Effect of wind turbulence on extreme load analysis of an offshore wind turbine

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Evaluation of dynamic responses under extreme environmental conditions is important for the structural design of offshore wind turbines. Previously, a modified environmental contour method has been proposed to estimate extreme responses. In the method, the joint distribution of environmental variables near the cut-out wind speed is used to derive the critical environmental conditions for a specified return period, and the turbulence intensity of wind is assumed to be a deterministic value. To address more realistic wind conditions, this paper considers the turbulence intensity as a stochastic variable and investigates the impact on the modified environmental contour. Aeroelastic simulations are run over a range of mean wind speeds at the hub height from 9-25 m/s and turbulence levels between 9%-15%. Dynamic responses of a monopile offshore wind turbine under extreme conditions were studied, and the importance of considering the uncertainties associated with wind turbulence is highlighted. A case of evaluating the extreme response for 50-year environmental contour is given as an example of including TI as an extra variant in environmental contour method. The result is compared with traditional method in which TI is set as a constant of 15%. It shows that taking TI into consideration based on probabilistic method produces a more optimistic prediction.

INTRODUCTION

In order to deal with energy shortage and global warming, seeking renewable energy to substitute fossil fuels is a prevailing trend. Wind power is a very promising source of renewable energy. With the advantages of less noise, less visual impact and ample untapped space offshore, the offshore wind industry grows vigorously, and there is a trend to build large-scale wind turbines at farther distances from the shore.

To design any types of offshore structures including offshore wind turbine (OWT), estimating the long-term extreme structure response or load effects for a given return period (50-yr for example) is an important step. Full long-term analysis (FLTA) is recognized as the most precise method to evaluate the extreme values. However FLTA is time consuming because it takes into account contributions from all environmental conditions whereas only a few environmental states contribute substantially. Environmental contour method (ECM) is proposed by [1] as a simplified method which proved to be relatively accurate to predict monotonic loads, including wave loads. It was most commonly based on Inverse First Order Reliability Method (IFORM) [2] which uncoupled environmental variables from structure response [3], but alternative contour method derived from direct Monte Carlo simulations was also proposed recently [4].

ECM is widely utilized in establishing utimate design loads of marine structures [5]. The first step of ECM requires a derivation of the contour surface described by environmental variables such as wind speed, wave height and wave period. Response calculation only needs to be performed for a set of selected points on the contour surface which enhances the efficiency [6]. However, for offshore wind turbine whose loads are imposed by wind and waves simultaneously, the loads induced by wind does not keep increasing as the wind speed rises. When the wind speed exceeds the cut-out wind speed, the wind turbine is parked, there will be a significant drop of loads. ECM is therefore no longer suitable for such cases. The modified environmental contour method (MECM) is used to overcome the problem by drawing multiple environmental contours to divide the region and make the load be a bijective function in the subregion.

Li et al. [7] evaluated the extreme responses of bottom-fixed offshore wind turbine by MECM with certain accuracy compared with FLTA. Environmental variables taken into consideration are wind speed (U_w)significant wave height (H_s) and peak spectral period (T_p) while set the turbulence intensity (TI) of wind as a fixed value (15%). However, TI, as an intrinsic characteristic of wind, follows a probability distribution function for a given wind speed in realistic conditions [8].

Since turbulence intensity is the main driver for fatigue loading and is related closely to the fatigue damage [9] and is proved to have larger effect on the fatigue and extreme loads of a 5 MW OWT compared with wind shear exponent [10], the variation of IT should be considered in extreme response analysis.

In order to reach acceptable reliability and safety requirements, international design standards IEC [11], DNV should be referred to at the design stage. The IEC 61400 standard requires to evaluate the extreme loads with a recurrence period of 50 years in which the turbulence intensity is given as a function of wind speed. While the turbulence intensity follows a conditional probability density distribution function (CPDF) for a specified wind speed in reality. So probabilistic methods can be utilized to fit the relationship between turbulence intensity and wind speed to improve the accuracy of calculating extreme response for a given failure probability for OWTs.

In this paper, the effect of wind turbulence on extreme load is investigated using FAST v8 [12] based on the NREL 5 MW monopile baseline model under various turbulent wind generated by Turbsim [13]. Turbulence intensity is selected between 9%-15%, another standard C level recommended by IEC 61400-3 is also considered in the analysis as a reference. Meanwhile, the CPDF of turbulence intensity is calculated based on the standard deviation of wind speed which is fitted by three parameter Weibull probability density function. Probabilistic methods are employed to derive the environmental contours considering wind speed, significant wave height, peak spectral period as well as turbulence intensity.

MODIFIED ENVIRONMENTAL CONTOUR METHOD (MECM)

Compared against the original ECM, the MECM is an improved method that is developed to deal with dynamic structures that have nonmonotonic response characteristics. A sudden drop of tower-bottom loads is observed for bottom-fixed horizontal-axis wind turbines when the wind speed is near the cut-out wind speed. The non-monotonic behavior causes significant deviation of the critical environmental conditions between 50-yr environmental contour and the realistic case. MECM bypasses the drop point and utilizes ECM for each monotonic area.

Assuming each 1-h period is an independent unit, the N-year extreme response cumulative distribution function (CDF) can be expressed as

$$F_{X_{1-hr},N-yr}(r) = [F^{LT}_{X_{1-hr}}(r)]^{N\cdot 365.25\cdot 24} \tag{1}$$

50-year extreme response CDF

$$\begin{aligned} &F_{X_{1-hr},50-yr}(r) \\ &= \{[F^{LT}_{X_{1-hr}}(r)]^{N\cdot 365.25\cdot 24}\}^{50/N} \\ &= [F_{X_{1-hr},N-yr}(r)]^{50/N} \end{aligned} \tag{2}$$

The basic idea of MECM is to use N-year 1-h extreme response CDF $F_{X_{1-hr},N-yr}(r)$ to extrapolate the 50-year 1-h extreme response CDF $F_{X_{1-hr},50-yr}(r)$. The $F_{X_{1-hr},N-yr}(r)$ is approximated by 1-hr short-term extreme responses CDF $F^{ST}_{X_{1-hr|U_w,H_s,T_p}}(r|u_N,h_N,t_N)$. N is smaller than 50 and the largest wind speed on N-year contour does not exceed the cut-out wind speed which bypass the discontinuity at the cut-out wind speed in order to ensure the viability of ECM.

Li et al. [7] has given a procedure for performing the MECM to deal with the non-monotonic wind loads which violate the assumption of original ECM. In the work, the turbulence intensity was set as a constant of 15% which deviates from the realistic wind conditions.

The model used is the NREL 5 MW monopile bottom-fixed wind turbine. The monopile is 30 m high located at 20 m shallow water. The range selection of TI is based on normal turbulence model C provided by the IEC-61400 standard. TI varying from 9% to 15% cover the total span of TI fluctuated under mean wind speed from 9 m/s to 25 m/s.The monopile bottom shear force is chosen to be target force concerned. For each combination of U_w, H_s, T_p and TI, twenty 800-s simulations with random seed numbers were performed. The first 200 s of start-up transients were removed during postprocessing. Assuming each 10-min as an independent interval, the 1-h extreme distribution can be calculated based on the 10-min extremes.

Trends of mean value of short-term monopile bottom response is shown in Fig.1. Most probable 1-h extreme extreme distribution can be acquired by global maxima method based on 20 data points for each environmental case. Fig.2 is presented as an example of the monopile bottom force. Trends in two figures clearly show that TI does have significant on the extreme response on both extreme value and peak point. It is meaningful to evaluate the effect of TI when considering extreme response.

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

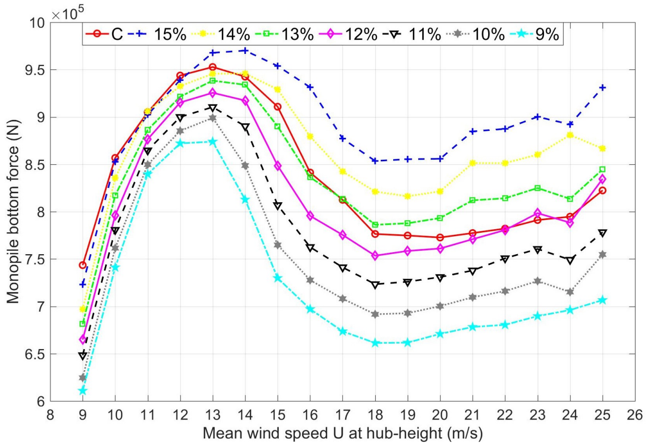

Fig. 1. The expected value of the short-term extreme value of monopile bottom force under different wind speed with varying TI

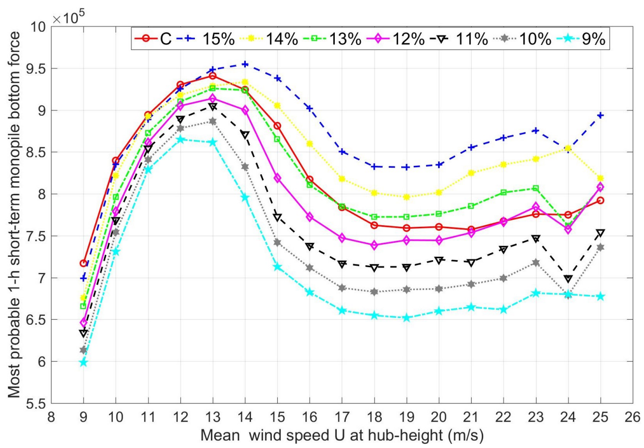

Fig. 2. Most probable 1-h short term extreme response of monopile bottom

by changing atmospheric stability conditions, varying roughness conditions [8]. 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 exhibits a statistical distribution around the mean wind speed too.

Larsen [8]proposed offshore wind mean value of the wind speed standard deviation expression

$$\sigma_{u,T} = \alpha U_T^{\beta} + \delta \tag{3}$$

Where U_T is the mean wind speed during limited time interval T, constants α, β, δ are determined by fitting the expression to data collected.

Standard deviation of the standard deviation formulated above follows a certain probability density function conditioned on mean standard deviation and an efficient number of statistical degrees of freedom [14].

In the succeeding data analysis, three parameter Weibull probability density function was selected to parameterize the

Table 1. Weibull parameters obtained from the performed fitting procedure [8]

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

measured data as a more empirical expression.

$$f(x;k,\alpha,\beta) = \frac{k}{\beta}\left(\frac{x-a}{\beta}\right)^{k-1}\exp\left[-\left(\frac{x-a}{\beta}\right)^{k}\right]; x \geq \alpha \tag{4}$$

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

Larsen [8] gave the three parameters for varying mean wind speed by fitting the expression to measured data of offshore wind climate on two shallow sites based on data analysis of offshore wind climate on two shallow water sites, the Vindeby and Gedser. The data included the mean wind speed within 10-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 succeeding data fitting. Larsen's data of Gedser are used in this paper. It is assumed that TI follows same conditional distribution for Site 15. This is an important assumption that should be emphasized here.A table of three parameters was provided (see Table1), where U_c denotes the center of the mean wind speed bin interval.

According to the table, the probability density function of standard deviation conditioned on the mean wind speed can be exhibited as well as the distribution function. Fig.3 and Fig.4 shows the CPDF and CDF of σ for mean wind speed bin ranging from 1 m/s to 3 m/s (U_c= 3 m/s) and 20 m/s to 22 m/s (U_c= 21 m/s).

Since the wind speed considered ranges from cut-in (3 m/s) to cut-out (25 m/s) wind speed at the hub-height of NREL 5MW wind turbine which is 89 m, the Weibull parameters obtained should be extrapolated to some extent by curve fitting to cover the total investigated range. A power law profile with the exponent α equal to 0.1 is used to carry out the wind speed transformation at different levels.

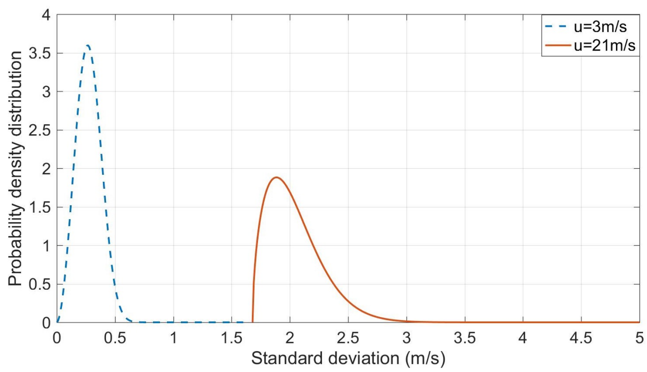

Fig. 3. CPDF of standard deviation under U_c= 3 m/s and U_c= 21 m/s

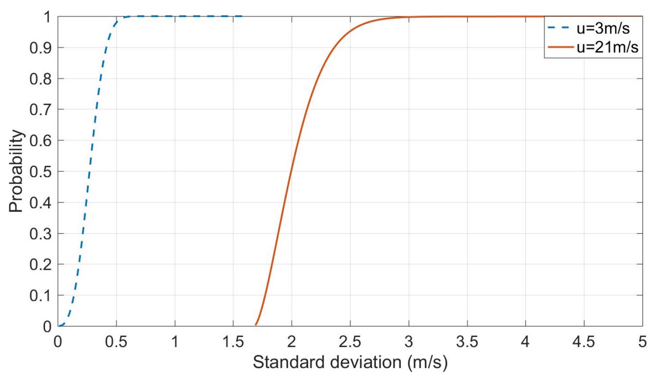

Fig. 4. CDF of standard deviation under U_c= 3 m/s and U_c= 21 m/s

$$U(z) = U_{30}(\frac{z}{30})^{\alpha} \tag{5}$$

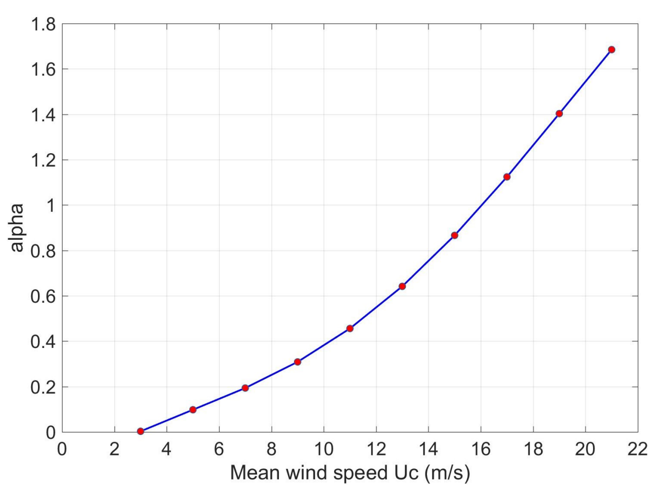

Fig. 5. The trend of α along the wind speed

Fig.5-7 shows the polynomial fitting of the three parameters along with different mean wind speed. The CPDF of σ

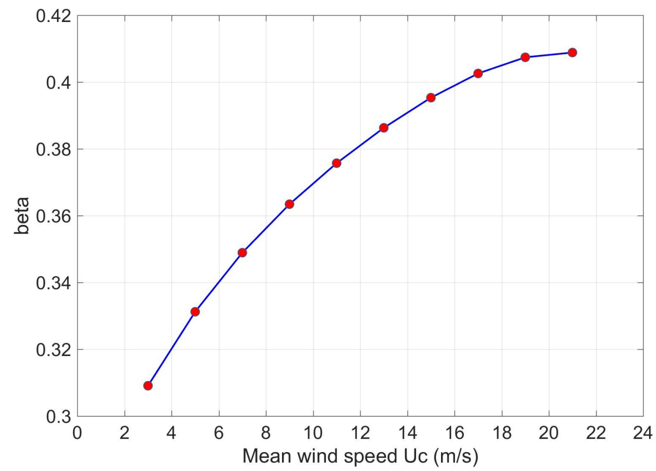

Fig. 6. The trend of β along the wind speed

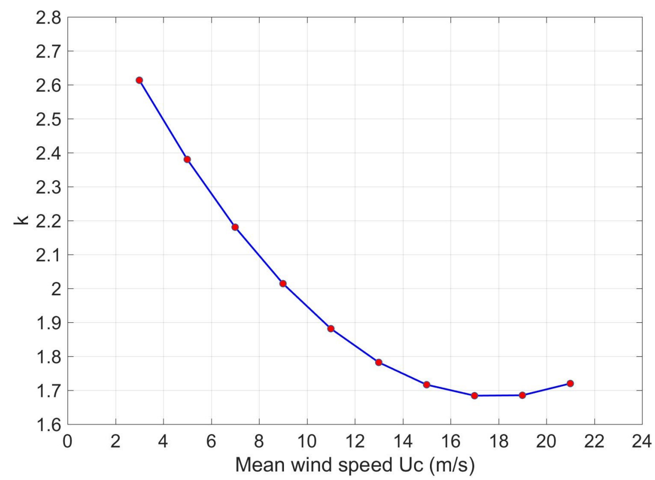

Fig. 7. The trend of k along the wind speed

can be given based on the fitting

$$f(\sigma;k,\alpha,\beta) = \frac{k}{\beta}(\frac{\sigma-a}{\beta})^{k-1}\exp[-(\frac{\sigma-a}{\beta})^{k}];\sigma \geq \alpha \tag{6}$$

Thus, the CPDF of TI can be expressed as

$$f_{TI|U}(Ti,u) = f(\sigma;k,\alpha,\beta)/u \tag{7}$$

From the trend of α and β showed in Fig.6 and Fig.7, the two may be negative for wind speed under 2 m/s. Since the k, α, β are required to be positive, the value of three parameters are determined as U_c= 3 m/s condition for wind speed under 3 m/s in this paper.

ENVIRONMENTAL CONTOUR CONSIDERING U_w, TI, H_s, T_p

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 [15].

Data of site 15 in North Sea area is used in this paper as the foundation to draw contour surfaces whose probability of exceedance corresponding to a return period of 50 years.

According to the prediction of long-term environmental conditions on site 15, the joint distribution of U_w, H_s, T_p can be expressed as follows.

$$f_{U_w}(u) = \frac{\alpha_U}{\beta_U}(\frac{u}{\beta_U})^{\alpha_U - 1}\exp[-(\frac{u}{\beta_U})^{\alpha_U}] \tag{8}$$

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

$$f_{H_s|U_w}(h|u) = \frac{\alpha_{HC}}{\beta_{HC}}(\frac{h}{\beta_{HC}})^{\alpha_{HC}-1}\exp[-(\frac{h}{\beta_{HC}})^{\alpha_{HC}}] \tag{9}$$

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

$$\begin{array}{l} \alpha_{HC} = a_1 + a_2 u^{a_3} \\ \beta_{HC} = b_1 + b_2 u^{b_3} \end{array} \tag{10}$$

where$a_1, a_2, a_3, b_1, b_2, b_3$ are acquired by fitting the expression to the raw data.

$$f_{Tp|U_w,H_s}(t|u,h) = \frac{1}{\sqrt{2\pi}\sigma_{\ln(T_p)}t}\exp(-\frac{1}{2}\frac{\ln(t)-\mu_{\ln(T_p)}}{\sigma_{\ln(T_p)}})^2) \tag{11}$$

$$\mu_{\ln(T_p)} = \ln[\frac{\mu_{T_p}}{\sqrt{1+\upsilon_{T_p}^2}}], \sigma^2_{\ln(T_p)} = \ln[\upsilon_{T_p}^2 + 1], \upsilon_{T_p} = \frac{\sigma_{T_p}}{\mu_{T_p}} \tag{12}$$

where μ_{T_p}, σ_{T_p} are mean value, standard deviation of T_p. υ_{T_p} is the coefficient of variance. And the $\mu_{T_p}, \upsilon_{T_p}$ were exhibited as the function of U_w and H_s.

$$\begin{array}{l} \bar{T_p}(h) = e_1 + e_2 \cdot h^{e_3} \\ \bar{u}(h) = f_1 + f_2 \cdot h^{f_3} \end{array} \tag{13}$$

where $\bar{T_p}(h), \bar{u}(h)$ are the expected spectral peak period and mean wind speed for a given H_s.

The coefficient of variation is assumed as

$$\nu_{T_p}(h) = k_1 + k_2 \cdot \exp(hk_3) \tag{14}$$

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

$$f_{U_w,H_s,T_p}(u,h,t) \approx f_{U_w}(u) \cdot f_{H_s|U_w}(h|u) \cdot f_{Tp|U_w,H_s}(t|u,h) \tag{15}$$

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

$$\begin{array}{l} f_{U_w,TI,H_s,T_p}(u,Ti,h,t) \approx f_{U_w}(u) \cdot f_{TI|U_w}(Ti|u) \\ \cdot f_{H_s|U_w}(h|u) \cdot f_{Tp|U_w,H_s}(t|u,h) \end{array} \tag{16}$$

where $f_{TI|U_w}(Ti|u)$ can be determined by (7).

Transformation of dependent environmental variables into independent standard normal variables u

Rosenblatt transformation [16] is used to transform the dependent environmental variables U_w, TI, H_s, T_p into independent standard normal variables u_1, u_2, u_3, u_4 in order to solve the reliability problem in the space u.

Rosenblatt transformatinon:

$$\begin{array}{l} \Phi(u_1) = F_{U_w}(u) \\ \Phi(u_2) = F_{H_s|U_w}(h|u) \\ \Phi(u_3) = F_{Tp|U_w,H_s}(t|u,h) \\ \Phi(u_4) = F_{TI|U_w}(Ti|u) \end{array} \tag{17}$$

where

$$\begin{array}{l} F_{U_w}(u) = \int f_{U_w}(u)du \\ F_{H_s|U_w}(h|u) = \frac{\int f_{U_w,H_s}(u,h)dh}{f_{U_w}(u)} = \int f_{H_s|U_w}(h|u)dh \\ F_{Tp|U_w,H_s}(t|u,h) = \frac{\int f_{U_w,H_s,T_p}(u,h,t)dt}{f_{U_w,H_s}(u,h)} = \int f_{Tp|U_w,H_s}(t|u,h)dt \\ F_{TI|U_w}(Ti|u) = \frac{\int f_{U_w,TI}(u,Ti)dTi}{f_{U_w}(u)} = \int f_{TI|U_w}(Ti|u)dTi \end{array} \tag{18}$$

Thus

$$\begin{array}{l} u = F_u^{-1}[\Phi(u_1)] \\ h = F_h^{-1}[\Phi(u_2)|u] \\ t = F_t^{-1}[\Phi(u_3)|u,h] \\ Ti = F_{Ti}^{-1}[\Phi(u_4)|u] \end{array} \tag{19}$$

Drawing environmental contour by transforming limiting boundary of u space into physical space

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

$$p_f = \frac{1}{50 \cdot 365.25 \cdot 24} \tag{20}$$

For standard normal variables, they have rotational symmetry property. Since the maximum dimensional space can be exhibited is three dimensional, different combinations should be chosen to display the transformation of four environmental variables. For contour surface considering three variables, the failure probability corresponding to a limit state surface of sphere with radius of r. Fig.8 shows the limit state surface in U space considering U_w, H_s, T_p

$$\Phi(r) = 1 - p_f \tag{21}$$

The sphere with radius of r in U-space can be transformed into limit state surface in physical space (Fig.9). The upper range of the contour tends to result in the extreme response. 2-D contour lines of H_s and T_p for various wind speed are often required to find the critical environmental variables combination corresponding to the extreme response. For site 15, the largest wind speed in 50 years is 27.2 m/s. Fig.10 shows the 2-D contour lines with wind speed ranging from 22 m/s-27.2 m/s.

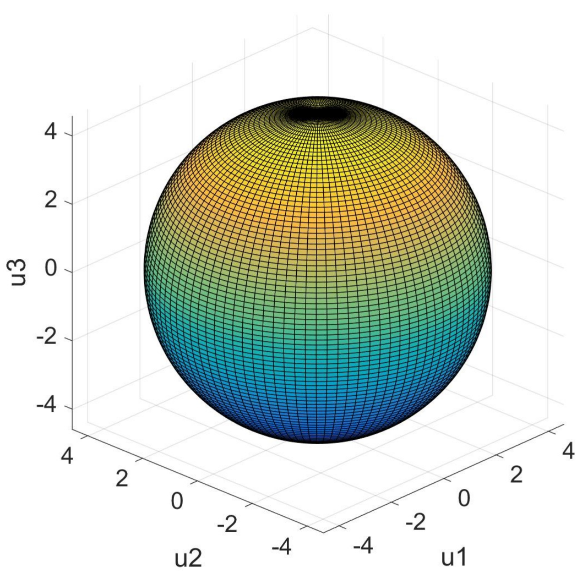

Fig. 8. Limit state surface in U space

Extra contours should be plotted to exhibit the extra variable TI. For site 15, the maximum U_w and H_s was 27.2 m/s and 9.5 m while taking the joint distribution of U_w, H_s, T_p into consideration. To better exhibit the distribution of the four variables, contour surface of TI, H_s, U_w and the corresponding 2D contour lines of TI, H_s for various U_w are shown in Figs.11 and 12. It should be mentioned that if drawing the contour surface for a given U_w and considering TI, H_s, T_p, or drawing the contour surface for a given H_s and considering U_w, TI, T_p is not advisable. H_s is a function of U_w. T_p is a function of U_w, H_s, TI. H_s, T_p will be affected for the value of U_w. Even though the contour surface of TI, H_s, T_p may be corresponded to 50-yr return period, the combination of U_w, TI, H_s, T_p is not corresponding to 50 years

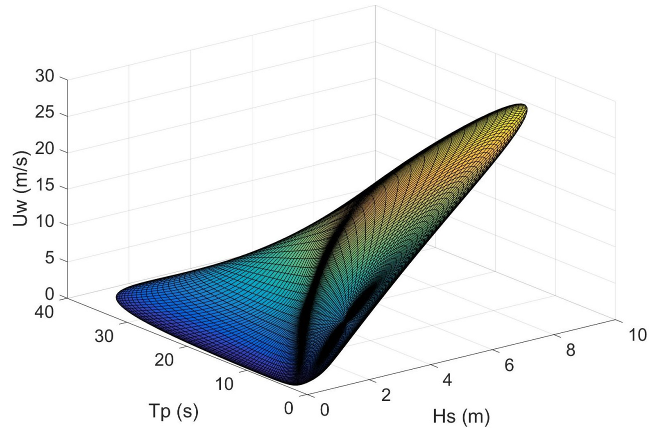

Fig. 9. Limit state surface in physical space with three variables

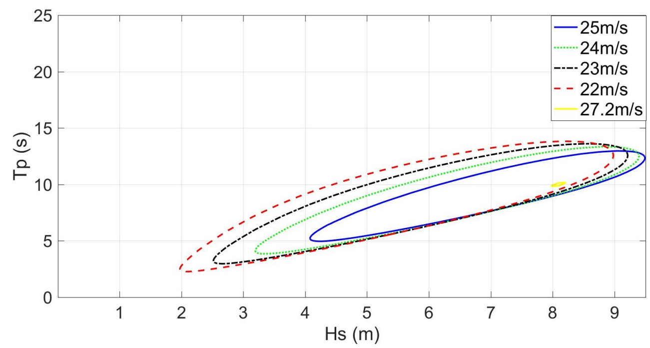

Fig. 10. 2D contour lines of H_s and T_p for different levels of U_w

return period anymore. Fig.13 and 14 show the contour surface and lines for a given wind speed of 27.2 m/s. From the 2D contour lines of H_s, T_p for different level of TI, it can be seen that the maximum H_s and T_p exceed the largest values under U_w =27.2 m/s (the dash lines corresponding the maximum values), the section outside the dash lines have a return period larger than 50 years.

Setting contour surface of TI, H_s, T_p under maximum wind speed 27.2 m/s for example (Fig.13). Its corresponding 2D contour lines are drawn in Fig.14. It should be pointed out that drawing the contour surface for a given largest variable U_w or H_s, the contour surface will be extrapolated to a contour surface with return period larger than 50 years. The extended part should be departed on the 2D contour lines.

RESULTS AND DISCUSSION

The extreme response on 50-year environmental contour is evaluated under three environmental variables considered and four environmental variables considered cases.

Extreme response evaluation based on 50-year environmental contour considering U_w, H_s, T_p

Since the upper region of the environmental surface (Fig.9) where both wind speed and significant wave height are large tends to cause extreme response, multiple 2-D contour lines are plotted for various wind speed around rated-

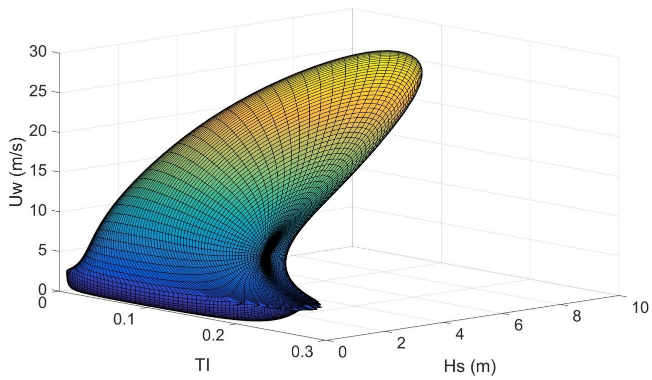

Fig. 11. Contour surface considering H_s, TI, U_w

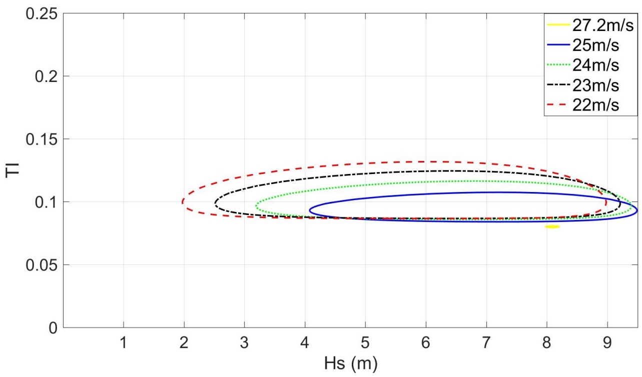

Fig. 12. 2D contour lines of H_s and TI for different levels of U_w

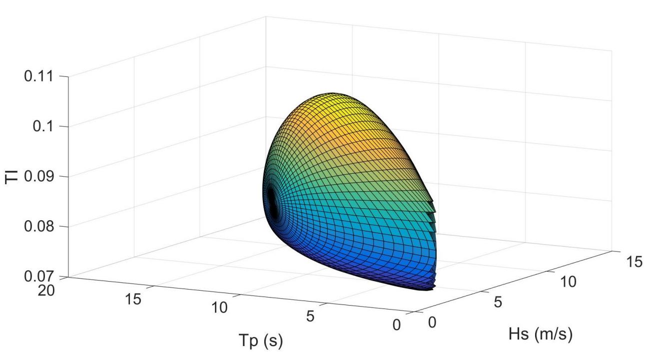

Fig. 13. Contour surface of H_s, TI, T_p for U_w =27.2 m/s

speed and cut-out speed where the wind loads response is large (Fig.15). See Fig.2, though the peak lies around the rated-wind speed for wind loads extreme response consideration and the extreme response cut-out wind speed nearby is a little smaller than that of rated speed, the significant wave height for higher wind speed is larger. Thus, both wind speed ranges are included. To evaluate the extreme response on 50-year environmental contour, multiple T_p and H_s combinations should be selected for each identified critical wind speed in order to find the largest one. Results are presented in tables. In Table2, the TI is assumed to be a constant 0.15. Values of TI for different quantiles from 90% to 70% is given in Table3 where U is the wind speed at hub-height. The trans-

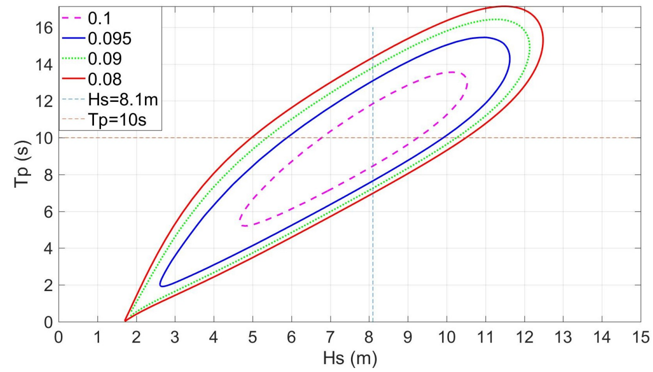

Fig. 14. 2D contour lines of H_s and T_p for different levels of TI

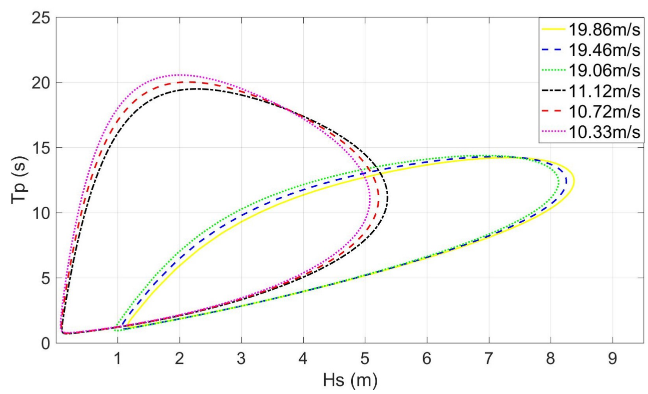

Fig. 15. 2D contour lines of H_s and T_p for different levels of U_w

Table 2. Extreme response evaluation based on 50-year environmental contour considering U_w, H_s, T_p with TI assumed to be 0.15

U (m/s)	TI	H_s (m)	T_p (s)	Monopile bottom response (N)
25	0.15	7.15	8.39	2630200
24.5	0.15	7.10	8.25	2574700
24	0.15	7.08	8.20	2565000
14	0.15	5.06	8.38	2189600
13.5	0.15	4.78	7.57	2173500
13	0.15	4.61	6.98	2143000

formation of U and U_w can utilize

$$U = U_{\mathrm{w}}(\frac{Z_{hub}}{10})^{\alpha} \tag{22}$$

Comparing different combinations of T_p, H_s for different wind speed with a given value of TI as 15% in order to find the largest extreme response. It can be seen that the extreme value appears at cut-out wind speed. Responses increase as

Table 3. Values of TI for different quantiles

U(m/s)	90% quantile	80% quantile	70% quantile
25	0.1126	0.1072	0.1037
24.5	0.1124	0.1068	0.1029
24	0.1117	0.1061	0.1019
14	0.0966	0.0879	0.0813
13.5	0.0952	0.0862	0.0799
13	0.0942	0.0855	0.0794

Table 4. Extreme response evaluation of monopile bottom force based on 50-year environmental contour considering U_w, H_s, T_p with TI determined by different quantiles

U(m/s)	90% quantile	80% quantile	70% quantile
25	2460400 (N)	2454000 (N)	2441400 (N)
24.5	2460200 (N)	2441400 (N)	2423800 (N)
24	2425000 (N)	2402200 (N)	2386400 (N)
14	2015833 (N)	1998167 (N)	1965667 (N)
13.5	2044167 (N)	2040500 (N)	2006000 (N)
13	2036333 (N)	2027333 (N)	2024333 (N)

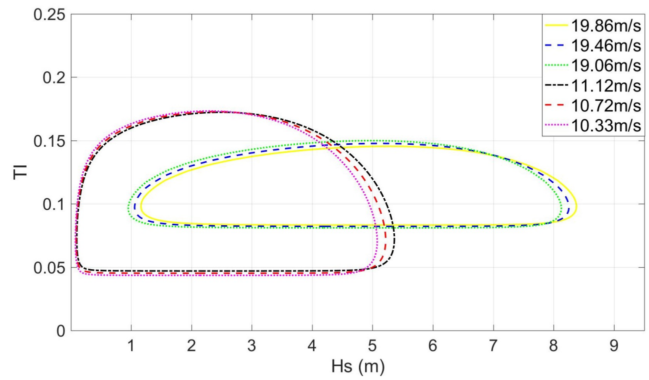

Fig. 16. Contour lines of TI, H_s for different levels of U_w

Table 5. Extreme response evaluation based on environmental contour considering U_w, H_s, T_p, TI

U(m/s)	TI	H_s	T_p	Monopile bottom response (N)
25	0.1387	6.99	8.80	2566000
24.5	0.1381	7.03	8.20	2536000
24	0.1373	7.02	8.17	2517000
14	0.126	4.9	7.59	2187500
13.5	0.1334	4.61	6.94	2159250
13	0.1341	4.49	6.73	2057000

the increase of wind speed. The peak lies at cut-out wind speed within 13 m/s- 25 m/s with a bin size of 0.5 m/s. Compared with response under wind loads only, it can be noticed that even though the largest wind loads appears at around rated wind speed, the peak of combined loads taking wave states into consideration appears around cut-out wind speed. The response around the rated wind speed under combined loads is significantly less than that of cut-out wind speed.

Choosing different quantiles of TI, evaluating the corresponding response for a determined critical wave states which is the same as the cases above whose TI is set as a constant of 15%. It can be clearly shown that TI does have a significant effect on the value of the extreme response. Normally, the larger TI results in larger extreme response for the same U, H_s, T_p. Minor TI variance results in large variance of the force.

Extreme response evaluation based on environmental contour considering U_w, H_s, T_p, TI

Taking TI as another variable, environmental contour surface considering TI, H_s, U_w (Fig.11) can be drawn and selecting multiple combinations of TI and H_s for identified critical wind speed (see Fig.16 whose T_p can be determined in 2D contour lines of H_s, T_p for corresponding wind speed in order to find the largest extreme value. Results are presented in Table5.

It can be shown that TI and T_p in the combinations considering four variables are a little different from that in combinations considering three variables. It is because the large variation range of TI for a determined U and H_s. As the response is positively related to the magnitude of TI, The value of H_s will be influenced in order to acquire relatively high TI during the combinations selection along the contour lines of TI and H_s. Using the probability distribution of TI to take the place of setting TI as a constant can give a more accurate result of extreme response which is more closed to the realistic environmental conditions. Compared Table 5 and Table 2, the extreme response of 50-year environmental contour evaluated for a given TI as 15% is 2.5 percent larger than evaluated by taking TI as a variant.

Conclusion and future work

This paper verifies the effect of various TI on the extreme response of an monopile offshore wind turbine by Fast simulation. The simulation results of monopile bottom force with TI selected from 9% and 15% show that lager TI tends to result in larger response for the same wind speed. Thus, larger TI tends to account for larger extreme response under wind loads only. To evaluate the effect of TI better,

TI is included as the forth environmental variable considered in environmental contour. Conditional probability density function of TI is given based on standard deviation σ whose CPDF is given as three parameters Weibull distribution. Extreme response calculation on 50-year environmental contour is presented as an example. The extreme response predicted for 50-year environmental contour by four variants contour method is smaller compared with the three variants contour method with TI set as a constant of 15%.

In order to predict the 50-year extreme response, merely evaluating the response on 50-year environmental contour is far from satisfactory. As monopile bottom force under wind loads which is one of dominate contribution to extreme response is larger at rated and cut-out wind speed than at largest wind speed in 50 years, the largest response evaluated based on 50-year environmental contour is smaller than 50-year extreme response. To extrapolate the most probable extreme response to the most probable value of the 50-year 1-h extreme response, environmental contours corresponding to multiple wind speeds between 9 m/s-25 m/s should be drawn to find the largest value. While selecting combinations along each environmental contour, the wind speed interval can be divided smaller in order to obtain more accurate results.

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