragforce of wind turbine airfoil

For a given airfoil, the lift and drag coefficient may be derived from theoretical or empirical test results where the coefficients formula are given as: $C_L = \frac{L}{\frac{1}{2}\rho A U_1^2}$ (2) and $C_D = \frac{D}{\frac{1}{2}\rho A U_1^2}$ (3)

HerCL and CD correspond to lift and drag coefficients respectively, while L and D denote lift and drag forces. From these coefficients, the performance power coefficients may be computed:

$$C_p = C_L\sqrt{1+\Lambda^2}\,(\Lambda - \Gamma^2) \tag{4}$$

W$\Lambda = \frac{W}{U}$and$\Gamma = \frac{C_D}{C_L}$denotes the blade tip speed which is the product of the blade radius and rotational speed. In addition to these equations, the NREL 5MW baseline wind turbine has the ability to change the angle of attack of the airfoils over a range of limited positive pitch values (pitch-to-feather). This pitch control is especially useful for FOWT, as the blade pitch counteracts the platform pitch, thus retaining the overall angle of attack. Combining the aforementioned facts, a series of parameter relationships can be drawn: platform pitch — blade pitch (angle of attack) — lift and drag coefficients power coefficient — power output.

To examine and isolate the platform pitch effect alone on the power output, the wind and wave loading parameters are set as:

Wind load is set to be constant with wind speed of 12 m/s, above the rated speed of 11.4 m/s (see Table 1).

This ensures the turbine has reached the maximum generated power capacity of 5MW. Since low frequency range governs the dynamics of FOWT, wave loads are divided into 3 different cases: (a) still water or no wave, (b) periodic wave, and (c) stochastic wave. The latter two conditions follow a "very rough" sea state condition, based on World Meteorogical Organization (WMO) Sea States Code 6 (Tumewu, 2016). Both wave profiles are chosen as a representative for above average wave condition with T = 11.3 sec and H = 5.49 m.

MIT/NREL TLP, ITI Energy Barge and OC4 DeepCWind Semi-submersible (SS) are first analyzed in FAST for still water condition with the following parameters:

Undeformed initial conditions in ElastoDyn, which computes structural dynamics of tower and platform.

Wind load is set to a constant wind speed of 12 m/s in AeroDyn and Inflow, for aerodynamic loads and inflow.

A default Bladed-style DLL is chosen for the pitch control, and the blade pitch rate is set to 2 deg/s for all platforms in ServoDyn. Future studies will investigate more refined pitch control systems.

Wave load model is set to still water condition and current is neglected in HydroDyn, which calculates hydrodynamic loads.

The Mooring Analysis Program MAP++ module, built-in the FAST software, is selected for all platforms in CompMooring for mooring system computation.

Total run time is set to 300 sec, with default time step 0.025 sec.

Platform pitch and blade pitch computed using FAST for all three platforms, along with the corresponding generated power for still water case are provided in Figure 6. As expected, the generated power from all three platforms is relatively steady since there are no wave loads that excite the platform. Small power drops are observed for the barge platform case. Comparing blade and platform pitch, an overall larger blade pitch rotation can be seen for all three cases, in particular for barge platform.

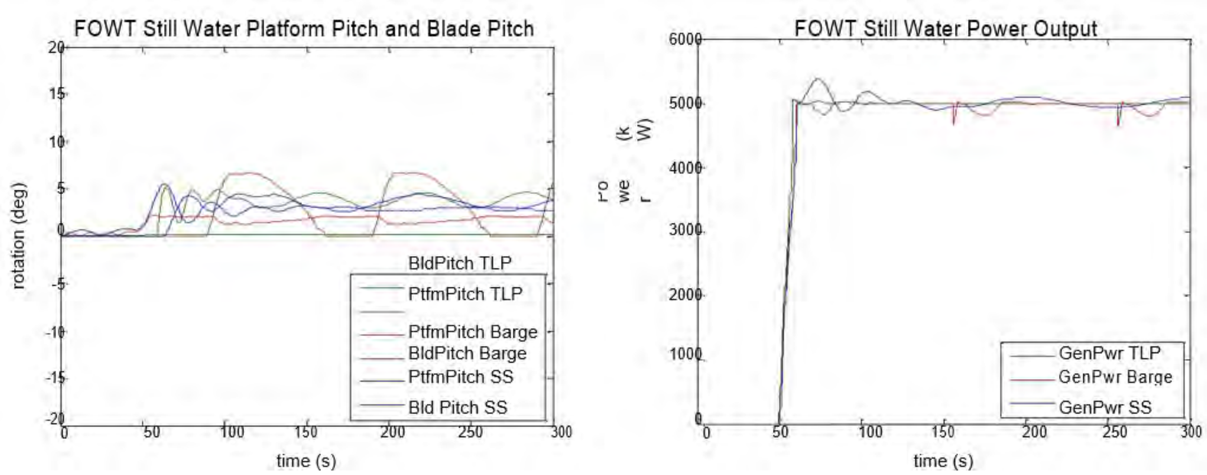

Figure 6. Platform vs Blade Pitch Responses (Left) and thePower Output (Right) for Still Water Case

For the periodic wave case, the three configurations are analyzed with the same parameters as the still water case, except for *HydroDyn* module input parameters: Airy wave is selected as wave load with period T = 11.3 sec and amplitude H = 5.49 m.

Significant and recurring power drops are observed for the TLP and barge platform (Figure 7), where the power outputs fluctuate and reduce to approximately half of the full 5MW capacity. These trends coincide with the larger blade and platform pitch rotation of both the floating platforms. The semi-submersible platform performs the best with relatively steady power output and a smaller blade pitch oscillation.

For the stochastic wave case, the HydroDyn wave load follows an irregular wave model based on the JONSWAP/Pierson–Moskowitz spectrum, with period T = 11.3 sec and amplitude H = 5.49 m. The generated power exhibits trends similar to the periodic wave case (Figure 8), as well as the platform and blade pitches.

The following conclusions can be drawn comparing the response of the different platforms under different wave loadings:

- Small oscillation, i.e. below 1 deg, in platform pitch does not necessarily guarantee a steady power output. This conclusion is valid, for both regular and irregular wave cases.
- The power output is heavily dependent on the blade pitch control. The effect is most apparent for periodic and stochastic wave loads in TLP and barge platforms, where the power output exhibits a trend similar to blade pitch.
- Although the semi-submersible is not the most stable in terms of platform pitch, the generated power is relatively the steadiest for both periodic and stochastic wave loads. This is due to the small oscillation in blade pitch caused by the platform rotation.

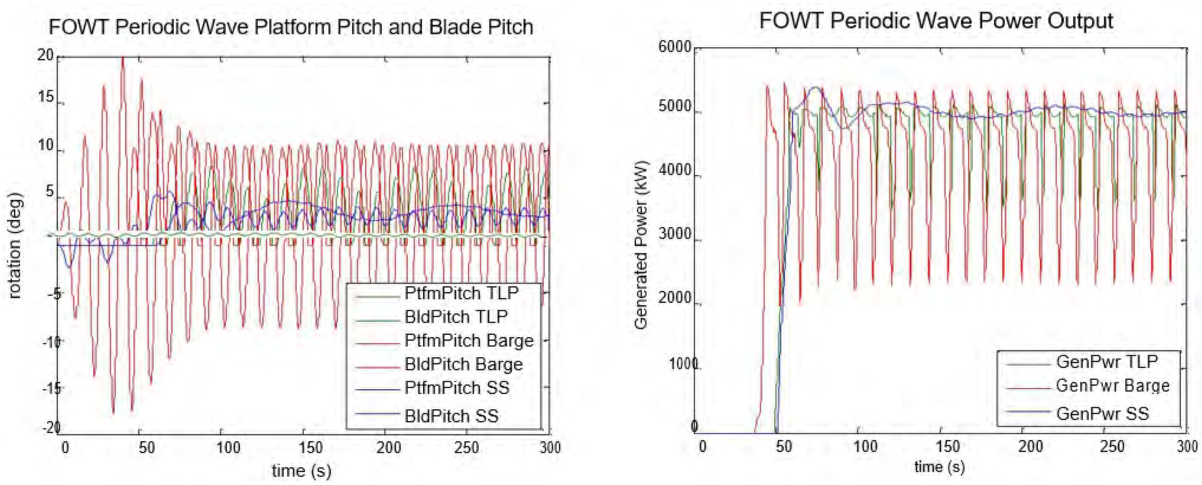

Figure 7. Platform vs Blade Pitch Responses (Left) and the Power Output (Right) for Periodic Wave Case

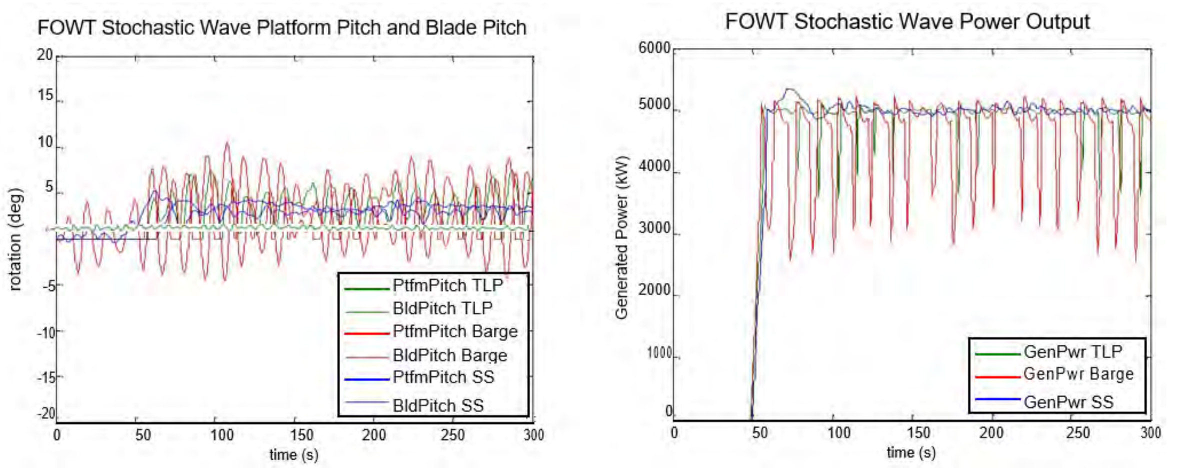

Figure 8. Platform vs Blade PitchResponses (Left) and the Power Output (Right) for Stochastic Wave Case

– Comparing the results of the three platforms, it can be concluded that the barge is the most susceptible to typical wave loads. This susceptibility translates to significant power fluctuation, where the power output repeatedly drops from full to almost half the capacity. Thus, further studies to control platform pitch by using semi-active and passive devices are recommended in order to utilize barge in full-scale floating platform.

5. Conclusion

The main goal of this research is to gain an understanding of the dynamic behavior and its relationship with the power performance of three different floating offshore wind turbines. For this purpose, a wind turbine simulation tool, FAST, is utilized. Before performing dynamic analyses of floating offshore wind turbines with FAST, the essential dynamics are identified by performing eigenvalue analysis using a limited DOF model for three floating platforms (TLP, barge and semi-submersible), and comparing with results from FAST simulations. In addition, it is established that low frequency oscillation, whose frequencies align with typical wave loads characteristics, will govern the dynamics of FOWT.

Using FAST, the influence of platform pitch motion on the wind turbine power output steadiness is examined. To isolate and examine the platform pitch effect on the power output, analyses are performed for the three platforms under defined loads of above rated wind speed of 12m/s and an above average wave load with T = 11.3 sec and H = 5.49. From the results, it is concluded that the power output fluctuation depends on the platform type and blade pitch. The effect of platform pitch on the steadiness of power output is only apparent in a large oscillating pitch motion, where recurring power drops are found.

The semi-submersible platform type performs the best with relatively steady power output. The downside of this platform is the large amount of material and high construction cost. TLP is a viable choice as well, with the lowest platform pitch motion. The main reason for this is the pre-tensioned mooring lines that increase the stiffness. These pre-tensioned lines are more prone to failure, especially during critical events. Since the TLP heavily relies on its mooring lines for stability, environmental effects such as corrosion and anchor design, become an important factor. The barge platform is found to be the most susceptible to wave loads, which ultimately result in least steady power output. Another problem that arises from the large blade pitch oscillation is the reduced fatigue life of the blades and the wind turbine tower. These detrimental effects are amplified in turbulent wind that affects the generated power fluctuation even more than constant wind. The barge platform design has an advantage in its lower construction and installation cost compared to the other floating platforms. Therefore, solutions that address the problems would increase the reliability of barge platform for full-scale offshore wind turbines.

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