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Multivariate analysis of extreme metocean conditions for offshore wind turbines

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ABSTRACT

Most offshore wind turbines (OWTs) are designed according to the international standard IEC 61400-3 which requires consideration of several design load cases under 50-year extreme storm conditions during which the wind turbine is not operational (i.e. the rotor is parked and blades are feathered). Each of these load cases depends on combinations of at least three jointly distributed metocean parameters, the mean wind speed, the significant wave height, and the peak spectral period. In practice, these variables are commonly estimated for the 50-year extreme storm using a simple but coarse method, wherein 50-year values of wind speed and wave height are calculated independently and combined with a range of peak spectral period conditioned on the 50-year wave height. The IEC Standard does not provide detailed guidance on how to calculate the appropriate range of peak spectral period. Given the varying correlation of these parameters from site-to-site, this approach is clearly an approximation which is assumed to overestimate structural loads since wind and wave are combined without regard to their correlation. In this paper, we introduce an alternative multivariate method for assessing extreme storm conditions. The method is based on the Nataf model and the Inverse First Order Reliability Method (IFORM) and uses measurements or hindcasts of wind speed, wave height and peak spectral period to estimate an environmental surface which defines combinations of these parameters with a particular recurrence period. The method is illustrated using three sites along the U.S. Atlantic coast near Maine, Delaware and Georgia. Mudline moments are calculated using this new multivariate method for a hypothetical 5 MW OWT supported by a monopile and compared with mudline moments calculated using simpler univariate approaches. The results of the comparison highlight the importance of selecting an appropriate range of the peak spectral period when using the simpler univariate approaches.

1. Introduction

Offshore wind is a vast resource with the potential to transform the energy economy of the world. In the United States, the National Renewable Energy Laboratory (NREL) has stated that an optimal (i.e. least cost) strategy for the U.S. to achieve its target of generating 20% of its electricity demand from wind energy by 2030 [1] should include the development of 54 GW of offshore wind capacity. Obtainment of this ambitious goal will require a significant reduction in the cost of energy which currently exceeds traditional, carbon-based energy sources by more than a factor of two [2]. Ways to reduce the cost of offshore wind energy include reducing financing and underwriting costs and eliminating excessive conservatism from design requirements, each of which would reduce capital costs. A possible means to such a reduction in capital costs is to more realistically model and estimate extreme metocean

Abbreviations: OWT, offshore wind turbine; V, hourly mean wind speed at elevation of 5 m above sea surface; H_s, significant wave height; T_p, wave peak spectral period; IFORM, Inverse First Order Reliability Method; NOAA, National Oceanic and Atmospheric Administration (USA); NREL, National Renewable Energy Laboratory (USA); R-LOS, R Largest Order Statistics; R, annual rate of occurrence; t_{lag}, time lag between the measurement of maximum V and the maximum H_s during an extreme event; CDF, cumulative distribution function; GEV, generalized extreme value; μ, location parameter of GEV distribution; σ, scale parameter of GEV distribution; ξ, shape parameter of GEV distribution; x_N, magnitude of a variable x with a recurrence period N, e.g. V_{50} is the 50-year wind speed; g, gravitational acceleration; T, extreme wave period; N, recurrence period; β, Radius of the sphere in standard uncorrelated normal space used in IFORM; Φ, cumulative distribution function for standard normal distribution.

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conditions and their associated loads on offshore wind turbines (OWTs), thereby minimizing uncertainty in extreme loading and design conservatism.

The most widely used international standard for the design of OWTs is IEC 61400-3 [3]. This Standard prescribes a suite of design load cases which require an estimation of loads during a variety of operational and metocean conditions. One subset of these load cases considers extreme loads under 50-year storm conditions during which the wind turbine is not operational (i.e. the rotor is parked and blades are feathered). The extreme loads depend on estimation of the 50-year magnitudes of two metocean parameters: the one-hour mean wind speed V and the significant wave height H_s. Often, in practice, the 50-year values of these parameters, V_{50} and $H_{s,50}$, are estimated independently using extreme value analysis based on a hindcast, typically spanning more than a decade at the installation location. The IEC Standard also permits selection of these 50-year wind and wave parameters based on the long term joint probability distribution of extreme wind and waves, but it does not provide any specific guidance on how to execute such an analysis.

The parameters, V_{50} and $H_{s,50}$, are used as inputs to simulate stochastic time series corresponding to extreme turbulent winds and the extreme sea state. A structural model is then analyzed, for six one-hour realizations of both time series simultaneously, and the average of the maximum structural response from each of the six analyses is recorded as a design demand. The wave time series for the extreme sea state is typically based on the JONSWAP spectral model [3], which requires an additional metocean parameter, the peak spectral period T_p. Note that the IEC Standard also requires consideration of loads due to swell, tides and currents, but these metocean parameters are neglected here for simplification.

In this paper, we discuss three methods to estimate the 50-year extreme values of V, H_s and T_p. The first, termed herein as "1D Exceedance," is a univariate method, commonly used in practice, wherein 50-year values of V and H_s are calculated independently along with a range of T_p deterministically conditioned on the 50-year H_s, and these conditions are assumed to occur simultaneously. The second is also univariate and referred to herein as "1D Reduced Combination." In this method, which is based on Annex F of ISO-2394 [4], a dominant metocean parameter is selected (either V or H_s) and a 50-year extreme value of this parameter is combined with a reduced value of the other parameter. Again, as with 1D Exceedance, a range of T_p conditioned on H_s is calculated deterministically. The third method is multivariate, considers the long term joint probability distribution of V, H_s and T_p, and is referred to herein as the 3D Inverse First Order Reliability Method or "3D IFORM."

IFORM is a general method for extrapolation of metocean parameters and is usually applied to joint distributions of two random variables. The result is an "environmental contour," which defines, in a sense, combinations of the two random variables that have a particular recurrence period [5]. In this paper, IFORM is applied to three jointly distributed random variables resulting in an "environmental surface" which provides, in a sense, combinations of three random variables which have a particular recurrence period. IFORM has been applied in 3D by other researchers [6,7] who have used this method to generate an environmental surface of wind speed, turbulence intensity and bending moments for calculating the design moment at the root of a wind turbine blade. In that case of 3D IFORM, which considers plentiful 10 min measurements of the joint data, the joint distribution of the three random variables is expressed through a series of conditional distributions which can be estimated directly from the measured data. Similarly, in the original introduction of IFORM [5], joint distributions were estimated based on distributions developed for the northern North Sea based on 3-h measurements of the significant wave height (modeled with a Weibull distribution) and the peak spectral period conditioned on significant wave height distribution (modeled as a lognormal distribution) [8]. The 3D IFORM method discussed here is a straightforward extension of IFORM as presented in [5], but the application presented here is novel in that it is based on sparse sets of extreme value data and therefore requires an approximation of the joint distribution, which, in this case, is approximated using the Nataf model. Extreme value data and distributions are favored here because such an approach more accurately represents distribution tail behavior which often is determined by different physical mechanisms than what determines the vast majority of hourly data [12]. In fact, the authors considered using hourly measurements modeled with the distributions proposed in [5], and found that, for the examples considered here, such distributions did not accurately represent the tails of the measurements.

As an example, we present results for all three methods at three sites along the Atlantic Coast where the U.S. National Oceanic and Atmospheric Administration (NOAA) maintains buoys which have multiple decades of wind and wave measurements. For each of the three sites, all three methods are compared by searching all combinations of V, H_s and T_p that are associated with a 50-year recurrence period to find the critical combination, defined as the combination resulting in the maximum structural effect. In this paper, the structural effect considered is the mudline base moment which is estimated by analyzing a structural model of the 5 MW National Renewable Energy Laboratory (NREL) reference offshore wind turbine supported by a monopile foundation [9].

The paper is organized as follows: first, some general background is presented on univariate and multivariate metocean assessment for structural design. The next section introduces and describes three example offshore locations which are located near the U.S. Atlantic Coast where NOAA buoys have been measuring metocean conditions for multiple decades. Next, the methods for identifying extreme values from measured data and then extrapolating these values to 50-year parameters using 1D Exceedance, 1D Reduced Combination and 3D IFORM are presented. The following section presents comparative results for each of the locations and each of the methods. The paper ends with discussion on the results and a summary of conclusions.

2. Background

The design of OWTs, and all engineered structures generally, relies on the estimation of load effects associated with environmental conditions that occur at a particular recurrence period. For many structures, the intensity of metocean conditions for different load types can be modeled independently and the likelihood of simultaneity of load types can be considered through prescriptive load combinations (e.g. ASCE 7-05 for buildings [10]), which typically combine extreme values for one load type and expected values from all other load types. In many cases, this is a reasonable assumption because statistics of different load types are often accurately characterized as independent (e.g. earthquake combined with wind loads) and the chance of extreme values of these load types occurring simultaneously is negligible.

In offshore engineering, the impact and variability of the correlation of metocean conditions from wind and wave influence design significantly, and methods for modeling such conditions as multivariate are described conceptually in design standards [3]. The extreme offshore environment is commonly characterized by statistical measures of coupled wind and wave random processes that are assumed to be stationary. In particular, the statistical measures employed by IEC 61400-3 are the mean hourly wind speed V,