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COUPLED DYNAMIC ANALYSIS OF A SPAR- TYPE OFFSHORE FLOATING WIND TURBINE

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ABSTRACT

The fully coupled dynamic analysis of spar type offshore floating wind turbine is presented and a brief conceptual dimension of floater, mooring, tower, and turbine properties were used. The numerical model is generated in ANSYS-AQWA & WAMIT along with the combined wind and wave actions on the structure are analyzed. The numerical results are generated in time domain. The delta catenary mooring is employed on the spar-type floater. The aero-hydro-servo-elastic simulation is used in the analysis of the spar-type floating wind turbine. Various Operational and extreme environment conditions have been simulated. Further, the power production and the effects of aerodynamic and hydrodynamic loads on the spar type floating wind turbine are investigated.

Keywords: Offshore floating wind turbine; Aero-servo-hydro-elastic simulation; Spar-type floater; Mooring; Hydrodynamic computation.

1. INTRODUCTION

The demand for renewable and reliable energy due to global warming, environmental pollution and energy crisis challenges the researcher's needs to look for potential sources of green and sustainable energy. Wind is a proven, reliable and practically extractable source of energy for desired power generation (Burton (2011)). Wind engineering, and use of offshore wind turbine has become a separate research area and wind atlas of Europe started enlarging since from 1950. The world wind energy association estimate global wind power would increase 600GW by 2015. However the power from wind has a maximum extracting efficiency limit called Betz limit 0.59. In order to improve the wind energy production and to get large scale generation of electricity, wind turbine technology needs offshore wind energy resources. So far, most projects of offshore wind farms are located in relatively shallow water using bottom-fixed type wind turbines. To extend wind turbine systems to deeper water, practical research of offshore floating wind turbine systems is required. Also, developing offshore floating wind farms is important because it can minimize the scenery disturbance, avoid the noise problems generated by wind-driven blades, provide high wind speed by low surface roughness, and make use of extremely abundant deep water wind resources. (Bagbanci et al. (2011b)). Various configurations such as spar, tri-floater, semi-submersible and barge-type floater concept of offshore floating turbines have been studied.

In the last few decades, a significant amount of work is carried out on the study of spar type floating wind turbine. Tong (1998) analyzed the technical and economic aspects of wind farms with brief conceptual design for FLOAT. Nielson et al. (2006) discussed the integrated dynamic analysis of spar type floating wind turbines. They developed simulation models for Hywind and compared their numerical results with model scale test results. Suzuki and Sato (2007) investigated the load on turbine blade induced by motion of floating platform and design requirement for the platform. Matsukuma and Utsunomiya (2008) performed motion analysis of a spar type floating wind turbine under steady wind

considering rotor rotation. Utsunomiya et al. (2009) continued the experimental validation for motion of a spar type floating offshore wind turbine. In this case the motion of a prototype spar wind turbine was determined under regular and irregular waves and a steady horizontal force that simulates the steady wind condition was analyzed.

In order to predict the loads and responses of floating wind turbine, the primary design code of wind turbines, FAST (Fatigue, Aerodynamics, Structures, and Turbulence) promoted by National Renewable Energy Laboratory is developed. Jonkman and Buhl (2007) presented fully coupled aero-hydro-servo-elastic simulation tools for a preliminary loads analysis of a 5 MW barge type wind turbine. They found that coupling between the turbine response and the barge pitch motion produces larger extreme loads in the floating turbine tower and blades. The barge was found to be susceptible to excessive pitching in extreme wave conditions. Wayman and Sclavounos (2006) presented the coupled dynamic modeling of floating wind turbine system in frequency domain. The floating wind turbine is kept in place by mooring lines. Iijima et al. (2010) described their numerical procedure for the fully coupled aerodynamic and hydroelastic time-domain analysis of an offshore floating wind turbine system including rotor blade dynamics, dynamic motions and flexible deflections of the structural system. Recently, a detailed review on offshore floating wind turbine, the effect of environment on design loads on monopole offshore wind turbine and dynamic analysis of spar type floating offshore wind turbine is studied by Bagbanci et al. (2011a,b, 2012a,b).

In this present study a spar configuration with delta mooring is analyzed. Wind and wind generated wave, current along with other environmental forces acting on the structure and the resulting dynamic responses due to such coupled aerodynamic and hydrodynamic forces are investigated. In addition, the effects of aerodynamic and hydrodynamic loads on the power production performance for various operating and extreme loadings are analyzed.

2. SPAR TYPE OFFSHORE FLOATING WIND TURBINE

The spar wind turbine comprises the floating foundation which is referred as the floater, the tower and the rotor-nacelle assembly (RNA). The floater may be towed in the horizontal position to calm waters near the deployment site. It is then upended, stabilized, and the tower and the RNA mounted by a derrick crane barge before finally being towed by escort tugs in the vertical position to the deployment site for connection to the mooring system. The floating foundation consist a steel and/or concrete cylinder filled with a ballast of water and gravels to keep the center of gravity well below the center of buoyancy which ensures the wind turbine floats in the sea and stays upright since it creates a large righting moment arm and high inertial resistance to pitch and roll motions.

The floater is ballasted by permanent solid iron ore ballast, concrete or gravel from a chute. Alternatively, the ballast tanks may be injected with grout. It should be remarked that the spar-buoy type is difficult to capsize. The draft of the floating foundation is usually larger than or at least equal to the hub height above the mean sea level for stability and to minimize heave motion. Therefore, it is necessary to have deep water for deployment of this spar-buoy type floating wind turbine as adequate keel to seabed vertical clearance is required for the mooring system to be effective. (Wang et al. (2010)

In the present study, the analysis is carried on the integrated model consisting of rotor, nacelle, tower and mooring system along with the conceptual specifications are used for the analysis. The platform and mooring catenary were analyzed for the hydrodynamic forces in six degrees of freedom surge, sway, heave, roll, pitch, yaw and the platform dynamic responses and the cable dynamics responses were also evaluated and the analysis is carried out using ANSYS-AQWA and WAMIT.

3. MODELLING OF THE FLOATER

3.1 Modelling Of the Conceptual Floater

The NREL 5MW Spar-type floating wind turbine is considered for the analysis. The hydrodynamic analysis of the spar-type floating wind turbine is also carried out, and the detailed descriptions for the study are as follows. The wind turbine properties, platform properties and mooring system properties are kept the same as described in OC3 Hywind (see Jonkman, 2010). The typical geometrical particulars of the platform with conceptual dimensions are given as

Table 1: Spar-type platform properties

Total Draft	120 m
Depth to Top of Taper Below Sea Water Level	4 m
Depth to Bottom of Taper Below Sea Water Level	12 m
Platform Diameter Above Taper	6.5 m
Platform Diameter Below Taper	9.4 m
Platform Mass, Including Ballast	7,466,330 kg
Center of Mass Below Sea Level Along Platform Centerline	89.92 m
Platform Roll Inertia (I_{xx})	4,229,230,000 kg.m ²
Platform Pitch Inertia (I_{yy})	4,229,230,000 kg.m ²
Platform Yaw Inertia (I_{zz})	164,230,000 kg.m ²

The spar-type floater is modelled in Rhino Software and same was analysed for Hydrodynamic Forces and responses in ANSYS-AQWA. The Geometric Data File from Aqwa was the input for WAMIT software. The response results in time domain which includes exciting forces, added mass and hydrostatic forces were used as the primary input to HydroData in FAST code Jonkman and Bhul (2007), for the coupled analysis. Several assumptions were used for hydrodynamic analysis of the floater like Airy wave theory for linearisation and the viscous effects are not considered in the analysis.

Fig1: Conceptual spar-turbine tower model connected with delta catenary mooring in ANSYS-AQWA

3.2 Modelling Of the Tower and Turbine

The NWTC of NREL's developed the FAST code for the aero-hydro-servo-elastic simulations of floating offshore wind turbine. Multi body dynamics approach and BEM is used for aerodynamic properties (Karmirad (2011)). The nonlinear time domain simulator of FAST was used for modelling the tower, turbine and hub. The nacelle was modelled as rigid bodies and servo control logic was given in FAST code. The generalized specifications of the conceptual tower and turbine are as given in Table 2.

Table 2: Spar-type wind turbine properties

Hub Height	90 m
Center of Mass Location (From Sea Level)	43.4 m
Rotor Diameter	126 m
Number of Blades	3
Initial Rotational Speed	12.1 rpm
Blades Mass	53,220 kg
Nacelle Mass	240,000 kg
Hub Mass	56,780 kg
Tower Mass	249,000 kg
Power Output	5 MW
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s

3.3 Blade Structural Properties

The distributed blade structural properties of each blade having span of 61.5m were calculated at various distances at definite interval along length wise for 3 bladed turbine with FAST code using Aero Cent as the input parameter. The edge wise and flap wise section stiffness and structural twist angle were calculated for each station as a fraction of blade length. The blade torsion stiffness and extensional stiffness were also calculated.

Table 3: Undistributed blade structural properties

Length (w.r.t root along pre coned axis)	61.5 m
Mass Scaling Factor	4.536%
Overall mass	17,740 kg
Second mass moment of inertia (w.r.t Root)	11,776,047 kg-m ²
First mass moment of inertia (w.r.t Root)	363,231 kg-m ²
CM Location (w.r.t Root along Pre coned axis)	20.475 m
Structural Damping Ratio	0.477465%

The edge wise and flap wise inertia values and centre of mass offset values, elastic offset values, mass per section blade length were calculated for a given structural damping ratio 0.477%. The undistributed blade structural properties are as given in Table 3.

3.4 Distributed Blade Aerodynamic Properties

The FAST module uses 17 blade nodes for calculation of aerodynamic properties of the aerofoil sections along the span of each blade. The aerodynamic twist, element length, Chord Distribution for various aerofoil sections were calculated (Hansen (2000)). The following aerofoil data were used for the above calculation DU40A17, DU 35 A17, DU30 A17, DU25 A17, DU21A17, NACA64A17, NACA64A17 and Cylindrical Sections. DU (Delft University) and NACA (National Advisory Committee for Aeronautics). The lift and drag parameters were corrected for 2D and then estimated for 3D sections of the above aerofoil.

3.5 Hub and Nacelle Properties

The hub consists of the hub housing and a pitch system. The blade mount of the hub housing is reinforced to enhance structural strength, thereby making the equipment lighter in terms of total weight. The pitch control mechanism is electrically driven to ensure controllability, maintainability, environmental compatibility and other positive characteristics. The system also features three-axis independent control. The nacelle-yaw actuator natural frequency of 3Hz and damping frequency of 2% critical was used in FAST. The Nacelle and Hub properties are given in Table 4.

Table 4: Nacelle and hub properties of the wind turbine

Elevation of Yaw Bearing above ground	87.6 m
Vertical distance along Yaw axis from Yaw bearing to shaft	1,9256 m
Distance along Shaft from Hub Center to Yaw axis	5.01910 m
Distance along Shaft from Hub Center to Main bearing	1.912 m
Hub mass	56,780 kg
Hub Inertia about Low-Speed Shaft	115,926 kg-m ²
Nacelle Mass	240,000 kg
Nacelle Inertia about Yaw axis	2,607,890 kg-m ²
Nacelle CM Location Downwind to Yaw axis	1.9 m
Nacelle CM Location above Yaw Bearing	1.75 m
Equivalent Nacelle-Yaw-Actuator Linear-Spring constant	9,028,320,000 Nm/rad
Equivalent Nacelle-Yaw-Actuator Linear-Damping constant	19,160,000 Nm (rad/s)
Nominal Nacelle-Yaw Rate	0.3%

3.6 Drive Train Properties

No frictional losses for the gear box were assumed for the analysis and 5% critical damping ration was chosen (Karmirad (2011)). The Drive Train Properties are as given in Table 5:

Table 5: Drive train properties of the wind turbine

Rated Rotor Speed	121.1 rpm
Rated Generator Speed	1173.7 rpm
Gearbox Ratio	97:1
Electrical Generator Efficiency	94.4%
Generator Inertia about High-Speed Shaft	534.116 kg-m ²
Equivalent Drive-Shaft Torsional-Spring constant	867,637,000 Nm/rad
Equivalent Drive-Shaft Torsional-Damping constant	6,215,000 Nm (rad/s)
Fully-Deployed High-Speed Shaft Brake Torque	28,116.2 Nm
High-Speed Shaft Brake Time Constant	0.6 s

3.7 Tower Properties

The wind velocities increase at higher altitudes due to surface aerodynamic drag and the viscosity of the air. The variation in velocity with altitude, called wind shear, is most dramatic near the surface. Typically, in day time the variation follows the wind profile power law, which predicts that wind speed rises proportionally to the seventh root of altitude. On the other hand, at night time, wind speed close to the ground usually subsides whereas at turbine hub altitude it does not decrease that much or may even increase. As a result the wind speed is higher and a turbine will produce more power than expected from the 1/7 power law. The undistributed tower properties are given in Table 7.

Table 6: Undistributed tower properties of the wind turbine

Height above Ground	87.6 m
Overall Mass	347,460 kg
CM Location (w.r.t Ground along Tower Centerline)	38,234 m
Structural Damping Ratio	1%

The chosen tower base diameter and top diameter were 6m and 3.87m respectively. Young's modulus was 210GPa. The stiffness parameters, Inertia Parameters, Mass per unit length were calculated at definite interval along the total length of the tower and the same is presented Table 7.

Table 7: Tower properties of the wind turbine (Jonkman (2007))

HtFract	TMassDen	TwFASTif	TwSSStif	TwGJStif	TwEASTif	TwFAlner	TwSSIner	TwFACgOf	TwSScgOf
(-)	(kg/m)	(Nm ²)	(Nm ²)	(Nm ²)	(N)	(kg m)	(kg m)	(m)	(m)
0	4667	6.04E+11	6.04E+11	4.65E+11	1.15E+11	24443.7	24443.7	0	0
0.1	4345.28	5.18E+11	5.18E+11	3.98E+11	1.07E+11	20952.2	20952.2	0	0
0.2	4034.76	4.41E+11	4.41E+11	3.39E+11	9.97E+10	17847	17847	0	0
0.3	3735.44	3.73E+11	3.73E+11	2.87E+11	9.23E+10	15098.5	15098.5	0	0
0.4	3447.32	3.13E+11	3.13E+11	2.41E+11	8.52E+10	12678.6	12678.6	0	0
0.5	3170.4	2.61E+11	2.61E+11	2.01E+11	7.83E+10	10560.1	10560.1	0	0
0.6	2904.69	2.15E+11	2.15E+11	1.66E+11	7.18E+10	8717.2	8717.2	0	0
0.7	2650.18	1.76E+11	1.76E+11	1.35E+11	6.55E+10	7124.9	7124.9	0	0
0.8	2406.88	1.42E+11	1.42E+11	1.10E+11	5.95E+10	5759.8	5759.8	0	0
0.9	2174.77	1.14E+11	1.14E+11	8.74E+10	5.37E+10	4599.3	4599.3	0	0
1	1953.87	8.95E+10	8.95E+10	6.89E+10	4.83E+10	3622.1	3622.1	0	0

3.8 Stochastic Load Modelling

The ocean environment was modeled using a Gaussian stochastic wave field with Rayleigh distribution and JONSWAP (Bhattacharya (1978)) spectrum was used for representing the growing wind sea. The turbulent wind was represented by a Weibull probability distribution with power law as applicable for indicating the wind shear, roughness etc (Faltinsen (1993)). The turbulence of wind has been represented by Kimal Spectra for the present analysis. Suitable values of coherence function and turbulence intensity factor were chosen for the analysis at every load cases.

4. RESPONSE OF THE STRUCTURE

4.1 Hydrodynamic Response

The hydrodynamic added mass, damping and wave excitation force for the wave loading on the floater structure were calculated in frequency domain using ANSYS-AQWA and the same is compared with the result of WAMIT. The above were used as inputs for Hydro Data in FAST code for the Time domain coupled analysis. WAMIT uses panel method and the higher order effects and current effects are ignored in the analysis.

Fig 2: Pressure variation and forces due to motions at phase angles

The Pressure variations and related forces due to various motions at each phase angles are presented in Fig 2 to Fig 5.

Fig 3: Force (y-axis) due to surge (x-axis) at various phase angles

Fig4: Force (y-axis) due to sway (x-axis) at various phase angles

Fig5: Force (y-axis) due to yaw (x-axis) at various phase angles

4.2 Aero dynamic Response

The Turbulent wind inflow was prescribed by using the computer program Turbo Sim (Jonkman and Kilcher (2012)). The values of turbulent wind profile were linked to the Aero Data for calculating the aerodynamic force, structural dynamics module of FAST. The HydroDyn of FAST computes the hydrodynamic forces in time domain.

4.3 Coupling Of Responses

Interfacing of the various modules in FAST computes the nonlinear stochastic fully coupled dynamic response of the wind turbine in Time Domain. The summary of the fully Coupled total dynamics of the offshore floating wind turbine system is shown in Fig 6.

Fig 6: Fully coupled dynamics of offshore floating wind turbine (Jonkman (2007))

4.4 Load Cases Analyzed for Total Dynamics

The International Electro Technical Commission 61400-3 standard describes 35 different load cases for design analysis of an Offshore Wind Turbine, consist of operational and survival conditions. In the present analysis 10 load cases have been analyzed including operational and extreme conditions are given in Table 8.

Table 8: Load cases considered for the present analysis (Jonkman (2007))

Load Cases	Mean Wind Velocity(m/s)	Significant wave height of incident waves (meters)	Peak spectral period of incident waves (sec)	Turbulence Intensity Factor
Load Case 1	8	2.5	9.8	0.21
Load Case 2	11.2	3	10	0.19
Load Case 3	14	3.6	10.2	0.18
Load Case 4	17	4.2	10.5	0.17
Load Case 5	25	5.9	11.3	0.16
Load Case 6	30	7.1	11.9	0.15
Load Case 7	49	14.4	13.3	0.14
Extreme Coherent Gust With Direction Change	49	15	16	0.14
Extreme Turbulence model 1Year Return	40	15	16	0.11
Extreme Turbulence model 50Year Return	50	17	15	0.11

4.5 Power vs Wind Velocity Curve For Ideal Case

The rotor is parked if the wind speed is too high (Cut out wind speed) and too low (because of cost effectiveness).The rotor is operated between the cut in wind speed and rated wind speed for the rated rotation of the rotor. In the operating condition the turbine produces electricity. The ideal curve for the wind turbine is as shown in Fig 7.

Fig 7: Ideal power versus wind velocity performance curve (Burton (2011))

5. EQUATIONS OF MOTION

The rigid body equation of motion for a floating wind turbine is as follows (Jonkman and Bhul (2007))

$$(m + A_{\infty})\ddot{x} + D_{hydro1}\dot{x} + D_{hydro2}g_{hydro} + D_{aero1}\dot{x} + D_{aero2}g_{aero} + Kx = F(t, x, \dot{x}), \quad (1)$$

where, M is the frequency dependent mass matrix, m is the body mass, A is the frequency dependent added mass, C is the frequency dependent potential damping mass, D_{hydro1} is the linear viscous hydrodynamic damping matrix, D_{hydro2} quadratic viscous hydrodynamic damping matrix, D_{aero1} linear aerodynamic damping matrix, D_{aero2} is the quadratic aerodynamic damping matrix. K is the position dependant hydrostatic stiffness matrix. The viscous effects are ignored in the analysis.

6. RESULTS AND DISCUSSION

The hydrodynamic added mass matrix subscripts are as Surge = 1, Sway = 2, Heave = 3, Roll = 4, Pitch = 5, Yaw = 6. The variation added mass with frequency obtained from ANSYS AQWA analysis is shown in Fig 8(a-d).

(a)

(b)

(c)

(d)

Fig 8: Added mass for (a) surge, (b) sway, (c) pitch and (d) yaw

The fully coupled dynamic response of the spar-buoy offshore floating wind turbine is analyzed for generated power output, torque, wind velocity, wave elevation, surge, sway, yaw, roll, pitch and heave motions. The force and moments at the blade root and at the tower base were calculated and presented. In Fig 9(a) the generated power is obtained with mean wind velocity 8m/s and turbulence intensity factor 0.21.

(a)

(b)

Fig 9: (a) Generated power and (b) generated torque versus time for load case 1

(a)

(b)

Fig 9 (c) Wind velocity and (d) wave elevation versus time for load case 1

(a)

(b)

Fig 10 (a): Motion (soft) and (b) motion (stiff) versus time for load case 1

(c)

(d)

Fig 10(c): Forces at the blade root and (d) moments at the blade root versus time for load case 1

Fig 11(a): Forces at the tower base and (b) moments at the tower base versus time for load case 1

Fig 12: Mean wind velocity versus hub height grid for load case 1

The average values of the generated power output and maximum values of the various parameters including the torque, wind velocity, wave elevations, soft motions, stiff motions, forces and moments at the each blade root and tower base are plotted as performance curves of the wind turbine.

Fig 13: Wind velocity versus (a) average generated power, (b) generator torque and (c) total surge

Fig 14: Wind velocity versus (a) sway, (b) heave, (c) pitch, (d) roll and (e) yaw

7. CONCLUSION

In the present study, the performance of the spar-type offshore floating wind turbine is analyzed using the fully coupled aero-servo-hydro-elastic simulation. The numerical model is generated and compared using ANSYS-AQWA & WAMIT for conceptual dimension of floater, mooring, tower and turbine properties. The combined wind and wave actions on the structure are analyzed and the delta catenary mooring is used on the spar-type floater. The simulation is carried out for various operational and extreme environment conditions and the power production and the effects of aerodynamic and hydrodynamic loads on the spar-type floating wind turbine are investigated. It is observed that the performance curves follows the trend with similar analysis done in the past and matching the theoretical curve for performance for this particular spar-type wind turbine.

8. ACKNOWLEDGMENT

Jose Prasobh acknowledges the support of Indian Maritime University, Vishakhapatnam, Ministry of Shipping, Government of India to pursue this research work.

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