Extended environmental contour methods for long-term extreme response analysis of offshore wind turbines*

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Environmental contour method is an efficient method for predicting the long-term extreme response of offshore structures. The traditional environmental contour is obtained using the joint distribution of mean wind speed, significant wave height and spectral peak period. To improve the accuracy of traditional environmental contour method, a modified method was proposed considering the non-monotonic aerodynamic behavior of offshore wind turbines. Still, the modified method assumes constant wind turbulence intensity. In this paper, we extend the existing environmental contour methods by considering the wind turbulence intensity as a stochastic variable. The 50-year extreme responses of a monopile-based offshore wind turbine are compared using the extended environmental contour methods and the full long-term method. It is found that both the environmental contour method and the modified environmental contour method, with the wind turbulence intensity included as an individual variable, give more accurate predictions compared with those without. Using the full long-term method as a benchmark, this extended approach could reduce the nonconservatism of the environmental contour method and conservatism of the modified environmental contour method. This approach is effective under wind-dominated or combined wind-wave loading conditions, but may not be as important for wave-dominated conditions.

1 Introduction

Recently, progress has been made regarding installation and operation of wind turbines in various conditions [1–3]. In the design of any type of offshore structure, including offshore wind turbines (OWTs) and wave energy converters, estimating the long-term extreme structure response or load effects for a given return period (50 yrs, for example) is an important step. Full long-term analysis (FLTA) is an accurate but time-consuming method as it takes all environmental conditions into consideration, whereas only a few environmental states contribute substantially to the overall results. The efficiency of FLTA can be improved by either increasing the computing efficiency of the short-term data or reducing the number of required response calculations [4]. The Environmental contour method (ECM) proposed by [5] is a simplified Inverse First Order Reliability Method (IFORM) [6], which has proved to be relatively accurate in predicting monotonic loads. ECM uncouples environmental variables

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from structure response [7], allowing the response to environmental conditions to be evaluated at selected points along the contour. Higher fractile or multiplication factors can be introduced for different responses to compensate for omitted responses and to determine the extreme response. An alternative contour method derived from direct Monte Carlo simulation was also proposed recently [8].

ECM is widely used to establish utimate design loads of marine structures [9]. The first step of ECM requires a derivation of the contour surface described by environmental variables considered. The response calculation only needs to be performed for a set of selected points on the contour surface which enhances the efficiency [10]. However, for OWTs, which are subjected to loads imposed by wind and waves simultaneously, the load induced by wind does not increase indefinitely as the wind speed increases. When the wind speed exceeds the cut-out wind speed, the wind turbine is parked and there is a significant drop in load. Traditional ECM with three environmental variables including mean wind speed (U_w), significant wave height (H_s), and peak spectral period (T_p) is therefore unsuitable for cases in which the non-monotonic loads are included. A modified ECM (MECM) was proposed to overcome this problem by drawing multiple environmental contours to divide the region such that the load is represented by a bijective function in the subregion. MECM is widely used for bottom-fixed wind turbines [11], semi-submersible wind turbines [12], integrated offshore renewable energy devices [13], etc., and has been shown to have good accuracy.

However, in most of the environmental contour methods, turbulence intensity TI was excluded as an environmental variable or was set as a fixed value (15%) [14]. Exclusion of TI as an environmental variable will probably result in significant deviation between the extreme response predicted and the realistic one, especially for the combined wind and wave loads or the loads dominated by wind. Because turbulence intensity, as an intrinsic characteristic of wind, follows a probability distribution function for a given wind speed in realistic conditions [15]. And it is the main driver for fatigue loading, is closely related to fatigue damage [16] and has been shown to have a greater effect on the fatigue and extreme loads of a 5 MW OWT than the wind shear exponent [17]. Thus, variation in TI should be considered in order to better approximate realistic wind conditions. To meet reliability and safety requirements, international design standards IEC [18] and DNV should be referred to at the design stage. The IEC 61400-3 standard requires evaluation of extreme loads with a recurrence period of 50 yrs in which the turbulence intensity is given as a function of wind speed, whereas the turbulence intensity follows a conditional probability density function (CPDF) for a specified wind speed for a specified wind speed. Probabilistic methods can be used to fit the relationship between turbulence intensity and wind speed to improve the accuracy of extreme response calculation for a given failure probability of OWTs.

In this work, the effect of wind turbulence on extreme load is investigated using FAST v8 [19] based on the NREL 5 MW monopile baseline model under various turbulent winds generated by Turbsim [20]. Turbulence intensity is integrated into the environmental contour methods based on the CPDF of standard deviation of wind speed, which is fitted by the three-parameter Weibull probability density function. Probabilistic methods are employed to derive the environmental contours, considering wind speed, significant wave height, and peak spectral period, as well as turbulence intensity. The content of how to include TI as an extra environmental variable has been introduced in detail in [21]. Encouraged by the work presented in OMAE2019 conference [21], further research about extended environmental contour methods for long-term extreme response analysis of offshore wind turbines has been carried out based on that. The 50-yr extreme responses of the NREL 5 MW monopile wind turbine, including monopile base reaction force, monopile base pitching moment, tower base force, and tower base pitching moment are evaluated using ECM and MECM. Comparison of the cases including and excluding the TI as an extra variable is performed for both methods. The results obtained by the two methods are compared with those of FLTA.

2 Methodology

2.1 Theoretical consideration of wind turbulence intensity

Turbulence intensity is defined as the standard deviation of the wind speed divided by mean wind speed. Standard deviation (σ), reflects a natural variability over time induced by changing atmospheric stability conditions, and varying roughness conditions. It is not a constant for a given wind speed but follows a probability distribution conditioned on the mean wind speed. Thus, the turbulence intensity also exhibits a statistical distribution around the mean wind speed.

Larsen [15] proposed the following expression for the offshore wind mean value of the wind speed standard deviation expression:

$$\sigma_{u,T} = \varepsilon_1 U_T^{\varepsilon_2} + \varepsilon_3 \tag{1}$$

Where U_T is the mean wind speed during a limited time interval T and constants $\varepsilon_1, \varepsilon_2, \varepsilon_3$ are determined by fitting the expression to the data collected.

The standard deviation as formulated above follows a probability density function conditioned on the mean standard deviation and a specified number of statistical degrees of freedom [22].

In the following data analysis, the three-parameter Weibull probability density function is used to parameterize the data to obtain a more empirical expression:

$$f(x;k,\alpha,b) = \frac{k}{b}\left(\frac{x-\alpha}{b}\right)^{k-1}\exp\left[-\left(\frac{x-\alpha}{b}\right)^{k}\right]; x \geq \alpha \tag{2}$$

where x is the variable, k is the shape parameter, α is the position parameter and b is a scaling parameter (k, α, b are required to be positive).

Table 1. Weibull parameters obtained from the fitting procedure [15]

U_c (m/s)	k	β	α
3	2.82	0.31	0.00
5	2.12	0.33	0.11
7	2.14	0.35	0.18
9	2.11	0.36	0.30
11	1.75	0.37	0.47
13	1.83	0.41	0.66
15	1.81	0.39	0.84
17	1.62	0.37	1.12
19	1.90	0.44	1.42
21	1.55	0.40	1.68

Larsen [15] obtained three parameters for varying mean wind speed by fitting this expression to offshore wind climate data obtained from two shallow water sites, Vindeby and Gedser. The data included the mean wind speed within a10-min time span ranging from 2 m/s to approximately 22 m/s. 21622 10-min time series of wind data were observed at 30.0 m height for the subsequent data fitting. Larsen's data from Gedser are used in this paper. Importantly, it is assumed that TI follows same conditional distribution for Site 15. Three parameters conditioned on different wind speeds are provided in Table 1, where U_c denotes the center of the mean wind speed bin interval at 30 m height.

Polynomial fitting was used to extrapolate the discrete distribution to cover the total investigated wind speed [21]. The probability density function of the standard deviation conditioned on U_c was obtained, as well as its distribution function. Fig. 1 shows the CPDF and Cumulative distribution function (CDF) of σ for mean wind speed intervals from 2 m/s to 4 m/s (U_c= 3 m/s) and 20 m/s to 22 m/s (U_c= 21 m/s).

The wind speed ranged from cut-in (3 m/s) to cut-out (25 m/s) at the hub-height of NREL 5MW wind turbine, and a power law profile with the exponent a equal to 0.1 was used to carry out the wind speed transformation at different levels [23]. U_w in Eq (3) represents the mean wind speed at 10 m height.

$$U(z) = U_w(\frac{z}{30})^a \tag{3}$$

Fig. 2 shows the polynomial fitting of the three parameters with different mean wind speeds. The CPDF of σ was obtained based on the fitting

$$f(\sigma;k,\alpha,b) = \frac{k}{b}(\frac{\sigma-\alpha}{b})^{k-1}\exp[-(\frac{\sigma-\alpha}{b})^k];\sigma \geq \alpha \tag{4}$$

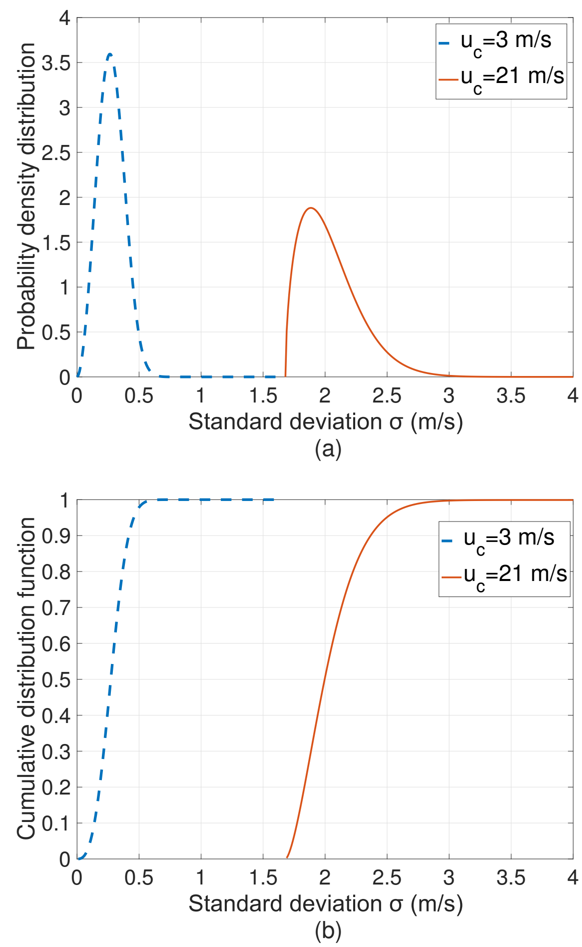

Fig. 1. CPDF (a) and CDF (b) of wind standard deviation under U_c= 3 m/s and U_c= 21 m/s

As TI is defined as the wind standard deviation divided by the mean wind speed, after obtaining the distribution of σ, the TI can be included as an extra variable. Based on the trends of α and b as showed in Fig. 2, the two values may be negative for wind speeds under 2 m/s. As k, α, b are required to be positive, these three parameters were set assuming U_c= 3 m/s for values of U_c under 3 m/s.

2.2 Environmental contour considering U_w, TI, H_s, T_p

As both ECM and MECM obtain the extreme response by evaluating responses under different environmental cases selected along the environmental contour, drawing the contour is an indispensable part of the process. In this work, environmental contours were drawn by Rosenblatt transformation according to the joint distributions of environmental variables considered.

2.2.1 Joint distribution of U_w, TI, H_s, T_p

Long-term joint distributions of mean wind speed at 10 m height (U_w), significant wave height, and spectral peak period of five European offshore sites were provided in [23]. Data from site 15 in North Sea area were used in this work

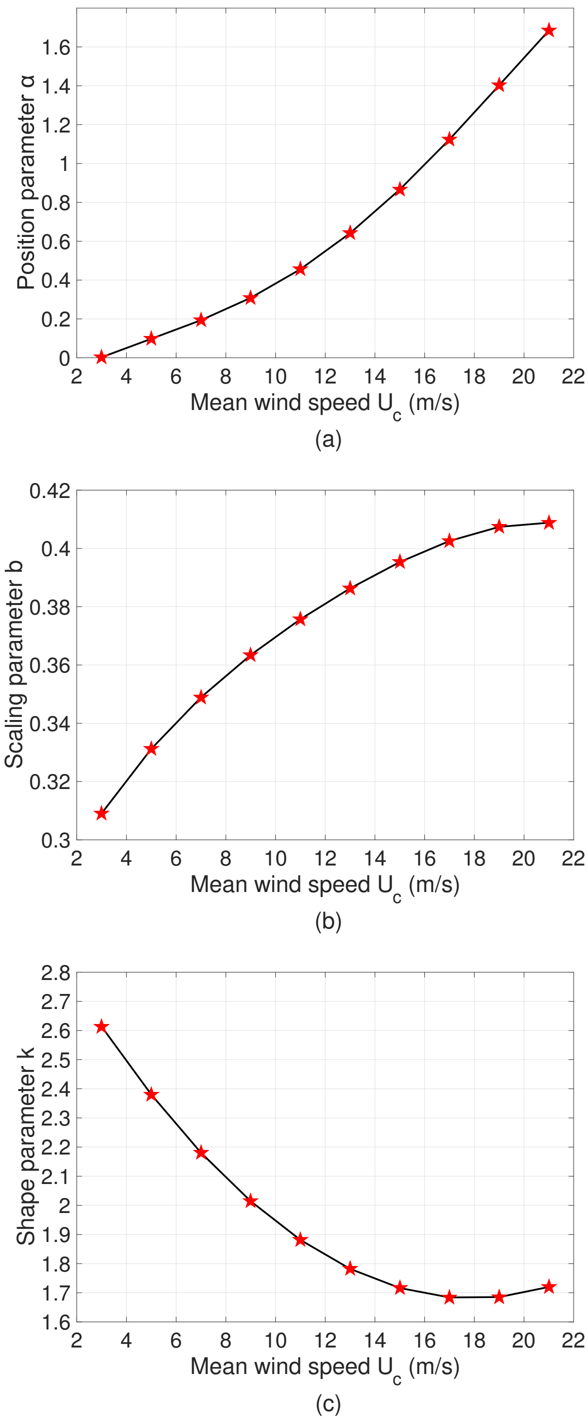

Fig. 2. Trends of three parameters under different wind speeds

to draw contour surfaces whose probability of exceedance corresponding to a return period of 50 yrs.

According to site 15, the 1-hr joint distribution of U_w, H_s, T_p can be expressed as follows:

$$f_{U_w}(u) = \frac{\alpha_U}{\beta_U}(\frac{u}{\beta_U})^{\alpha_U - 1}\exp[-(\frac{u}{\beta_U})^{\alpha_U}] \tag{5}$$

where f_{U_w}(u) is the marginal distribution of mean wind speed U_w, and α_U and β_U refer to the shape and scale parameters, respectively.

$$f_{H_s|U_w}(h|u) = \frac{\alpha_{HC}}{\beta_{HC}}(\frac{h}{\beta_{HC}})^{\alpha_{HC}-1}\exp[-(\frac{h}{\beta_{HC}})^{\alpha_{HC}}] \tag{6}$$

where $f_{H_s|U_w}(h|u)$is the CPDF of H_s, and α_{HC} and β_{HC} refer to the shape and scale parameters, respectively, and are fitted as power functions of mean wind speed

$$f_{Tp|U_w,H_s}(t|u,h) = \frac{1}{\sqrt{2\pi}\sigma_{\ln(T_p)}t}\exp(-\frac{1}{2}\frac{\ln(t)-\mu_{\ln(T_p)}}{\sigma_{\ln(T_p)}})^2) \tag{7}$$

$$\mu_{\ln(T_p)} = \ln[\frac{\mu_{T_p}}{\sqrt{1+\upsilon_{T_p}^2}}], \sigma^2_{\ln(T_p)} = \ln[\upsilon_{T_p}^2 + 1], \upsilon_{T_p} = \frac{\sigma_{T_p}}{\mu_{T_p}} \tag{8}$$

where μ_{T_p}, σ_{T_p} are mean and standard deviation of T_p, υ_{T_p} is the coefficient of variance, and μ_{T_p} and υ_{T_p} are functions of U_w and H_s.

Thus the simplified joint distribution of U_w, H_s, T_p can be expressed as

$$f_{U_w,H_s,T_p}(u,h,t) \approx f_{U_w}(u)\cdot f_{H_s|U_w}(h|u)\cdot f_{Tp|U_w,H_s}(t|u,h) \tag{9}$$

Provided the wind turbulence intensity is independent of H_s, T_p and only related to U_w, TI follows a certain conditional distribution for a given U_w. The joint distribution of the fours variables can be expressed as follows:

$$\begin{aligned} &f_{U_w,TI,H_s,T_p}(u,Ti,h,t) \approx f_{U_w}(u)\cdot f_{TI|U_w}(Ti|u) \\ &\cdot f_{H_s|U_w}(h|u)\cdot f_{Tp|U_w,H_s}(t|u,h) \end{aligned} \tag{10}$$

Since $f_{TI|U_w}(Ti|u)$ can not be obtained directly, TI is included as an environmental variable based on $f_{\sigma|U_w}(\sigma|u)$ which is the conditional probability density function of σ for a given U_W. The detailed process is described in Rosenblatt transformation.

2.2.2 Transformation of dependent environmental variables into independent standard normal variables

Since we can obtain the $f_{\sigma|U_w}(\sigma|u)$ directly, Rosenblatt transformation [24] was used as follows to transform the dependent environmental variables U_w, σ, H_s, and T_p into independent standard normal variables u_1, u_2, u_3, and u_4 in order to solve the reliability problem in the space U. When transforming the limit state surface in U-space back to the physical space, the TI can be calculated by Eq (11).

$$TI = \sigma/u \tag{11}$$

Rosenblatt transformatinon:

$$\begin{aligned} \Phi(u_1) &= F_{U_w}(u) \\ \Phi(u_2) &= F_{H_s|U_w}(h|u) \\ \Phi(u_3) &= F_{Tp|U_w,H_s}(t|u,h) \\ \Phi(u_4) &= F_{\sigma|U_w}(\sigma|u) \end{aligned} \tag{12}$$

where $\Phi(u)$ represents the standard normal distribution and

$$\begin{aligned} &F_{U_w}(u) = \int f_{U_w}(u)du \\ &F_{H_s|U_w}(h|u) = \frac{\int f_{U_w,H_s}(u,h)dh}{f_{U_w}(u)} = \int f_{H_s|U_w}(h|u)dh \\ &F_{Tp|U_w,H_s}(t|u,h) = \frac{\int f_{U_w,H_s,Tp}(u,h,t)dt}{f_{U_w,H_s}(u,h)} = \int f_{Tp|U_w,H_s}(t|u,h)dt \\ &F_{\sigma|U_w}(Ti|u) = \frac{\int f_{U_w,\sigma}(u,\sigma)d\sigma}{f_{U_w}(u)} = \int f_{\sigma|U_w}(\sigma|u)d\sigma \end{aligned} \tag{13}$$

Thus

$$\begin{aligned} u &= F_u^{-1}[\Phi(u_1)] \\ h &= F_h^{-1}[\Phi(u_2)|u] \\ t &= F_t^{-1}[\Phi(u_3)|u,h] \\ Ti &= F_\sigma^{-1}[\Phi(u_4)|u]/u \end{aligned} \tag{14}$$

2.2.3 Drawing environmental contours by transforming limiting boundary of U-space into physical space

The 50-yr contour surface can be solved by transforming it to a reliability problem. Setting each 1-h time span as an independent unit, there are $50 \cdot 365.25 \cdot 24$ numbers of 1-h units. The failure probability is $1/(50 \cdot 365.25 \cdot 24)$:

$$p_f = \frac{1}{50 \cdot 365.25 \cdot 24} \tag{15}$$

Standard normal variables have the property of rotational symmetry. As the maximum dimensional space that can be visualized is three dimensional, different combinations should be chosen to display the transformation of four environmental variables. For a contour surface considering three variables, the failure probability corresponds to a limit state surface of a sphere with radius of r.

$$\Phi(r) = 1 - p_f \tag{16}$$

The sphere with radius of r in U-space which considers U_w, H_s, and T_p can be transformed into limit state surface in physical space (Fig. 3). The upper range of the contour tends to result in an extreme response. Two-dimensional contour lines of H_s and T_p for various wind speeds are often drawn to find the critical combination of environmental variables for each target extreme response.

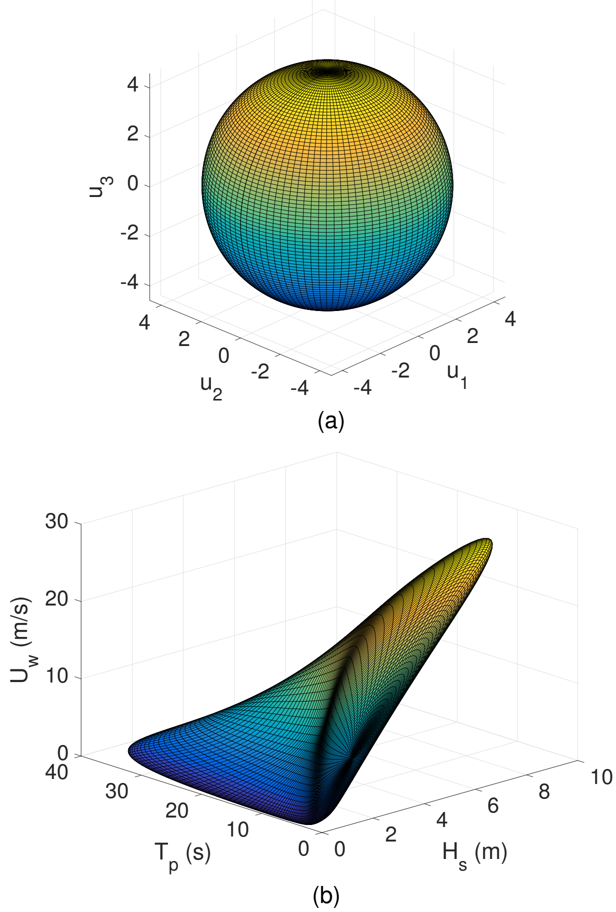

Fig. 3. Limit state surface in U-space (a) and physical space (b) corresponding to 50-yr return period considering H_s, T_p, and U_w

An extra contour surface including TI, H_s, and U_w as variables was plotted to determine the variance of TI (Fig. 4). The corresponding two-dimensional contour lines of TI and H_s for various values of U_w were also used to identify the critical environmental conditions.

3 Results and discussion

After integrating TI as an additional environmental variable, the extreme response was obtained based on the environmental contour with four environmental variables. Monopile base reaction force (F_1), monopile base pitching moment (M_1), tower base force (F_2), and tower base pitching moment (M_2) were evaluated based on ECM and MECM. Defination of the target forces and moments are shown in Fig. 5. For ECM, conditions including TI as a stochastic parameter were compared with conditions where TI was set to a constant value of 0.15. The results of the two methods were compared.

3.1 Effect of wind turbulence intensity on the extreme response

To determine the effects of TI on different extreme responses of a bottom-fixed OWT, a monopile OWT under

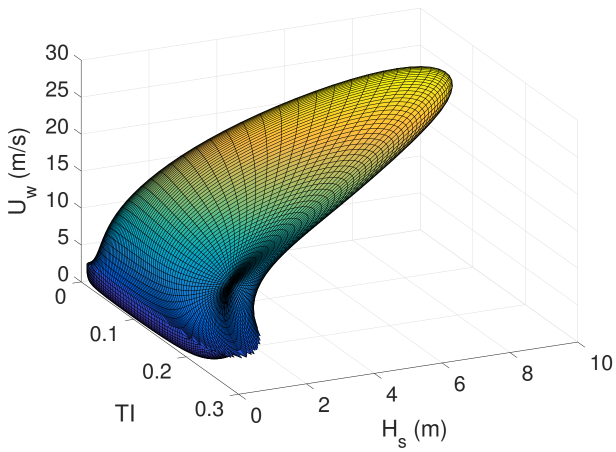

Fig. 4. Limit state surface in physical space corresponding to 50-yr return period considering H_s, TI, and U_w

wind load only was first simulated using the Fast software developed by NREL. Monopile base reaction force (F_1) and tower base force (F_2) were used to represent responses dominated by wave load and wind load, respectively.

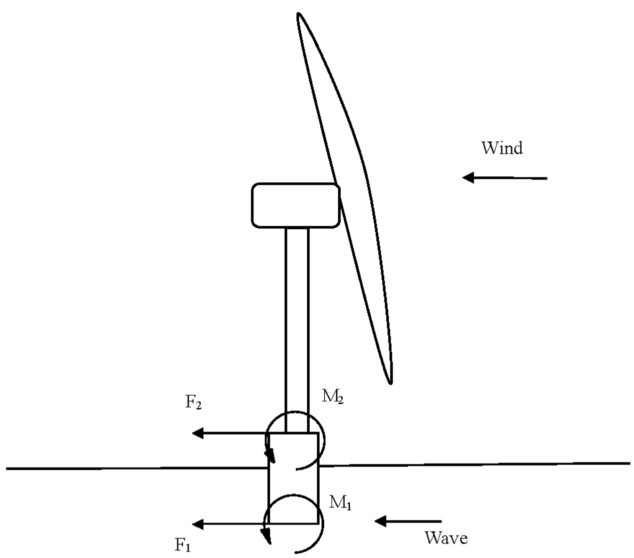

Fig. 5. Definition of forces and moments at the tower bottom and the monopile bottom

The NREL 5 MW baseline OC3 monopile bottom-fixed wind turbine with a rigid foundation was used as a model whose detaied information is in the Table.2. The monopile is 30 m high and located int 20 m shallow water. The range of TI was selected based on the normal turbulence model C as recommended by the IEC-61400 standard. TI varying from 9% to 15% covers all probable fluctuations. As a sudden drop in response induced by wind load is observed for bottom-fixed horizontal-axis wind turbines when the wind speed approaches the cut-out speed, their extreme responses tend to appear within the operational region of the wind turbine. Therefore, the hub-height wind speeds investigated ranged from 3 m/s to 25 m/s. For each combination of U_{hub} and TI, 800-s simulations with 20 random seed numbers were performed. The first 200 s of start-up transients were removed during postprocessing.

Table 2. Gross properties chosen for the NREL 5MW baseline wind turbines [25]

	Monopile OWT
Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Nacelle Mass	240,000 kg
Tower Mass	347460 kg
Rotor diameter	126 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s,11.4 m/s, 25 m/s
Hub height	90 m
Tower base above the waterline	10 m
Tower top above the waterline	87.6 m
Water depth	20 m

Trends of mean values of 20 extremes for each case of monopile base reaction force and tower base force under wind load only are displayed in Fig. 6, clearly showing that TI does affect extreme responses with respect to both extreme value and peak point. In general, the larger the value of TI, the larger the extreme value. Therefore, it is meaningful to take the variation of TI into consideration when considering extreme responses.

3.2 Environmental contour method

In FLTA, only small part of environmental conditions considered actually contribute to the extreme response calculation. In order to improve the efficiency while maintaining acceptable accuracy, several methods have been proposed as simplifications, including ECM and MECM.

ECM is a simplified IFORM that does not include response as a variable, which means that it decouples the response and the environmental parameters such that the contour consists of the environmental parameters only. To predict the 50-yr extreme response, ECM uses a 50-yr environmental contour. Different environmental conditions are selected along this contour in order to find the critical one with the largest response, and a higher fractile or multiplication factor is used to obtain the 50-yr extreme response. In ECM, the case where TI is included as an variable is compared with the case where TI is set to a constant value of 15% to further

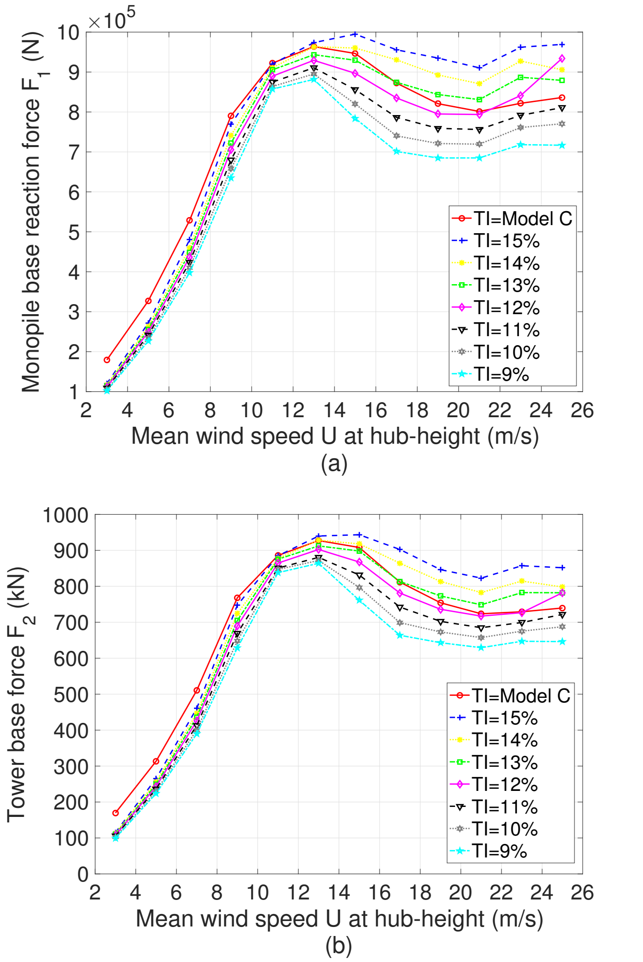

Fig. 6. Expected value of the short-term extreme value of monopile base reaction force (a) and tower base force (b) under different wind speeds with varying TI

evaluate the effect of TI on the extreme responses.

The basic idea is presented as follows:

$$F_{x_{1-hr,50-yr}}(\xi) \approx F^{ST}_{x_{1-hr|U_w,H_s,T_p,TI}}(\xi|u_{50},h_{50},t_{50},Ti_{50}) \quad (17)$$

where the $F_{x_{1-hr,50-yr}}(\xi)$ is the 50-yr 1-h extreme CDF, and $F^{ST}_{x_{1-hr|U_w,H_s,T_p}}(\xi|u_{50},h_{50},t_{50})$ is the 1-h short-term extreme CDF whose environmental parameter combinations are selected along the 50-yr environmental contour with the largest response.

In order to find the value of $F^{ST}_{x_{1-hr|U_w,H_s,T_p,TI}}(\xi|u,h,t,Ti)$, 20 random seeds were used to carry out 10-minute simulations for each environmental condition. The Gumbel method, Weibull tail method, and up-crossing rate method can all be used to carry out short-term response analysis; in this work, the Gumbel method was used. The extreme values gained in all simulations were fitted by Gumbel distribution using Eq. (17), which provides the 10-minute short-term extreme CDF $F^{ST}_{x_{10-min|U_w,H_s,T_p,TI}}(\xi|u,h,t,Ti)$ for each case:

$$F_x = e^{-e^{-(x-\mu)/\beta}} \quad (18)$$

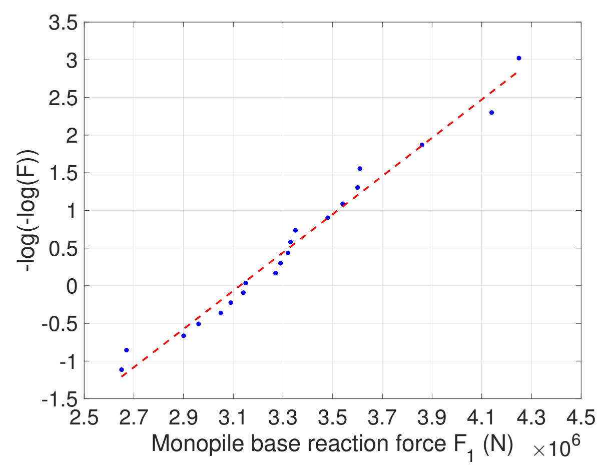

Fig. 7. An example of Gmbel fitting of the 20 seeds for F_1

Fig. 7 shows a Gumbel probability plot of F_1. The horizontal axis is linear, showing the observation response x and the vertical axis represents the reduced variable $-log(log(F(x)))$. Parameter estimation was performed by fitting a straight line to the empirical distribution functions based on the relations in Eq. (18) to connect parameters to intercepts and slopes of the estimated lines [26]:

$$-log(log(F(x;\mu,\beta))) = x/\beta - \mu/\beta \quad (19)$$

Assuming each 10-min interval is independent, $F^{ST}_{x_{1-hr|U_w,H_s,T_p,TI}}(\xi|u,h,t,Ti)$ can be expressed as

$$F^{ST}_{x_{1-hr|U_w,H_s,T_p,TI}}(\xi|u,h,t) = F^{ST}_{x_{10-min|U_w,H_s,T_p,TI}}(\xi|u,h,t,Ti)^6 \quad (20)$$

The most probable value of the Gumbel distribution is μ, after extrapolation, the extrapolated new most probable value can be expressed as follows:

$$M_{Ox_{1-hr,50yr}}(u_{50},h_{50},t_{50},Ti_{50}) = \mu + \beta ln6 \quad (21)$$

where the $M_{Ox_{1-hr,50yr}}(u_{50},h_{50},t_{50},Ti_{50})$ is extrapolated new most probable value. All the extreme responses listed in the tables are extrapolated new most probable value $M_{Ox_{1-hr,50yr}}(u,h,t,Ti)$. The identified extreme responses and critical environmental conditions are provided in Tables 3-4 and Tables 6-7. The detailed information are attached in the Appendix.

3.2.1 Extreme response evaluation based on ECM considering U_w, H_s, and T_p with TI set to 15%

In the upper region of the environmental surface in physical space (Fig. 3 (b)), the combination of high wind

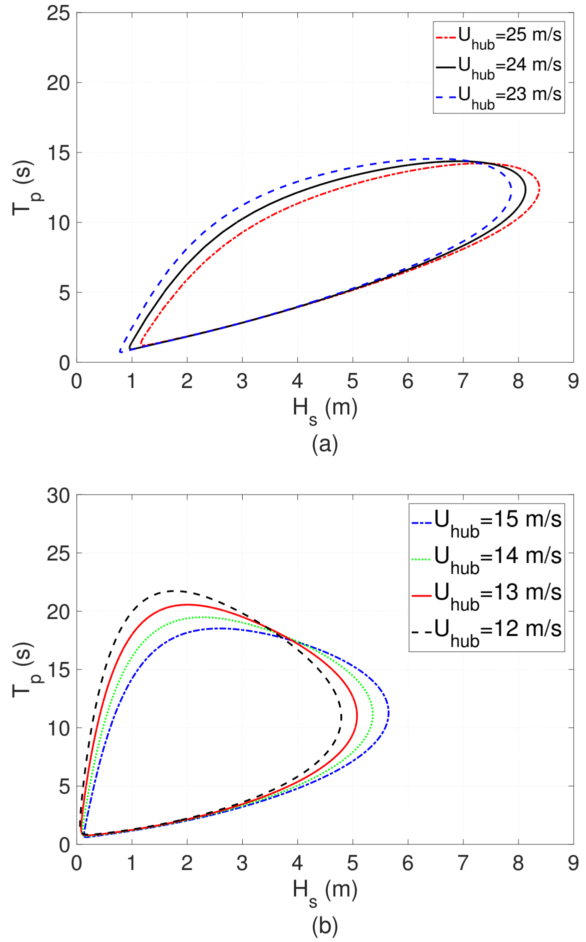

Fig. 8. Contour lines of H_s and T_p under different U_{hub} for F_1 (a) and M_1 (b) based on ECM

Table 3. Selection of critical environmental conditions based on ECM with TI assumed to be 0.15

	Unit	U_{hub} (m/s)	TI	H_s (m)	T_p (s)	
F_1	(N)	25	0.15	7.08	8.23	3.99E+06
M_1	(N*m)	14	0.15	3.96	4.94	1.17E+08
F_2	(kN)	34	0.15	-	-	7.49E+02
M_2	(kN*m)	34	0.15	-	-	4.05E+04

speed and significant wave height tends to cause extreme responses. Thus, multiple contour lines are plotted in Fig. 8 for various wind speeds around the rated speed and cut-out speed for large responses induced by wind load and wave load, respectively. As shown in Fig. 6, the extreme response under wind load only occurs around the rated wind speed, whereas the response at the nearby cut-out wind speed is a little smaller; however, for the response dominated by wave

Table 4. Selection of critical environmental conditions based on ECM with TI included as an extra environmental variable

	Unit	U_{hub} (m/s)	TI	H_s (m)	T_p (s)	
F_1	(N)	25	0.1377	7.09	8.28	3.88E+06
M_1	(N*m)	14	0.1639	3.70	4.51	1.19E+08
F_2	(kN)	17	0.1693	-	-	1.06E+03
M_2	(kN*m)	17	0.1693	-	-	7.93E+04

load, the greater significant wave height that occurs at higher wind speeds tends to result in much larger responses. Therefore, for each probable critical wind speed, environmental combinations should be evaluated along the corresponding contour line to find the largest one.

In Figure. 8 (a), contour lines of H_s and T_p under different U_{hub} ranging from 23 to 25 m/s with 1 m/s increments are plotted for the evaluation of extreme response of F_1, which is dominated by wave load. In Figure. 8 (b), contour lines of H_s and T_p under different U_{hub} ranging from 12 to 15 m/s with 1 m/s increments are plotted for the evaluation of the extreme response of M_1, which is dominated by wind load. It is assumed that TI is a constant with value 0.15. The transformation of U and U_w used Eq. (3). The extreme value of F_1 appears at cut-out wind speed owing to the relatively large significant wave height, whereas the extreme value of M_1 appeared above the rated wind speed at 14 m/s owing to the larger response induced by wind.

As F_2 and M_2 determined by wind, when TI is assumed to be a constant of 0.15, the contour surface was reduced to a point with mean wind speed included as the only variable. Wind speed corresponding to 50-yr return period is 34 m/s at hub-height. The results are shown in Table 2.

3.2.2 Extreme response evaluation based on ECM considering U_w, H_s, T_p, and TI

Taking TI as an additional variable, an environmental contour surface considering TI, H_s, and U_w (Fig. 4) was drawn. Additional contour lines of TI and H_s for different wind speeds (Fig. 9) were drawn to identify environmental conditions with varying TI. Multiple combinations of TI, H_s, and U_w were selected, and values of T_p were determined from the contour lines of H_s, T_p for the corresponding wind speeds to find the largest extreme value. For F_2 and M_2, the U-space and physical space consisted of two variables, TI and U_w (Fig. 10), as they were dominated by wind load only.

The results are presented in Table 3. The critical environmental combinations of four variables were a little different from those of three variables, because the variation extreme response in general is positively related to the magnitude of TI. For F_1, the influence on the critical environmental

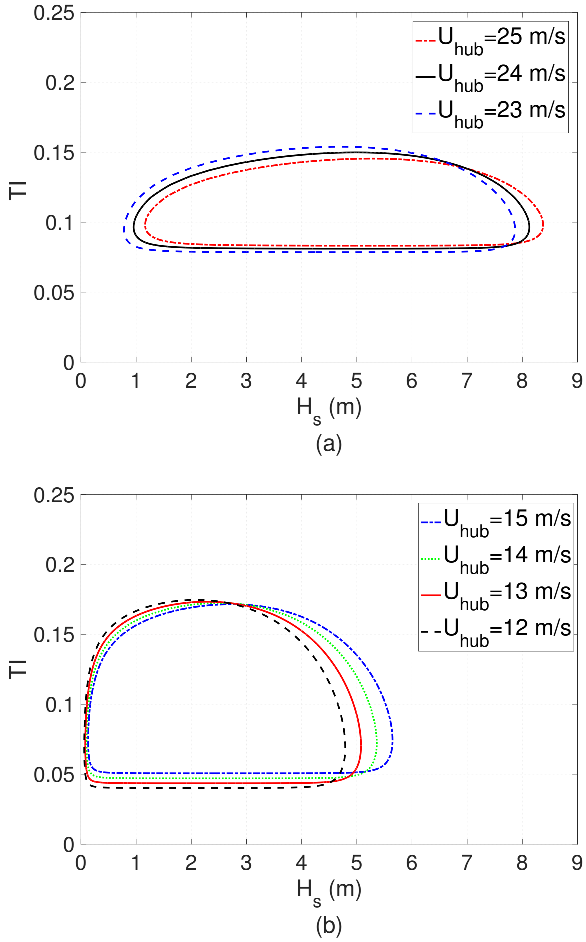

Fig. 9. Contour lines of H_s and TI under different U_{hub} for F_1 (a) and M_1 (b) based on ECM

Table 5. Comparison of inclusion TI as a variable with regard to set TI as a constant of 15% based on ECM

TI	F_1 (N)	M_1 (N*m)	F_2 (kN)	M_2 (kN*m)
15%	3.99E+06	1.17E+08	7.49E+02	4.05E+04
Varying	3.88E+06	1.19E+08	1.06E+03	7.93E+04
	-2.76%	+1.71%	+41.52%	+95.80%

condition selected was minor because F_1 was dominated by wave load. Including TI as an extra environmental variable contributed to a slight decrease in the extreme response of F_1 owing to the smaller TI in the critical environmental condition. For M_1, the wave state was selected in order to acquire a relatively high TI, which also resulted in a larger response.

For F_2, M_2, various TI not only influenced the values of extreme responses but also the location of the peak. Using a probability distribution of TI rather than setting TI as a constant can provide a more accurate result of extreme response which is closer to realistic environmental conditions. Integrating TI into ECM allows for consideration of the non-monotonic characteristics of the responses induced by wind. As is shown in Table 4, varying TI resulted in 41.52% increase for F_2 and 95.80% increase for M_2. This indicates that ignorance of the TI variation could lead to nonconservative designs of OWT support structures.

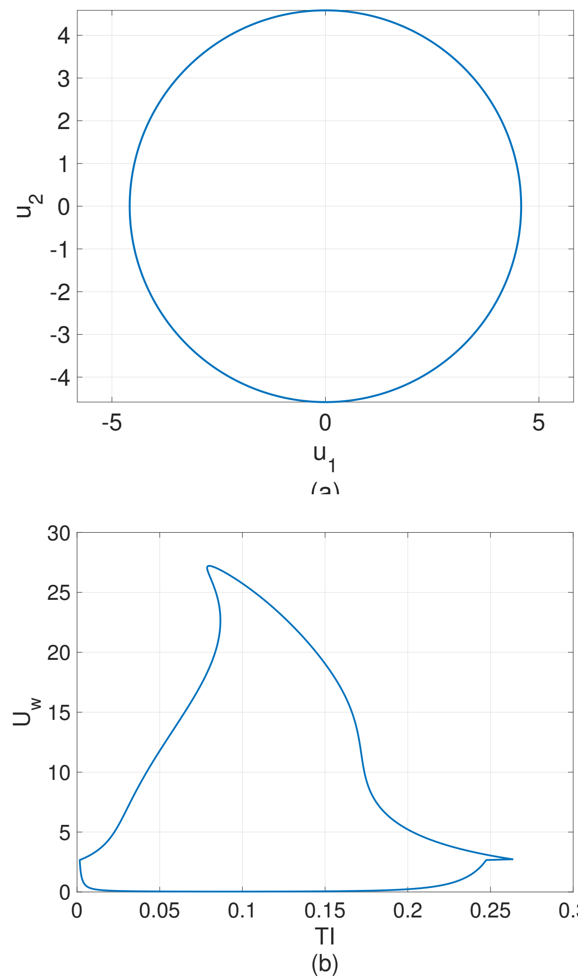

Fig. 10. Limit state surface in U space (a) and physical space (b) corresponding to 50-yr return period considering U_w and TI

3.3 Extreme responses evaluation based on modified environmental contour method (MECM)

OWTs are parked with their blades feathered when the wind speed exceeds the cut-out wind speed. The wind load of OWT drops significantly around cut-out wind speed, which means the response induced by wind load does not monotonously increase with increasing wind speed. This non-monotonic response results in deviations in the critical environmental condition between the real and predicted values of extreme responses in both the combined loads case and wind-dominated load cases. Therefore, ECM is modified to solve this problem, as follows:

$$F_{x_{1-hr,50-yr}}(\xi) = F_{x_{1-hr,N-yr}}(\xi)^{50/N} \quad (22)$$

$$F_{x_{1-hr,N-yr}}(\xi) \approx F^{ST}_{x_{1-hr|U_w,H_s,T_p,TI}}(\xi|u_N, h_N, t_N, Ti_N) \quad (23)$$

where the $F_{x_{1-hr,N-yr}}(\xi)$ is the N-yr 1-h extreme CDF, $F^{ST}_{x_{1-hr|U_w,H_s,T_p}}(\xi|u_N, h_N, t_N)$ is the 1-h short-term extreme CDF whose environmental parameter combination is selected along the N-yr environmental contour with the largest response. $F^{ST}_{x_{1-hr|U_w,H_s,T_p}}(\xi|u_N, h_N, t_N)$ is used to represent the $F_{x_{1-hr,N-yr}}(\xi)$ and can be extrapolated to represent $F_{x_{1-hr,50-yr}}$. N is appropriately selected to ensure good ECM performance.

The most probable 50-yr extreme response is given by Eq. (23)

$$Mo_{x_{1-hr,50yr}}(u_N, h_N, t_N, Ti_N) = \mu + \beta ln(6 \times 50/N) \quad (24)$$

When N is much smaller than 50, an appropriate number of simulations must be performed to ensure the error of β is small. Rewriting Eq. (17) in linear form as Eq. (24), simple linear regression was used to fit the parameters.

$$x = \beta(-ln(-lnF)) + \mu \quad (25)$$

One way to determine whether the number of simulations is sufficient is to check the 95% confidence interval. Assuming the errors of the extremes follow a normal distribution, the confidence interval can be obtained by Eq. (25) [27]

$$\begin{aligned} Mo_{CI\pm}(n) &= \widehat{Mo} \pm t_{0.975,n-2}\sqrt{var(Mo(n))/(N-2)} \\ \widehat{Mo}(n) &= \widehat{\mu}(n) + \widehat{\beta}(n) ln(6 \times 50/N) \end{aligned} \quad (26)$$

where $\widehat{\mu}$ and $\widehat{\beta}$ are the estimations from the Gumbel distribution based on n simulations. $t_{0.975}$ is the 97.5% fractile value of Student's t-distribution with $(n-2)$ degrees of freedom. *CI* is calculated as follows:

$$CI(n) = \frac{\widehat{Mo}_{CI+}(n) - \widehat{Mo}_{CI-}(n)}{\widehat{Mo}(n)} \leq 3\% \quad (27)$$

3.3.1 Extreme response evaluation based on MECM considering U_w, H_s, and T_p with TI set to 15%

Fig. 11 shows the trends of short-term expected forces and moments extrapolated from 10-min simulations under different wind speeds with the most probable wave states and the value of TI set to be a constant of 15%. The largest F_1 occurred at the cut-out wind speed, whereas the largest

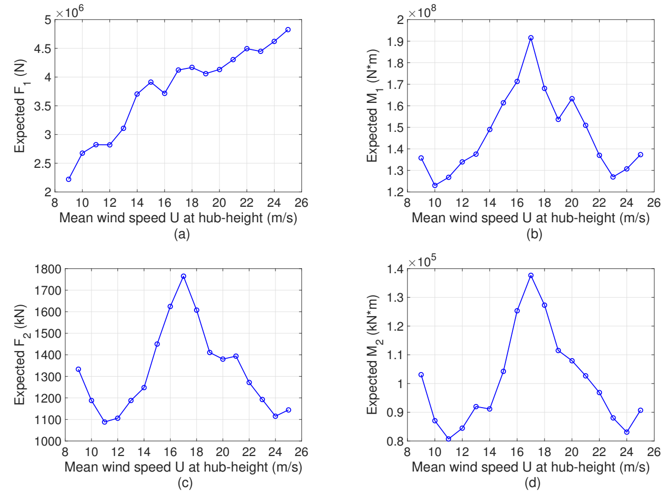

Fig. 11. Expected value of the short-term extreme value of target forces and moments under different wind speeds

M_1, F_2, and M_2 values were found above to the rated wind speed at 17 m/s. Contours were drawn according to these two critical wind speeds for further selection of environmental conditions to find the largest responses for different forces and moments. Their corresponding return periods N were obtained by Eq. (27)

$$N = 1/((1 - F_{U_W}) * 365.25 * 24) \quad (28)$$

where $1 - F_{U_W}$ is the probability that wind speed U_W exceeded.

Environmental contour surfaces corresponding to the return periods (6.19×10^{-2}-yr for F_1 and 1.53×10^{-3}-yr for M_1, F_2, M_2) of the most important wind speeds were drawn to perform MECM. Based on the *CI*, 60 random seeds and 80 random seeds were provided for the environmental conditions with 6.19×10^{-2}-yr and 1.53×10^{-3}-yr return period, respectively, to ensure reliable results.

Fig. 12 (a) shows contour lines for H_s and T_p for U_{hub} values ranging from 23 to 25 m/s with 0.5 m/s increments for extreme response analysis of F_1. Similarly, Fig. 12 (b) shows contour lines for U_{hub} values ranging from 15 to 17 m/s with 0.5 m/s increments for extreme response analysis of M_1. Evaluating the responses of environmental combinations of H_s, T_p and U_{hub} selected along the contour lines with TI set to be a constant of 15% to find the largest one. For F_2 and M_2, when TI is assumed to be a constant of 0.15, the contour surface was reduced to a point with mean wind speed included as the only variable. The results are shown in Table 5.

3.3.2 Extreme response evaluation based on MECM considering U_w, H_s, T_p, and TI

Fig. 13 shows the trends of short-term expected forces and moments extrapolated from 10-min simulations under different wind speeds with the most probable wave states and

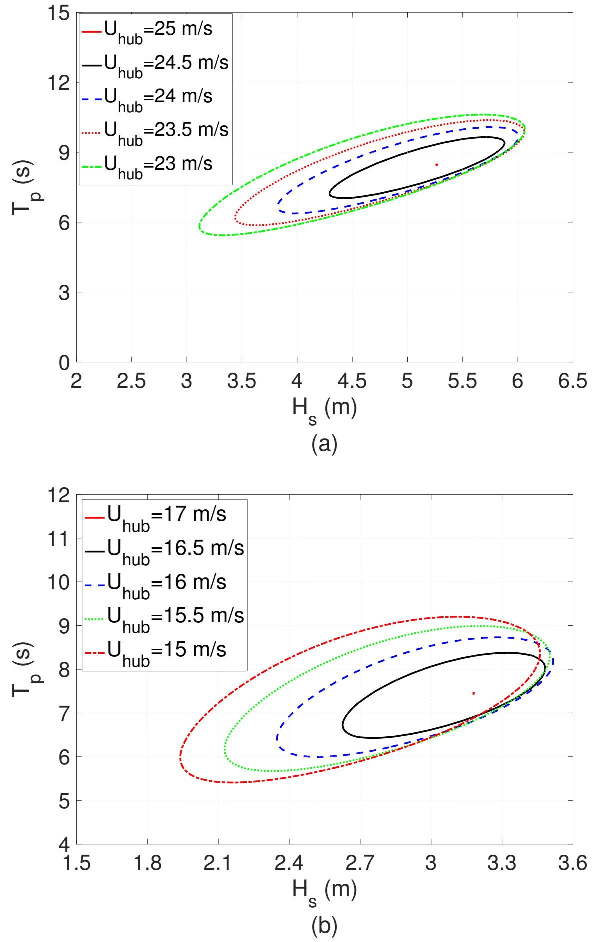

Fig. 12. Contour lines of H_s and T_p under different U_{hub} for F_1 (a) and M_1 (b) based on MECM

Table 6. Selection of critical environmental conditions for F_1 based on MECM with TI set to be a constant of 15%

	Unit	U_{hub} (m/s)	TI	H_s (m)	T_p (s)	
F_1	(N)	24	0.15	6.00	9.54	4.72E+06
M_1	(N*m)	17	0.15	3.18	7.46	1.87E+08
F_2	(kN)	17	0.15	-	-	1.63E+03
M_2	(kN*m)	17	0.15	-	-	1.26E+05

TI values. The largest F_1 occurred at the cut-out wind speed, whereas the largest M_1, F_2, and M_2 values were found closed to the rated wind speed. Contours were drawn according to these two critical wind speeds for further selection of environmental conditions to find the largest responses for different forces and moments.

Environmental contour surfaces corresponding to the return periods (6.19×10^{-2}-yr for F_1 and 6.00×10^{-4}-yr for

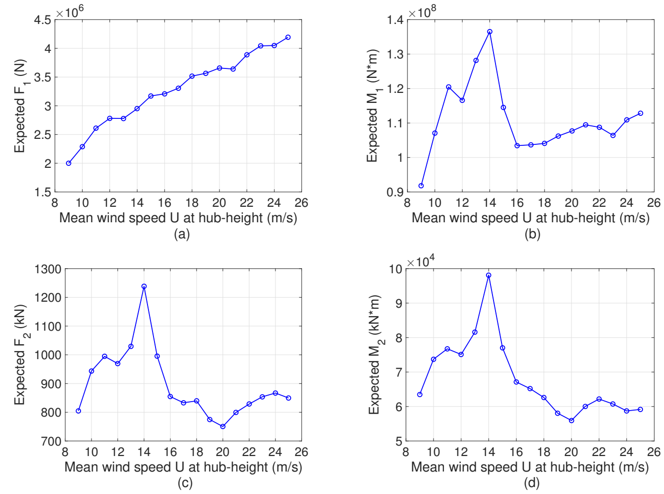

Fig. 13. Expected value of the short-term extreme value of target forces and moments under different wind speeds

M_1, F_2, M_2) of the most important wind speeds were drawn to perform MECM.

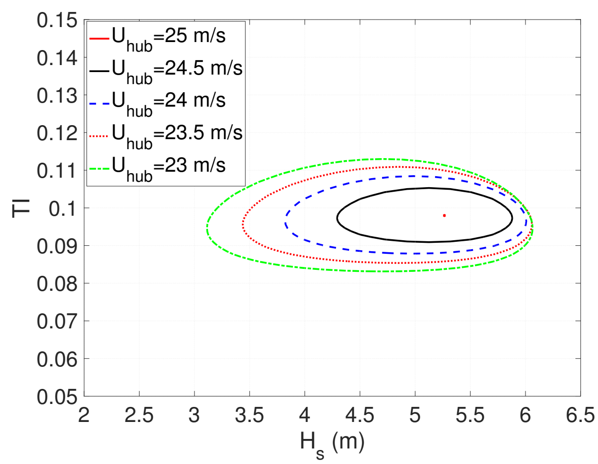

Fig. 14. Contour lines of H_s and TI under different U_{hub} for F_1 based on MECM

Fig. 14 shows contour lines for H_s and TI for U_{hub} values ranging from 23 to 25 m/s with 0.5 m/s increments for extreme response analysis of F_1. Similarly, Fig. 15 shows contour lines for U_{hub} values ranging from 12 to 14 m/s with 0.5 m/s increments for extreme response analysis of M_1. Contour line of U_w and TI are plotted in Fig. 16 for the selection of critical wind condition for F_2 and M_2. As shown in Tables 5 and 6, the results obtained by MECM were much larger than those from ECM. Table 7 shows that for MECM methods, setting TI as a constant of 15% caused more than 20% deviation of the responses under combined loads and wind-dominated responses with those of which the TI was included as a variable. And the variable TI caused the difference of the critical environmental selection. The results of the two methods were also compared with those of FLTA,

Table 7. Selection of critical environmental conditions based on MECM with TI included as an extra environmental variable

	Unit	U_{hub} (m/s)	TI	H_s (m)	T_p (s)	
F_1	(N)	23.5	0.0946	6.05	9.92	4.56E+06
M_1	(N*m)	13.5	0.0717	2.68	7.50	1.37E+08
F_2	(kN)	14	0.0723	-	-	1.26E+03
M_2	(kN*m)	14	0.0723	-	-	9.86E+04

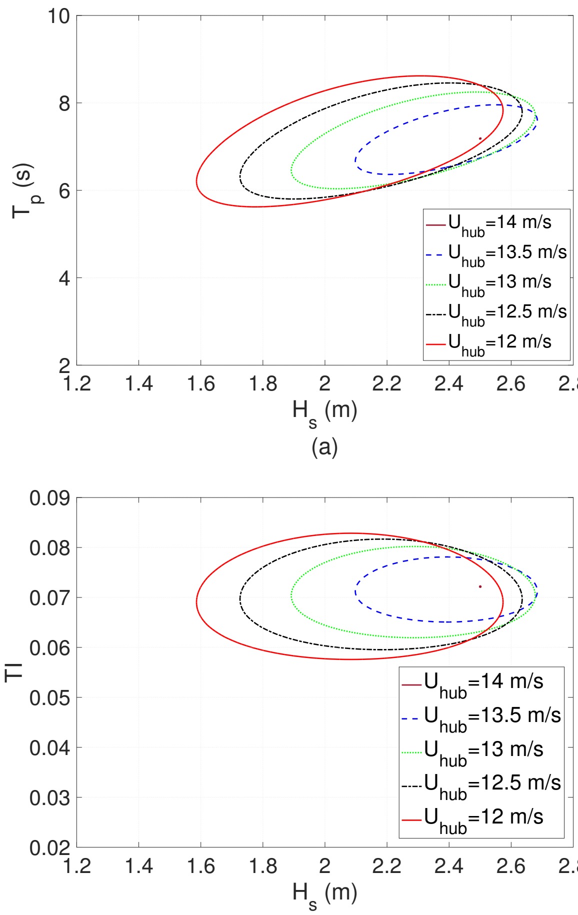

Fig. 15. Contour lines of H_s and T_p (a), H_s and TI (b) under different U_{hub} for M_1 based on MECM

which was used as a benchmark.

3.4 FLTA

FLTA is a time-consuming but accurate method for calculating long-term extreme responses. It considers all possible combinations of the environmental variables and calculates the extremes by directly integrating all environmental

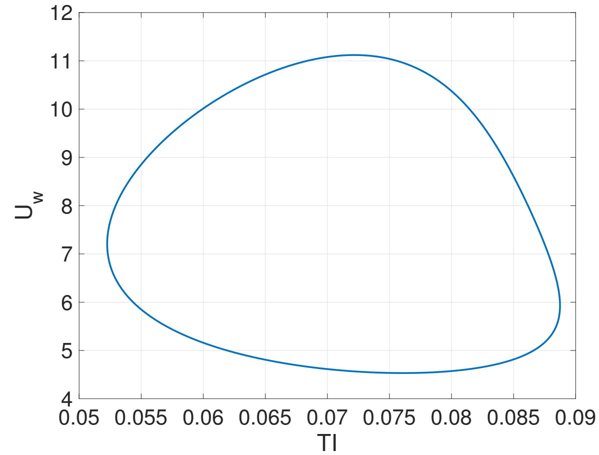

Fig. 16. Contour line of U_w and TI for F_2, M_2 based on MECM

Table 8. Comparison of inclusion TI as a variable with regard to set TI as a constant of 15% based on MECM

TI	F_1 (N)	M_1 (N*m)	F_2 (kN)	M_2 (kN*m)
15%	4.72E+06	1.87E+08	1.63E+03	1.26E+05
Varying	4.56E+06	1.37E+08	1.26E+03	9.86E+04
	-3.39%	-26.74%	-22.70%	-21.75%

variables and the corresponding short-term response probability distribution function as in Eq. (28).

$$
\begin{aligned}
&F^{LT}_{X_{1-hr}}(\xi) \\
&= \int\int\int F^{ST}_{x_{1-hr|U_w,H_s,T_p,TI}}(\xi|u,h,t,Ti) \\
&\times f_{U_w,TI,H_s,T_p}(u,Ti,h,t)dudhdtdti \\
&= \sum F^{ST}_{x_{1-hr|U_w,H_s,T_p,TI}}(\xi|u,h,t,Ti) \\
&\times f_{U_w,TI,H_s,T_p}(u,Ti,h,t)\Delta u\Delta Ti\Delta h\Delta t
\end{aligned} \tag{29}
$$

where $F^{LT}_{X_{1-hr}}(\xi)$ is the 50-yr 1-hr extreme probability distribution, $F^{ST}_{x_{1-hr|U_w,H_s,T_p,TI}}(\xi|u,h,t,Ti)$ is the 1-hr short-term extreme probability distribution, calculated based on the maximum responses of 10-min periods.

For the 50-yr extreme response calculation, ξ can be obtained by Eq. (29)

$$
F^{LT}_{X_{1-hr}}(\xi) = 1 - \frac{1}{50 \cdot 365.25 \cdot 24} \tag{30}
$$

The range of environmental variables is shown in Table

Table 9. The range of environmental variables for FLTA

Variables	Unit	Min	Max	Increment
U_{hub}	(m/s)	2	34	2
TI	%	4	24	4
H_s	(m)	1	10	1
T_p	(s)	2	24	2

Table 10. Comparison of the extreme responses obtained by FLTA, ECM, MECM considering U_w, H_s, T_p, and TI (* denotes methods including TI as an extra environmental variable)

Method	F_1	M_1	F_2	M_2
	(N)	(N*m)	(kN)	(kN*m)
FLTA	4.95E+06	1.41E+08	1.30E+03	9.95E+04
ECM	3.99E+06	1.17E+08	7.49E+02	4.05E+04
ECM*	3.88E+06	1.19E+08	1.06E+03	7.93E+04
MECM	4.72E+06	1.87E+08	1.63E+03	1.26E+05
MECM*	4.56E+06	1.37E+08	1.26E+03	9.86E+04

9. If all the environmental conditions were taken into consideration, 17 wind speeds, 6 turbulence intensity, 10 significant wave heights and 12 spectral peak period are used. Since for each environment combination, 20 random seeds are given to carry out 10-minute simulations. The FLTA requires simulations of $(17 \times 6 \times 10 \times 12 \times 20)$ cases for combined wind and wave. That would be very cumbersome and time-consuming. A simplified FLTA method, verified in [14], was used in this work. The basic idea was to truncate the environmental conditions that contribute little to the overall extreme response by substituting their $F^{ST}_{x_{1-hr|U_w,H_s,T_p,TI}}(\xi|u,h,t,Ti)$ values with a value of 1:

$$\begin{aligned} & F^{LT}_{X_{1-hr}}(\xi) \\ & = \sum_{u_i,h_i,t_i,Ti_i} F^{ST}_{x_{1-hr|U_w,H_s,T_p,TI}}(\xi|u,h,t,Ti) \\ & \times f_{U_w,TI,H_s,T_p}(u,Ti,h,t)\Delta u\Delta h\Delta t\Delta Ti \\ & + \sum_{u_c,h_c,t_c,Ti_c} 1 \times f_{U_w,TI,H_s,T_p}(u,Ti,h,t)\Delta u\Delta h\Delta t\Delta Ti \end{aligned} \tag{31}$$

where u_i,h_i,t_i,Ti_i represent the important cases and u_c,h_c,t_c,Ti_c are the unimportant ones.

In this paper, the range of important environmental conditions are cases whose wind speed at hub-height is within the range 10-24 m/s. The probability of the selected important cases account for 50.45% of the total. The results of FLTA and the comparison of extreme responses obtained by these three methods are shown in Table 9 and the percentage differences are shown in Table 10. Since multiplying a factor is a reasonable and efficient method to design the offshore bottom-fixed wind turbines preliminarily, comparison of the results obtained by different methods is based on the multiplication factor which is more straight forward. For methods with four environmental variables, in ECM, multiplication factor 1.28, 1.18, 1.23 as well as 1.25 should be applied to monopile base reaction force, monopile base pitching moment, tower base force, and tower base pitching moment, respectively. Including TI as an extra environmental variable significantly reduce the nonconservatism associated with the traditional ECM. For the MECM with fixed TI of 0.15, although the predictions are better than those of ECM, including TI as an extra variable will significantly reduce the responses under combined wind-wave loads or wind-dominated loads, because a constant TI of 15% is too conservative. In this sense, the proposed approach reduce the conservatism associated with MECM.

Table 11. Percentage difference of ECM and MECM with regard to FLTA considering U_w, H_s, T_p, and TI (* denotes methods including TI as an extra environmental variable)

Method	F_1	M_1	F_2	M_2
	(N)	(N*m)	(kN)	(kN*m)
ECM	-19.39%	-17.02%	-42.38%	-59.30%
ECM*	-21.62%	-15.60%	-18.46%	-20.30%
MECM	-4.65%	32.62%	25.38%	26.63%
MECM*	-7.88%	-2.84%	-3.08%	-0.90%

4 Conclusions

This paper includes a method that includes turbulence intensity as a stochastic variable for extreme response analysis of a monopile wind turbine based on environmental contour, taking four environmental variables (mean wind speed, significant wave height, spectral peak period, and turbulence intensity) into consideration. An example of evaluating 50-yr extreme dynamic responses including TI as an extra variable is given. The results obtained by ECM and MECM are compared with those of the FLTA method as a benchmark. The following conclusions can be drawn.

(1) The effects of various TI values on the extreme response of an monopile OWT were verified by simulations using Fast software developed by NREL. Simulations of the target forces and moments with TI values ranging from 9% to 15% under wind load only showed that lager TI values tend to result in larger responses for the same wind speed. For the response dominated

by wind load in particular, TI influenced not only the extreme value but also the location of the critical environmental condition.

(2) The TI was integrated into ECM and MECM as an extra environmental variable based on standard deviation σ, whose CPDF was given as a three-parameter Weibull distribution. For ECM, integrating TI as a variable allows for the consideration of the non-monotonic characteristic of the aerodynamic behaviour of the wind turbine. It improved the accuracy of the ECM significantly, especially for wind-dominated responses. After comparing with the results obtained by FLTA, multiple factor for investigated responses ranges from 1.2 to 1.3 which is common used by offshore oil and gas industry structures. It proves that including TI as an extra environmental variable enabled ECM to predict responses induced by wind loads with the same satisfactory accuracy as responses induced by wave loads.

(3) Although after comparing with FLTA, MECM gave closer prediction than ECM, it is found that MECM, with the wind turbulence intensity included as an individual variable, gave more accurate predictions compared with those without. MECM with varying TI produced reliable results which were very closed to those of FLTA with 7.88% difference for response dominated by wave load and less than 4.00% difference for responses dominated by wind load. While MECM with TI set to be a constant of 15% caused too conservative responses predicted under combined loads or wind-dominated load because of the much larger value of TI compared with realistic TI in the critical environmental condition. Setting TI as a constant will effect the accuracy of the results significantly.

Turbulence intensity, as an important characteristic of wind and should be integrated into ECM and MECM as a variable to more accurately approximate realistic environmental condition. Further study could be the application of ECM and MECM with TI included as an extra environmental variable in the extreme response analysis of floating wind turbines, where platform movement and the tension forces of mooring lines may be sensitive to wind condition, therefore, TI may play a more important role.

Acknowledgements

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Appendix: Detailed selection of the critical environmental condition (the items shown in bold are the most critical environmental conditions and the corresponding extreme responses.)

Table A1. Selection of critical environmental conditions for F_1 based on ECM with TI assumed to be 0.15

U_{hub} (m/s)	TI	H_s (m)	T_p (s)	F_1 (N)
25	**0.15**	**7.08**	**8.23**	**3.99E+06**
24	0.15	6.93	8.16	3.91E+06
23	0.15	6.81	8.23	3.77E+06

Tables A1-A3 show the detailed selection of the critical environmental conditions and identified extreme responses based on ECM with TI set to be a constant of 15%. For F_1, U_{hub} ranging from 23 to 25 m/s with 1 m/s increments, while for M_1, U_{hub} ranging from 12 to 15 m/s with 1 m/s increments. As F_2 and M_2 are dominated by wind only, the contour surface is reduced to be a point which corresponds to the largest wind speed in 50 yrs.

Table A2. Selection of critical environmental conditions for M_1 based on ECM with TI assumed to be 0.15

U_{hub} (m/s)	TI	H_s (m)	T_p (s)	M_1 (N*m)
15	0.15	3.47	6.37	1.16E+08
14	**0.15**	**3.96**	**4.94**	**1.17E+08**
13	0.15	4.00	5.29	1.17E+08
12	0.15	4.07	6.10	1.10E+08

Table A3. Selection of critical environmental conditions for F_2, M_2 based on ECM with TI assumed to be 0.15

U_{hub} (m/s)	TI	F_2 (kN)	M_2 (kN*m)
34	**0.15**	**7.49E+02**	**4.05E+04**

Table A4. Selection of critical environmental conditions for F_1 based on ECM

U_{hub} (m/s)	TI	H_s (m)	T_p (s)	F_1 (N)
25	**0.1377**	**7.09**	**8.28**	**3.88E+06**
24	0.1394	6.92	8.20	3.86E+06
23	0.1399	6.79	8.20	3.74E+06

Similarly, Tables A4-A6 show the detailed selection of the critical environmental conditions and identified extreme responses based on ECM with varying TI.

Tables A7-A9 and Tables A10-A12 show the detailed selection of the critical environmental conditions and identified extreme responses based on MECM with TI set to be a constant of 15% and MECM with varying TI respectively.

Table A5. Selection of critical environmental conditions for M_1 based on ECM

U_{hub} (m/s)	TI	H_s (m)	T_p (s)	M_1 (N*m)
15	0.1689	3.44	3.86	1.18E+08
14	**0.1639**	**3.70**	**4.51**	**1.19E+08**
13	0.1526	4.01	5.40	1.16E+08
12	0.1601	3.53	4.64	1.14E+08

Table A6. Selection of critical environmental conditions for F_2, M_2 based on ECM

U_{hub} (m/s)	TI	F_2 (kN)	M_2 (kN*m)
18	0.1679	1.01E+03	7.49E+04
17	**0.1693**	**1.06E+03**	**7.93E+04**
16	0.1703	1.02E+03	7.64E+04
15	0.1714	1.02E+03	7.59E+04
14	0.1720	9.85E+02	7.41E+04

Table A7. Extreme response evaluation for F_1 based on MECM with TI set to be a constant of 15%

U_{hub} (m/s)	TI	H_s (m)	T_p (s)	F_1 (N)
25	0.15	5.27	8.49	4.47E+06
24.5	0.15	5.87	9.25	4.66E+06
24	**0.15**	**6.00**	**9.54**	**4.72E+06**
23.5	0.15	6.04	9.75	4.65E+06
23	0.15	6.05	10.05	4.63E+06

Table A8. Selection of critical environmental conditions for M_1 based on MECM with TI assumed to be 0.15

U_{hub} (m/s)	TI	H_s (m)	T_p (s)	M_1 (kN*m)
17	**0.15**	**3.18**	**7.46**	**1.87E+08**
16.5	0.15	3.48	7.95	1.82E+08
16	0.15	3.51	8.12	1.70E+08
15.5	0.15	3.50	8.25	1.69E+08
15	0.15	3.46	8.36	1.54E+08

Table A9. Selection of critical environmental conditions for F_2, M_2 based on MECM with TI assumed to be 0.15

U_{hub} (m/s)	TI	F_2 (kN)	M_2 (kN*m)
17	**0.15**	**1.63E+03**	**1.26E+05**

Table A10. Extreme response evaluation for F_1 based on MECM

U_{hub} (m/s)	TI	H_s (m)	T_p (s)	F_1 (N)
25	0.0979	5.27	8.49	4.15E+06
24.5	0.0960	5.87	9.26	4.42E+06
24	0.0958	6.01	9.62	4.54E+06
23.5	**0.0946**	**6.05**	**9.92**	**4.56E+06**
23	0.0932	6.06	10.05	4.52E+06

Table A11. Selection of critical environmental conditions for M_1 based on MECM

U_{hub} (m/s)	TI	H_s (m)	T_p (s)	M_1 (N*m)
14	0.0724	2.50	7.18	1.36E+08
13.5	**0.0717**	**2.68**	**7.50**	**1.37E+08**
13	0.0799	2.38	6.45	1.28E+08
12.5	0.0801	2.41	6.55	1.23E+08
12	0.0741	2.54	7.36	1.21E+08

Table A12. Selection of critical environmental conditions for F_2, M_2 based on MECM

U_{hub} (m/s)	TI	F_2 (kN)	M_2 (kN*m)
14	**0.0723**	**1.26E+03**	**9.86E+04**
13	0.0802	1.00E+03	7.84E+04
12	0.0828	1.00E+03	7.60E+04
11	0.0847	9.63E+02	7.52E+04