Wind and Wave Environments that Lead to Extreme Loads on Offshore Structures

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***Abstract*—Large wind gusts and rare wave groups create design issues that wind turbines must overcome. These design level gusts and waves generate bending moments on the tower which may lead to failure, or at least accelerated failure. The loads on the wind turbines that lead to failure are not necessarily the result of an extreme gust or a design wave, but may be from a rare combination of the two that leads to an extreme response. To investigate the relationship between wind and wave loading, the stochastic gaussianization iteration method was used in conjunction with the Design Loads Generator to investgate extreme values of the tower base bending moment of a reference floating wind turbine. The response was investigated under three different conditions: Monte Carlo simulations; the Design Loads Generator with a gaussian mask; and the stochastic gaussianization iteration method using the Design Loads Generator to estimate extremes from waves. It was determined that the stochastic gaussianization iteration method with the DLG to maximize the bending moment due to waves resulted in the largest predicted bending moments in a given exposure period.**

***Index Terms*—Combined Loads, Extreme Values, Offshore Wind Turbines**

I. Introduction

The failure of offshore structures due to extreme conditions is generally the result of some rare combination of wind and waves. Design rules and practices, however, dictate the application of extreme loads from wind and/or waves as single uncorrelated entities, either as an extreme thousand-hour wave occurring at the same time as an extreme thousand-hour wind gust, or simply the application of one of the two sources [1]. With this approach, the design level is likely incorrect for what the structure will actually see in its design life. It is much more probable that the combination of, say, the 10-hour extreme wave and 10-hour extreme wind will occur simultaneously and, depending on the level of safety sought, should be the design point.

The prediction of extreme loads on wind turbines is one of the key drivers in wind turbine design. While a majority of the design process is centered around fatigue, wind turbines need to operate for a number of years before recovering the investment and therefore must survive rare events with return periods on the order of 50-100 years. It follows that accurate prediction of extreme events in the life span of the wind turbine is a study area of current interest.

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The hydro-aero nexus creates a difficult problem to solve when attempting the determine extreme loads. Additionally, the different time scales of wind and waves dictate that the stationarity of wind is about 10 minutes as where ocean waves are stationary for about 1-3 hours. As such, many strategies have been developed to estimate the extreme responses due to the combined effect of wind and waves on ocean structures.

The current guidelines for offshore wind turbines by DNV-GL suggest some linear combination of the characteristic or design wind load effect and the characteristic or design wave load effect to estimate a representative load effect, or to run simulations with wind and waves [1]. While easy to implement, there is potential to lose important relationships between wind and waves. The application of the 50-year wave and 5-year wind, among other load effects, may lead to a structure with substantial strength, but also may represent an event that would never occur in several lifetimes of the wind turbine and result in over-design. It remains a challenge to discover wind and wave events with a significant probability of occurence that drive the design of the structure.

Another way to analyze the combined loading effect of wind and waves is through First Order Reliability Method (FORM). FORM can be used to estimate extreme values by way of determining sets of fourier coefficients associated with wind speed and wave elevation that lead to responses that exceed some prescribed threshold with the highest probability [2]. Generally, this is done by first linearizing about a point in the fourier coefficient domain in which the failure surface, which is the difference between the response and prescribed threshold response and is defined by the fourier coefficients of wave and wind, is closest to the origin. Then, an optimization is performed to find the most probable response. In [3], FORM was applied to estimate extreme loads on offshore wind turbines. The combined use of Monte Carlo simulations and FORM provided basis for the extrapolation of Monte Carlo results using the relationship between the reliability index and the peak scaling factor on the wind and wave spectra. With the ability to extrapolate Monte Carlo simulations, very rare events can be estimated. Also, FORM has the ability to generate the most probable wave and wind values that lead to extreme events.

More classical techniques to estimate the extreme responses of a floating wind turbine were taken in [4]. The peaks of non-linear spar motions were sampled at different levels and then Weibull tails were fit. The authors found that the Weibull distribution fit the tails of the peak distributions well, but acknowledged uncertainities in both parameters for the Weibull distribution as well as in the sample size of the data.

In [5], three offshore wind turbine models (a monopile, a spar, and a semi-submersible,) were subjected to 50-year extreme environmental conditions as prescribed by the Inverse First Order Reliability Method (IFORM), which was recommended by IEC 61400-3. In the IFORM, a 50-year contour is created based off of significant wave height and wind speed observations in a given area. The paper used FAST, an offshore wind turbine simulator, to create a large ensemble of simulations for each of the three turbine models under different specifications such as wind and non-linear wave effects, wind and linear wave effect, and purely wind. With the ensembles, the authors found that the coefficient of variation of the maximum bending moment could be reasonably estimated by the mean and variance of said response.

While significant results can be acheived through FORM, extrapolating tails on estimated distributions, generating ensembles of data, the potential information lost in linearization, extrapolation, and the computational costs debilitate designers from accurately investigating many different scenarios. Ideally, the extreme value pdf could be recovered for one or more scenarios while keeping important infomation about the time series near extreme values for use in related applications. In this paper, methods to estimate the extreme value pdf and to generate short ensembles of extreme realizations of the tower base bending moment in a offshore wind turbine are developed. To do so, the offshore wind turbine simulator OpenFAST is used to model wind turbine dynamics and the stochastic gaussian iteration method is used in conjunction with the Design Loads Generator to estimate the extreme value characteristics of the tower base bending moment.

A. OpenFAST

OpenFAST [6] is a series of codes that together simulate the complex Aero-Hydro-Servo-Elastic interaction of offshore wind turbines and is the successor to FAST. Various types of turbines can be tested and many additional modeling constraints can be inplemented in OpenFAST. OpenFAST generates solutions in the time domain. In this paper, OpenFAST will be used to generate solutions for the DTU 10 MW reference turbine [7]. The DTU 10 MW reference turbine was initially modelled without offshore usage, but was adapted in [8] as an offshore wind turbine and for implementation into OpenFAST.

B. The Design Loads Generator

The Design Loads Generator (DLG) is a program that generates ensembles of extreme realizations of gaussian processes, and the inputs that lead to those extremes [9]. Based on the phase relationships between the input time series and transfer function, the phases of the response of interest are optimized using a modified gaussian distribution, coupled with the acceptance rejection method, such that the target extreme value of interest is reached. The DLG has shown the capability to predict non-gaussian extremes from combined loading via usage of surrogate processes [10] and in short crested seas [9]. In this paper, the short-crested seas approach will be adapted to predict extremes from wind and wave forcing. However, due to the non-linear filter through which the bending moment of a wind turbine tower is obtained from wind and waves, the use of the DLG will require an iterative gaussianization of the response.

C. The Stochastic Gaussianization Iteration Method

The stochastic gaussianization iteration method (SGIM) involves the transformation of a stochastic, non-gaussian time series/process into a pseudo-gaussian process through the gaussian transformation, or normal score transformation. The transformation first generates a stochastic uniform process by sampling the original, non-gaussian process through its cdf. Then, the stochastic uniform process is sampled by a gaussian cdf via inversion to generate a pseudo-gaussian process.

The transformation of the non-gaussian process to the pseudo-gaussian process is based off of probability distribution. It is a one-to-one transformation, so it follows that rare events in the gaussian space are also rare in the non-gaussian space. As such, the DLG can be used in tandem with the SGIM to generate extreme realizations of the pseudo-gaussian process. The input that leads to those extreme realizations can then be input into the non-gaussian model to produce candidates for extreme values in the non-gaussian space. Due to phase relationships, these non-gaussian extremes, which are conditioned on the pseudo-gaussian process having an extreme at time $t = 0$, do not necessarily have a value that lies on the extreme non-gaussian pdf at time $t = 0$. As such, an iteration scheme is formed by regaussianizing the non-gaussian time series, entering back in the DLG, and then running the inputs that lead to DLG extremes into the non-gaussian model. The criteria for convergence is, ideally, convergence of the sample extreme pdf of the non-gaussian process with the true extreme pdf.

II. Method

The SGIM was used to generate ensembles of wave sets that lead to extreme bending moments. After convergence, or pseudo-convergence, was acheived, the wave sets were paired with random, unconditioned wind from a Kaimal spectrum. The resulting time series were compared with Monte Carlo simulations and a set of time series that were generated by using the DLG with the Monte Carlo simulations and a gaussian mask. The gaussian mask is similar to the SGIM in that a non-gaussian process is gaussianized for use in the DLG, but after a single run through DLG, the ensembles of the gaussian response are transformed through the inverse operator that initially gaussianized the non-gaussian process. For the case where there are two inputs and transfer functions are not easily recoverable from a gaussianized process, this method allows the response spectrum and a unit transfer function to be the input into DLG.

For use in conjunction with the DLG, the transfer function of the bending moment with respect to waves was found separately, without the effect of wind. Given the non-gaussian time domain solution OpenFAST provides, the transfer functions for the DLG are from the gaussian input (wave time series) to the gaussianized versions of the training data (bending moment).

Each OpenFAST simulation was performed in the parked condition, i.e. setting the blade pitch to 90^o and rotor speed to zero. While the turbine may be able to perform in most of the conditions applied throughout this study, accurate transfer functions regarding the behavior of the turbine when in the parked condition were sought to better characterize the response in emergency conditions. It should therefore be noted that a controller was not used in these analyses.

A. Monte Carlo Simulations

In OpenFAST, the bending moment of the tower is some function of the material properties, the relationships between other turbine degrees of freedom, and the forcing from the wind and waves. Due to intrinsic non-linearities, gaussian input in the form of waves and wind will generally result in non-gaussian bending moment. The DLG selects phases such that a gaussian process reaches a maximum value, so it follows that the non-gaussian bending moment must initially be gaussianized. Along with the gaussianization, a new transfer function between the gaussianized response and the selected input must be formed. The following equation details the response of interest along with the gaussianized transfer functions.

$$\eta_{BM,g}(t) = \sum_{j=0}^{\infty} \vec{H}_{g,j}(\omega_j)^T \vec{\zeta}_j(\omega_j; t) \tag{1}$$

where $\eta_{BM,g}$ is the tower bending moment, $\vec{H}_{g,j}(\omega_j)$ is the vector of gaussianized transfer functions from wind and wave elevation to bending moment, and $\vec{\zeta}_j(\omega_j; t)$ is the vector of the wind and wave fourier decompositions.

Note that it is assumed this level of linearity is conserved, in that the response due to wind and wave can be considered separately and then be combined by linear superposition.

This paper seeks to highlight the need to consider an extreme wind-wave combination rather than solely wind or waves. As an initial step, the SGIM was used to determine the extreme response due to waves and then add in random, unconditioned wind. This step is important in understanding the relationship between wind and waves. As such, the SGIM with solely waves and eventual addition of random, unconditioned wind was compared to Monte Carlo simulations. To do so, Monte Carlo simulations were performed with: 1) waves only; 2) wind and waves.

1) Wave Only Simulations: To determine the gaussianized transfer function from waves to tower bending moment, four 15-minute simulations with just waves generated from a JONSWAP spectrum were performed using OpenFAST. The significant wave height was chosen as 6m and the modal period was 12s. While the bending moment response was expected to be nearly gaussian, inclusion of second order forces in OpenFAST neccesitated the gaussianization of the bending moment when forced by only waves. The average gaussianized wave-to-bending moment transfer function was determined by averaging the four gaussianized transfer functions found from the 15-minute simulations.

2) Wind and Wave Simulations: In the wind and wave simulations, the same wave spectra used in the individual simulations, along with the same respective parameters, was used. For the wind time series, a Kaimal turbulence spectrum [11] with mean wind speed of 12 m/s and a turbulence intensity of 0.25 was used to generate random ensembles, which are unconditioned on the wave time series. Twenty 40-minute simulations were run to gather extreme bending moments to form a baseline for convergence in the SGIM.

The twenty 40-minute simulations were also used for the DLG with a gaussian mask. Each simulation was gaussianized and then a mean response spectrum was determined using the newly gaussianized time series and WAFO [13]. The mean response spectrum was used as the input spectrum for the DLG and the transfer function was set as unitary. The resulting ensemble of extreme gaussian responses were tranformed back into the non-gaussian space and the maxima were recorded

B. The SGIM and OpenFAST

With the initial transfer functions for each case generated, the iteration process may begin. For each case, the extreme gaussian realization was generated using the DLG and the input that led to that extreme were recorded. For each case and iteration, 24 realizations of 200 seconds were produced to ensure that the transfer functions were accurate and to have enough extreme values to represent the extreme value pdf. In the wave only case, the extreme inputs were iterated upon without contribution from wind. The SGIM was continued for each case until the extreme bending moment cdfs of concurrent cdfs had an acceptable Kullback-Leibler divergence [14]. After the statistics converged, random and unconditioned wind velocity time series were combined with the extreme wave realizations as inputs into FAST.

III. Results

The following sections provide the results of the SGIM and DLG. Also, note that the values in the extreme cdfs are magnitudes of the bending moment.

A. Waves Only

Fig. 1 shows the evolution of the extreme tower base bending moment emprical cdf and kernel density estimation fit cdf after running the SGIM on the wave-bending moment transfer function and Fig. 2 shows an example realization of the bending moment after convergence and with the addition of unconditioned, random wind normalized by the root mean square of the bending moment from the final SGIM with solely

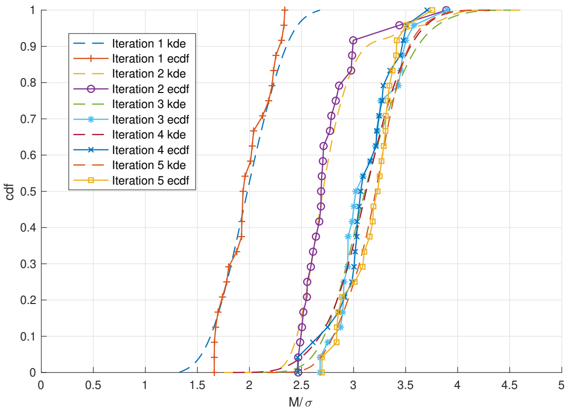

Fig. 1. The extreme tower bending moment cdfs from the waves only methods after five stochastic gaussianization iterations.

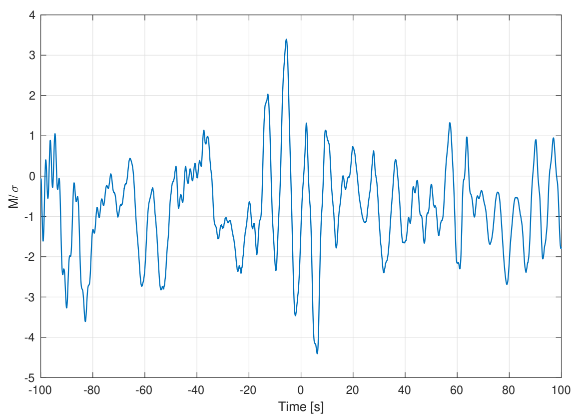

Fig. 2. A realization of the converged SGIM waves only extreme cdf with the addition of unconditioned wind. Note that the bending moment is normalized by the rms of the bending moment of the final SGIM with solely waves iteration and that the extreme value is negative.

waves iteration. Note that the kernel function used for the kernel density estimation was the gaussian function.

The target extreme value, which is the estimated most probable maximum value of a gaussian process in a given exposure in terms of the rms of the process, associated with the exposure time of 40 minutes was 3.57. While the DLG provides the lower bound [9], the converged values are lower than expected.

After the Kullback-Leibner divergence dropped to 0.1, the SGIM was stopped and the process was assumed to have converged. The cdf made two significant jumps in the first three iterations. Following the jumps, the movement became more subtle.

B. Wind-Wave and Waves Only Comparison

Fig. 3 shows the cdf from the bending moment Monte Carlo simulations, the estimated extreme explicit and kde fit cdf of the Monte Carlo simulations, the gaussian mask with wind and waves, the final SGIM waves only approach, the SGIM waves only approach with unconditioned wind, and the TEV associated with an exposure time of 40 minutes.

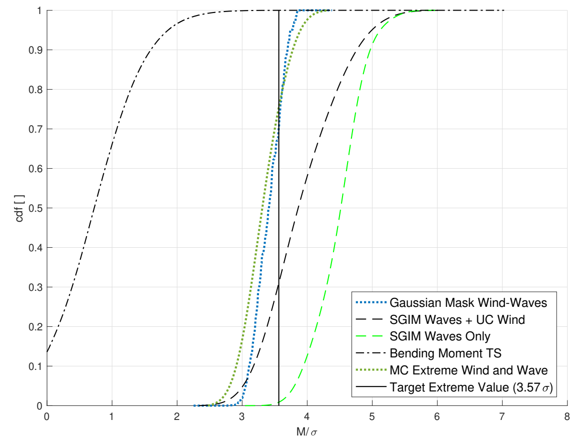

Fig. 3. The extreme cdfs of the SGIM with waves only as well as the gaussian mask approach with wind and waves, the Monte Carlo estimated extreme cdf from wind and waves, the cdf of the bending moment, and the target extreme value associated with the exposure time.

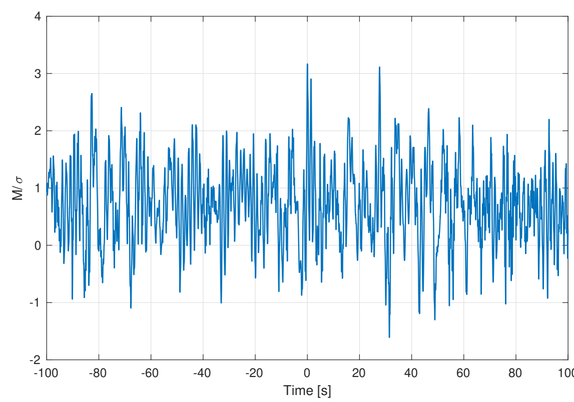

Fig. 4. A portion of a Monte Carlo simulation near an extreme (negative) value. Note that the bending moment is normalized by the rms of the Monte Carlo bending moment simulations.

Note that the bending moment is normalized by the rms of the Monte Carlo simulations and that all cdfs were determined using kernel density estimation.

The waves only SGIM approach provided a cdf with a larger median and variance compared to the Monte Carlo simulations. The addition of random, unconditioned wind unexpectedly lowered the median response compared to the SGIM with solely wind. It is theorized that the addition of wind detuned the system, adding stiffness to the system when the mooring lines became stretched from the mean pitch and surge offset the wind provided. This detuning likely increased the natural frequency and therefore diminished the effect of the focused frquency the waves developed by the SGIM with solely waves seemed to have developed, as noted in the discussion.

Also, it can be noted that the gaussian mask technique had a level of agreement with the Monte Carlo simulations. However, that while the gaussian mask extreme cdf intersects the Monte Carlo extreme cdf at the TEV of interest, the underlying distribution differs.

IV. Discussion

It is interesting to note that the wave only approach generated events that were larger than expected in the exposure time, at least compared to the Monte Carlo simulations. To investigate, the input wave time series near bending moment extremes for the SGIM wave only approach and the Monte Carlo simulations were compared. Figure 5 shows the ensemble average of the input waves for the wave only approach and the Monte Carlo runs.

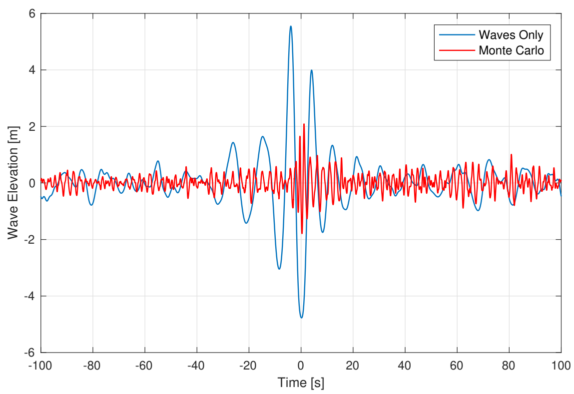

Fig. 5. The ensemble average of the input waves near the maximum bending moment for the wave only case and the Monte Carlo simulations.

After inspection of the input wave time series, it is evident that the magnitude of the waves and frequency/phase content that the SGIM recovered may have tripped a resonant response and was responsible for the larger than expected response. Ultimately, it appears that both the wind-wave approach and extreme SGIM wave with unconditioned wind may be candidates for the extreme value pdf. While values as large as those implied by the SGIM with waves only approach did not occur in the training data, the declaration that the SGIM with waves only cdf is incorrect cannot be made, mostly due to the limited amount of Monte Carlo runs with wind and waves for comparison.

The increased variance and uncertainty associated with the waves only SGIM with unconditioned waves is an issue to be addressed as well. Given the relatively small amount of simulations and the inversely proportional relationship between variance of the sample mean and number of samples, the median of the SGIM waves is approximately normally distributed about the sample median value of about 3.85 with a standard deviation of 0.17. The addition of wind therefore adds a significant amount of uncertainty to anaylsis.

Along with uncertainty, the addition of wind unexpectedly lowered the extreme responses compared to the SGIM with solely wind. The sudden appearance of additional frequency content and proposed increase in natural frequency affected the focused frequency content of the SGIM produced wave sets that led to extremes. As such, the median response lowered and the variance of the extreme cdf, with respect to the SGIM with waves only, increased.

There is also the issue of misalignment in terms of the TEV. In the gaussianization, it is unknown what happens to the time scales. As such, the TEV used for each SGIM iteration is likely erroneous and could therefore alter results. The potential TEV error can be noted in Figure 3 in where the potential extreme cdfs intersect the TEV line. Since the true extreme cdf is unknown, it cannot be said where we expect the potential cdfs should intersect the TEV line. In the extreme value theory for gaussian processes, the intersection would occur at the most probable maximum and would have a probability of execeedance approximately equal to $1 - e^{-1}$, where e is the Euler constant [15]. The fact that the SGIM with addition of random, unconditioned wind intersects the TEV at around 0.3, though that is not the exact region of highest probability of occurence, and has a similar tail to what is expected in extreme value theory may suggest a level of validity. However, as noted, the shift in time scales upon gaussianization is unknown and therefore there are likely errors in the levels of extreme values presented.

V. Conclusion

In this paper, three methods to determine extreme bending moments in a given exposure time were compared with each other. The Monte Carlo wind-wave and the wind-wave gaussian mask methods were similar, as anticipated, and were generally lower than the wave only SGIM approach. While the wave only SGIM approach estimated larger bending moments, there was a larger amount of variance in the response and uncertainty associated with the relatively limited amount of simulations. Regardless, it appears that the wave only SGIM approach was more viable in terms of estimating larger extreme bending moments in the exposure period.

In future work, the SGIM approach applied to wind with unconditioned waves would provide an interesting comparison. Also, the ability to separate wind and wave transfer functions from a gaussianized response would allow for the SGIM approach for the wind-wave combination. Such an approach would perhaps show that more common environmental conditions can lead to extreme events, rather than extreme waves or wind.

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