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Nonlinear short term extreme response of spar type floating offshore wind turbines

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ABSTRACT

In this work, the dynamic characteristics of spar based floating 5 MW offshore wind turbine (OWT) are studied under operational and survival conditions for offshore Indian conditions. The spar with OWT is installed in 320 m water depth. The OWT is subjected to combined wind and wave loads according to irregular Pierson-Moskowitz spectrum. After obtaining nonlinear spar platform responses, 3-h short term extreme motions are calculated which are useful for the design of an OWT. Extreme values provide realistic estimates to the associated risk of an event since the tail region governs the largest/smallest events or even the events over a threshold in a sample. In this paper, the extreme values are obtained by fitting the peaks in the tail regime using a Weibull-distribution. While one obtains Gaussian responses under the survival loads, the operational conditions have non-Gaussian responses and also larger than survival ones. The results show one should exercise caution for generating the extreme values for non-Gaussian responses and do a proper sensitivity analysis with respect to samples used for generation of extremes.

1. Introduction

Off late, the study of offshore wind turbines (OWT) in deep waters is gaining prominence. Floating support structures such as spars (ballast stabilized); TLPs (mooring stabilized); semi-submersibles, barges (mooring stabilized) etc., are being used for installation of the wind turbines. These concepts are adaptations of offshore structures that are widely used in oil and gas industry. A floating offshore wind turbine (FWT) is required to function properly during the operational time and to survive under harsh environmental conditions. Therefore for proper performance, the accurate prediction of extreme response of FWT is important. As of now, research are being carried out for the FWT in deep waters. Offshore winds are stronger and less turbulent which result in more power. Also FWT are free from land acquisition issues and visual impact. However, this comes at a cost. With strong winds, waves tend to become higher; and therefore, FWT in deep waters are more flexible and stand in need of stronger support structures. Consequently, the survivability of the FWT turns into all the more challenging. The prospects of the offshore wind energy would therefore considerably depend on the response of FWT under combined wind and wave action.

The installation of FWT depends on wind-wave conditions, water depth, sea-bed characteristics and the cost factor. In past, there existed studies on spar platforms (Haslum and Faltinsen, 1999; Spanos et al., 2005; Kim, 2012) in offshore waters and also some studies with wind turbines atop. Before moving ahead, the existing literature on spar supported FWTs are briefly discussed. Tong (1998) have performed extreme and fatigue analyses. The various design details regarding tower, hull, turbine, installation nature were mentioned and the results were obtained and they were observed to match with 1:48 scaled experimental results under both irregular and regular waves. Jonkman and Sclavounos (2006) created a new numerical time domain analysis tool FAST for obtaining the response of the FWT. The analysis was performed to understand the coupled response effects under aero-hydro-elastic loading. The platform model was developed in such a way that the nonlinear kinematics were simultaneously accounted for along with hydrodynamic loads applied on the spar support platform (Jonkman and Matha, 2011). The dynamics due to mooring lines was also included in the tool. Apart from the static instability due to large over-turning moment, the dynamic instabilities occurring due to the critical loads were captured using time domain analysis. Karimirad (2011) performed the coupled analysis of the spar FWT under both wind and wave survival conditions in North Sea. The significant wave height was chosen to be 15 m whereas the average wind speed was taken as 50 m/s. The time domain analysis was carried out using software DeepC. The author concluded that the nonlinear effects have more influence around the natural frequencies and less effect at the wave frequency. Moreover, he also commented that the mean compo-

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nent of the responses were wind induced whereas the standard deviation of responses were wave induced. Mayilvahanan and Selvam (2011) studied the static and dynamic analysis of the three different types of floater concepts namely, barge type, semi-submersibles type and deep drafted column structure that supports the 5 MW wind turbine located in Indian coastal waters. He carried out hydrodynamic response analysis in frequency domain under wave loading only in all six degrees of freedom and found out the stable and feasible floater configuration. Recently, two companies Statoil and Seimens installed a spar based full scale 2.3 MW Hywind turbine deployed in 220 m water depth in the North Sea.

The survival of a structure under the environmental loads requires that the wind turbines be designed against the extreme load. For a specific metocean condition, the FWT response is measured due to the combined wind-wave induced load. The information is then successively extrapolated in order to predict the short term extreme estimate, if the current environmental condition is maintained for a longer time. The estimate of the responses will be used by the offshore farm for proper control and monitoring of the offshore wind turbine. The quantification or measure that can be important is therefore the short term responses, i.e., the estimate of the maximum response for the next stationary period (say 3 h) or several periods, on the assumption that the existing condition will prevail for a longer time. Some works related to short term estimates are reported in Naess and Moan (2012) and Suominen and Kujala (2010). Extrapolation of the data in order to obtain extremes from a given met-ocean condition is important to obtain design load for wind turbines. Almost all the methods have their reliance on the extreme value theory with the data following a host of distributions (e.g., Gaussian, Lognormal, Gumbel, Rayleigh, etc.). Another important distribution that is used for fitting exceedances of data sets beyond 'high' thresholds is the generalized Pareto distribution (Davison and Smith, 1990). Cheng (2002) used comparisons of various methods to extract the extreme turbine loads. Moriarty et al. (2004) have developed the peak extraction methods for estimation of extremes for wind turbine. Moriarty (2008) proposed two safety factors as an alternative to extrapolation. He concluded that the safety factors calculated from the median of extreme wind loads were less uncertain than those obtained from mean and standard deviation. Agarwal and Manuel (2009) obtained the long term extremes using the inverse first order reliability method and showed that the extreme forces are guided by wind speeds just above the rated wind speeds as control actions becomes important in that regime.

In this work, the objectives are: i) to obtain the dynamic characteristics of a spar type supporting FWT, and (ii) also predict the short term extreme responses for metocean conditions in Indian offshore. First, the 5 MW NREL benchmark offshore wind turbine (Jonkman et al., 2009) installed on a spar is modelled and the numerical simulations are performed. The spar is modelled based on OC3-Hywind spar (Jonkman, 2010) platform in 320 m water depth. The combined wind and wave response is obtained by coupling the aerodynamic software FAST (Jonkman and Bull Jr, 2005) and the hydrodynamic software ANSYS-AQWA (2010). The non-linear time domain response takes into account of the forces due to mooring line, the viscous forces, the aerodynamic and hydrodynamic forces due to instantaneous position due to motion. The wave condition (H_s=6 m, Tp=10 s (NIOT, 2014)) is guided by Pierson-Moskowitz (P-M) spectrum and the turbulent wind follows Kaimal spectrum. Two mean wind speeds are considered, one around rated wind speed of 11.5 m/s and one at survival wind speed of 30.0 m/s. Moreover the loads are stochastic and also to rule out epistemic uncertainty, 100 Monte Carlo simulations of responses of spar supported FWT are simulated. Using these time domain realizations, the short term extreme responses (3 h) of the spar are calculated. The extremes are calculated based on a method based on the peaks (local maxima). These peaks are then fit with a Weibull distribution in the tail regime (TWM) to obtain the extremes. These extremes would be effective in design of components and monitoring of FWT.

2. Numerical modelling of wind turbines

2.1. Aerodynamics

The present work uses the finite element based numerical code FAST v7 (Jonkman and Bull Jr, 2005) to generate the aerodynamic load time series. The stochastic nature of the wind velocities are realized using the external tool TurbSim (Jonkman and Kilcher, 2012), which generates the time–series of wind fields. For generating turbulent wind, one requires to specify the turbulence intensity (0.10), power spectral density of turbulence (Kaimal spectrum (Kaimal et al., 1972)), and the hub-height mean wind speed. The hub-height wind speed and its standard deviation of wind speed are used to define the normal turbulence model used in the analysis. The vertical variation of wind speed are represented using power law with the exponent value as 0.14 (IEC-61400-3, 2009). The output is a time–series of the combined mean and turbulent wind, forming a grid of wind speeds suitable as an input to FAST. The induced wind loads on the rotor are obtained using the blade element momentum (BEM) theory. The aerodynamic forces can be calculated individually and integrated along the blade span in order to calculate the total forces and moments which act on the turbine. The aerodynamic loads are calculated using the AeroDyn (Moriarty and Hansen, 2005) module of the FAST. In FAST v7 (Jonkman and Bull Jr, 2005), an additional hydrodynamic module is augmented to model the offshore spar platform. This module includes the modelling of the incident wave loads on the structure as well as the wave kinematics. The benchmark NREL 5 MW horizontal axis wind turbine is housed on a spar platform. The spar platform supports the tower on which the 3-bladed rotor and nacelle are placed. The structure of a three–bladed wind turbine is modelled by 24 degrees of freedom (DOF), which represents the flexibilities of the blades, the tower, and the drive-train. However, the translational and rotational displacements of the structure are also presented. This model representation captures 1 − st and 2 − nd mode flexibilities of the structures.

2.2. Hydrodynamics

Linear wave theory is used for the hydrodynamic load calculation which is applicable for deep waters. In this wave theory, the sea water is considered to be in-viscid and incompressible along with the motion of the fluid being irrotational. The wave elevation is assumed to be of sinusoidal variation and whose wave amplitude, wavelength and wave period is assumed to be constant.

$$\zeta = \zeta_a \sin(\omega t - kx) \tag{1}$$

Using the kinematic boundary conditions and dynamic free surface conditions, one can find velocity potential and thus wave kinematics as water particle velocity and acceleration in wave propagating direction as (Faltinsen, 1993)

$$u_w = \omega \zeta_a \frac{\cosh k(z+h)}{\sinh(kh)} \sin(\omega t - kx), \tag{2}$$

$$a_w = \omega^2 \zeta_a \frac{\cosh k(z+h)}{\sinh(kh)} \cos(\omega t - kx), . \tag{3}$$

Here ζ_a is the regular wave amplitude; k is the wave number; h is the water depth; and ω is the wave frequency. Once this velocity and acceleration is found, one can calculate the forces and also the pressure force on the wetted surface of the body. This wave theory is only applicable for non-breaking wave condition. According to offshore design code (DNV-RP-C205, 2007), waves break when the ratio of the wave height to the water depth is greater than 0.78 for the shallow water conditions and for the case of deep water the ratio of wave height to the wavelength exceeds from 0.14 as most of the waves break near the coast and not preferably in deep offshore.

FAST uses the Morison Eq. (Faltinsen, 1993) to determine the wave