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Extreme response estimation of offshore wind turbines with an extended contour-line method

Jan-Tore Horn[1] and Steven R. Winterstein[2]

[1]Centre for Autonomous Marine Operations and Systems (NTNU AMOS), Department of Marine Technology, NTNU, Otto Nielsens veg 10, 7491 Trondheim, Norway
[2] Probability-Based Engineering, Menlo Park, CA, USA

E-mail: `jan-tore.horn@ntnu.no`

Abstract.   The contour-line method is a simplified approach for finding the long-term extreme values by a small number of short-term analyses. It is assumed the response with a return period of T years occurs during a sea-state with a shorter or equal return period. This provides good extreme response estimates for structures with a response behaviour monotonically increasing with the severity of the sea-state. For an offshore wind turbine, the power production stops at a certain wind speed to reduce wear, changing the dynamics of the system dramatically, from wind to wave load dominated. Also, there is a non-negligible probability for the turbine being unable to operate although the wind speeds would suggest so, due to e.g. grid- or mechanical failure. Therefore, the original contour-line method for extreme response estimation is not applicable without some modifications to account for changing dynamics. In the present work, it is suggested to treat the operational and non-operational conditions as two sub-populations and estimate the T-year response in each population by a standard contour-line method. Next, the results from each sub-population are combined in order to estimate the total T-year response in consistent manner.

1. Introduction
A method for long term extreme value analysis of a system with multiple sub-populations of dynamic response characteristics is presented. The approach is suggested in [1] to combine environmental sub-populations related to load directions and sub-populations related to different response models. Offshore wind turbines (OWTs) have, simply formulated, two dynamic response models; one for operating turbine, and one for an idle or parked turbine. Depending on the response parameter of interest, both sub-populations may be important to consider in both FLS and ULS design.

The present work investigates whether such an approach is feasible on a large, bottom-fixed, monopile-mounted OWT in a water depth of 30 meters. Typical responses of interest are; forces and moments in the transition between tower and foundation, soil deformation, blade root loads, bending moments in the foundation and nacelle accelerations affecting the drive train loads. Here, the two latter responses will be investigated. The long-term extreme values are to be found with environmental contours and the inverse first-order reliability method (IFORM) [2] for parked and operational turbine, and verified with an extreme value distribution based on a full long-term analysis (FLTA). The method has previously been used on OWTs for assessing extreme loads during operation in e.g. [3, 4].

The issue with applying simplified methods for extreme value analyses of OWTs are presented along with suggested remedies for the response discontinuities in [5, 6]. For comparison, the present work will also use the contour-line method, but instead of modifications, the original method presented in [2] will be performed on several sub-domains of the problem. Hence, the response discontinuities presented in e.g. [7] will not be present in the chosen sub-populations. The final step is to combine the results to obtain a extreme response consistent with the required exceedance probability, a non-trivial problem illustrated in [8] for responses dependent on load directionality.

This paper will first present approaches used for long term extreme value analyses and combined responses. Next, the response sub-populations, environmental- and numerical model will be presented. Finally. results and discussions will evaluate the applicability and consequences of the suggested approach.

2. Extreme response estimation

Two methods for estimation of extreme response will presented. The full long-term analysis (FLTA) taking into account weighted response contributions from the complete environmental domain is considered exact and will be used to verify the IFORM-based environmental contour method (ECM).

2.1. Full long-term analysis

For sub-population 1, the CDF of the maximum response in a 1-hour sea state using an FLTA is found by numerical integration as [9]:

$$F_{X_{1h}}^{(1)}(x) = \exp\left\{ \int_v \int_h \ln F_{X_{1h}|V,H_S,T_P}^{(1)}(x|v,h,t_e)\, f_{V,H_S}^{(1)}(v,h)\, dv\, dh \right\} \tag{1}$$

where the wind speed and significant wave height are described by their joint distribution, while the expected peak period t_e is used. Similarly for sub-population 2:

$$F_{X_{1h}}^{(2)}(x) = \exp\left\{ \int_h \int_t \ln F_{X_{1h}|V,H_S,T_P}^{(2)}(x|v_e,h,t)\, f_{H_S,T_P}(h,t)\, dt\, dh \right\} \tag{2}$$

where the significant wave height and peak period are described by their joint distribution, while the expected wind speed v_e is used for response calculations. Here, Eq. (1) and (2) are evaluated numerically using the bins in Tab. 1 and 90 10-minute simulations are performed in each bin for sufficiently accurate results. It is assumed that the extreme value in each 10-minute simulation is Gumbel distributed, so that the 1-hour extreme value distribution for each simulation bin is found by a power of six:

$$F_{X_{1h}|V,H_S,T_P} = \left[F_{X_{10min}|V,H_S,T_P} \right]^6 \tag{3}$$

Parameter	Min	Max	Step
V [m/s]	4	36	1
H_S [m]	0	10	0.5
T_P [s]	2	18	1

Table 1: Bins for FLTA

2.2. Environmental contour method

The ECM is a method for estimating the extreme response by limiting the number of sea-states. The method is very useful when extreme responses are dominated by a small number of environmental conditions. More specifically, the extreme response with a return period of T years is approximated by a sea-state with a similar return period. The environmental parameters describing this sea-state is here v_T for wind speed, h_T for significant wave height and t_T for peak period. When the CDF of the 1-hour extreme response for this sea-state is established by e.g. time-domain simulations, the extreme response x_T is found by:

$$x_T \approx F^{-1}_{X_{1h}|V,H_S,T_P}(\alpha|v_T, h_T, t_T) \tag{4}$$

for some appropriate fractile α. For a range of wave-driven offshore problems, typical α values have been found in the range 0.75-0.95 [10]. Note that only 2D environmental domains will be considered in the present work, meaning that one of the three environmental parameters will be replaced by their expected value conditioned on the remaining parameters, as described in detail later.

2.3. Combined extreme response

For each operational sub-population, the extreme response functions are evaluated separately, and later combined into a total extreme response. Let X_{1h} denote the 1-hour extreme response of a given parameter, $F_{X_{1h}}$ is its cumulative distribution and $G_{X_{1h}} = 1 - F_{X_{1h}}$ is the complementary CDF (CCDF). The total response CDF is simply found by a weighted sum of the contributing populations:

$$F_{X_{1h}}(x) = \sum_i p_i F^{(i)}_{X_{1h}}(x) \tag{5}$$

and simlarly with the CCDFs:

$$G_{X_{1h}}(x) = \sum_i p_i G^{(i)}_{X_{1h}}(x) \tag{6}$$

where p_i is the probability of sub-population i. The CDF conditioned on response sub-population i can be evaluated accurately with an FLTA, or with the ECM [10]. The objective is to extended the latter for use with offshore wind turbines, which is done with an alternative approach in [5, 6].

3. Proposed method

The proposed procedure for estimating long term extremes using the ECM in several response sub-populations is:

a) Estimate extreme response x_T in each sub-population for two return periods, say $T_1 = 50$ and $T_2 = 500$. Use the ECM and Eq. 4, assuming only this population is acting.

b) Estimate the response CCDF $G^C_{X_{1h}}(x)$, where C denotes *contour*, for each sub-population using the obtained responses. Use the relation $G^C_{X_{1h}}(x_T) = 1/(T \cdot 365 \cdot 24)$ for finding the two fitting points used for linear fitting.

c) Find the total $G^C_{X_{1h}}(x)$ using Eq. 6.

Of course, the response CCDFs can be found with more fitting points from the ECM and a curved CCDF may be obtained. However, the linear assumption is used in the present work for simplicity. The linear fit can for instance be performed using:

$$-\log_{10} G^C_{X_{1h}}(x) = A\,B^{c(x)}; \ c(x) = \frac{\ln x - \ln x_{T_1}}{\ln x_{T_2} - \ln x_{T_1}} \tag{7}$$

where $A = \log_{10} T_1$ and $AB = \log_{10} T_2$. The choices of fitting form, and the return periods T_1 and T_2 used in these fits, are discussed further in [1].

4. Sub-populations

The system dynamics of an OWT is considerably different between parked and operational state. Hence, it is natural to divide the lifetime into fractions as function of the up-time of the turbine. The sub-populations defining the dynamic response models are illustrated in Fig. 1 with corresponding probabilities of occurrence, and are defined as:

1. Operational turbine within operational wind speed limits
2. Parked turbine due to general unavailability independent of wind speeds
3. Parked turbine due to wind exceeding operational wind speed limit (25 m/s)
4. Parked turbine due to wind below lower operational wind speed (4 m/s)

To limit the number of sub-populations, the CDFs from population 3 and 4 are taken as constants. Assuming that $p_4 F^{(4)}_{X_{1h}} \approx p_4$ is expected to be a good approximation due to small response in this population. Also, it is assumed that the extreme response for $V > 25$ is mostly covered by sub-population 2, so that we can assume $p_3 F^{(3)}_{X_{1h}} \approx 0$. The actual contribution from sub-population 3 is left for future work. Hence, only sub-populations 1 and 2 will be evaluated here. The total availability is set to 90% in accordance with [11].
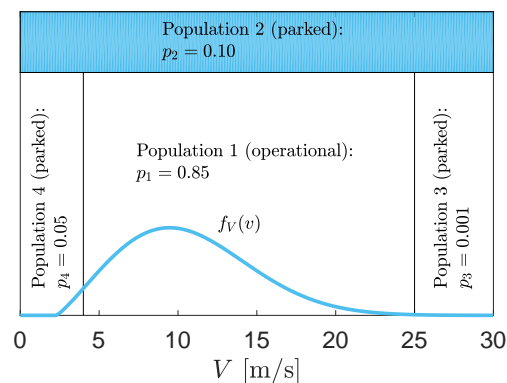

Figure 1: Sub-populations with lifetime fractions p_i

5. Environmental model

The environmental parameters to be considered are the hub-height mean wind speed, significant wave height and peak period. Turbulence intensity is set to 10%, and the wind field is calculated with TurbSim [12] using the Kaimal spectrum. For the irregular waves, the JONSWAP spectrum with long-crested formulation with co-directional wind and waves. Due to dynamic properties in the two sub-populations and to limit the problem to two environmental dimensions in each sub-population, slightly different environmental descriptions are used. For sub-population 1, meaning operational turbine, the wind speed and significant wave height are assumed to be the governing parameters and will be treated as stochastic, while for the peak period, the expected value is used. For sub-population 2, and parked turbine, wave loads are assumed to be dominating, meaning that the significant wave height and peak period are stochastic, while the wind speed is the expected wind speed conditioned on the peak period.

5.1. Joint distributions

The joint distribution of hub-height mean wind speed and significant wave height is:

$$f_{V,H_S}(v,h) = f_V(v; \alpha_v, \beta_v, \gamma_v) \, f_{H_S|V}(h; \alpha_h(u), \beta_h(u), \gamma_h(u)) \tag{8}$$

where both are assumed to be Weibull distributed with three parameters α, β and γ. To be used with sub-population 1, the joint distribution is modified as:

$$f_{V,H_S}^{(1)}(v,h) = \begin{cases} \frac{f_{V,H_S}(v,h)}{F_V(25)-F_V(4)} & \text{for } 4 \leq v \leq 25 \\ 0 & \text{else} \end{cases} \tag{9}$$

to account for operational wind speed limits. Further, the significant wave height and peak period joint distribution is given as:

$$f_{H_S,T_P}(h,t) = \int_0^\infty f_{V,H_S}(v,h)\,dv\, f_{T_P|H_S}(t; \mu_{\log t}(h), \sigma_{\log t}(h)) \tag{10}$$

where the peak period distribution condition on significant wave height is assumed lognormally distributed.

5.2. Wind
The chosen location for the environmental basis is Dogger Bank in the central North Sea [13], where the parameters in the 3-parameter Weibull-distributed wind speed are found as:

$$\alpha_v = 9.5 \tag{11a}$$
$$\beta_v = 2.2 \tag{11b}$$
$$\gamma_v = 2.3 \tag{11c}$$

5.3. Wind sea
The significant wave height is described with a 3-parameter Weibull distribution with the parameters conditioned on the wind speed v as:

$$\alpha_h(v) = 0.70 + 1.3\,e^{-120\,v^{-2}} \tag{12a}$$
$$\beta_h(v) = 1.5 + 44\,v^{-1.4} \tag{12b}$$
$$\gamma_h(v) = -0.60 + 0.007\,v^2 \tag{12c}$$

Further, the peak period is lognormally distributed with the mean and variance conditioned on the significant wave height as:

$$\mu_{\log t}(h) = 1.6\,h^{0.24} \tag{13a}$$
$$\sigma_{\log t}(h) = 0.14\,h^{-0.21} \tag{13b}$$

For sub-population 1, the wave peak period is modelled deterministically as a function of the mean wind speed v using the curve-fitted relation:

$$t_e = 1.99 + 0.17\,v_e^{1.24} \tag{14}$$

The inverse relation is used in sub-population 2, where the mean wind speed is a function of the peak period.

5.4. Environmental contours
In Fig. 2, the two-dimensional 50- and 500-year environmental contour-lines created using the Rosenblatt transform [14] are shown for both sub-populations. Specific sea-states to be checked when using the ECM are outlined.
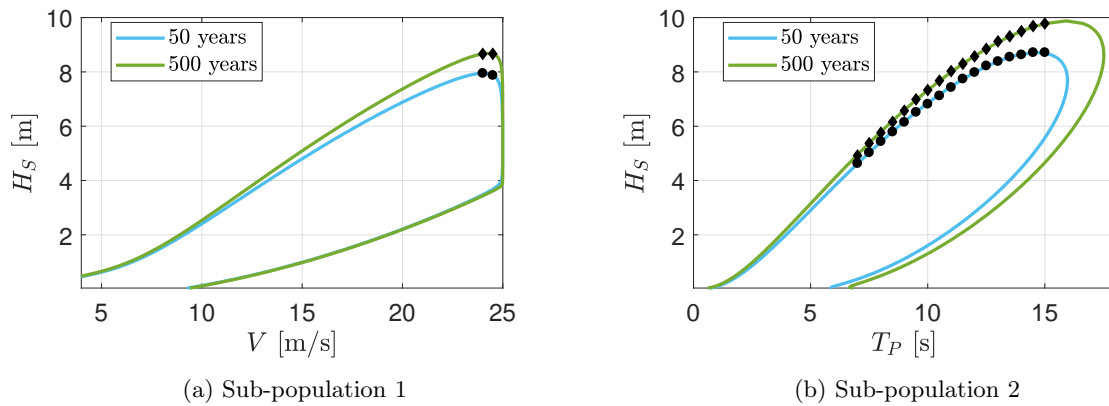
(a) Sub-population 1   (b) Sub-population 2

Figure 2: 2D environmental contours including points used with IFORM

6. Numerical OWT model

The numerical model is an FEM model in USFOS/vpOne of the 10MW DTU reference wind turbine [15] mounted on a monopile in 30 meters water depth at Dogger Bank in the central North Sea. See Fig. 3 for illustration and main dimensions of tower and foundation. First fore-aft natural period is 4.4 seconds. For the load calculations, unsteady BEM theory [16] is used for the blades, and for wave loads; the first order wave theory with a vertical stretching to the free surface [17]. When the turbine is parked, or idling, the blade pitch is set to 82 degrees with respect to incoming wind direction, resulting in a slowly rotating rotor and small wind loads.
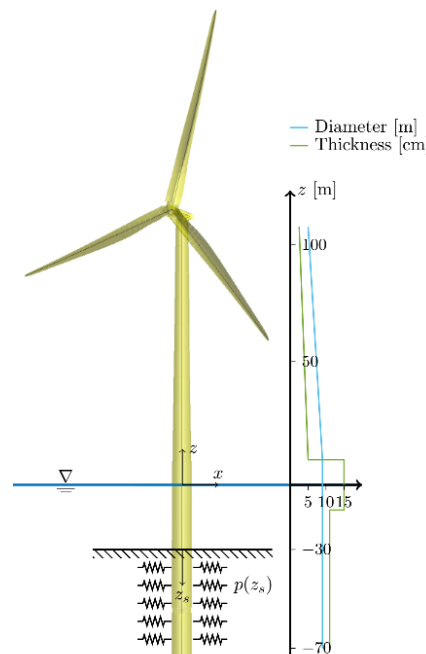

Figure 3: Illustration of numerical FEM model in USFOS/vpOne

7. Results

In this section, results from the combined extreme response analyses using the ECM and the FLTA are presented.

7.1. Nacelle acceleration

The environmental contours and isoquants for the nacelle tower-top acceleration are shown in Fig. 4. For each combination of significant wave height and peak period, 90 10-minute simulations are performed in order to predict the 1-hour response at a fractile of $\alpha = 0.8$ with sufficient confidence. The discretization are performed with a step of 0.5m for H_S, and 1s for T_P, excluding combinations outside the 500 year environmental contour. For sub-population 1, the response is mostly affected by wind loads at lower wind speeds, but wave driven for approximately $H_S > 2$m. When the turbine is parked, an amplification in the response is seen around $T_P = 5$s, where the first natural period of the turbine is excited. Elsewhere, responses systematically increase with H_S and decrease with T_P.

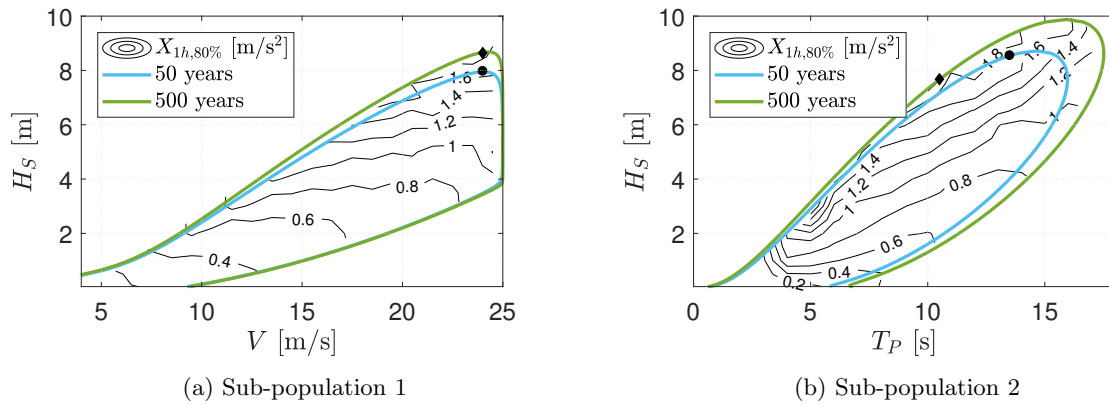(a) Sub-population 1   (b) Sub-population 2

Figure 4: Isoquants for short-term nacelle acceleration with the fractile $\alpha = 0.8$ in Eq. (4). Sea-states leading to the most severe responses on the two contours are highlighted.

In Fig. 5, the results from the combined extreme value analysis is presented. In Fig. 5a, the exact CCDFs along with the linear curve-fits using the sea-states marked in Fig 4a and the optimal fractiles in Tab. 2. It is seen that a linear fit is a good approximation for response values with high return periods. The combined response using Eq. 6 is shown in Fig. 5b, indicating that the correct 50-year nacelle acceleration is slightly above 1.8m/s^2.
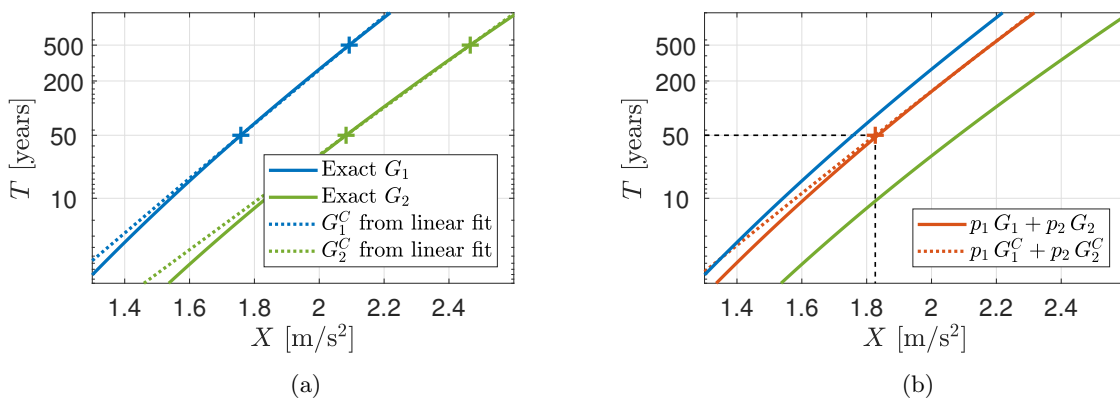

(a)   (b)

Figure 5: Response CCDFs and combined extreme response for nacelle acceleration. Sub-population 1 in blue and sub-population 2 in green.

T [years]	α_1	α_2
50	0.93	0.95
500	0.97	0.97

Table 2: Optimal fractiles for extreme nacelle acceleration

The response fractiles in Tab. 2 are the fractiles needed to best approximate the CCDFs between 50 and 500 years return period. The fractiles needed in both sub-populations are quite similar, with higher fractiles for longer return periods. Also, fractiles for longer return periods are excpected to increase due to more dominant response variability, which is indeed reflected in Tab. 2. Figure 6 show the Gumbel fits for the sea-states used with ECM. It is found that 90 10-minute simulations are sufficient to predict the 10-minute extremes. The 1-hour extreme distribution is then found by applying Eq. 3. For future work, the accuracy of such a transformation may be investigated, compared to performing 1-hour simulations.
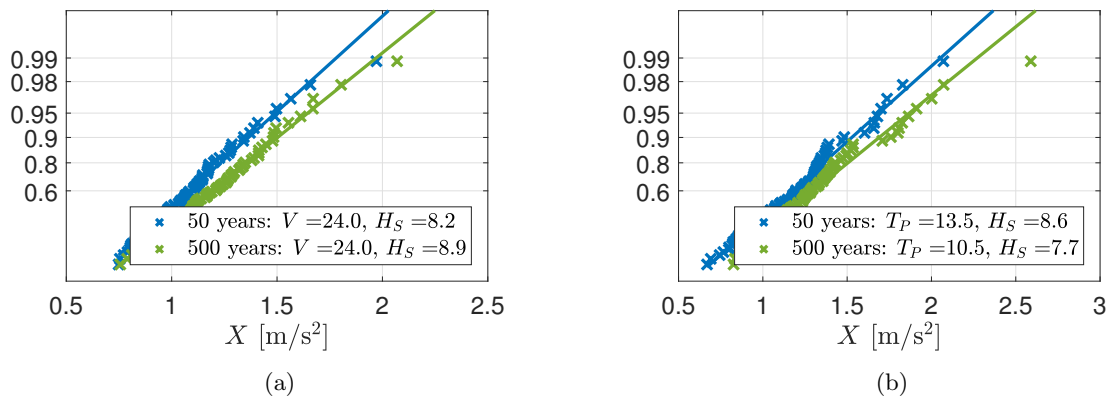

(a)

(b)

Figure 6: CDFs and Gumbel fits for 10-minute extreme nacelle acceleration with sea-states chosen for T-year response estimates with ECM.

7.2. Bending moment

Isoquants for the extreme bending moment at mudline is shown in Fig. 7 for both populations using the same simulations as for the nacelle acceleration case. The response dependency on the environmental parameters are similar to the nacelle acceleration. However, the operational case is dominating due to the large static moment induced by the mean wind speed. Also, H_S is the most important parameter for the non-operational turbine as seen by the dominating sea-states in Fig. 7. The exact and ECM-created CCDFs are shown in Fig. 8a for the bending moment at mudline and combined CCDF is plotted in Fig. 8b using the optimal fractiles in Tab. 3. In contrast to the nacelle acceleration, the operational sub-population is dominant and the combined response is very little affected by the parked turbine. Also, for the extreme bending moment, considering only sub-population 1 is slightly conservative.
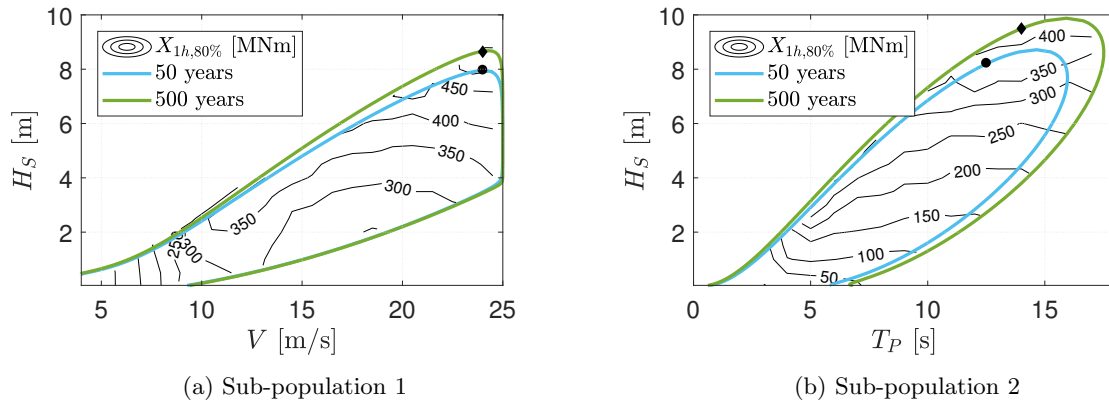
(a) Sub-population 1

(b) Sub-population 2

Figure 7: Isoquants for short-term mudline bending moment with the fractile $\alpha = 0.8$ in Eq. 4.
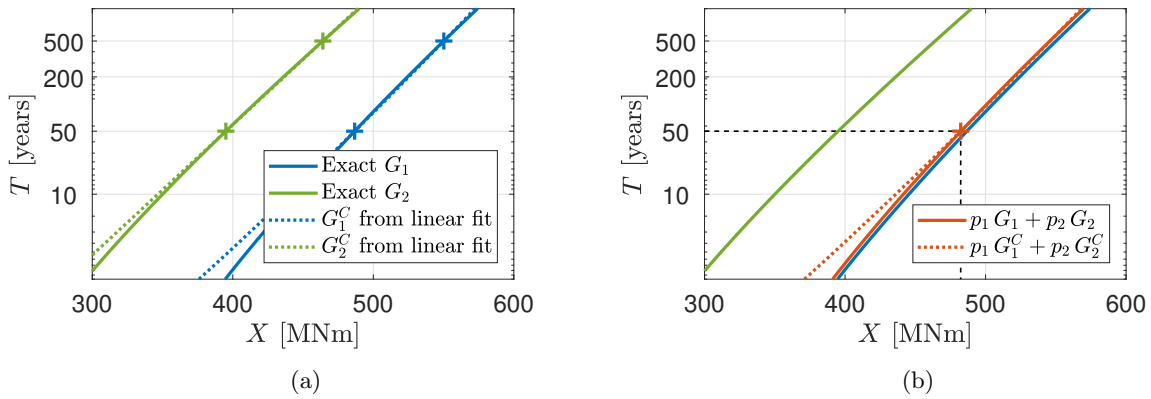

(a)

(b)

Figure 8: Response CCDFs and combined extreme response for bending moment at mudline. Sub-population 1 in blue and sub-population 2 in green.

T [years]	α_1	α_2
50	0.83	0.88
500	0.92	0.92

Table 3: Optimal fractiles for extreme bending moment

8. Conclusion

A method for estimation of the T-year extreme response from several response sub-populations is presented. The method is applied to an offshore wind turbine with different response characteristics during operational and parked state. Compared to an FLTA, the environmental contour method is very efficient and can provide good results given appropriate response fractiles.

For response parameters dominated by the operational state of the offshore wind turbine, using the extreme values assuming the turbine is 100% operational will yield an upper bound of the extreme response. Similarly, for response parameters dominated by a parked turbine, an upper bound is obtained by assuming a turbine which is always idling. In the latter case, the upper bound is expected to be quite conservative due to the small probability of this sub-population. Depending on which response parameter that is important for ULS design,

combining all sub-populations may both increase or decrease the true 50-year response compared to a fully operational turbine, as seen in the presented results. Although the relative differences are minor in the present case, the method is useful to establish this fact, and may be used for more response parameters and other types of offshore wind turbine structures.

It is worthwhile to mention that the low-damped parked turbine state is expected to contribute more to the combined response if a wave load model of higher order is used, see e.g. [17, 18].

Acknowledgments

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