Extreme Response Estimation of Offshore Wind Turbines with an Extended Contour-line Method

Jan-Tore Horn[(a)], Steven R. Winterstein [(b)]

[(a)]Centre for Autonomous Marine Operations and Systems (NTNU AMOS), Trondheim, Norway,

[(b)] Probability-Based Engineering, Menlo Park, CA.

Email: jan-tore.horn@ntnu.no

NTNU AMOS
Centre for Autonomous Marine Operations and Systems

Introduction

A method for long term extreme value analysis of a system with multiple sub-populations of dynamic response characteristics is presented. Offshore wind turbines have, simply formulated, two dynamic response models; one for operating turbine, and one for an idle or parked turbine. Depending on the response of interest, both sub-populations may be important to consider in FLS and ULS design. The present work investigates whether such an approach is feasible on a large monopile-mounted offshore wind turbine for extreme response analysis. The long-term extreme values are to be found with environmental contours for parked and operational turbine, and verified with an extreme value distribution based on a full long-term analysis (FLTA). The work is inspired by [1].

Basic Concept

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, and $F_{X_{1h}}$ is its cumulative distribution and $G_{X_{1h}}$ is the complementary CDF (CCDF). The total response CCDF is simply found by a weighted sum of the contributing populations:

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

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 a contour-line approach [2]. The objective is to extended the latter for use with offshore wind turbines, which is done with an alternative approach in [3].

Models

The environmental parameters to be considered are the wind speed V, significant wave height H_S and peak period T_P. Turbulence intensity is set to 10% and the JONSWAP wave spectrum with long-crested formulation aligned with the wind is used. Sub-populations defining the dynamic response models in a consistent manner are shown in Fig. 1 with probabilities of occurrence. It is assumed that $p_3 \cdot F_3 \approx 0$ due to small p_3, and that $p_4 \cdot F_4 \approx p_4$ due to small response. Hence, only sub-populations 1 and 2 will be evaluated here. The total availability is set to 90% in accordance with [4].

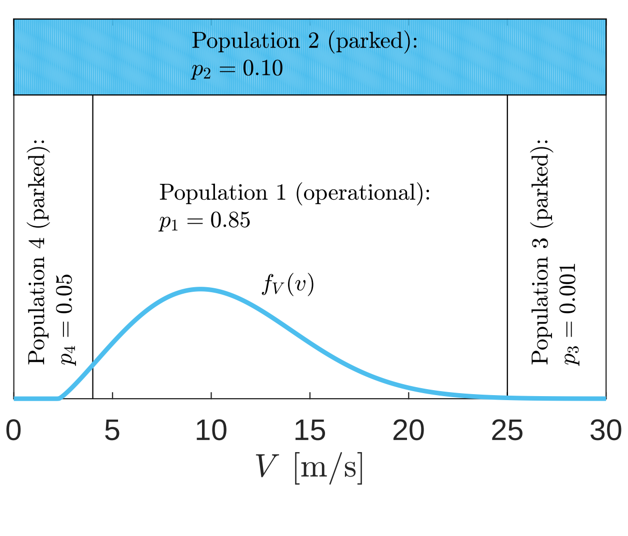

Figure 1: Sub-populations

The numerical model is an FEM model in USFOS/vpOne of the 10MW DTU reference wind turbine mounted on a monopile in 30 meters water depth at Dogger Bank in the central North Sea. The nacelle/tower-top acceleration is the investigated response parameter in this case, as it is prone to low fore-aft damping when the turbine is parked. First fore-aft natural period is 4.4 seconds.

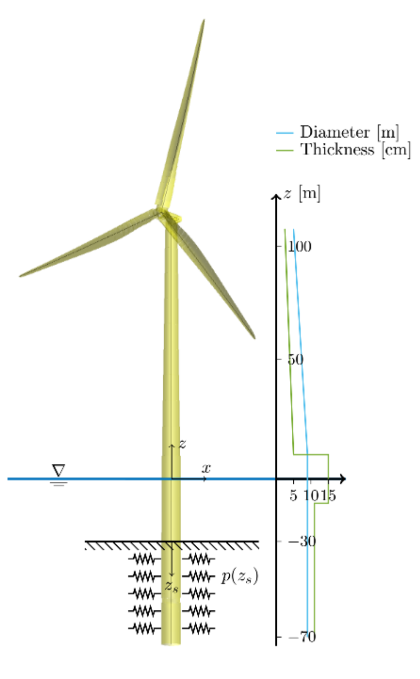

Figure 2: Model

Procedure

For sub-population i, the CDF of the maximum response in a 1-hour sea state using a full long-term analysis is found by numerical integration as:

$$F^{(i)}_{X_{1h}}(x) = \iiint F^{(i)}_{X_{1h}|V,H_S,T_P}(x|v,h,t) f^{(i)}_{V,H_S,T_P}(v,h,t) dv\, dh\, dt$$

where $F^{(i)}_{X_{1h}|V,H_S,T_P}$ is the short-term CDF of the maximum response in population i and $f^{(i)}_{V,H_S,T_P}$ is the environmental joint distribution conditioned on population i. The triple integral is evaluated numerically using 90 independent 10-minute simulations for each environmental combination. The maximum from these short term simulations are assumed Gumbel distributed, which is raised to the power of six for estimate of the 1-hour maximum response CDF. The environmental contour method assume that the long term extreme response with T years return period can be estimated using a sea-state on the T-year contour line:

$$F_{X_{1h}}(x_T) \approx F_{X_{1h}|V,H_S,T_P}(x_\alpha | v_T, h_T, t_T)$$

at some fractile α, typically between 0.7 and 0.9. To estimate the 50-year combined response using the extended contour-line approach, the procedure is as follows:

1. Estimate extreme response x_T in each sub-population for two return periods, say $T = 50$ and $T = 500$. Use the standard contour-line method, assuming only this population is acting. Typical points on contour-lines are shown in Fig. 3 and 4.
2. Estimate $G_{X_{1h}}(x) = 1 - F_{X_{1h}}(x)$ for each sub-population using the obtained responses, using e.g. a linear fit in Gumbel paper.
3. Find the total $G(x)$ using Eq. (1).

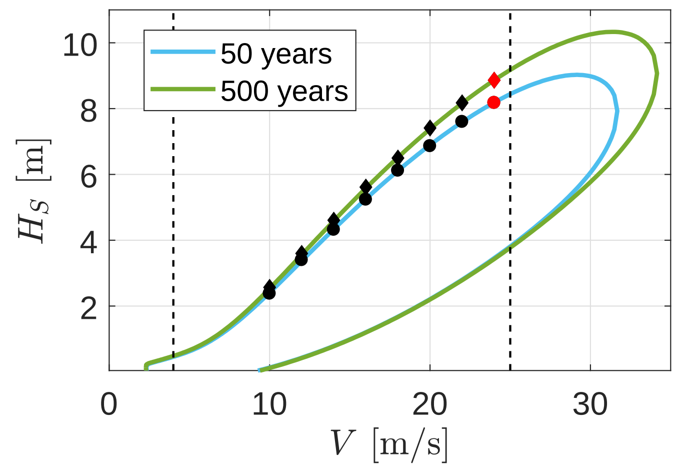

Figure 3: Contours for wind speed and significant wave height used for sub-population 1, expected T_P given H_S is used. Dashed lines indicate sub-population limits. Sea-states used in red.

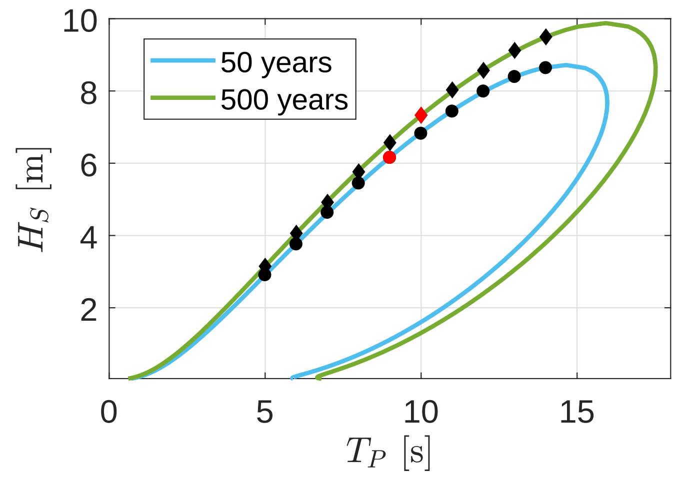

Figure 4: Contours for significant wave height and peak period used for sub-population 2, expected V given H_S is used. Sea-states used in red.

Results and discussion

In Fig. 5, a characteristic nacelle acceleration as function of wind speed is illustrated. Due to low aerodynamic damping, the response in the parked population is in general larger. From the FLTA, exact exceedance probability functions $G(x)$ are plotted in Fig. 6, with the corresponding contour-line estimates. Relatively high fractiles of 0.96-0.99 are used for the contour method estimates to account for variations in environmental parameters not present in the 2D contours. The best linear fits $G^C(x)$ are shown in Fig. 6, and the combined response in Fig. 7.

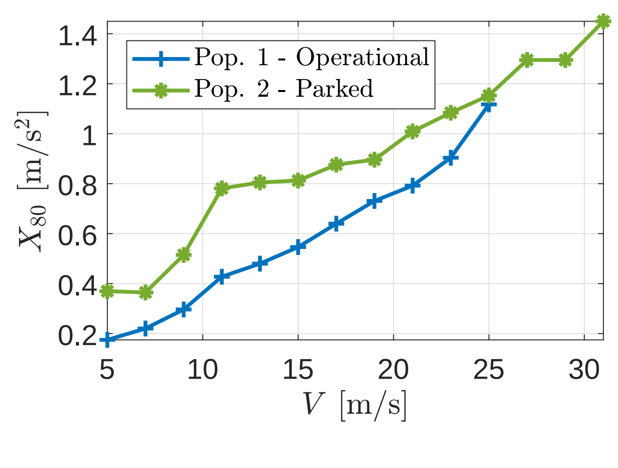

Figure 5: 80% fractile response given wind speed bin

Results show that a reasonable estimate for the combined response from several operational sub-populations can be obtained using an extended contour-line method. However, calibration of response fractiles and possible extension to 3D contour is recommended and will be elaborated on in the paper to follow.

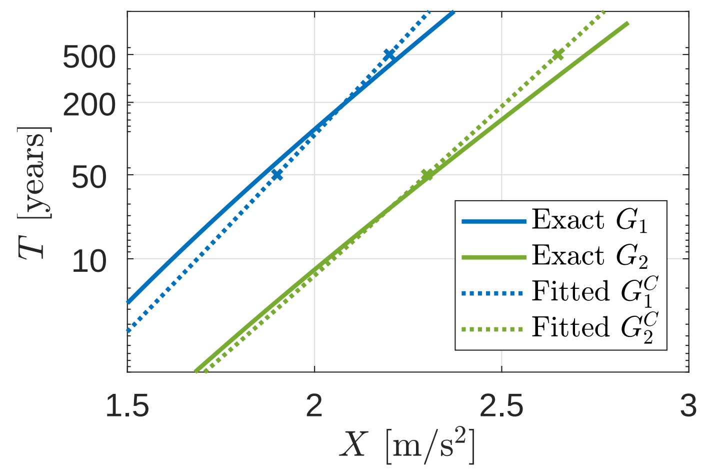

Figure 6: Results from each sub-population

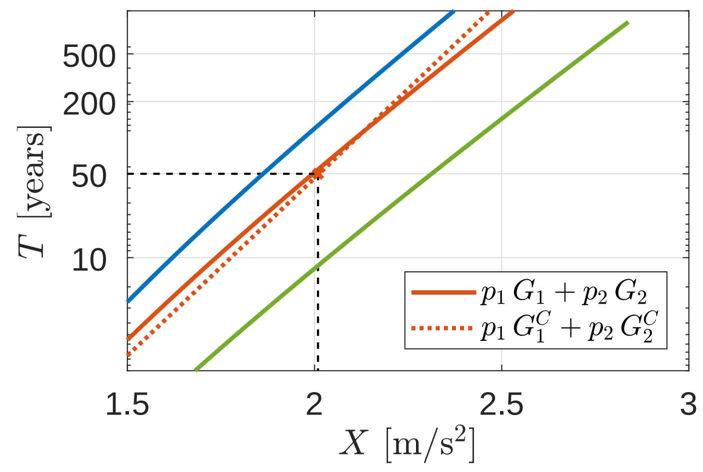

Figure 7: Combined CCDFs and total response estimate

References

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