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Predicting Short Term Extreme Response of Spar Offshore Floating Wind Turbine

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Abstract

In this paper, the short term extreme response of spar offshore 5MW NREL benchmark wind turbine is predicted. The spar is installed in a water depth of 320 m. The coupled wind and wave analysis is performed by coupling aerodynamic software FAST (Jonkman and Bull Jr,2005) and hydrodynamic software ANSYS-AQWA(2010). The global time domain responses of the spar type OWT is calculated for 600 s. The wave spectrum has significant wave height 6m and peak spectral period 10s and follows Pierson-Moskowitz spectrum. For safe operation, the structures should survive against different environmental conditions. The OWT can fail either in the operational regime or in the harsh environmental conditions. Therefore the dynamic simulation is carried out for two wind speeds, *i.e.*, one in operational (hub height wind speed as 11.5 m/s) regime and another in idling condition (30 m/s) using the above wave parameters. Monte Carlo method is used to simulate the OWT responses in irregular wave loading condition. After obtaining the time-domain nonlinear responses, the 3-hr short term extreme responses are obtained which are useful for design of OWT. The 3-hr extreme response is obtained using Global Maxima Method (GMM). In Global Maxima Method, one maximum is taken from each time series and the maxima are fitted to two Generalized Extreme Value distributions, *viz.*, Gumbel and Weibull distribution. The results show that Weibull fit is on a conservative side than Gumbel fit. Since the calculation of extremes is dependent on time domain simulations, a comparative study is also done for 100 and 20 samples so as to understand the sensitivity of extreme values due to lower sample size.

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Keywords: Offshore wind turbines, Spar, Dynamic analysis, Extreme analysis

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1. Introduction

Offshore Wind Turbines (OWT) has gained widespread importance due to the increased dependence on the renewable energy. Majority of the OWT that have been deployed are of fixed type such as monopile, jacket, tripod etc. in smaller water depth but with greater demand for energy focus has shifted to deeper water and offshore structural concepts such as spar, TLPs, barges being used. The major ongoing research is to achieve their dynamic characteristics so as to achieve larger operational period in deep water. As with stronger and longer winds, the waves tend to become bigger and higher; survivability of these structure under the environmental conditions become incomprehensible.

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The design load on the wind turbines is obtained usually by extrapolating the data (local maxima/peaks) of the time series. Majority of these extreme extrapolation methods have their foundation in the extreme value theory which mentions that when the local maxima/peak follows a host of continuous parent distributions (e.g., Normal, Gumbel, Rayleigh, etc.) with regularity conditions (well-behaved tail), then the extreme value distribution would be either Gumbel, Weibull or Fréchet. Another important way of obtaining extremes, is by fitting the exceedances of data sets beyond a threshold value to 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 proposed safety factors for extremes wind loads for wind turbine (Moriarty,2008). Agarwal and Manuel(2009) studied the long term extremes using the inverse first order reliability method and the estimates are done using confidence intervals. Based on the above literature, the objective of this paper is to predict the $3-h$ short term extreme responses. The extremes are based on a method based fitting the maxima using the Gumbel and Weibull distributions. In this paper, an easily implementable and conservative estimate for short-term loads is proposed for estimating the extremes provided the mean and the standard deviation of the process is known.

2. Numerical Model

2.1. The Model

The wind turbine model used in this study is NREL benchmark 5 MW wind turbine (Jonkman et al.,2009) whose properties are reproduced in Table 1. The tower is made of 10 different sections of varying thickness up to a height of 87.6 m. The rotor-nacelle-assembly is made of cylindrical sections. The top of the tower contains the rotor and nacelle mass as given in Table 1. The center of gravity (CoG) position and mass moment of inertia are calculated to be used in hydrostatic and hydrodynamic modelling. In order to support the wind turbine, presently the spar type floater is selected for the study whose properties given in the Table 2 and a sketch with dimension is given in Fig. (1). This spar floater details are initially adopted from OC3-Hywind concept (Jonkman,2010).

The spar supporting platform is to be modelled as rigid body with six–DOF in hydrodynamic solver package ANSYS-AQWA(2010). The purpose behind spar designing is to obtain the hydrostatics results for future dynamic analysis. The model is now run for the hydrostatic results to check its basic stability properties which are given in Table 3. Here, the BG refers to the distance between center of gravity (CoG) to center of buoyancy (CB) and GM is the metacentric height. For further details one can refer to Aggarwal et al.(2014) while the control aspects can be obtained from Manikandan and Saha(2013).

Table 1: 5 MW NREL wind turbine specifications (Jonkman et al.,2009)

Power output	5 MW
Blades, rotor orientation	3, upwind
Hub height	90 m
Rotor, hub diameter	126 m, 3 m
Control type	Variable speed, collective pitch
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone angle	5 m, 5°, 2.5°
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower mass	347,460 kg

Table 2: Properties of Spar platform supporting wind turbine

Draft	120 m
Platform diameter above taper	6.5 m
Platform diameter below taper	9.4 m
Water depth	320 m
Platform mass	7,466,330 kg
CG below MSL	89.9 m
Roll Inertia	422923×10^4 kg m^2
Pitch inertia	422923×10^4 kg m^2
Yaw inertia	16423×10^4 kg m^2

Table 3: Spar FOWT static stability

Overall CoG	-78.39 m
Centre of buoyancy (CB)	-62.499
BG	-15.8923 m
GM	15.94018 m
Displaced volume	80708.1 kN

The spar supporting structure once hydrostatically stable in free floating condition is then moored by three catenary mooring lines at 120° fairlead angle applied near the CoG position of the system with properties as given in Table

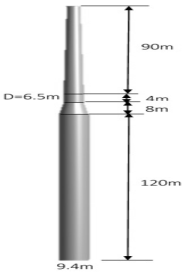


Fig. 1: Sketch of spar platform supporting wind turbine tower

Table 4: Catenary mooring line properties

Number of mooring lines	3
Mooring line angles	120°
Line diameter	0.09 m
Un-stretched length of mooring	902.00 m
Mooring line mass density	77.71 kg/m
Mooring line weight in water	698.094 N/m
Mooring line extensional stiffness	3.842×10^8 N
Mooring attachment point at structure	70.0 m
Mooring attachment point at seabed	320.00 m

4. The mooring line applied in this case is to station-keep the spar supporting FOWT. The point of attachment of the mooring line to the structure is 70.0 m below the mean sea level. The mooring line stiffness matrix obtained is added to the hydrostatic stiffness of the support structure for the initial hydrostatic simulation. In this analysis, the linearized mooring stiffness is used for getting the natural frequency of the system. The natural frequency of the spar is low compared to the higher elastic mode frequency of the top of the turbine tower. The tower is flexible in nature and moreover the low natural frequency also avoids the slightly higher wave induced resonance. The lower frequency modes can be excited by the wind loading, that's where controlling the aerodynamic damping can reduce the resonance conditions in the operating conditions.

2.2. Time domain simulations considering both wind and wave induced loads

The time domain simulations for the coupled wind and wave analysis are generated by interfacing the aerodynamic software FAST, with the hydrodynamic parameters obtained from ANSYS-AQWA. The interfacing is done using a MATLAB based computer program. This ensures that the wind and wave components are coupled to obtain the final response. Accordingly one can obtain responses without effects of wind or wave by delinking the various modules of the coupled analysis. The validation of the hydrodynamic module of FAST has been done by considering the time series of FAST, with no wind condition for a regular sea state and results are in good agreement with response. In order to investigate the effect of coupled wind and wave loads, numerical time domain responses for 600 s are calculated from BEM theory and using the hydrodynamic parameters. The hydrodynamic parameters obtained from ANSYS-AQWA are linked with FAST. The 10 min average wind speed at hub height is kept (10 m/s) to get the response. The chosen wind speed is taken close to the rated wind speed. A turbulence intensity is kept as 0.1 using the Kaimal wind spectrum. This would generate random simulations of each time series due to turbulent wind conditions. A sample realization of time series is shown in Fig. (2) for the two representative DOFs of the platform *i.e.*, surge and yaw. The surge response is about 34 m and such excessive displacement should be predicted in order to remain in safe limit under survival condition. In this condition, the wind turbine is kept idle *i.e.*, no power is generated.

(a) Surge

(b) Yaw

Fig. 2: A sample time series for the platform motions under combined wind and wave loading

3. Random simulations

For the extreme load effects prediction, one requires to extrapolate the stochastic motions in surge, heave, pitch and yaw direction. Note that sway and roll motion is the mirror reflection of the surge and pitch motion behavior for perpendicular wave heading direction. The yaw motion is also important mode as substantial amount of non-linearity arises due to the mooring lines and also due to drag forces. Therefore, it is required that suitable extreme value distribution should be fitted to accurately estimate the design response in yaw motion. The wind loading random samples are obtained due to the turbulent wind field. Presently the simulator Turbsim (Jonkman and Kilcher,2012) is used to model probabilistic nature of the environmental wind loads and ensemble size is collected for the two different samples size 100 and 20. The smaller sample size may be practically feasible for majority of the wind turbine conditions, the larger ensemble size may be required for nonlinear problems and also used as a estimate of any uncertainty. The wave input condition is given by irregular wave spectrum *i.e.*, P-M spectrum where wave parameter is chosen near rough sea state ($H_s = 6$ m, $Tp = 10$ s). The irregular P-M spectrum also introduces randomness in phase during generation of wave elevation. Two wind conditions are taken, one is assumed to be parked scenario for survival condition another is an operational wind turbine situation. Parked wind turbine represent the condition where blades are locked and the wind turbine has to survive under the harsh environment where as in the operating condition wind turbine is operating at ideal situation giving proper efficiency. The wind speed refers to the operating condition of 11.5 m/s while the wind speed above 25 m/s refers to the condition of parked wind turbine, therefore wind speed above the cut out wind speed is chosen as 30 m/s. The extreme response is obtained for both the wind speed condition and compared for the two ensemble sizes 100 and 20.

4. Extreme value distributions

Floating offshore wind turbine (FOWT) experiences extreme environmental condition in terms of wave as well as wind loading depending on the site locations. The extreme ocean conditions can change drastically over a small period of time. After passage of such time, the structure should be able to survive and continue operation after the same. Therefore, it is extremely important to accurately predict the response for design consideration of the wind turbine in operating as well as in survival conditions. Fisher and Tippett(1928) were the pioneers of the extreme value analysis theory and derived the three probability distributions (Weibull, Gumbel and Fréchet) of the random sample space in extreme scenarios. The extreme value theory (EVT) differs from the central limit theory (CLT) although they resembles same in the way that CLT concerns about the limit behavior of the partial sums distributed sample space where as EVT concerns about the limit behavior of the either extreme maxima or extreme minima. Moreover the EVT theory also accounts for large fluctuation about the mean from the set of given random variable and offers outcomes on the asymptotic behavior of the either extreme maxima or extreme minima. Let us take the arrangement of independent and identical random variable $\{X_1, X_2, \ \ldots, X_n\}$ with the common distribution function $F_X(x)$. Now taking the subset of the maximum values from the set of the given sequence and the maxima of these processes over particular block of time will be defined as $M_n = \max\{X_1, \ldots, X_n\}$. Then the distribution of M_n for all n, can be defined as:

$$\begin{aligned} F_{M_n}(x) = \Pr(M_n < x) &= \Pr(X_1 < x, \ldots, X_n < x) \\ &= \Pr(X_1 < x) \cdot \ldots \Pr(X_n < x) \\ &= (F_X(x))^n \end{aligned} \tag{1}$$

Here the possibility of discrepancies in the prediction of the $F_X(x)$ will cause large incongruities in$(F_X(x))^n$. Therefore introduction of the sequences b_n, a_n converges F_{M_n} (a max-stable distribution) as

$$\Pr\left[\frac{M_n - b_n}{a_n} \leq x\right] \rightarrow G(x) \quad \text{as} \quad n \rightarrow \infty \tag{2}$$

where, G in non-degenerate distribution function and may belong to one of the Generalized Extreme Value (GEV) distribution namely Gumbel, Weibull, Fréchet. The GEV is the parent distribution for all the extreme value methods and depending on the location, shape and scale parameters, these are usually classified (Kotz and Nadarajah,2000). The single distribution (GEV) representing all the family of the distributions can be therefore written as:

$$G(x) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} \tag{3}$$

where, $-\infty < \mu, \xi < \infty, \sigma > 0$. The different kind of distributions are obtained from the above GEV distribution with the appropriate parameters are defined as

1. $\xi < 0$ Weibull type with upper bound nature,
2. $\xi = 0$ Gumbel type, with limit as $\xi \to 0$ and unbounded nature, and
3. $\xi > 0$ Fréchet type with lower bound nature.

The most commonly used probability distributions for fitting are the Gumbel and Weibull distribution as recommended by the IEC-61400-3(2009) with the offshore wind turbine application and in this paper both the distributions have been attempted to obtain extremes.

4.1. Gumbel Distribution

The cumulative distribution function for the Gumbel distribution given by equation (4) is also known to be extreme value type I distribution. The equation is:

$$F_G(x; a, b) = \exp\left(-\exp\left(-\frac{x-b}{a}\right)\right) \tag{4}$$

where, $a, b > 0$ are the location and scale parameters of the Gumbel distribution. This distribution is double exponential with having very light tail of sample data. The shape of this distribution is said to be skewed towards the left and shape will remain same although the shifting may happen with variation in the location parameter.

4.2. Weibull Distribution

The cumulative distribution function for this type of distribution is given by equation (5) and one can note that distribution is bounded upper tail. This distribution is best suited to fit the sample of data when there is a definite maximum.

$$F_W(x; a, c) = 1 - \exp\left[\left(\frac{x}{a}\right)^c\right] \tag{5}$$

where a, c are Weibull parameters defining the shape and scale bounds. Here two parameter Weibull distribution is used. Depending on the parameters the distribution can be used to model the life data analysis for predicting the extreme response of offshore wind turbine as previously it was used for floating structures used for the application of oil and gas industry (Chen and Mills,2010).

4.3. Global Maxima Method (GMM)

In the Global Maxima Method (GMM), only one peak which is absolute maxima is extracted from one time series. So, given an ensemble sizes of 100 and 20, one would obtain as many maxima. The GMM therefore usually suffers from impoverishment of data. After the maxima/peaks are obtained, these peaks are then fitted with the Weibull and Gumbel distribution which is then extrapolated to obtain the extreme values. This method is also known as Gumbel method and as usually one uses Gumbel distribution. For GMM as per IEC-61400-3(2009) recommendations, one may use both the above mentioned distributions. In this paper, both the distributions has been attempted. $F_{G(10\,\mathrm{min})}(x)$, representing the fitted values from the ensemble sample size which taken to be 100 and 20 in the present study with using the distribution function of the equation (4).

$$F_{G(10\,\mathrm{min})}(x) = \exp\left(-\exp\left(-\frac{x-b}{a}\right)\right) \tag{6}$$

The estimation of the parameter a, b is based on the mean and standard deviation and taken from the large sample size of 100 which is obtained from the time domain simulation in previous chapter. From this 600s simulation the data is the extrapolated to predict the response for 3−h extremes, as number of times the peak periods would occur is 18, therefore equation (7) can be written as

$$F_{G(3hr)}(x) = \left[F_{G(10\,\mathrm{min})}(x)\right]^{18} = \exp\left(-\exp\left(-\frac{x-b}{a}\right)\right) \tag{7}$$

Then the extreme value which is likely expected is estimated as:

$$\mathbf{E}\left[G(3hr)\right] = \int_0^\infty x\left[f_{G(3hr)}(x)\right]dx \tag{8}$$

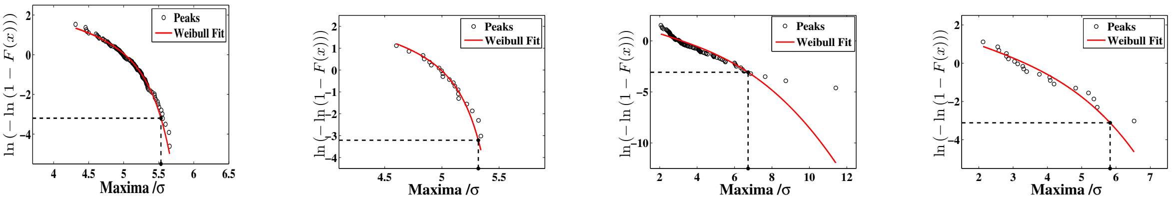
A similar exercise would also give the extremes value in case the maxima are fitted to Weibull distribution to obtain $\mathbf{E}\left[W(3hr)\right]$.

5. Extreme Value Results

In this section, Global Maxima Method (GMM) is used to estimate short term extremes by fitting two distributions - Gumbel and Weibull. Each of the extremes are estimated for operational wind speed (at 11.5 m/s) and at extreme condition (at 30 m/s).

5.1. *GMM using Weibull and Gumbel distributions in operational wind speed of* 11.5 *m/s*

Weibull distributions are fitted to the GMM for each of the time series and the 3− h extreme values are reported in Table 5. The results are shown for rated wind speeds 11.4 m/s for ensemble sizes of 100 and 20 respectively. In the tables, the extreme values are reported as μ+(κ)σ , where μ is the ensemble mean and σ is the ensemble standard deviation. A similar table for maxima values fitted using Gumbel distribution is shown in Table 6. The values are reported in this way, as the author feels that given any mean and standard deviation, the author can guess the extreme values with the κ value. Note that there is not much change in μ and σ values for 100 and 20 samples and therefore only the values corresponding to 100 samples are reported in Tables 5 and 6. Figs. (3) shows typical plots for translational motions (surge) as well as rotational motions (yaw) using ensemble sizes of 100 and 20 at rated wind speed of 11.5 m/s. The Gumbel distribution is fitted using the Global Maxima Method as shown in Fig. (4) at rated wind speed of 11.5 m/s.

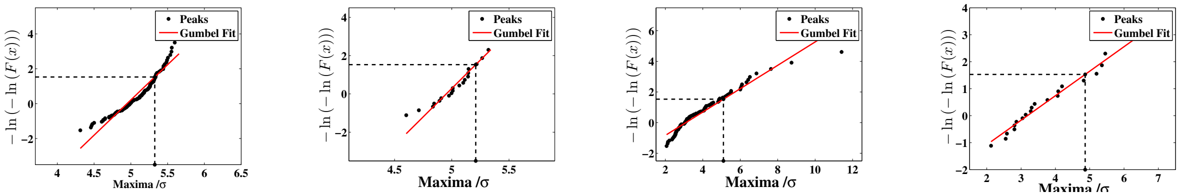


(a) Surge (100 samples) (b) Surge (20 samples) (c) Yaw (100 samples) (d) Yaw (20 samples)

Fig. 3: Weibull fitted using GMM in surge and yaw motions at rated wind speed 11.5 m/s for different sample sizes.

5.2. *GMM using Weibull and Gumbel distributions at survival wind speed of* 30.0 *m/s*

As mentioned earlier, a similar exercise is being done for the extremes estimation for wind speeds beyond cut out wind speed. The extreme values are reported in the Table 7. For the extreme wind speed, the extrapolated values are obtained using the Weibull distribution in the Global Maxima Method (GMM). Fig. (5) show how the Weibull distribution fits the peak data. For the extreme wind speed, the extrapolated values are again obtained using the Gumbel distribution in the Global Maxima Method (GMM) and shown in Fig. 6. The corresponding extreme values are reported in the Table 8.



(a) Surge (100 samples) (b) Surge (20 samples) (c) Yaw (100 samples) (d) Yaw (20 samples)

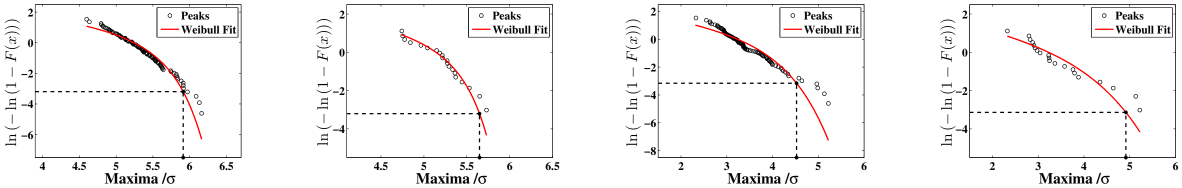
Fig. 4: Gumbel fitted using GMM in surge and yaw motions at rated wind speed 11.5 m/s for different sample size.

Table 5: κ values using Weibull distribution fit by GMM at rated wind speed 11.5 m/s (Note, EV=μ+$\kappa\sigma$).

Ensemble Size →			100	20
Motion ↓	μ	σ	κ	κ
Surge	18.99	6.07	2.65	2.50
Heave	-0.42	1.94	3.63	3.78
Pitch	3.95	3.45	3.20	3.08
Yaw	0.18	1.06	6.55	5.67

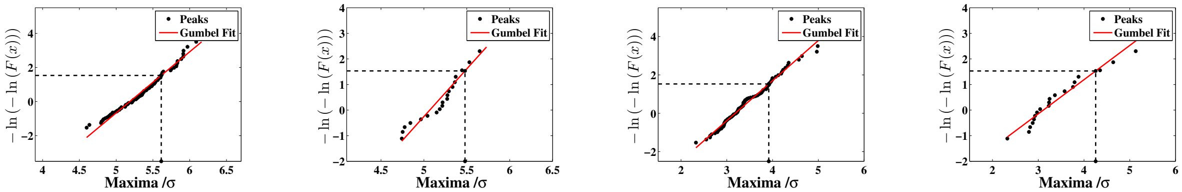
Table 6: κ values using Gumbel distribution fit by GMM at rated wind speed 11.5 m/s (Note, EV=μ+$\kappa\sigma$).

Ensemble Size →			100	20
Motion ↓	μ	σ	κ	κ
Surge	18.99	6.07	2.44	2.39
Heave	-0.42	1.94	2.96	3.16
Pitch	3.95	3.45	2.86	2.90
Yaw	0.18	1.06	4.93	4.70



(a) Surge (100 samples) (b) Surge (20 samples) (c) Yaw (100 samples) (d) Yaw (20 samples)

Fig. 5: Weibull fitted using GMM in surge and yaw motions at extreme wind speed 30 m/s for different sample sizes.



(a) Surge (100 samples) (b) Surge (20 samples) (c) Yaw (100 samples) (d) Yaw (20 samples)

Fig. 6: Gumbel fitted using Global maxima in surge and yaw motions at extreme wind speed 30 m/s for different sample sizes.

Table 7: κ values using Weibull distribution fit by GMM at extreme wind speed 30 m/s (Note, EV=μ+$\kappa\sigma$).

Ensemble Size →			100	20
Motion ↓	μ	σ	κ	κ
Surge	18.99	6.07	3.17	2.95
Heave	-0.42	1.94	3.40	3.35
Pitch	3.95	3.45	3.12	2.9
Yaw	0.18	1.06	4.24	4.62

Table 8: κ values using Gumbel distribution fit by GMM at extreme wind speed 30 m/s (Note, EV=μ+$\kappa\sigma$).

Ensemble Size →			100	20
Motion ↓	μ	σ	κ	κ
Surge	18.99	6.07	2.87	2.79
Heave	-0.42	1.94	2.73	2.83
Pitch	3.95	3.45	2.67	2.62
Yaw	0.18	1.06	3.64	3.96

6. Closure

In this paper, the numerical simulation of 5 MW NREL (Jonkman et al.,2009) benchmark offshore wind turbine is performed. The offshore wind turbine is installed on a spar platform in the water depth of 320 m. The combined wind and wave response is performed by coupling aerodynamic software FAST (Jonkman and Bull Jr,2005) and hydrodynamic software ANSYS-AQWA(2010). The time domain simulation is obtained for the combined wind and wave loads in irregular sea states. The power spectral densities of the response is obtained by using the transfer function of the system. Now for an irregular sea state defined by Pierson-Moskowitz spectrum, where wave parameter is chosen near rough sea state ($H_s = 6$ m, $Tp = 10$ s), the random time series are generated for wind speeds near rated wind speed wind speed 11.5 m/s and an survival wind speed of 30 m/s. Monte Carlo simulations are run for 100 realizations. As 100 simulations are time-consuming for complex structures as floating offshore wind turbine, a smaller sample size of 20 is also taken. Using the time domain simulations, the short extreme motion responses of the top of the spar are calculated for a 3 h period using the Global Maxima method (GMM). In the GMM, only one peak which is absolute maxima is extracted from one time series. So, given an ensemble of 100 and 20, one would obtain as many maxima. Note that for small samples, the GMM therefore usually suffers from impoverishment of data. After the maxima/peaks are obtained, these peaks are then fitted with the Weibull and Gumbel distribution which is then extrapolated to obtain the extreme values. This method is also known as Gumbel method and as usually one uses Gumbel distribution. For GMM as per IEC-61400-3(2009) recommendations, one may use both the above mentioned distributions. In this work, both these distribution have been attempted. The results show that not much variation in extrapolated extremes using Weibull and Gumbel distribution. The Gumbel method shows lower values compared to extremes estimated using Weibull method. One of the reasons may be as the Weibull model is bounded on the upper side. The sensitivity to sample size is also not significant. However, further statistical analysis is necessary using upcrossing methods (Saha and Naess,2010,Saha et al.,2014) to check the sensitivity with respect to sample size, which forms part of the future work.

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