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Wind/Wave Misalignment in the Loads Analysis of a Floating Offshore Wind Turbine

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Wind resources far from the shore and in deeper seas have encouraged the offshore wind industry to look into floating platforms. As a result, the International Electrotechnical Commission is developing a new technical specification for the design of floating offshore wind turbines that extends existing design standards for land-based and fixed-bottom offshore wind turbines. The work summarized in this paper supports the development of best practices and simulation requirements in the loads analysis of floating offshore wind turbines by examining the impact of wind/wave misalignment on the system loads under normal operation.

We conducted simulations of a spar-type floating offshore wind turbine system under a wide range of wind speeds, significant wave heights, peak-spectral periods, and wind/wave misalignments using the aero-servo-hydro-elastic tool FAST. The extreme and fatigue loads were calculated for all of the simulations. The extreme and fatigue loading as a function of wind/wave misalignment are represented as load roses and a directional binning sensitivity study is performed. This study focused on identifying the number and type of wind/wave misalignment simulations needed to accurately capture the extreme and fatigue loads of the system in all possible meteorological and ocean conditions considered, and for a down-selected set of conditions identified as the generic U.S. East Coast site.

For this axisymmetric platform (except for the mooring lines), perpendicular wind and waves play an important role in the loading of the support structure. Therefore, including these conditions in the design loads analysis can improve the estimation of extreme and fatigue loads. However, most support-structure locations experience their highest extreme and fatigue loads when the wind and waves are aligned. These findings are specific to the spar-type platform, but we expect that the results presented here will be similar to other floating platforms.

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Abbreviations

Meteorological ocean parameters

W_s	wind speed at hub height in m/s
W_d	wind/wave misalignment in degrees
H_s	significant wave height in m
T_p	wave peak-spectral period in s

Structural locations[§§]

Anch1Ten	anchor tension of the first mooring line
Anch2Ten	anchor tension of the second mooring line
Anch3Ten	anchor tension of the third mooring line
Fair1Ten	fairlead tension of the first mooring line
Fair2Ten	fairlead tension of the second mooring line
Fair3Ten	fairlead tension of the third mooring line
IPDefl1	in-plane deflection of blade 1
OoPDefl1	out-of-plane deflection of blade 1
LSSGagMya	rotating low-speed shaft-bending moment about the y_a axis
LSSGagMza	rotating low-speed shaft-bending moment about the z_a axis
RootMxc1	first blade in-plane root-bending moment about the x_{c1} axis
RootMyc1	first blade out-of-plane root-bending moment about the y_{c1} axis
TwrBsMxt	tower-base roll bending moment about the x_t axis
TwrBsMyt	tower-base pitch bending moment about the y_t axis
YawBrMxp	yaw-bearing roll bending moment about the x_p axis
YawBrMyp	yaw-bearing pitch bending moment about the y_p axis

I. Introduction

MOST fixed-bottom offshore wind turbine support structures are axisymmetric and stiff enough to ensure that wave loads do not have a significant impact on the overall structural loads of the system above the water. It is often conservative to assume that the winds, waves, and currents are co-directional for fixed-bottom offshore wind turbines because fore-aft loadings, which drive the design of their support structures, are highest when the winds, waves, and currents are from the same direction. However, in a floating wind turbine system there is greater potential for motion of the support structure, which combined with a lack of aerodynamic damping in the side-to-side direction, may cause wind, wave, and current directionality to more heavily impact both extreme and fatigue loading.

The goal of this work is to examine the importance of wind/wave misalignment when assessing the extreme and fatigue loads in a floating wind turbine system. We focused on identifying the number and type of wind/wave misalignment simulations needed to accurately capture the loads of the system over a large range of possible meteorological ocean (met-ocean) conditions. Specifically, this paper addresses the impact of wind/wave misalignment on the extreme and fatigue loading for a spar-type floating platform. This work is affiliated with the International Electrotechnical Commission (IEC) working group 3-2, with the intent of informing an upcoming floating wind turbine design technical specification.

To date, a few studies have been conducted that investigate the impact of wind/wave misalignment on the response of floating wind turbine platforms. Philippe et al.[1] studied the impact of wind/wave misalignment on a floating wind turbine located on a barge platform and discovered that the sway, roll, and yaw response amplitude operators (RAOs) increased with misaligned wind and waves, especially for a misalignment of 90º. Ramachandran et al.[2] studied the importance of wind/wave misalignment on a tension-leg platform (TLP) platform under wind

[§§] See FAST documention[4] for a definition of the different coordinate systems excitation of 10 m/s, and showed the significance of 90º and 180º misalignments in both the spectral energy contents and the time series of the platform motions. Kokubun et al.[3] modeled a 1/34.5-scale prototype of a wind turbine with a spar-buoy platform in an ocean engineering basin and were able to recreate storm situations—with blades fully feathered—using aligned wind, waves, and current and misaligned wind and waves. In this paper, misalignment situations created higher platform motions. These studies show the impact of wind/wave misalignment on floating platforms, especially in the side-to-side direction caused by increased compliance of the floating support structure.

II. Methods

This study uses the wind turbine computer-aided engineering tool FAST[4] to simulate the Offshore Code Comparison Collaboration (OC3)-Hywind spar-buoy platform[5] supporting the National Renewable Energy Laboratory (NREL) 5-MW reference wind turbine.[6] FAST is a nonlinear aero-hydro-servo-elastic tool that uses AeroDyn[7] to compute the rotor aerodynamics and HydroDyn[8] to compute the platform hydrodynamics. FAST models wind turbines as a combination of rigid and flexible bodies, and allows the user to turn individual degrees of freedom (DOFs) on or off. All relevant structural DOFs were enabled in the present simulations.

We performed an exhaustive series of simulations with the OC3-Hywind system to examine the met-ocean conditions that produce the largest motions and loads in the structure during power production according to the IEC wind turbine standard's design load cases 1.1 and 1.2. No discrete-event, fault, start, stop, parked/idling, or transport cases were considered in this study. Instead, we considered variations in mean wind speed at hub height, wave direction, significant wave height, and peak-spectral wave period (which define the wave spectrum; modeled using a modified Pierson Spectrum).[9] The wind direction was fixed at 0º with no nacelle yaw so the wind/wave misalignment was equal to the wave direction. Future work will consider separate wind and wave direction distributions to more accurately characterize fatigue damage accumulation, but for the extreme load and preliminary fatigue analyses presented in this study, the simplification of fixed wind direction allows one less variable to be considered. Figure 1 shows the different directions of importance in this study.

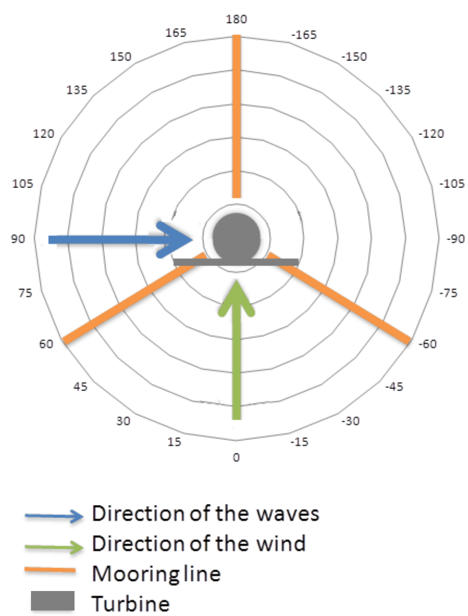

Figure 1. Schematic showing the floating offshore wind turbine and direction of the waves and wind. The wind is fixed at 0° so the wave propagation direction is equal to the wind/wave misalignment. (The 90˚ wave direction is shown.)

Instead of choosing values for these parameters (shown in Figure 1) that were site-specific, we chose a range of values for the expected conditions that an operating floating wind turbine could encounter almost anywhere offshore of the United States, as shown in Table 1. To consider all of the possible combinations of the four parameters' values, 370,656 simulations are required per seed. For our study, only one time-domain realization (one seed) of the wind/wave spectrum for a given combination was used. We ran time-domain simulations that were 10 minutes in length (after removal of the first 60 seconds of transient behavior with initial conditions chosen properly for each wind speed).[10] In addition, we used random turbulent wind fields created in TurbSim.[11] Furthermore, we examined the following system responses: the platform motions and the loads/moments in the blade root, low-speed shaft (LSS), yaw bearing, tower base, and fairlead and anchor connections of the mooring lines.

In order to run all of these simulations, we used the high-performance computing (HPC) resources at NREL (a cluster with about 200 cores available for simulations). A Perl script, RunIEC,[12] was also used to create all of the FAST input files and batch files to submit to the HPC.

Table 1. Values for the different parameters of the met-ocean conditions.

	Bin width	Numbers of bins*	Minimum value	Maximum value
Wind speed at hub height (Ws)	2 m/s	11	3 m/s	25 m/s
Significant wave height (Hs)	0.5 m	26	0 m	13 m
Peak-spectral period (Tp)	0.5 s	54	0 s	27 s
Wave direction (Wd)	15°	24	-180°	180°

* The bins were simulated at their midpoints, except for the wave direction, which used the bin endpoints.

Once the simulations from all of the combinations of the four met-ocean parameters were complete, we interpreted the data for a given site's specific conditions (and its associated probabilities). Specifically in this study, the results were interpreted at a generic site located on the East Coast of the United States. The site was created as part of a previous study (reference forthcoming) that examined data provided by buoys that were located offshore from all of the U.S. coasts. Buoys with at least 5 years of data containing both wind and wave direction were kept and grouped into coastal regions depending on their locations: East Coast, West Coast, and the Gulf of Mexico. For each buoy, conditional distributions related to the four parameters were fit, including:

- the wind speed at hub height was fitted with a two-parameter Weibull distribution;
- the wind/wave misalignment was fitted with a two-parameter Von Mises distribution with parameters conditioned on the wind speed;
- the significant wave height was fitted with a two-parameter Gamma distribution with parameters conditioned on wind speed and wind/wave misalignment;
- the peak-spectral wave period was fitted with a two-parameter Gamma distribution with parameters conditioned on wind speed and wave height.

For each coastal region, we created a "generic" site with the average parameters of all the buoys in the area. From this, a four-dimensional array was created containing the probabilities of each combination of met-ocean parameters for the East Coast generic site. This information was used to analyze the simulation outputs.

III. Extreme Load Results

The extreme loading (taken here as the maximum positive value) experienced on various components of the floating wind turbine system were extracted from the simulation outputs using MExtremes.[13] When considering all of the possible met-ocean conditions (370,656 simulations), we found that the highest significant wave height (12.75 m) caused the highest loads for the blade-root, LSS, yaw-bearing, and tower-base bending moments, as well as for the anchor and fairlead tensions of mooring line 1 (which is directed downwind), as shown in Table 2. Also, more than half of these extreme loads were caused with a misalignment higher than 75°.

However, a 12.75-m significant wave height value is an extremely rare occurrence at most offshore sites, thus the simulation set was filtered to only include conditions that pass a 50-year return period threshold as shown in Table 2. To create this subset of simulations, the individual joint probabilities from the East Coast generic site were sorted in descending order, and a cumulative sum array was created from this sorted list. The 50-year probability of $3.7*10^{-8}$ (the probability of a 10-minute event in 50 years) could then be applied to the cumulative sum array such that all simulations with lower probability are considered to have a return period larger than 50-years. This analysis reduced the number of simulations from 370,656 to around 70,000. This process filtered out simulations with high significant wave heights and high wind/wave misalignments (wave heights at real offshore sites tend to diminish with increasing wind/wave misalignmnent). A more accurate way of finding the 50-year return period uses the inverse first-order reliability method (IFORM), which will be investigated in future work.

With simulations of the most extreme conditions no longer present, the extreme loads observed at the (filtered) East Coast generic site were significantly lower than previously found and now occur at milder conditions. The significant wave height that caused these extreme loads decreased from 12.75 m to between 3 and 8 m, and aligned wind and waves were responsible for more than half of the extreme loads shown in Table 2. Of particular note is the reduction of the side-to-side tower-base moment from 322 MN-m to 173 MN-m and the 31% reduction in the fore-aft tower-base moment. Also note that in Table 2, mooring line 1 is the downwind line, so higher wind speeds (corresponding to higher rotor thrust) relieve the tension on this line, hence the extreme tensions occur at the lowest wind speeds; the other two mooring lines will be examined in future work.

To determine the general importance of the wind/wave misalignment on the extreme loads of the system, we compared the extreme loads for each angle of wind/wave misalignment (presented in load roses in Figure 2). Generally, we observe the importance of the 90° and -90° wind/wave misalignment for the side-to-side wind turbine loadings; the anchor and fairlead tensions for the three mooring lines experienced more significant loads in waves directed along the mooring line (the three lines are positioned at the 0°, 120°, and 240° angles around the platform; see Figure 1). The yaw bearing side-to-side bending moment, as well as the blade-root bending moments, blade deflection, and LSS moments (not shown here) are more impacted by high waves as their load rose profiles changed significantly from all conditions to those of the East Coast site with the 50-year return threshold. For the East Coast site, the load rose profiles show a dominant direction between -30 and 30 degrees, except for the yaw-bearing side-to-side bending moment, in which the perpendicular directions are more important.

Table 2. Extreme loads for different components of the floating wind turbine and the corresponding met-ocean conditions that produced these extremes. A comparison is made between the extreme loads for all conditions and for the U.S. East Coast conditions with a 50-year threshold.

		All Conditions (All)	East Coast (50-Year)	% Decrease From All to 50-Year	All	50-Year	All	50-Year	All	50-Year	All	50-Year
Locations	Units	Maximum loads	Maximum loads		Ws (m/s)	Ws (m/s)	Hs (m)	Hs (m)	Tp (s)	Tp (s)	Wd (°)	Wd (°)
RootMxc1	kN-m	12,422.0	11,743.3	5%	14	24	12.75	7.25	12.75	2.25	-105°	-90
RootMyc1	kN-m	26,780.5	23,721.3	11%	10	10	12.75	4.75	20.75	12.75	-135°	15
YawBrMxp	kN-m	13,920.5	10,662.0	23%	16	16	12.75	6.25	6.75	5.25	90°	90
YawBrMyp	kN-m	18,517.8	15,674.6	15%	24	24	12.75	6.75	6.25	6.25	0°	-15
TwrBsMxt	kN-m	322,110.4	173,271.4	46%	16	18	12.75	7.75	6.75	5.25	90°	75
TwrBsMyt	kN-m	391,964.1	269,252.2	31%	12	16	12.75	6.25	8.25	6.25	180°	0
Fair1Ten	kN	1,554.3	1,360.0	13%	4	4	12.75	3.25	16.25	17.75	0°	0
Anch1Ten	kN	1,291.9	1,098.8	15%	4	4	12.75	3.25	16.25	17.75	0°	0

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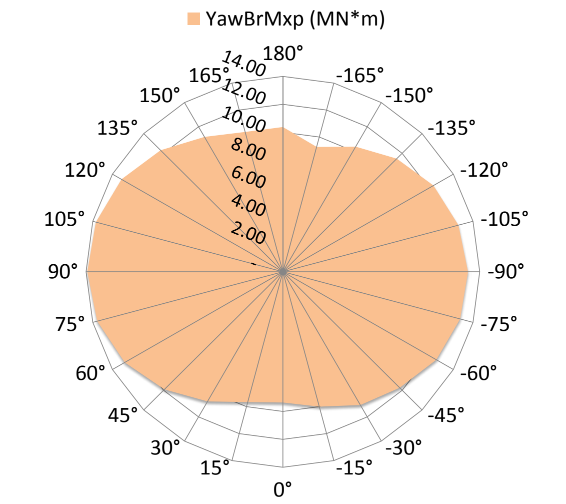
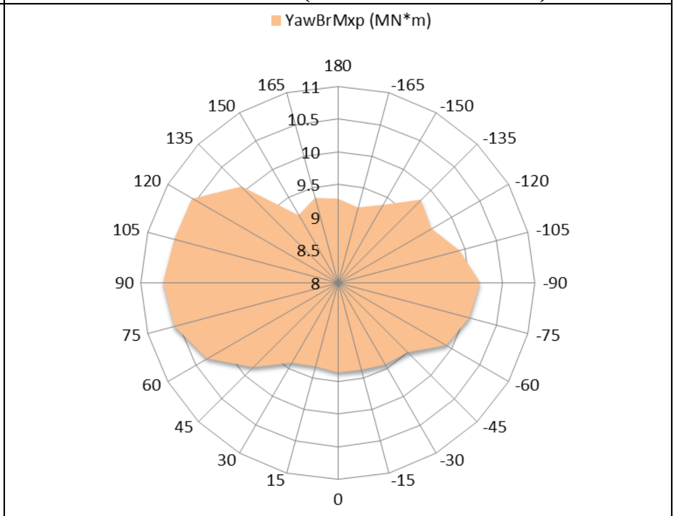
<tr><td>
</td><td>
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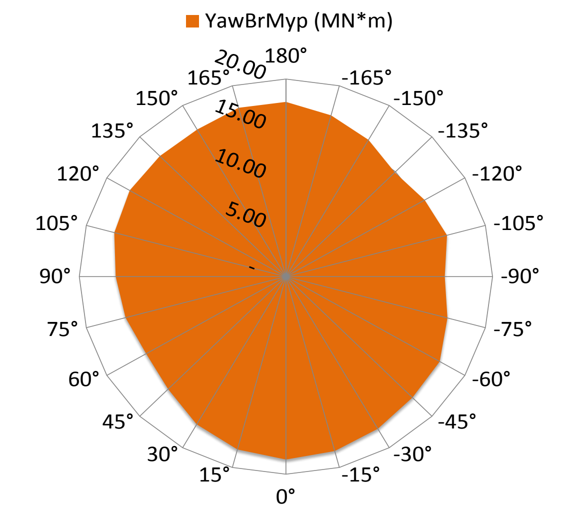
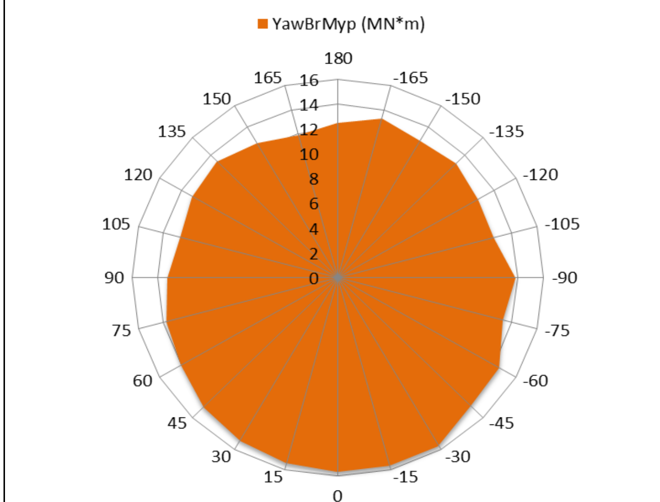
<tr><td>
</td><td>
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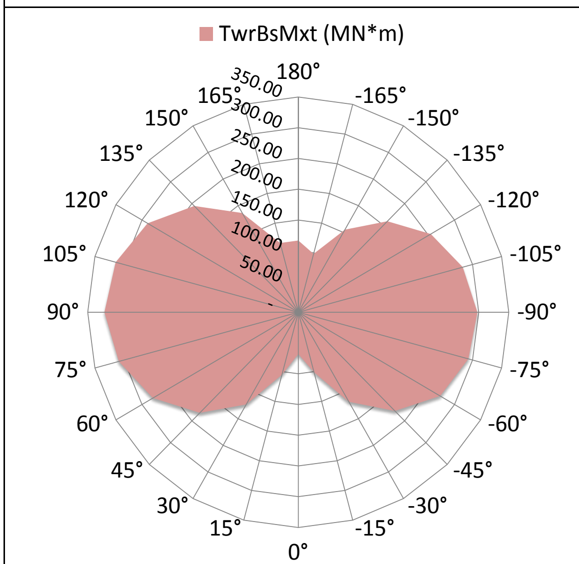
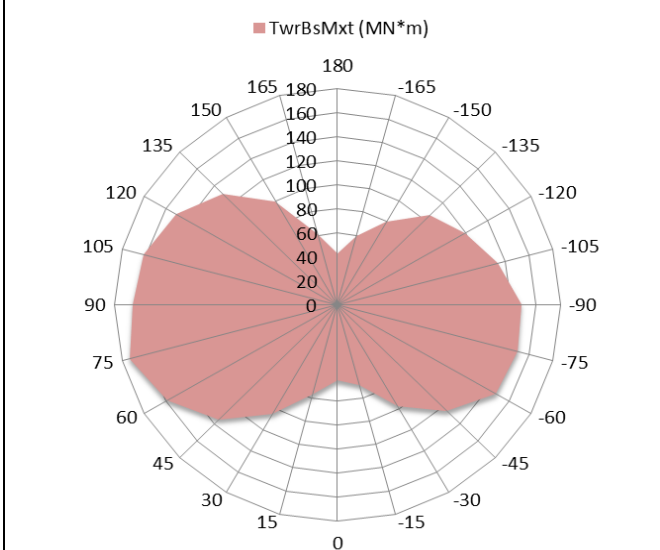
<tr><td>
</td><td>
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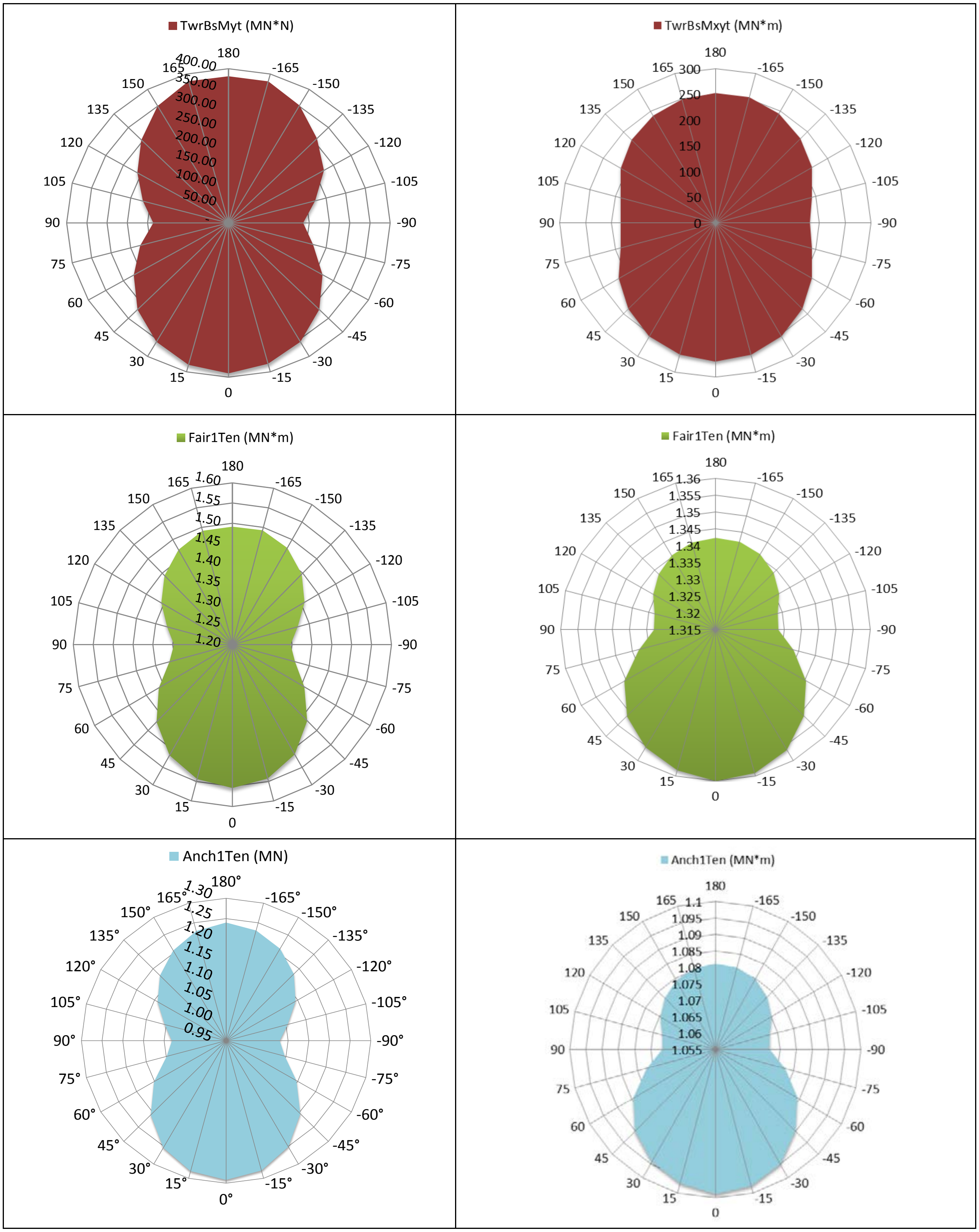

Figure 2. Loads roses representing the extreme loads as a function of the wave direction. From top to bottom: yaw-bearing side-to-side and fore-aft bending moments; tower-base side-to-side and fore-aft bending moments; anchor and fairlead tensions of mooring line 1. The roses on the left correspond to the complete range of met-ocean conditions and the roses on the right correspond to the generic U.S. East Coast site.

IV. Extreme Loading Directional Binning Sensitivity

In this study, we addressed a second issue: the minimum resolution of the wind/wave misalignment needed to accurately capture the extreme loads. To investigate this issue, we used the results from the East Coast generic site (provided in the previous section), and examined the extreme loads for varying numbers of simulated wave directions. In Figure 3, the various bars represent different directional binning schemes, with each configuration having the number of bins specified with even bin spacing around 360°. The loads are normalized by the 24-bin case.

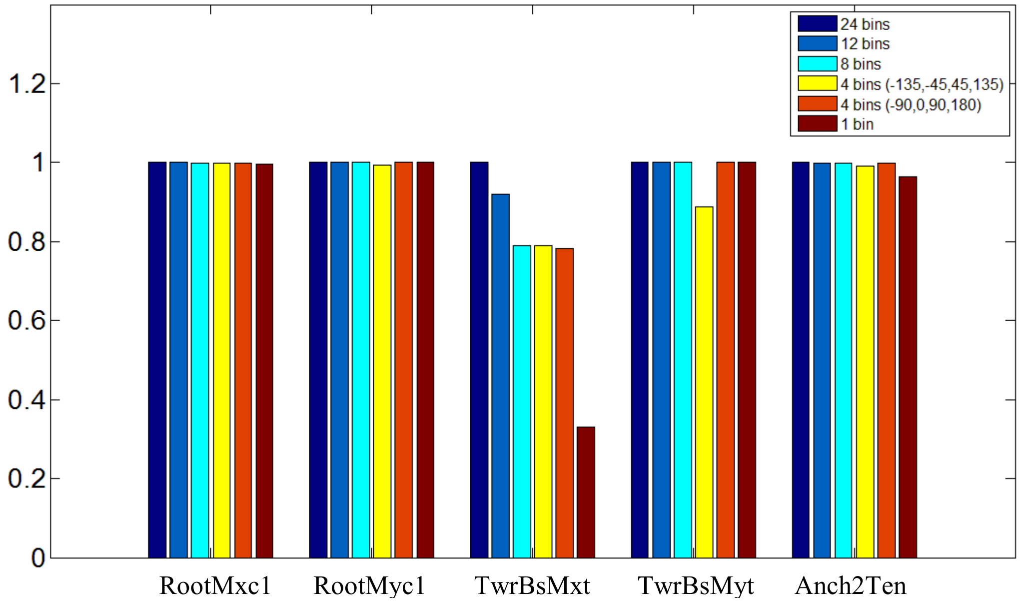

Figure 3. Comparison of the extreme loads when considering different numbers of wave direction bins. The extreme loads are normalized by the 50-year extremes with all 24 misalignment bins.

For most of the loads, aligned wind and waves produced the maximum values, therefore only one bin (0 degrees) was needed to capture the extreme load. However, for the tower-base side-to-side loading, considering only aligned wind and waves resulted in an extreme load that is three times less than what would be experienced when wind/wave misalignment is considered. Still, tower-base fore-aft bending moments are higher in magnitude than tower-base side-to-side bending moments. Finally, the lower extreme loads for the offset 4-bin case (-135°, -45°, 45°, 135°) for most channels can be explained by the absence of the important bins of 0°, 90°, and -90° wind/wave misalignment. From these initial results, considering 0° as well as either -90° or 90° should be sufficient to characterize the extreme load for this system. More work needs to be done concerning this question however, because this study only included one 10-minute simulation for each combination of met-ocean parameters, and extreme loads may change with the addition of more seeds.

V. Fatigue Load Results

Similar analyses were conducted to investigate the impact of wind/wave misalignment on the fatigue loads considering the set of simulations that represent the East Coast generic site with a 50-year return period. The goal of this analysis was to determine the necessary simulations needed to accurately characterize the fatigue of this floating platform. We used a customized version of the postprocessor MLife[14] that includes the capability to consider a four-parameter probability distribution in the fatigue calculations. With this addition, MLife is able to use the four-parameter conditional probability distribution derived from our East Coast generic site to calculate lifetime fatigue.

From the various MLife runs, the fatigue lifetime damage was obtained as a function of the wind/wave misalignment. We calculated the lifetime fatigue damage by determining the short-term fatigue damage from each separate simulation using a rainflow-counting algorithm, and summing these short-term fatigue damage values weighted by their probability. Load roses for the fatigue lifetime damage similar to those used for the extreme loads are shown in Figure 4. The Wöhler exponents used are 10 for the blade root-bending moments and 4 for the other structural locations (typical Wöhler exponents are 3−5 for steel and 8−12 for fiberglass blade materials).[15] Figure 4 shows that similar trends were found: the side-to-side tower-base and yaw-bearing loadings experience their highest lifetime damage towards the 90° and -90° directions and the other locations experience their highest lifetime damage towards the 0° direction.

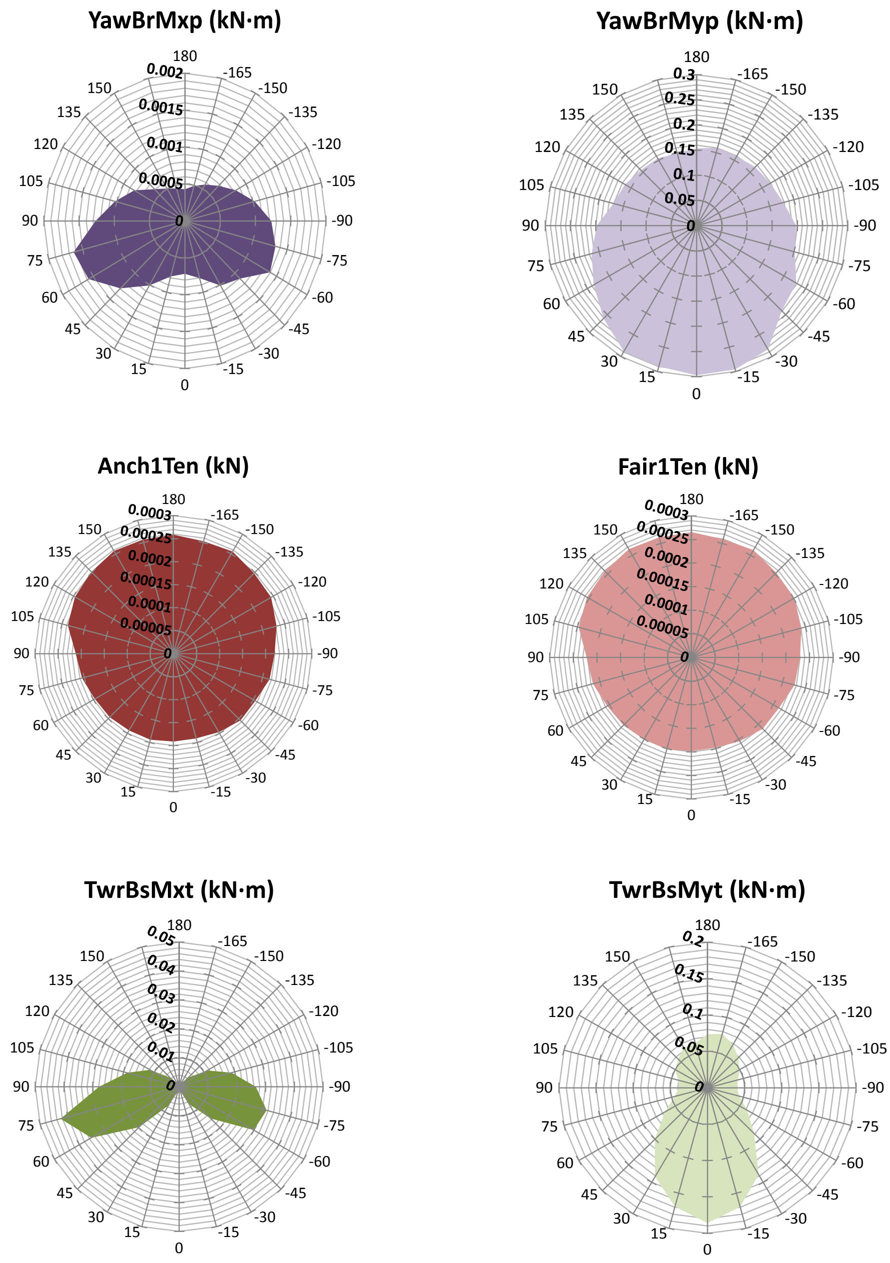

Figure 4. Lifetime fatigue damage roses for the U.S. East Coast generic site.

VI. Fatigue Loading Directional Binning Sensitivity

We analyzed several directional bin sizes, which was the same analysis conducted for the extreme loads. Figure 5 shows the effect of changing the wind/wave misalignment bins on the lifetime fatigue damage-equivalent loads of the edgewise and flapwise blade root-bending moment, fore-aft and side-to-side tower-bending moment, and anchor tensions. A two-bin case was added for this analysis, in which only 0° and 90° bins were considered, but the probability of the 0° bin was combined with the probability of the 180° bin, and the -90° bin probability was added to the 90° bin to ensure that the total probability remained equal. From Figure 5, it can be determined that blade and anchor tension loads are not strongly affected by wave misalignment. Of note is that the only anchor tension considered in Figure 5 is the mooring line directed along the wind; future work will look at the other two mooring lines as well. The side-to-side and fore-aft tower loads show the importance of considering wind/wave misalignment; with only one bin (aligned wind/waves), side-to-side tower damage is underpredicted by approximately 50%, and fore-aft tower fatigue is overpredicted by more than 5%.

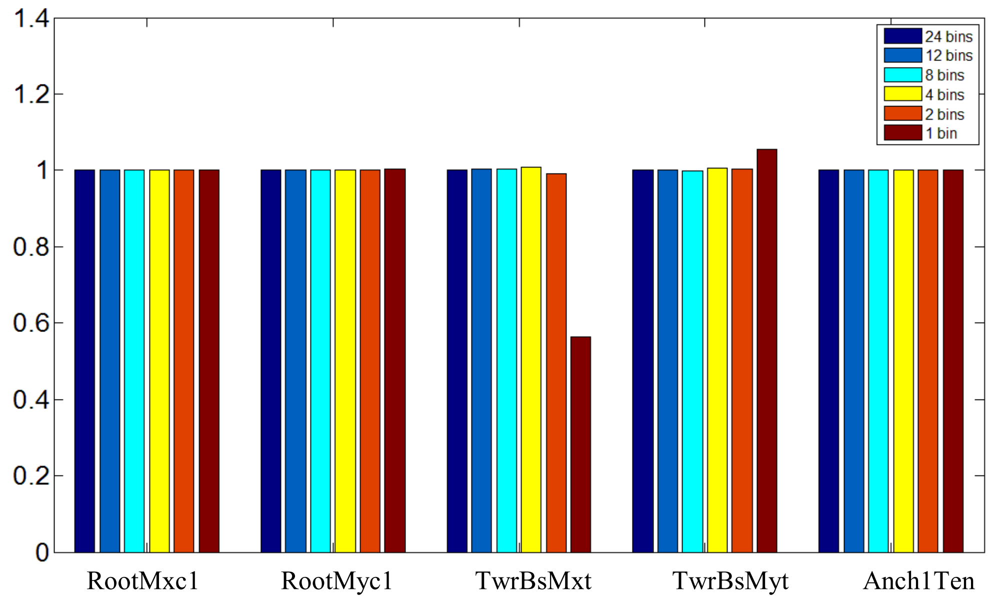

Figure 5. Comparison of the damage-equivalent loads when considering different numbers of wind/wave misalignments for the U.S. East Coast generic site. The loads are normalized by the case with all 24 misalignment bins.

VII. Conclusions

This study investigates the importance of wind/wave misalignment in predicting the loads for an offshore floating wind turbine with a spar-type floating platform. A wide range of met-ocean conditions were investigated and the extreme loads were found to occur at the maximum significant wave height and for high wind/wave misalignments. The set of simulations was then filtered by using a four-parameter joint probability distribution representing a generic site on the U.S. East Coast with a 50-year return period. Once filtered, the extreme loads occurred mostly during aligned wind and waves or low misalignment values and lower significant wave heights. Tower-base side-to-side bending moments showed a strong dependency on the perpendicular wind and waves cases. This finding was demonstrated by a sensitivity study in which the extreme side-to-side tower loads were three times smaller when considering only aligned wind and waves. For other structural locations, extreme loads can be well estimated by aligned wind and wave situations. The fatigue analysis for the same U.S. East Coast generic site showed similar trends. However, considering only aligned wind and waves leads to an underestimation of the tower-base side-to-side bending moment by approximately 50% and an overestimation of the tower-base fore-aft bending moment by about 5%. Based on these results, we recommend considering at least two wave directions (aligned with the wind and 90˚ misaligned) to precisely capture the extreme and fatigue characteristics of a spar-type platform.

Future work will consider separate wind and wave direction distributions to increase the accuracy of the fatigue damage calculation, as well as investigate the validity of the 50-year return period approach with joint probability distributions. Other floating platforms must be investigated to fully understand the impact of wind/wave misalignment, especially for nonaxisymmetric platforms.

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