INFLUENCE OF MET-OCEAN CONDITIONS ON THE LOADS ANALYSIS OF A FLOATING WIND TURBINE

A Thesis in
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by
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ABSTRACT

Better wind resources far from the shore and in deeper seas have encouraged the offshore wind industry to look into floating platforms. The International Electrotechnical Commission (IEC) is now working on creating a new standard for floating wind turbines derived from existing standards for land-based and fixed-bottom offshore wind turbines. This work aims to determine the best practices in the loads analysis of floating wind turbines to ensure reliable designs and address the unknown impact of wind/wave misalignment on the designs of floating platforms. In order to provide some guidance on how to take this misalignment into account, an aero-hydro-servo-elastic computer-aided engineering tool for horizontal axis wind turbines, FAST, was used to simulate the operation of a floating offshore wind turbine under a wide range of metocean conditions (wind speed, significant wave height, peak-spectral wave period and wind/wave misalignment). Ultimate and fatigue loads analysis were carried out for the OC3-Hywind spar buoy platform and the National Renewable Energy Laboratory (NREL) 5 MW reference wind turbine. From this extensive analysis we are able to determine the impact of misaligned winds and waves on the structure and the importance of taking it into account in the design of a floating platform. Also investigated is the most critical metocean conditions combinations for the structural integrity of the floating offshore wind turbine. Finally the impact of considering misaligned wind and waves in the levelized cost of energy calculations was investigated.
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NOMENCLATURE

\( \sigma_i \) stress level
\( A \) availability of the wind turbine
\( CAPEX \) capital costs
\( D \) lifetime damage
\( DELs \) Damage Equivalent Loads
\( D_{ij}^{ST} \) is the accumulated damage from time-series \( j \)
\( d_t \) duration of timestep \( i \)
\( E_{\text{sim}_{k,j}} \) simulation \( k \) with a wind/wave misalignment \( j \)
\( E_{\text{sim}_k} \) energy production for simulation \( k \)
\( E_{\text{sim}} \) energy production per simulation in kWh
\( f^{eq} \) is the DEL frequency
\( f_{cr} \) fixed-charge rate
\( f_j^{Life} \) lifetime extrapolation factor for simulation \( j \)
\( GenPwr_i \) power produced by the generator at timestep \( i \)
\( H_s \) Significant Wave Height in m
\( LCOE \) levelized cost of energy
\( m \) Wöhler or fatigue exponent of a material (see S-N curves)
\( n_i \) number of cycles at stress level \( \sigma_i \)
\( n_j^{STeq} \) equivalent counts for simulation \( j \)
\( n_{ji} \) \( j^{th} \) cycle count of the \( j^{th} \) simulation
\( n_{ji}^{Life} \) extrapolated number of cycles over the lifetime of the system
\( N_i \) number of cycles to failure at stress level \( \sigma_i \)
\( N_j \) number of simulations with the wind/wave misalignment \( j \)
\( N_j^{eq} \) is equivalent number of cycles until failure for time-series \( j \)
\( OPEX \) operating costs
\( p_k \) probability of occurrence of simulation \( k \)
\( p_l^V \) probability of a wind speed \( V \) in the bin \( l \)
\( t \) time in s
\( T^\text{Life} \) design lifetime period (s)
$T_j$ is the duration of time-series $j$.

$T_i$ total time for all simulation that have a mean wind speed falling into the bin $l$

$T_p$ Wave Peak Spectral Period in s

$V_{in}$ cut-in wind speed (3 m/s)

$V_j$ the wind speed of simulation $j$

$V_{out}$ cut-out wind speed (25 m/s)

$V_{xi}$ $x$-component of the wind velocity at timestep $i$

$Wd$ Wind/wave misalignment in degrees

$Welev$ wave elevation at time $t$

$Ws$ Wind Speed in m/s

**FAST nomenclature:** (see FAST User guide for additional explanations and coordinate systems)

- $Anch1Ten$ anchor tension in N of the first mooring line
- $Anch2Ang$ anchor angle in degrees of the second mooring line
- $Anch2Ten$ anchor tension in N of the second mooring line
- $Anch3Ang$ anchor angle in degrees of the third mooring line
- $Anch3Ten$ anchor tension in N of the third mooring line
- $Fair1Ten$ fairlead tension in N of the first mooring line
- $Fair2Ten$ fairlead tension in N of the second mooring line
- $Fair3Ten$ fairlead tension in N of the third mooring line
- $IPDefl1$ in-plane deflection of blade 1
- $LSSGagMya$ low speed shaft torque about the ya axis
- $LSSGagMza$ low speed shaft torque about the xa axis
- $OoPDefl1$ out-of-plane deflection of blade 1
- $RootMxc1$ first blade root bending moment about the xc1 axis
- $RootMyc1$ first blade root bending moment about the yc1 axis
- $TwrBsMxt$ tower base moment about the xt axis
- $TwrBsMxyt$ tower base moment about the yt axis
- $YawBrMxp$ yaw bearing moment about the xp axis
- $YawBrMyp$ yaw bearing moment about the yp axis
Chapter 1
Introduction

Background

More and more electricity is produced by wind turbines and the role of wind energy in the energy market will keep increasing as the wind power share of global electricity demand is predicted to reach between 6% (New Policies scenario) to 11.7% (Advanced Scenario) by 2020 (Global Wind Energy Council, 2012) with global cumulative wind power capacities between 586 GW and 1.15 TW. (Global Wind Energy Council, 2012). Currently, offshore wind farms represent only a small percentage of the global installed capacity, less than 2%, but it is predicted to reach 10% of the global installed capacity by 2020 (Global Wind Energy Council, 2012). Offshore wind represents a good opportunity of growth for the wind sector, and because it is more technically challenging, an important part of the R&D in wind energy is dedicated to offshore wind technologies and environments.

Offshore wind farms present advantages such as: a greater wind resource due to less flow obstructions and lower turbulence levels which causes less fluctuations in the loads experienced by the structure (Tony Burton, 2011). Moreover, in the US, offshore wind resources are also closer to big coastal cities where, not only is it harder to build onshore wind farms nearby, but the winds are weaker than inland, as it can be seen on the maps in Figure 1-1. The National Renewable Energy Laboratory estimates that the potential of offshore wind represents about four times the total generating capacity from all sources. (M. Schwartz, 2010)

However installing wind farms offshore remains much more expensive and more challenging: dedicated vessels are needed, the installation is more difficult and subject to weather constraints, it's harder to access the turbines for maintenance and obtaining permits can be challenging around some countries. Europe has been solving some of these issues by supporting the development of an offshore wind industry with the participation of the governments to define development zones for offshore wind farms in some European countries. In the US, even though there are no offshore wind farms commissioned yet, some projects are being developed and offshore wind research is currently well supported by the Department of Energy.
Since the first one, Vindeby, was built in 1991 in Denmark, offshore wind farms have been developed across the world, mostly in Europe, in the North, Baltic and Irish Seas. As of 2012, about 4,995 MW of offshore wind farms are installed totaling over 1,660 turbines (European Wind Energy Association, January 2013). China has some demonstration projects installed as well. In the US several projects in
the planning stages are underway in New Jersey, Massachusetts, Delaware, Texas, Rhode Island and Ohio.

Existing offshore wind farms use fixed-bottom foundations with support platforms fixed on the seabed. These technologies, jackets, monopiles, gravity base and tripods, are valid for shallow waters and transitional depths, as shown in Figure 12. For deeper seas, floating platforms become more cost-efficient. As there is limited coastal space with shallow waters and transitional depths, especially in the US, the interest and research on floating offshore wind farms is growing.

![Diagram showing different offshore wind farm technologies](image)

**Figure 1-2**: Adapted fixed-bottom and floating technologies for different depths with an estimate of the energy resources. (J. M. Jonkman, 2007)

The first full-scale floating wind turbine, Hywind, was installed in the North Sea off of Norway in 2009 by Statoil. The float tower was a design of Technip and the 2.3 MW wind turbine was built by Siemens Wind Power. The prototype is still operating and another design, that could carry a bigger rotor, is under development.
The WindFloat design by Principle Power was installed with a 2 MW wind turbine in late 2011 in Portugal's seas. This semi-submersible prototype is the first full scale prototype of this type of platform which prevents the wind turbine from experiencing large amplitude motions during operation.

Sway AS installed a 1:6 scaled prototype of a future 5 MW turbine with a ballasted, tension-moored tower. The National Renewable Energy Laboratory is participating in some testing studies to get a better understanding of this floating offshore wind turbine.
Another prototype recently installed in the US, the first in the US waters, is a design from the University of Maine, VolturnUS, installed in Castine Harbor. It's a 1:8 scale of a future 6-MW system with a semi-submersible platform. Other designs are also being developed in Europe, in the US and in Asia.

![Figure 1-5: Picture of the prototype of Sway AS from SWAY AS®.](image-url)
Platform technologies

As mentioned before, there are two main categories in offshore wind technology: “fixed-bottom” platforms and floating platforms attached to the seabed by mooring lines. Floating platforms can be distinguished by the mechanism or the combination of mechanisms used to achieve static stability: buoyancy, ballast and mooring lines. The spar-buoy platform uses the weight of the spar to have a system with a center of mass below the center of buoyancy so that when the system is pitched or rolled, a restoring moment is created to restore stability. A Tension-Leg-Platform (TLP) uses taut mooring lines to maintain stability, it creates less motions of the wind turbine with the waves but the failure of a mooring line causes the whole system to collapse. Semi-submersible platforms achieve stability with a combination of a large water plane area and ballasts.
Standards

To help the development of the floating wind energy industry, main certification organizations are developing design standards and recommendations for floating wind turbines. GL (Germanischer Lloyd) addresses the recommendations for floating wind turbine in its “Guideline for the Certification of Offshore Wind Turbines”. DNV is working on publishing its own floating wind turbines standard. The IEC (International Electrotechnical Commission) is developing a floating wind turbine standard IEC/TS 61400-3-2 Ed. 1.0. The Technical Committee 88 is responsible for IEC’s standards’ development. This study was the results of a collaboration with Jason Jonkman (NREL), Amy Robertson (NREL), Denis Matha (University of Stuttgart), Lorenz Haid (University of Stuttgart), Matthew Lackner and Gordon Stewart (University of Massachusetts). This research group conducted studies about the loads analysis processes of floating offshore wind turbine to issue recommendations to the Technical Committee 88.
**Previous studies**

The study of the research group preceding this work was led by Lorenz Haid and focused on the simulation length needs for the loads analysis of a floating offshore wind turbine composed of the OC3-Hywind spar buoy platform and the NREL 5 MW reference wind turbine. Ultimate loads analysis and fatigue analysis have been carried out for this design for different simulation lengths: 10 minutes, 20 minutes, 1 hour, 3 hours and 6 hours. Comparison of the results and in-depth research on the rainflow counting algorithm led to a recommendation of a length of 10 minutes (Haid et al., 2013).

The National Renewable Energy Laboratory is leading the research on floating offshore wind turbine and has conducted many studies on different floating concepts (Jonkman, 2011; Jonkman, 2007; Roald, 2013, Robertson, 2011). The processes used for loading and fatigue analysis come from the analyses of onshore and fixed-bottom wind turbines. Guidance on loads analysis techniques can be found in a technical report of Sandia National Laboratories (Sutherland, 1999). An extensive study of loads analysis has been carried out by Barone et al. using high performance computing resources to simulate decades of operation of an onshore wind turbine (Barone, Paquette, Resor, & Manuel, 2012). The same amount of simulations for offshore wind turbines would require even more computational resources, however this study gives good insights on the extrapolation techniques of the lifetime extremes loads.

The impact of misaligned wind and waves on the loads experienced by an offshore wind turbine has been studied mainly for fixed-bottom offshore wind turbines. Kuhn’s thesis provides a comparison of the damage equivalent stress range on the tower for different wind/wave misalignment (collinear versus misaligned) for an offshore wind turbine on a monopile support. It shows that considering misaligned wind and waves leads to reduced damage on the tower circumference in the prevailing wind direction and a slight increase in damage in the lateral direction (Kühn, 2001). Fisher et al. (2011) also analyzed the importance of wind and wave misalignment for monopile wind turbines and found increased side-to-side loading on the support structure for the 90° and 270° wind/wave misalignments (Fisher, 2011). Another study confirmed the increase in the loading with misalignment wind and waves from measurement on a monopile structure of an offshore wind turbine at the Bockstigen wind farm (Trumars et al, 2006). Sensors were placed 2 m from sea bottom on the monopile structure and side-to-side loadings measurements at this location showed an increase with misaligned wind and waves.

From these previous studies and knowing that floating offshore wind turbines are more sensitive to waves than fixed-bottom offshore wind turbines, it seems that misaligned wind and waves
might create important loads on the floating offshore wind turbine and should be taken into consideration during the design process. To determine if and how it should be taken into account in the design process for the OC3-Hywind spar buoy model is the goal of this study.
Chapter 2
Floating wind turbine system

NREL 5 MW Turbine

The National Wind Technology Center (NWTC) of the National Renewable Energy Laboratory (NREL) has conceived a reference 5 MW wind turbine to represent a typical multi-megawatt wind turbine used in onshore and offshore utility-scale wind projects. The size and power capacity of this reference wind turbine have been chosen in order to be cost effective in the case of deep water installations. This also enables comparisons with existing wind turbines (AREVA M5000, Repower 5M). Though no information from the industry was available, several research projects developed conceptual 5 MW and 6 MW wind turbines (RECOFF or Recommendations for Design of Offshore Wind Turbine project, DOWEC or Dutch Offshore Wind Energy Converter project, WindPACT or Wind Partnerships for Advanced Component Technology). From these conceptual designs, NWTC was able to develop its own reference wind turbine. The main properties are indicated in Table 2-1. More information on the turbine can be found in the literature (J. Jonkman, 2009) including the blades, hub, nacelle, drive train and tower properties and the baseline control system properties.

Table 2-1: Main properties of the 5 MW reference wind turbine developed by NREL (J. Jonkman, Butterfield, Musial, & Scott, 2009)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating Power</td>
<td>5 MW</td>
</tr>
<tr>
<td>Rotor</td>
<td>Upwind, 3 Blades</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>126 m</td>
</tr>
<tr>
<td>Hub Height</td>
<td>90 m</td>
</tr>
<tr>
<td>Cut-in, rated, cut-out wind speeds</td>
<td>3 m/s, 11.4 m/s and 25 m/s</td>
</tr>
<tr>
<td>Rotor, Nacelle, Tower masses</td>
<td>110, 240 and 347.46 tones</td>
</tr>
</tbody>
</table>
The Platform design used for the current study is the Spar Buoy design developed for Phase IV of the OC3 Project (Offshore Code Comparison Collaboration). The aim of OC3 is to compare the different existing aero-hydro-servo-elastic codes developed by different research institutions. The Phase IV aimed to compare results for a floating wind turbine of the Spar Buoy concept developed by Statoil. Detailed information of the platform and mooring system were provided by Statoil to NREL to create publicly available data. The data have been adapted for the 5 MW reference NREL wind turbine. The result of this work is the publicly available “OC3-Hywind” platform design.

A brief summary of the main data can be found in Table 2-2. More detailed data can be found in Jonkman (Jonkman J. , Definition of the Floating System for Phase IV of OC3)

Table 2-2: Main properties of the OC3-Hywind platform design

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of the platform elevation</td>
<td>10 m</td>
</tr>
<tr>
<td>Draft of the platform</td>
<td>120 m</td>
</tr>
<tr>
<td>Platform shape</td>
<td>2 cylinders (6.5 and 9.4 m of diameter)</td>
</tr>
<tr>
<td>Mass (includes ballast)</td>
<td>7,466 tones</td>
</tr>
</tbody>
</table>

The natural frequencies of the platform can be found in Table 2-3 (Matha, 2009)
### Table 2-2-3: Natural frequencies of the OC3 Hywind Platform

<table>
<thead>
<tr>
<th>Mode</th>
<th>Platform surge</th>
<th>Platform sway</th>
<th>Platform heave</th>
<th>1st Tower S-S</th>
<th>2nd Tower S-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Frequency [Hz]</td>
<td>0.0080</td>
<td>0.0080</td>
<td>0.0324</td>
<td>0.4573</td>
<td>4.2584</td>
</tr>
<tr>
<td>Mode</td>
<td>Platform roll</td>
<td>Platform pitch</td>
<td>Platform yaw</td>
<td>1st Tower F-A</td>
<td>2nd Tower F-A</td>
</tr>
<tr>
<td>Natural Frequency [Hz]</td>
<td>0.0342</td>
<td>0.0343</td>
<td>0.1210</td>
<td>0.4732</td>
<td>3.7512</td>
</tr>
</tbody>
</table>

Impact of the environment on the system

Any offshore wind turbine is subjected to various sources of loadings from its environment:

- **Aerodynamics loads:**
  - Steady loads (incoming mean wind speed)
  - Fluctuating loads (turbulence, gusts)
  - Periodic loads (wind shear, tower shadow, off-axis winds)
  - Other loads (icing, lightning)

- **Hydrodynamic loads:** from waves, currents, and tides.

In addition to these environmental loads, the wind turbine is also subject to:

- **Gravitational and inertial loads** (from gravity, vibration, centrifugal and gyroscopic forces and seismic activity)
- **Actuation loads** resulting from the operation and control of the turbines (torque control, yaw and pitch control, mechanical brakes)

These fluctuating sources create fluctuating stresses on the structure over its lifetime. Hence not only the highest loads during the system lifetime are important for the design process, the damage created by these fluctuating loads is a design-driver for wind turbines. Standards and certification organizations provide guidance on how to carry out analyses to take into account different situations from which high loads or damage can arise. The different situations include normal operation, faults during operation, parked wind turbine and idling wind turbine. The main reference for the design loads cases is the IEC standard 61400-1 for onshore wind turbines or 61400-3 for offshore wind turbines (IEC, 2009). The focus of this study will be on DLC 1.1 as defined by the IEC Standard, this load case covers normal operation between the cut-in wind speed and the cut-out wind speed with no yaw misalignment. From
this load case, ultimate loads and fatigue loading can be calculated. In the offshore wind IEC standard it is mentioned that significant wave conditions should be simulated and that the wind and wave misalignment doesn’t have to be taken into account except if it is of particular importance for the design.

Figure 2-2: Loads on a floating wind turbine (Jonkman J., Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine, 2007)
Chapter 3

Met-ocean Conditions

Introduction

Met-ocean conditions are critical for the installation of a floating wind turbine. The whole design is determined by the wind conditions (average and 50-year extreme wind speeds, maximum 3-s gust speed, distribution of wind speeds, turbulence intensity, directionality, wind shear) and the wave’s conditions (significant wave height and peak-spectral period distribution, extreme wave height, wave directionality). These conditions determined the length of the rotor and hence the whole dimensioning of the system, the structural strength needed, the rated power and the energy production and the control system characteristics.

Buoys data

The met-ocean data for this study comes from the NOAA floating data buoys all around the US coast (Stewart, 2013). Buoys with at least 5 years of data and containing both wind and wave directions data were kept and grouped into coastal regions depending on their locations: East Coast, West Coast and Gulf of Mexico. For each buoy, distributions related to the four parameters were fitted:

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

Finally, for each coastal region a “generic” site was created with the average parameters of all the buoys in the area. From this, a 4D table was created containing the distribution values for the East Coast generic site. This information was used to analyze the simulations outputs.
Wind/wave misalignment

Wind/wave misalignment is the difference between the wind and wave directions. For the simulations of this study, the wind always comes from the 0° direction and the wave direction varies from -180° to 180° to obtain the range of possible misalignments.

![Diagram showing wind and wave directions](image)

**Figure 3-1:** Schematic showing the floating offshore wind turbine, the direction of the wind and the direction of the waves. (The wind is fixed at 0° so the wave direction is equal to the wind/wave misalignment.)

The wind measurements of the buoys were made at 5 m above the sea level for most of the buoys. Then the wind speeds were scaled to their values at 90 m using the COARE shear model (Stewart, 2013). This model uses the atmospheric conditions (air pressure, humidity, air temperature, and water temperature) of the site to calculate the wind shear profile, it is said to be more accurate than the power law for offshore sites. The air pressure, humidity, air and water temperatures are measured by the data buoys. However, only the wind speeds were scaled and not the wind directions. The winds at 5 m might be more correlated with the waves and hence the misalignment might be lower in average than if we were considering the wind direction at 90 m but wind measurements at 90 m offshore for the US Coasts are not publicly available.
Chapter 4
Methodology

We will describe in this section the different tools used to simulate the behavior of the floating offshore wind turbine and carry out its structural analysis. The different tools were provided by the National Renewable Energy Laboratory (NREL, s.d.). Most of them are publicly available, especially the main code: FAST. The post-processing codes can also be found on NREL’s website but for this study modified versions; that are not yet publicly available; were used. All these tools are frequently updated and corrected and support is available through the NREL engineers. (NREL, s.d.)

Computational facilities

The High Performance Computer (HPC) resources at NREL were used for this study. Due to the significant quantity of simulations, more memory and calculation performance were required than what is available on a standard computer. NREL’s cluster offered good calculation performance. It is composed of three enclosures of ten nodes composed of eight cores which makes a total of about 240 cores. 200 of these cores are available to submit simulations and about 30 cores were dedicated for this study. Codes, input files and results were stored on a server with Terabytes of memory available.

All of the codes, input files and simulation submission scripts are stored on the server. To run a simulation on the HPC, we have to submit a job that contains the information of one or more simulations. The jobs are described in batch files (.bat) that can be launched using the command window and specifying where they should run (on the HPC or locally on the server). As the HPC resources are shared, a compromise is made between reducing the number of jobs submitted at once and getting all of the simulations done in a “reasonable” period of time. Submitting jobs containing 200 simulations created a reasonable number of jobs on the HPC and took a sensible amount of time to run all the simulations. The total running time is estimated to be about two weeks if they had been run uninterrupted. The jobs were stopped several times due to some scheduled and unscheduled restarts of the HPC. Once the simulations run, binary output files are created on the server and are available for post-processing. Using binary files reduced the memory needed for the output files. With the pertinent simulations, codes and scripts were generated to automate the post-processing of the files.
FAST

The wind turbine modeling tool used was the non-linear aero-hydro-servo-elastic computer-aided engineering tool for horizontal axis wind turbines FAST (Fatigue, Aerodynamics, Structures and Turbulence) (NREL, s.d.). It uses a combined modal and multibody dynamics formulation. The whole system is broken down in different rigid bodies (e.g. support platform, nacelle and hub) and flexible bodies (tower, blades and drive shaft) modeled with a linear modal representation. For three-bladed horizontal-axis wind turbine (HAWT) a total of 24 degrees of freedom (DOF) are available: six for the platform motions relative to the inertia frame, four for the tower motions, three for the yawing motion, the generator azimuth angle and the compliance in the drivetrain between the generator and the hub, nine for the blades flapwise (first and second modes) and edgewise motions (first mode) and two for the rotor- and tail-furl. Any DOF can be activated or not during the simulations.

One simulation consists of 10-minute long time-marching calculations of the nonlinear equations of motions by interfacing with two modules for the aerodynamics and hydrodynamics loads: AeroDyn (Hansen, 2005) and HydroDyn (Jonkman, 2007) as shown in Figure 5-1. The input wind flows used were random turbulent full-field wind files created by TurbSim. (Jonkman B., 2009)

![Diagram](image)

Figure 5-1: The different modules composing the FAST code (Jonkman, 2007)

Input files

The primary input file contains information about:

- Basic simulations parameters such as the time step, the duration, the selection of DOFs to be used and the initial conditions.
- The turbine control parameters
- The turbine configuration (positions of the nacelle, hub, tower-top and rotor)
- Drivetrain, generator, yaw and brakes parameters
- The list of structural locations to output

It must also contain the names of the input files for the platform, the tower, the aerodynamics and the blades.

The platform file contains information on the onshore or offshore support: the initial position of the platform, the type of platform, the mooring lines, the waves and current parameters (including the wave direction). The waves can be created as regular waves or as irregular waves from a modified Pierson-Moskowitz spectrum (Faltinsen, 1990) or a user-defined spectrum. For floating platforms, this input file must reference a file created by Wamit, Inc (Newman, 1999) containing different matrices needed to model the hydrodynamics of the platform.

Information on the blades and tower geometry will be found in their respective input files. The input file for AeroDyn contains the airfoil data and options on the aerodynamics models to be used.

The wind files used are binary files, with the extension .wnd, containing the information of the wind speed for each point of the grid. The grid height is 179.26 m and the grid width is 248.26 m. A formula to estimate the grid size necessary can be found in Haid et al., 2013. The grid contains 40x55 grid points which corresponds to about 4.6 m between each point vertically and horizontally. The wind file is created for 660 s but the first 60 s give transients that aren’t analyzed. Initial values were defined in (Haid et al., 2013) for the spar-buoy platform to reduce the transients from 200 s to 60 s. A time step of 0.05 s was used so the wind file must contain 12000 values for each components of the wind speed for the 600 s of simulation. We are using the Normal Turbulence Model, assuming a zero-mean Gaussian distribution for turbulence and a uniform shear model, as defined by the IEC (IEC, 2009).

**Calculations**

The calculations are carried out by the Fortran 90 files that are compiled in the FAST executable file. This executable needs to be called from a command window with the name of the primary input file. In the command window, information about the time of the simulation and the time steps already calculated is reported. When running the simulations by batch jobs on the HPC there is no instantaneous feedback, message files containing what would be shown in the command window are created on the server for each simulation. After the simulations were run, the message and output files were checked to verify that the output files are non-empty and that no error occurred that could
have stopped the simulations. When some simulations stopped, the "FAST Aborted" error code was generated and written in the message file, after finding and fixing the issues, the simulations were run again until all simulations were successful. More information on the simulations errors is given in the RunIEC section of this chapter. The last step is to check the output files for numerical instabilities in the results. The numerical instabilities can also be detected during the post-processing step.

Output files

A FAST output file contains the information on the different DOFs as a function of the time steps, which is called “time series”; the displacements, the forces and moments are reported as well as the different components of the wind speed and the wave elevation. The output files can be text files or binary files. As indicated before, binary files were used for memory purposes. So in order to visualize the time series, MATLAB® scripts were used to read the data in the output files. The main structural locations of interest for this study are the blade roots, the yaw bearing, the low-speed shaft and the tower-base as well as the mooring lines’ anchors and fairleads points shown in Figure 4-2. Of great importance is also the wind and wave data as well as the platform motions (displacements and angular motions) to capture the impact of the offshore environment on the system.

The different platform degrees of freedom are the surge (x-axis), the sway (y-axis) and the heave (z-axis) for the displacements and the roll (x-axis), pitch (y-axis) and yaw (z-axis) for the angular motions as shown on Figure 4-3.

The tower-base and yaw-bearing moments about the x-axis and the y-axis can be referred to as “side-to-side” and “fore-aft”. For the blades moment, two motions are distinguished: motions that remains in the rotor plane, e.g. in-plane deflection also called edgewise deflection, and motions perpendicular to the rotor plane (following the x-axis), e.g. out-of-plane deflection also called flapwise deflection.
Figure 4-1: Different components of the nacelle from the U.S. DOE’s Office of Energy Efficiency and Renewable Energy (EERE).

Figure 4-2: Anchor and fairlead locations on a mooring line. The anchor is attached to the seabed and the fairlead is attached to the floating platform.
RunIEC

To be able to run all of the FAST simulations, a Perl script (Buhl, 2012) was used that automates the running process of many FAST simulations by taking the input files, modifying the parameters that are varying, creating the batch files to run the simulations on the HPC and writing the output and message files back onto the server. It can also work locally on the server. For this study, the varying parameters were the wind speeds- and so the wind file, wave direction, significant wave height and wave peak-spectral period. The last two are used to define the wave spectrum (the modified Pierson-Moskowitz spectrum was used). These parameters were specified to RunIEC as an input table containing all the combinations of these four parameters with values contained between extrema defined in Table 4-1. The input table contained a total of 370,656 simulations: one for each combination of metocean conditions.

Table 4-1: Values for the different parameters of the metocean conditions for this study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bins’ width</th>
<th>Numbers of bins*</th>
<th>Minimum value</th>
<th>Maximum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed at hub height</td>
<td>2 m/s</td>
<td>11</td>
<td>3 m/s</td>
<td>25 m/s</td>
</tr>
<tr>
<td>Significant Wave Height (Hs)</td>
<td>0.5 m</td>
<td>26</td>
<td>0 m</td>
<td>13 m</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------</td>
<td>----</td>
<td>-----</td>
<td>------</td>
</tr>
<tr>
<td>Peak spectral period (Tp)</td>
<td>0.5 s</td>
<td>54</td>
<td>0 s</td>
<td>27 s</td>
</tr>
<tr>
<td>Wave direction (Wd)</td>
<td>15°</td>
<td>24</td>
<td>-180°</td>
<td>180°</td>
</tr>
</tbody>
</table>

* The bins are defined by their midpoints

After running RunIEC, the simulations were checked to assure that they were run successfully. To automate this process, some MATLAB® scripts were written to read every message files and look for the sentence “FAST terminated” which means the simulation ran correctly. Any empty output file or message file containing “FAST aborted” meant the simulation had to be run again and two reruns were needed to obtain all successful simulations. It was found that, the simulations that failed did so because of network failures probably because they were submitted on some deficient nodes in the HPC. During the last run, where we refined the selection of nodes to be used, no simulations failed.

Another script was written to generate the list of all the successful simulations and their respective folder location. This list is very helpful for the post-processing of the simulations.

**Extreme events code**

The extreme events analysis aims to look at the highest loading on the system for the IEC 61400-3 design load case 1.1. Thus, for this study, the standard operating conditions are of interest. The extreme loads can be found by reading all the output files and extracting the maximum for every file and then taking the maximum of all the files. The post-processor MExtremes (MExtremes by Greg Hayman, s.d.), which consists of several MATLAB® scripts, carries out this process and writes the maximum and minimum loads experienced for the forces, moments and displacements selected by the user in a text and/or an Excel output file. This post-processor can be run in MATLAB® or with this executable.

Running MExtremes in MATLAB® enables the user to save the matrix containing all the maxima for all the files. This provided an ability to check the script by comparing the maxima of all the files to the ones MExtremes gives in its output file. After making sure the correct method was being used to calculate the extreme events, the method was refined to calculate the extreme events only for certain wind/wave misalignment. Hence, the extreme events for each wind/wave misalignment as well
as for groups of wind/wave misalignments were obtained. The groups of wind/wave misalignments used are described in Chapter 5.

Selection of extreme events for the East Coast generic site

By using the joint probability distribution created for the East Coast site, the probability of each simulation can be calculated. As a wide range of metocean conditions were calculated, all the non-zero probabilities of the distribution were represented by a simulation. Ordering the probabilities of the simulations by their value enables one to select the simulations with probabilities above a 50-year old threshold, i.e. 3.7*10^{-8}. The selection for this 50-year old threshold contains 30,313 simulations that best represent the East Coast generic site. By grouping the simulations by their wind/wave misalignment, extreme loads per wind/wave misalignment and for different groups of wind/wave misalignment were obtained for the East Coast site.

Memory and time considerations

The more simulations involved in post-processing and the more structural points included in the analysis, the more memory MExtremes will need. Indeed, MExtremes stores two main matrices with the maximum and the minimum of each simulations for all the structural points as well as the values of time, wave elevation and wind speed at which the extreme happens:

\[
\text{ChanMinAssocValues} = \text{zeros}\left(\text{nEEvChans, nEEvInfPlusChans, TotalFiles, 'single'}\right);
\text{ChanMaxAssocValues} = \text{zeros}\left(\text{nEEvChans, nEEvInfPlusChans, TotalFiles, 'single'}\right);
\]

nEEvChans is the number of channels (structural points) being analyzed, nnEEvInfPlusChans is nEEvChans plus time, wind speed and wave elevation and TotalFiles is the total of all the simulations that will be post-processed. 'single' is the precision of the number in the matrix, using 'single' versus 'double' allow saving some memory as a single number needs 4 bytes of memory versus 8 bytes for a double number. In post-processing 300,000 files and 50 channels, 50*53*300,000*4 = 758 MB of memory is needed for each matrices, i.e. 1.5 GB for the two matrix and a little bit more the rest of the code. If you want to increase the number of channels by two, you'll increase the memory by four, i.e. 6 GB of memory.
Running MExtremes for all of the simulations and for 10 structural points of interest takes about twelve hours and can run overnight. It helps to break down the simulations into smaller subsets of about 5,000 simulations. MExtremes has a save/restore function that enables it to run several times with each subset and compile the final results. This feature helps keeping the memory used by MATLAB® low and prevents having to start from the beginning if there’s an unscheduled stop (i.e. a restart of the server or a power outage).

Fatigue analysis code

Theory

The fatigue analysis was carried out using MLife v1.00.00h-gjh (Hayman, MLife by G.J. Hayman, v1.00.00h-gjh, 2013), another publicly available post-processor developed and frequently updated by NREL. It’s also based on MATLAB® scripts but can also be run with its executable. It follows the recommendations that the standard IEC 61400-1 (IEC, 2009) provides in its Annex G “Miner’s rule with load extrapolation for the fatigue analysis of wind turbines”. The Miner’s rule or Palmgren-Miner linear damage rule, first developed by Palmgren in 1924 and then promoted by Miner in 1945 (Miner, 1945), states the relationship, shown in equation (1), between the number of cycles $n_i$ at different stress levels ($\sigma_i$) and the number of cycles to failure $N_i$ of these stress levels and the damage created by these stress cycles.

$$\sum_{i=1}^{M} \frac{n_i(\sigma_i)}{N_i(\sigma_i)} = D \quad (1)$$

Miner’s also stated that structural failure happens when the damage is equal to one, whereas in reality it can vary between 0.79 and 1.53. (Sutherland, 1999). This “macroscopic” approach of fatigue considers the damage created by the fluctuating loads. Load cycles (Figure 5-4) are counted by taking the local maximum and paring it with a local minimum that completes the cycle using a rain-flow cycle counting algorithm. The theory of MLife and how to use it are well documented in (Hayman, MLife Theory Manual for Version 1.00, 2012) and (G.J. Hayman, 2012).
When calculating the lifetime damage, each cycle counted \((n_{ji})\) for the \(i^{th}\) cycle count of the \(j^{th}\) simulation) in every simulation needs to be multiplied by an extrapolation factor \(f_{j}^{Life}\) (for the \(j^{th}\) simulation) to obtain the extrapolated number of cycles over the lifetime of the system \(n_{ji}^{Life}\).

\[
\begin{align*}
  n_{ji}^{Life} &= f_j^{(Life)} \times n_{ji} \quad (2) \\
  f_j^{Life} &= \frac{T_j^{Life} \times A \times p_j^V}{T_l}, \quad V_{in} < V_j < V_{out} \quad (3)
\end{align*}
\]

\(V_{in}\) and \(V_{out}\) represent the cut-in and cut-out wind speeds of the turbine, respectively.

\(p_j^V\) is the probability, often given from a Weibull distribution, of a wind speed \(V\) in the bin \(l\).

\(V_j\) is the wind speed of the simulation

\(T_j^{Life}\) is the design lifetime periods (s)

\(T_l\) is total time for all simulation that have a mean wind speed falling into the bin \(l\).

However, in this study, the different metocean parameters (wind speed, significant wave height, peak-spectral period and wave direction) need to be considered in the fatigue calculations. That’s why MLife had to be modified to be able to use a joint probability of the four metocean parameters in the extrapolation factor. In order to add this capability, the script for calculating the extrapolation factor was replaced by a script able to read a four parameter distribution given in a binary data file. This capability was tested comparing the results using the one parameter distribution to the
four parameter distribution, making sure that the probabilities used corresponded and importantly that the total probability remained the same.

Input file

When running MLife with MATLAB the mlife.m function (the main function) is called with an input file .mlif. This input file contains parameters about the fatigue analysis to be carried out: the list of simulations to be analyzed listed by the full paths of their output files, the mean values of the four metocean parameters for each simulation, information about the type and format of the output, the list of structural points to be analyzed and parameters regarding the fatigue analysis theory like the design lifetime in seconds, the availability, the multiplier for binning unclosed cycles and the type of analyses you want to carry out (short-term or lifetime). Examples of input files are available with the code to provide the user with the layout to respect.

Output file

MLife can output to text files or Excel spreadsheets containing the short-term and/or lifetime results as the user chooses.

Both short-term and lifetime results are given for various S-N curves, i.e. for various fatigue exponents, \( m \), which represent different materials. This exponent is used in the calculation of the number of cycles to failure \( (N_j) \) mentioned earlier. Low values of \( m \) are typical of welded materials; with 3 and 6 commonly taken for steel and aluminum; and high values for composite materials such as fiberglass used in the blades for which exponents larger than 10 are considered. (Sutherland, 1999)

The lifetime results are the lifetime damage; time until failure in seconds and the lifetime damage-equivalent loads (DELs), which is a “constant-amplitude fatigue-load that occurs at a fixed load-mean and frequency and produces the equivalent damage as the variable spectrum loads” (Hayman, MLife Theory Manual for Version 1.00, 2012).

\[
D_{j}^{ST} = \sum_{i} \left( \frac{n_{ji}}{N_{ji}} \right) = \frac{n_{j}^{STeq}}{N_{j}^{eq}} = \frac{f_{eq} \cdot T_{j}}{N_{j}^{eq}} \tag{4}
\]

\( D_{j}^{ST} \) is the accumulated damage from time-series \( j \).
$N_{eq}^j$ is equivalent number of cycles until failure for time-series $j$.

$f_{eq}^j$ is the DEL frequency.

$T_j$ is the duration of time-series $j$.

The short-term results contains the damage-rates (damage divided by the duration of the time-series) for each simulation and the short-term DELs, where the cycles’ counts are not extrapolated over the lifetime, also for each simulation.

**Memory considerations**

MLife, like MExtremes, reads each file and saves the minima and maxima of the loads in order to calculate the load cycles. However, MLife uses more memory as it requires additional calculations after this. Hence, the memory becomes an issue for MLife with a consequent number of simulations. This is why only the East Coast site’s simulations were processed for this study.
Chapter 5 Loads Analysis Results

Extreme loading results

All conditions

The extreme loading experienced on different parts of the floating system were extracted from the simulations output using MExtremes (MExtremes by Greg Hayman, s.d.). The wide range of metocean conditions is considered here so the 370,656 simulations are included in this analysis. When considering a wide range of metocean conditions, which will be defined as “all conditions” in the rest of this thesis, it was found that the highest significant wave height creates the highest loads for all the locations investigated, except for the generator torque, as shown in Table 6.1. Also, most of these extreme loads were created with a misalignment higher than 75°, which shows the importance of the wind/wave misalignment.

Table 6.1 Metocean conditions creating the maximum loads

<table>
<thead>
<tr>
<th>Locations</th>
<th>Maximum loads</th>
<th>Units</th>
<th>Ws (m/s)</th>
<th>Hs (m)</th>
<th>Tp (s)</th>
<th>Wd (°)</th>
<th>t (s)</th>
<th>Vxi (m/s)</th>
<th>Welev (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RootMxc1</td>
<td>12,422.0</td>
<td>kN*m</td>
<td>14</td>
<td>12.75</td>
<td>12.75</td>
<td>-105°</td>
<td>314.8</td>
<td>19.1</td>
<td>7.4</td>
</tr>
<tr>
<td>RootMyc1</td>
<td>26,780.5</td>
<td>kN*m</td>
<td>10</td>
<td>12.75</td>
<td>20.75</td>
<td>-135°</td>
<td>239.6</td>
<td>10.1</td>
<td>4.9</td>
</tr>
<tr>
<td>LSSGagMya</td>
<td>16,862.9</td>
<td>kN*m</td>
<td>14</td>
<td>12.75</td>
<td>12.75</td>
<td>75°</td>
<td>288.2</td>
<td>9.0</td>
<td>-3.1</td>
</tr>
<tr>
<td>LSSGagMza</td>
<td>19,923.1</td>
<td>kN*m</td>
<td>10</td>
<td>12.75</td>
<td>12.75</td>
<td>75°</td>
<td>301.6</td>
<td>16.6</td>
<td>-0.4</td>
</tr>
<tr>
<td>YawBrMxp</td>
<td>13,920.5</td>
<td>kN*m</td>
<td>16</td>
<td>12.75</td>
<td>6.75</td>
<td>90°</td>
<td>336.4</td>
<td>15.4</td>
<td>3.8</td>
</tr>
<tr>
<td>YawBrMyp</td>
<td>18,517.8</td>
<td>kN*m</td>
<td>24</td>
<td>12.75</td>
<td>6.25</td>
<td>0°</td>
<td>138.4</td>
<td>20.3</td>
<td>-5.4</td>
</tr>
<tr>
<td>TwrBsMxt</td>
<td>322,110.4</td>
<td>kN*m</td>
<td>16</td>
<td>12.75</td>
<td>6.75</td>
<td>90°</td>
<td>336.3</td>
<td>15.3</td>
<td>2.5</td>
</tr>
<tr>
<td>TwrBsMxyt</td>
<td>391,964.1</td>
<td>kN*m</td>
<td>12</td>
<td>12.75</td>
<td>8.25</td>
<td>180°</td>
<td>336.2</td>
<td>11.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Fair1Ten</td>
<td>1,554.3</td>
<td>kN</td>
<td>4</td>
<td>12.75</td>
<td>16.25</td>
<td>0°</td>
<td>100.0</td>
<td>2.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Fair2Ten</td>
<td>2,689.5</td>
<td>kN</td>
<td>10</td>
<td>12.75</td>
<td>21.75</td>
<td>105°</td>
<td>634.8</td>
<td>15.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Fair3Ten</td>
<td>2,675.7</td>
<td>kN</td>
<td>10</td>
<td>12.75</td>
<td>21.75</td>
<td>-105°</td>
<td>634.8</td>
<td>15.7</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Impact of wind/wave misalignment on the extreme loadings

The dependence of the extreme loading on the wind/wave misalignment is shown in the load roses in Figure 5-1. The loads are plotted at the wind/wave misalignment value that created them. These roses are different from wind roses as the degrees are values of misalignment and not values of wind direction, hence the convention to have the 0° or North direction on top of the rose doesn’t really apply here and having the 0° on the bottom of the roses enables us to differentiate these load roses from wind roses.
From the load roses, it can be observed that the extreme loads of the fairlead and anchor tensions of the mooring lines are dominated by waves. Indeed when waves are coming from or to their direction, they experienced the highest loads. The side-to-side loadings however tend to increase with a perpendicular misalignment on the contrary of the fore-aft loadings that increase more with aligned wind and waves. The blades deflections and root bending moments seem to show less dependence on wind/wave misalignment probably due to their strongest dependence on the aerodynamics. Finally, the low-speed shaft moments show almost constant loads when the direction varies although a misalignment of 75° does increase the loads slightly.

Directional Binning Sensitivity

To determine the resolution of wind/wave misalignment that results in an accurate loading assessment for the system, different groups of directions were created containing different numbers of directions: 1, 4, 4’ (also four directions but not including 0°, 90°, -90° and 180°), 8, 12 and 24. The directions included in each group are defined in Table 5.2 and these groups will be the same later for the East Coast analysis.

Table 5-2: Misalignments considered in the different direction groups
Ratios of the extreme loading found for the different direction groups to the extreme loadings found for the group with 24 directions, which contains every simulations, were calculated and are shown in Table 5.3. Depending on the location, more or less directions are needed to get an accurate estimation of the extreme loading. It shows that the 0° direction underestimates the extreme loadings for most locations with loadings as low as 21, 67 and 59% for the tower and yaw bearing side-to-side moments and the low-speed shaft z-axis moment, respectively. Considering four directions definitely improves the estimation for all locations except for the blade deflections, for which, considering eight directions would give more accurate estimations. The same results are represented in bar plots shown in Figure 5.2.

<table>
<thead>
<tr>
<th>Percentage of the extreme loads when increasing the number of directions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of directions</strong></td>
</tr>
<tr>
<td>RootMxc1 kN*m</td>
</tr>
<tr>
<td>RootMyc1 kN*m</td>
</tr>
<tr>
<td>LSSGagMya kN*m</td>
</tr>
<tr>
<td>LSSGagMza kN*m</td>
</tr>
<tr>
<td>YawBrMxp kN*m</td>
</tr>
<tr>
<td>YawBrMyp kN*m</td>
</tr>
<tr>
<td>TwrBsMxt kN*m</td>
</tr>
<tr>
<td>TwrBsMxyt kN*m</td>
</tr>
<tr>
<td>Fair1Ten kN</td>
</tr>
<tr>
<td>Fair2Ten kN</td>
</tr>
<tr>
<td>Fair3Ten kN</td>
</tr>
<tr>
<td>Anch1Ten kN</td>
</tr>
<tr>
<td>Anch2Ten kN</td>
</tr>
<tr>
<td>Anch3Ten kN</td>
</tr>
</tbody>
</table>
The same analyses were carried out for the East Coast generic site, using a 50-year return threshold of $3.7 \times 10^{-8}$ that reduces the number of simulations to 30,313. The corresponding 30,313 simulations were selected from the 370,656 simulations run before. The extreme loads shown for all conditions were mainly created by the highest significant wave height and high misalignments, however, at real offshore sites - high significant wave height tend to happen at lower misalignments and high misalignments occur with lower significant wave heights. For this reason, the extreme loads observed at the East Coast generic site, shown in Table 5.4, are lower and no longer happen under the same conditions. Lower significant wave heights are creating the extreme loads for the East Coast.
generic site but high peak-spectral periods are responsible for most of the extreme loads. It can be noted that half of the extreme loads shown in Table 5.4 happen for misalignments between -15 and 30°, showing the importance of aligned wind and waves for half of the structural locations.

Table 5-4: Metocean conditions creating the maximum loads for the East Coast site

<table>
<thead>
<tr>
<th>Locations</th>
<th>Maximum loads</th>
<th>Units</th>
<th>Ws (m/s)</th>
<th>Hs (m)</th>
<th>Tp (s)</th>
<th>Wd (°)</th>
<th>t (s)</th>
<th>Vxi (m/s)</th>
<th>Welev (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RootMxc1</td>
<td>11,387.5</td>
<td>kN*m</td>
<td>24</td>
<td>2.25</td>
<td>1.75</td>
<td>-60</td>
<td>565.2999878</td>
<td>20.72</td>
<td>-0.10</td>
</tr>
<tr>
<td>RootMyc1</td>
<td>23,342.0</td>
<td>kN*m</td>
<td>10</td>
<td>3.75</td>
<td>13.25</td>
<td>0</td>
<td>178.8000031</td>
<td>12.25</td>
<td>-2.16</td>
</tr>
<tr>
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<td>11,904.2</td>
<td>kN*m</td>
<td>24</td>
<td>5.25</td>
<td>10.75</td>
<td>30</td>
<td>333.6000061</td>
<td>20.34</td>
<td>-1.99</td>
</tr>
<tr>
<td>LSSGagMza</td>
<td>10,533.1</td>
<td>kN*m</td>
<td>22</td>
<td>5.75</td>
<td>8.75</td>
<td>-15</td>
<td>633.0999756</td>
<td>23.50</td>
<td>-2.60</td>
</tr>
<tr>
<td>YawBrMxp</td>
<td>10,564.5</td>
<td>kN*m</td>
<td>12</td>
<td>4.75</td>
<td>8.25</td>
<td>120</td>
<td>422.2000122</td>
<td>11.47</td>
<td>0.35</td>
</tr>
<tr>
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<td>15,052.6</td>
<td>kN*m</td>
<td>24</td>
<td>4.75</td>
<td>6.25</td>
<td>-15</td>
<td>138.3999939</td>
<td>20.25</td>
<td>-2.00</td>
</tr>
<tr>
<td>TwrBsMxt</td>
<td>159,354.2</td>
<td>kN*m</td>
<td>16</td>
<td>5.75</td>
<td>6.75</td>
<td>75</td>
<td>336.2999878</td>
<td>15.30</td>
<td>1.14</td>
</tr>
<tr>
<td>TwrBsMxyt</td>
<td>260,735.3</td>
<td>kN*m</td>
<td>16</td>
<td>5.75</td>
<td>6.25</td>
<td>0</td>
<td>541.7999756</td>
<td>13.33</td>
<td>-2.04</td>
</tr>
<tr>
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<td>1,350.7</td>
<td>kN</td>
<td>4</td>
<td>2.25</td>
<td>16.75</td>
<td>0</td>
<td>363</td>
<td>2.30</td>
<td>0.12</td>
</tr>
<tr>
<td>Fair2Ten</td>
<td>2,085.8</td>
<td>kN</td>
<td>10</td>
<td>3.75</td>
<td>13.75</td>
<td>-75</td>
<td>243.1000061</td>
<td>10.08</td>
<td>0.17</td>
</tr>
<tr>
<td>Fair3Ten</td>
<td>2,043.2</td>
<td>kN</td>
<td>10</td>
<td>2.75</td>
<td>15.25</td>
<td>-105</td>
<td>635.0999756</td>
<td>14.91</td>
<td>0.32</td>
</tr>
<tr>
<td>Anch1Ten</td>
<td>1,089.5</td>
<td>kN</td>
<td>4</td>
<td>2.25</td>
<td>16.75</td>
<td>0</td>
<td>363</td>
<td>2.30</td>
<td>0.12</td>
</tr>
<tr>
<td>Anch2Ten</td>
<td>1,824.5</td>
<td>kN</td>
<td>10</td>
<td>3.75</td>
<td>13.75</td>
<td>-75</td>
<td>243.1000061</td>
<td>10.08</td>
<td>0.17</td>
</tr>
<tr>
<td>Anch3Ten</td>
<td>1,782.0</td>
<td>kN</td>
<td>10</td>
<td>2.75</td>
<td>15.25</td>
<td>-105</td>
<td>635.0999756</td>
<td>14.91</td>
<td>0.32</td>
</tr>
</tbody>
</table>

When comparing the extreme loading results for the East Coast site to the previous "all conditions" extreme loading results, as shown in Table 5.5, the average decrease is 22% and the highest decrease is seen for the tower base side-to-side loading which was the location that depended most on misaligned wind and waves. Most metocean conditions changed, except the wind speed, which remains unchanged for more than half of the locations.

Table 5-5: Comparison of the extreme loadings and their metocean conditions between the East Coast site (with the 50 year old threshold) and for the wide range of met-ocean conditions

<table>
<thead>
<tr>
<th>Locations</th>
<th>All conditions (AL)</th>
<th>East Coast (EC)</th>
<th>EC/AL</th>
<th>AL</th>
<th>EC</th>
<th>AL</th>
<th>EC</th>
<th>AL</th>
<th>EC</th>
<th>Wd (°)</th>
<th>Wd (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RootMxc1</td>
<td>12,422.0</td>
<td>11,387.5</td>
<td>92%</td>
<td>14</td>
<td>24</td>
<td>12.75</td>
<td>2.25</td>
<td>12.75</td>
<td>1.75</td>
<td>-105°</td>
<td>-60</td>
</tr>
<tr>
<td>RootMyc1</td>
<td>26,780.5</td>
<td>23,342.0</td>
<td>87%</td>
<td>10</td>
<td>10</td>
<td>9.75</td>
<td>3.75</td>
<td>20.75</td>
<td>13.25</td>
<td>-135°</td>
<td>0</td>
</tr>
<tr>
<td>LSSGagMya</td>
<td>16,862.9</td>
<td>11,904.2</td>
<td>71%</td>
<td>10</td>
<td>24</td>
<td>12.75</td>
<td>5.25</td>
<td>12.75</td>
<td>7.55</td>
<td>75°</td>
<td>30</td>
</tr>
<tr>
<td>LSSGagMza</td>
<td>19,923.1</td>
<td>10,533.1</td>
<td>53%</td>
<td>14</td>
<td>22</td>
<td>12.75</td>
<td>5.75</td>
<td>12.75</td>
<td>8.75</td>
<td>75°</td>
<td>-15</td>
</tr>
<tr>
<td>YawBrMxp</td>
<td>13,920.5</td>
<td>10,564.5</td>
<td>76%</td>
<td>16</td>
<td>12</td>
<td>12.75</td>
<td>4.75</td>
<td>6.75</td>
<td>8.25</td>
<td>90°</td>
<td>120</td>
</tr>
</tbody>
</table>
Impact of wind/wave misalignment on the extreme loadings

The impact of wind/wave misalignment on the extreme loading follows the same trend as for all conditions. Small changes appeared as high misalignment are less frequent:

<table>
<thead>
<tr>
<th></th>
<th>kN*m</th>
<th>18,517.8</th>
<th>15,052.6</th>
<th>81%</th>
<th>24</th>
<th>24</th>
<th>12.75</th>
<th>4.75</th>
<th>6.25</th>
<th>6.25</th>
<th>0°</th>
<th>-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>YawBrMyp</td>
<td>kN*m</td>
<td>322,110.4</td>
<td>159,354.2</td>
<td>49%</td>
<td>16</td>
<td>16</td>
<td>12.75</td>
<td>5.75</td>
<td>6.75</td>
<td>6.75</td>
<td>90°</td>
<td>75</td>
</tr>
<tr>
<td>TwrBsMxt</td>
<td>kN*m</td>
<td>391,964.1</td>
<td>260,735.3</td>
<td>67%</td>
<td>12</td>
<td>16</td>
<td>12.75</td>
<td>5.75</td>
<td>8.25</td>
<td>6.25</td>
<td>180°</td>
<td>0</td>
</tr>
<tr>
<td>Fair1Ten</td>
<td>kN</td>
<td>1,554.3</td>
<td>1,350.7</td>
<td>87%</td>
<td>4</td>
<td>4</td>
<td>12.75</td>
<td>2.25</td>
<td>16.25</td>
<td>16.75</td>
<td>0°</td>
<td>0</td>
</tr>
<tr>
<td>Fair2Ten</td>
<td>kN</td>
<td>2,689.5</td>
<td>2,085.8</td>
<td>78%</td>
<td>10</td>
<td>10</td>
<td>12.75</td>
<td>3.75</td>
<td>21.75</td>
<td>13.75</td>
<td>105°</td>
<td>-75</td>
</tr>
<tr>
<td>Fair3Ten</td>
<td>kN</td>
<td>2,675.7</td>
<td>2,043.2</td>
<td>76%</td>
<td>10</td>
<td>10</td>
<td>12.75</td>
<td>2.75</td>
<td>21.75</td>
<td>15.25</td>
<td>-105°</td>
<td>-105</td>
</tr>
<tr>
<td>Anch1Ten</td>
<td>kN</td>
<td>1,291.9</td>
<td>1,089.5</td>
<td>84%</td>
<td>4</td>
<td>4</td>
<td>12.75</td>
<td>2.25</td>
<td>16.25</td>
<td>16.75</td>
<td>0°</td>
<td>0</td>
</tr>
<tr>
<td>Anch2Ten</td>
<td>kN</td>
<td>2,428.5</td>
<td>1,824.5</td>
<td>75%</td>
<td>10</td>
<td>10</td>
<td>12.75</td>
<td>3.75</td>
<td>21.75</td>
<td>13.75</td>
<td>105°</td>
<td>-75</td>
</tr>
<tr>
<td>Anch3Ten</td>
<td>kN</td>
<td>2,414.7</td>
<td>1,782.0</td>
<td>74%</td>
<td>10</td>
<td>10</td>
<td>12.75</td>
<td>2.75</td>
<td>21.75</td>
<td>15.25</td>
<td>-105°</td>
<td>-105</td>
</tr>
</tbody>
</table>
Figure 5.3 - Load roses for East Coast
- Blade root bending moment, out-of-plane deflection for the first blade and in-plane deflections now achieve their highest loads for the 0° direction or for the whole -90° to 90° zone. Out-of-plane deflections for the two others blades present a less chaotic dependence on misalignment as their highest loads are mainly for high negative misalignment: -135 and -165°.

- Mooring lines now experiences their highest loads at the anchors when the waves come from the opposite direction.

- Tower base moments kept similar trends with a strong dependence on 0° and 180° for fore-aft loads and a strong dependence on close to perpendicular misalignment for side-to-side loading. Yaw bearing moments were reduced significantly but kept similar trends as well.

- The low-speed shaft moments now have a more defined behavior as a function of misalignment, the 60/75° misalignments create the highest loads for both moments.

**Directional Binning Sensitivity**

The results per directions groups for the East Coast site show, in Table 5.6 and Figure 5.4, a clear increase of the ratio of the extreme loads for one direction to the extreme loads for 24 directions. Except for side-to-side loadings (tower base and yaw bearing) you can estimate the extreme loadings with only the 0° loading with less than 4% under-estimation. This clearly indicates, for this site, that the 0° direction simulations would be sufficient, except for the two side-to-side loadings.

**Table 5.6 - Ratios of the extreme loads for each direction groups to the extreme loads for the group with 24 directions for the East Coast site.**

<table>
<thead>
<tr>
<th>Number of directions</th>
<th>1</th>
<th>4</th>
<th>4'</th>
<th>8</th>
<th>12</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>RootMxc1 kN*m</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>RootMyc1 kN*m</td>
<td>100%</td>
<td>100%</td>
<td>99%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>LSSGagMya kN*m</td>
<td>98%</td>
<td>98%</td>
<td>99%</td>
<td>99%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>LSSGagMza kN*m</td>
<td>99%</td>
<td>99%</td>
<td>96%</td>
<td>99%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>YawBrMxp kN*m</td>
<td>89%</td>
<td>91%</td>
<td>92%</td>
<td>92%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>YawBrMyp kN*m</td>
<td>100%</td>
<td>100%</td>
<td>95%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>TwrBsMxt kN*m</td>
<td>33%</td>
<td>78%</td>
<td>79%</td>
<td>79%</td>
<td>92%</td>
<td>100%</td>
</tr>
<tr>
<td>TwrBsMxyt kN*m</td>
<td>100%</td>
<td>100%</td>
<td>89%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Fair1Ten kN</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Fair2Ten kN</td>
<td>97%</td>
<td>100%</td>
<td>99%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
Table 5.7

<table>
<thead>
<tr>
<th></th>
<th>kN</th>
<th>97%</th>
<th>99%</th>
<th>100%</th>
<th>100%</th>
<th>100%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fair3Ten</td>
<td>kN</td>
<td>99%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Anch1Ten</td>
<td>kN</td>
<td>97%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Anch2Ten</td>
<td>kN</td>
<td>96%</td>
<td>100%</td>
<td>99%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Anch3Ten</td>
<td>kN</td>
<td>97%</td>
<td>99%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Verification

When comparing the results to a previous study carried out by Matha (2010), it was observed that extreme loadings in the same range were obtained in both studies, as shown in Table 5.7. The tower base side-to-side loading really increased in the current study which can be explained by the clear dependence of this load on the wind/wave misalignment. Running additional seeds for the simulations of this study would probably lead to higher loads exceeding the one obtained in (Matha, 2010) where several seeds were run for the simulations. However before running several seeds, a selection of the most important met-ocean conditions need to be done in order to reduce significantly the number of simulations to be run.

Figure 5.4 - Bar representation of the extreme loads for the different direction groups for the East Coast site
Table 5.7 - Comparison of results with a precedent study on the OC3-Hywind model (Matha, 2010)

<table>
<thead>
<tr>
<th>Locations</th>
<th>Units</th>
<th>Extreme loads</th>
<th>Ws (m/s)</th>
<th>Hs (m)</th>
<th>Tp (s)</th>
<th>Vxi (m/s)</th>
<th>Maximum loads</th>
<th>%</th>
<th>Ws (m/s)</th>
<th>Hs (m)</th>
<th>Tp (s)</th>
<th>Vxi (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RootMxc1</td>
<td>kN*m</td>
<td>11,100.0</td>
<td>24</td>
<td>5.5</td>
<td>12.7</td>
<td>27.8</td>
<td>11,387.5</td>
<td>103</td>
<td>24</td>
<td>1.75</td>
<td>10.8</td>
<td>20.72</td>
</tr>
<tr>
<td>RootMyc1</td>
<td>kN*m</td>
<td>20,500.0</td>
<td>14</td>
<td>3</td>
<td>12</td>
<td>14.5</td>
<td>23,342.0</td>
<td>114</td>
<td>24</td>
<td>2.25</td>
<td>13.3</td>
<td>12.25</td>
</tr>
<tr>
<td>LSSGagMya</td>
<td>kN*m</td>
<td>14,600.0</td>
<td>22</td>
<td>4.7</td>
<td>13.4</td>
<td>25.5</td>
<td>11,904.2</td>
<td>82</td>
<td>24</td>
<td>3.75</td>
<td>13.7</td>
<td>15.31</td>
</tr>
<tr>
<td>LSSGagMza</td>
<td>kN*m</td>
<td>14,000.0</td>
<td>24</td>
<td>5.5</td>
<td>18.3</td>
<td>22.9</td>
<td>10,533.1</td>
<td>75</td>
<td>22</td>
<td>5.75</td>
<td>8.75</td>
<td>23.50</td>
</tr>
<tr>
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<td>kN*m</td>
<td>8,800.0</td>
<td>24</td>
<td>5.5</td>
<td>12.7</td>
<td>24.9</td>
<td>10,564.5</td>
<td>120</td>
<td>24</td>
<td>4.75</td>
<td>8.25</td>
<td>11.47</td>
</tr>
<tr>
<td>YawBrMyp</td>
<td>kN*m</td>
<td>15,700.0</td>
<td>24</td>
<td>5.5</td>
<td>18.3</td>
<td>29.6</td>
<td>15,052.0</td>
<td>96</td>
<td>24</td>
<td>4.75</td>
<td>6.25</td>
<td>20.25</td>
</tr>
<tr>
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<td>kN*m</td>
<td>68,100.0</td>
<td>22</td>
<td>4.7</td>
<td>11</td>
<td>18.3</td>
<td>159,354.2</td>
<td>234</td>
<td>16</td>
<td>5.75</td>
<td>6.75</td>
<td>15.30</td>
</tr>
<tr>
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<td>kN*m</td>
<td>241,000.0</td>
<td>14</td>
<td>3</td>
<td>12</td>
<td>13.7</td>
<td>260,735.3</td>
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<td>16</td>
<td>5.75</td>
<td>6.25</td>
<td>13.33</td>
</tr>
<tr>
<td>Fair1Ten</td>
<td>kN</td>
<td>1,400.0</td>
<td>6</td>
<td>1.8</td>
<td>12.7</td>
<td>3.66</td>
<td>1,350.7</td>
<td>96</td>
<td>4</td>
<td>2.25</td>
<td>16.8</td>
<td>2.30</td>
</tr>
<tr>
<td>Fair2Ten</td>
<td>kN</td>
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<td>10</td>
<td>2.2</td>
<td>17.6</td>
<td>9.98</td>
<td>2,085.8</td>
<td>98</td>
<td>10</td>
<td>3.75</td>
<td>13.8</td>
<td>10.08</td>
</tr>
<tr>
<td>Fair3Ten</td>
<td>kN</td>
<td>2,160.0</td>
<td>10</td>
<td>2.2</td>
<td>17.6</td>
<td>10.4</td>
<td>2,043.2</td>
<td>95</td>
<td>10</td>
<td>2.75</td>
<td>15.3</td>
<td>14.91</td>
</tr>
<tr>
<td>Anch1Ten</td>
<td>kN</td>
<td>1,140.0</td>
<td>6</td>
<td>1.8</td>
<td>12.7</td>
<td>3.62</td>
<td>1,089.5</td>
<td>96</td>
<td>4</td>
<td>2.25</td>
<td>16.8</td>
<td>2.30</td>
</tr>
<tr>
<td>Anch2Ten</td>
<td>kN</td>
<td>1,140.0</td>
<td>10</td>
<td>2.2</td>
<td>17.6</td>
<td>10.3</td>
<td>1,824.5</td>
<td>160</td>
<td>10</td>
<td>3.75</td>
<td>13.8</td>
<td>10.08</td>
</tr>
<tr>
<td>Anch3Ten</td>
<td>kN</td>
<td>1,900.0</td>
<td>10</td>
<td>2.2</td>
<td>17.6</td>
<td>10.1</td>
<td>1,792.0</td>
<td>94</td>
<td>10</td>
<td>2.75</td>
<td>15.3</td>
<td>14.91</td>
</tr>
</tbody>
</table>

**Failure of the 2nd and 3rd mooring lines**

When looking into the time series of some extreme events, it was observed that the anchors of the 2nd and 3rd mooring lines see some positive angles. In this model, a positive angle means that the line would pull out of the seabed and this is consider a failure of the mooring line. In reality, drag-embedded anchors would be used with catenary mooring lines used for this design, they withstand horizontal forces but are not designed to withstand vertical or inclined forces, which is why the mooring lines would need to be long enough to be un-stretched and come horizontally at the anchor. What is called “failure” here can be resolved by increasing the length of the mooring lines so that no positive angles are seen.

The met-ocean conditions leading to these failures were analyzed. Only the 30313 simulations of the East Coast generic site with the 50 year old threshold were considered here too.

To gain more understanding of the conditions that create these failures, every failure is plotted into scatter plots depending on its conditions, each dot represents a failure. Both mooring lines show the same results. Figures for the second mooring line are included in Annex A.

The first series of scatter plots show the misalignment in the y-axis, the anchor angle with the colors and the other parameters: wind speed, significant wave height and peak-spectral period on the x-axis of the different plots. From these, it can be observed that the failures only happen from 8 to 14 m/s,
more or less around rated wind speed and that a significant wave height of 4.25 m/s creates higher angles.

In the second series of scatter plots, only the last one show a clear trend, which is that the combination of close to rated wind speeds and high surges actually create these failures. The highest anchor angles are not created by a combination of the highest surges and the highest wind speeds but by the rated wind speed and close to the highest surges.

**Fatigue analysis Results**

**East Coast generic site**

Interpretation of MLife’s results

The point of interest of this study is the impact of the wind/wave misalignment on the fatigue analysis. For this, the lifetime damage dependence on wind/wave misalignment is examined.

The first approach is to process the East Coast simulations for each wind/wave misalignment. For example if the misalignment of 60° is considered, a probability distribution that has zeros for all the other misalignment and a non-zero probability for the 60° misalignment is needed. This is why 24 different probability distributions were needed. In order to compare every wind/wave misalignments between each other, the total probability of each distribution must be equal to one, which means that the probability for the 60° misalignment in the example must be equal to the frequency of the simulations with a wind/wave misalignment of 60°: 1224 files have a 60° misalignment so the probability must be 1/1224 which is 0.001006036. The number of simulations per wind/wave misalignment and the non-zero probability used for the different distributions is shown in Table 5-6.

<table>
<thead>
<tr>
<th>Wind/wave misalignment</th>
<th>Number of simulations</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>-165</td>
<td>907</td>
<td>0.0011</td>
</tr>
<tr>
<td>-150</td>
<td>927</td>
<td>0.0011</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>-135</td>
<td>994</td>
<td>0.0010</td>
</tr>
<tr>
<td>-120</td>
<td>1077</td>
<td>0.0009</td>
</tr>
<tr>
<td>-105</td>
<td>1150</td>
<td>0.0009</td>
</tr>
<tr>
<td>-90</td>
<td>1300</td>
<td>0.0008</td>
</tr>
<tr>
<td>-75</td>
<td>1398</td>
<td>0.0007</td>
</tr>
<tr>
<td>-60</td>
<td>1531</td>
<td>0.0007</td>
</tr>
<tr>
<td>-45</td>
<td>1556</td>
<td>0.0006</td>
</tr>
<tr>
<td>-30</td>
<td>1653</td>
<td>0.0006</td>
</tr>
<tr>
<td>-15</td>
<td>1670</td>
<td>0.0006</td>
</tr>
<tr>
<td>0</td>
<td>1687</td>
<td>0.0006</td>
</tr>
<tr>
<td>15</td>
<td>1660</td>
<td>0.0006</td>
</tr>
<tr>
<td>30</td>
<td>1612</td>
<td>0.0006</td>
</tr>
<tr>
<td>45</td>
<td>1601</td>
<td>0.0006</td>
</tr>
<tr>
<td>60</td>
<td>1508</td>
<td>0.0007</td>
</tr>
<tr>
<td>75</td>
<td>1367</td>
<td>0.0007</td>
</tr>
<tr>
<td>90</td>
<td>1224</td>
<td>0.0008</td>
</tr>
<tr>
<td>105</td>
<td>1058</td>
<td>0.0009</td>
</tr>
<tr>
<td>120</td>
<td>1005</td>
<td>0.0010</td>
</tr>
<tr>
<td>135</td>
<td>918</td>
<td>0.0011</td>
</tr>
<tr>
<td>150</td>
<td>843</td>
<td>0.0012</td>
</tr>
<tr>
<td>165</td>
<td>814</td>
<td>0.0012</td>
</tr>
<tr>
<td>180</td>
<td>853</td>
<td>0.0012</td>
</tr>
</tbody>
</table>

The second approach is to define the binning sensitivity of the wind/wave misalignment distribution, i.e. what interval of misalignment should be considered. The fatigue analysis is carried out for the different group of direction: 1 direction (0°), 4, 8, 12 and 24 directions, which is equivalent to decreasing the bin size from 360° to 90°, 45°, 30° and 15°. The probability distribution has to be modified to be able to keep the same total probability when increasing the bin size: the directions not included in the group had to be deleted from the probability distribution matrix, the values have to be averaged over the bin and in the distribution file that MLife reads for the analysis, the number of bins has to be updated for each group. The difference between the distributions can be seen in Figure 5-3.
24 directions with threshold

Wind/wave misalignment in degrees
Probability values

12 directions
Wind/wave misalignment in degrees
Probability values
Figure 5-3: Bar representation of the different probability distributions used in the fatigue analysis.

Each MLife run with a different probability distribution will give the lifetime damage for the different structural locations analyzed and for different Wöhler exponent. All the lifetime damages will then be compared to investigate the impact of considering different bin sizes.

Lifetime damage sensitivity to wind/wave misalignment

When analyzing at the values of wind/wave misalignment which gives the highest lifetime damage, as reported in Table 5-6, more or less the same trends as for the extreme loads are obtained, except for: the tensions at the first mooring line where the opposite direction is creating the highest lifetime damage; the side-to-side root bending moment and the side-to-side yaw bearing moment. The rest of the structural locations experience highest lifetime damage for the same direction as their highest extreme loads. Of particular note is that aligned wind and waves seem to be the dominant combination for lifetime damage for most structural locations.

Table 5-7: Wind/wave misalignment values that creates the highest lifetime damage compared to the values that created the highest loads. (Wöhler exponent values of 4 and 10)

<table>
<thead>
<tr>
<th>Locations</th>
<th>Units</th>
<th>Wd (°)</th>
<th>Maximum loads</th>
<th>Wd (°)</th>
<th>Lifetime damage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kN·m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>------</td>
<td>---</td>
<td>-----</td>
<td>-----</td>
<td></td>
</tr>
<tr>
<td>RootMxc1</td>
<td>-60</td>
<td>11,387.5</td>
<td>30</td>
<td>4.87864E-13</td>
<td></td>
</tr>
<tr>
<td>RootMyc1</td>
<td>0</td>
<td>23,342.0</td>
<td>0</td>
<td>2.4504E-13</td>
<td></td>
</tr>
<tr>
<td>LSSGagMya</td>
<td>30</td>
<td>11,904.2</td>
<td>30</td>
<td>2.17754</td>
<td></td>
</tr>
<tr>
<td>LSSGagMza</td>
<td>-15</td>
<td>10,533.1</td>
<td>-15</td>
<td>2.1739</td>
<td></td>
</tr>
<tr>
<td>YawBrMxp</td>
<td>120</td>
<td>10,564.5</td>
<td>75</td>
<td>0.00163329</td>
<td></td>
</tr>
<tr>
<td>YawBrMyp</td>
<td>-15</td>
<td>15,052.6</td>
<td>0</td>
<td>0.2974</td>
<td></td>
</tr>
<tr>
<td>TwrBsMxt</td>
<td>75</td>
<td>159,354.2</td>
<td>75</td>
<td>0.0426692</td>
<td></td>
</tr>
<tr>
<td>TwrBsMxyt</td>
<td>0</td>
<td>260,735.3</td>
<td>0</td>
<td>0.18608</td>
<td></td>
</tr>
<tr>
<td>Fair1Ten</td>
<td>0</td>
<td>1,350.7</td>
<td>180</td>
<td>0.000265638</td>
<td></td>
</tr>
<tr>
<td>Anch1Ten</td>
<td>0</td>
<td>1,089.5</td>
<td>180</td>
<td>0.000258749</td>
<td></td>
</tr>
</tbody>
</table>

The dependence of lifetime damage on wind/wave misalignment seem to be less strong than for extreme load. Most of the lifetime damage roses show almost uniform circles except the yaw bearing and tower moment. The side-to-side yaw bearing and tower moments really depend on misalignment towards 90° and -90° whereas the fore-aft moments show a strong correlation with aligned wind and waves. However the magnitudes of side-to-side lifetime damages remain much less than the magnitudes of fore-aft lifetime damages, hence the latter remain design-driven and aligned wind and waves should be considered as the design-driving case.
Figure 5-4: Lifetime damage roses for Wöhler exponent values of 4 and 10.

**Directional binning sensitivity**

The following results for the directional binning sensitivity depends on the probability distributions used, which were explained previously. Further work is needed to assess the accuracy of the method used to create these distributions. Careful interpretation of these results is necessary here and further studies on the topic should be more detailed and accurate.

The lifetime damage results show an increase in lifetime damage when increasing the number of directions considered. However these results are influenced by the extrapolation factor presented earlier. This factor depends on the total length contained in one bin hence when we decreased the number of bins, we decreased the factor. The results clearly show that between 24 and 12 directions the lifetime damage decreased by two as between 12 and 8 and 8 and 4. Between 4 and 1, the factor decreased by four.
Figure 5-6: Bar representation of the lifetime damage for the different structural locations in function of the number of directions. The ratios are obtained by dividing by the lifetime damages obtained with one direction.

As the lifetime damage results don’t really show a physical difference in the fatigue loading, the lifetime damage-equivalent loads are analyzed and represented in Figure 5-6. For most structural locations, considering only one direction doesn’t under-estimate the lifetime damage-equivalent load. However for the fore-aft tower base and yaw bearing, the lifetime DELs decreased when the number of direction decreased, considering less than 24 directions would lead to an under-estimate. Surprisingly, the tower base side-to-side lifetime DEL increases when the number of directions decreases, considering less than 12 directions would lead to a significant over-estimate of about 10% of the lifetime DEL. The aligned wind and wave case drives the fatigue loading of this structural location instead of perpendicular wind and waves. If it was a design-driver load, considering only aligned wind and waves would lead to an unnecessary addition of material. Finally, the highest lifetime DEL for the yaw bearing side-to-side moment is obtained when considering four directions indicated the
importance of perpendicular wind and waves for this load. These results are quite surprising and additional studies will validate or not these results. (Stewart, 2013)

Figure 5-6: Bar representation of the damage-equivalent loads. The ratio are obtained by divided each damage-equivalent loads by the ones obtained with one direction.

Conclusions

The extreme loading analysis showed that for most structural locations it is conservative to consider aligned wind and waves. However, side-to-side loadings experience highest loads with perpendicular wind and wave and before considering only one direction; it should be proved that these are not design-driver loads. The analysis of the extreme loads also show many anchor failures for wind speeds around rated wind speed that happens with a high surge. These load cases should be used to determine a new length for the 2\textsuperscript{nd} and 3\textsuperscript{rd} mooring lines.

Concerning the fatigue analysis, it showed that it is also conservative for most structural locations to consider aligned wind and waves. However the fore-aft tower base and yaw bearing moment, the former being an important design-driver, experience highest lifetime damage-equivalent loads with 24 directions and at least 8 directions (45° intervals) should be included in the analysis for these loads for more accuracy. The fatigue analysis results need to be careful interpreted and follow-up studies will determined the accuracy of these recommendations.
Chapter 6

Economics considerations

In this chapter is investigated the effect of taking into account the wind/wave misalignment in the calculation of energy production and in the estimation of the cost of energy. As few prototypes of floating offshore wind turbine have been installed, data on the installation costs remains rare and not publicly available. Estimations will be used for the cost of energy, however in this study, the relative comparisons will be of importance.

Energy production

One of the output parameters of the FAST simulations is the power produced by the generator: GenPwr. In the output files the power produced in kW by the generator at each time step (0.1 s) is included. From this the energy production for each simulation can be calculated:

\[
Energy \text{ production per simulation in kWh} = E_{sim} = \sum_l GenPwr_l (kW) \times \frac{dt_l (s)}{3600}\]

When considering the energy production at the East Coast site, the probability that each simulation actually occurs needs to be taken into account. A lifetime of 30 years is considered here which means 1,577,880 10-mn periods. A 10-mn simulation with a probability of 0.003 will account for 4733.6 10-mn periods or 47336 mn of the lifetime. So to calculate the energy production of the East Coast site, the following formula is used:

\[
Energy \text{ production for the East Coast site in kWh} = \sum_k E_{simk} * p_k * 1577880\]

When only aligned wind and waves are considered and the energy production of these simulations is extrapolated to obtain the site energy production, you assume that misaligned wind/waves won't influence the energy production. However, as seen in Figure 6-1, the average and total energy productions per wind/wave misalignment changes with wind/wave misalignments. To obtain this figure, the energy production of the simulations were grouped by their wind/wave misalignments and then averaged by the number of simulations for each wind/wave misalignment:
Average energy production for misalignment \( j \) in kWh = \( \sum_{k}^{E_{\text{sim},k,j}} N_j \times 1577880 \)  

\( E_{\text{sim},k,j} \) correspond to simulations with a wind/wave misalignment of the value \( j \).

\( N_j \) corresponds to the number of simulations with the wind/wave misalignment of the value \( j \).

Figure 6-1: Total and average energy production in function of wind/wave misalignment.
The production for aligned wind/waves is higher than when there is some misalignment hence considering only aligned wind/waves will lead to an over-estimate of the energy production. However this impact on the estimation decreases when calculating the East Coast site energy production because of the wind/wave misalignment probability distribution – aligned wind and waves are more frequent.

To obtain the participation in the energy production of each wind/wave misalignments, the following formula was used:

\[
E_{\text{energy production for misalignment } j \text{ in kWh}} = \sum_k E_{\text{sim},k,j} * p_k * 1577880 \quad (8)
\]

\(E_{\text{sim},k,j}\) corresponds to simulations with a wind/wave misalignment of the value \(j\).

The participation of simulations with aligned wind and waves is much more important as shown in Figure 6-2.

Finally, the groups of wind/wave misalignment used for the extreme and fatigue loading analyses were considered here to evaluate the impact of considering only one or several misalignments in the energy production.
production estimation. To calculate the energy production for each group, the different wind/wave misalignments were grouped and their energy productions were summed. Since each group has a different number of simulations, we scaled up the total energy production with the ratio of the total number of simulations (30313) by the number of simulation in the group. The results show, see Table 6-1, that considering only aligned wind and waves leads to an overestimate of the energy production by nearly a factor of two.

<table>
<thead>
<tr>
<th>Wind/wave misalignment group</th>
<th>Number of simulations in the group</th>
<th>Total energy production of the group (GWh)</th>
<th>Scaling factor depending on the number of simulations</th>
<th>Total Energy Production of the group scaled (GWh)</th>
<th>Ratio of the Energy Production for each group by the Energy Production for the 24 directions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,687</td>
<td>67</td>
<td>18.0</td>
<td>1,199</td>
<td>194.0%</td>
</tr>
<tr>
<td>4</td>
<td>5,064</td>
<td>105</td>
<td>6.0</td>
<td>629</td>
<td>101.8%</td>
</tr>
<tr>
<td>8</td>
<td>10,133</td>
<td>206</td>
<td>3.0</td>
<td>616</td>
<td>99.7%</td>
</tr>
<tr>
<td>12</td>
<td>15,220</td>
<td>309</td>
<td>2.0</td>
<td>615</td>
<td>99.6%</td>
</tr>
<tr>
<td>24</td>
<td>30,313</td>
<td>618</td>
<td>1.0</td>
<td>618</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

### Cost of energy

The levelized cost of energy (LCOE) is calculated with the initial capital costs (CAPEX), the operating costs (OPEX), the fixed charge rate (fcr) and the energy production:

\[
LCOE \left( \frac{\$}{kWh} \right) = \frac{CAPEX (\$) \times fcr + OPEX (\$)}{\text{Energy production in kWh}} \tag{9}
\]

A 100% availability of the wind turbine is assumed, although the total probability of the 30,313 simulations being less than one, the energy productions calculated earlier don’t account for the whole lifetime and it will be considered that it accounts for down time and other non-operating conditions.

The CAPEX and OPEX are difficult to estimate as there are few prototypes installed and the companies didn’t release much information on costs. A study, Inventory of location specific wind energy cost, from WINDSPEED (WindSpeed, 2011) provides us with information on capital and operating costs. The costs are given in euros and the conversion rate used here is 1.3 $/€. The information about the CAPEX are reported in Table 6-2.
Table 6-2: Information on the different capital costs for a spar-buoy type floating offshore wind turbine

<table>
<thead>
<tr>
<th></th>
<th>€</th>
<th>$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication rate for steel pile</td>
<td>2600€/</td>
<td>338000</td>
</tr>
<tr>
<td>structures (used for the spar)</td>
<td>tones</td>
<td></td>
</tr>
<tr>
<td>Spar mass</td>
<td>1300</td>
<td></td>
</tr>
<tr>
<td>Unit cost of solid ballast</td>
<td>100€/</td>
<td>520000</td>
</tr>
<tr>
<td>Ballast mass</td>
<td>5250</td>
<td></td>
</tr>
<tr>
<td>Unit cost of anchors</td>
<td>120,000</td>
<td></td>
</tr>
<tr>
<td>Unit cost of mooring lines</td>
<td>600€/m &amp; length = 3*depth</td>
<td></td>
</tr>
<tr>
<td>Length mooring lines</td>
<td>3*depth (for each)</td>
<td></td>
</tr>
<tr>
<td>Turbine Supply 5 MW</td>
<td>9,000,000€</td>
<td>9000000</td>
</tr>
<tr>
<td>Installation costs</td>
<td>300,000€</td>
<td>300000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18,369,000.00</td>
</tr>
</tbody>
</table>

The annual operating expenses are evaluated in this study depending on the location (met-ocean data, depth, port location, number of O&M crew members needed). For the O&M costs for our spar-buoy, the estimation for a site with an average significant wave-height of 13 m will be used: 61,387€/MW/year, i.e. $79,803/MW/year. One wind turbine is considered here, as a prototype needs to be installed in the US first, so our capacity is 5 MW. The fixed-charge rate used by default is 12%.

Table 6-3 summarized the main parameters found from all these assumptions and estimations and Table 6-4 presents the LCOE calculations for the different misalignment groups used in the extreme and fatigue loading analyses.

Table 6-3: Estimation of the parameters for the LCOE calculation

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX ($)</td>
<td>18,369,000.00</td>
</tr>
<tr>
<td>OPEX ($)</td>
<td>399,015.50</td>
</tr>
<tr>
<td>fcr</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table 6-4: Annual Energy Production and LCOE for the different misalignment groups

<table>
<thead>
<tr>
<th>Wind/wave misalignment group</th>
<th>Total Energy Production of the group scaled (GWh)</th>
<th>Annual Energy Production (scaled) in kWh</th>
<th>LCOE $/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,199</td>
<td>39,966,667</td>
<td>0.06513667</td>
</tr>
</tbody>
</table>
The annual energy production was calculated from the total energy production for the East Coast Site - calculated previously – by dividing by 30 years and converting to kWh. The LCOE obtained when considering only aligned wind and waves is about half of the LCOEs obtained when considering some misalignment. Considering four directions enables a good estimate of the LCOE obtained for 24 directions. Indeed the energy production at +/-90° and 180° are more representative of the energy production of all misalignments whereas the energy production at 0° is really higher than the energy production at other misalignments. Considering only 0° leads to a lower LCOE because of the over-estimation of the energy production.

The fact that adding the wind/wave misalignments of +/-90° and 180° gives a better estimate of the LCOE brings the question of what creates lower energy production at these misalignments compared to aligned wind and waves. One of the structural location that really depends on perpendicular wind and waves is the side-to-side tower base moment. The increased side-to-side tower base moment, which is not critical in the structural analysis, could however be more critical in the cost of energy calculation. Indeed, increased side-to-side tower base moment is probably linked with high tower-top deflections. High tower-top deflections can influence the positions of the blades compared to the incoming wind and so can influence the angle of attack and so the lift and drag components at each blade segments. This should be investigated to link the importance of the +/-90° and 180° wind/wave misalignment in the energy production calculations for this floating platform.

Matha (2009) compared the loads and the generator production of three different floating platforms (Tension-Leg-Platform, Spar-buoy and Barge for the NREL 5 MW wind turbine). It was found that the Tension-Leg-Platform generator power production compares well with the generator power production of the land-based version of the wind turbine because with the limited motions of the Tension-Leg-Platform with the waves, the same control system can be used than the one of the land-based wind turbine. However for the spar-buoy and the barge that experience higher motions with the waves, different control systems had to be used to take into account the increased variation in platform motions.

Future investigations of the importance of the +/-90° and 180° wind/wave misalignment in the energy production calculations should include the role of the control system in reducing the motions of the OC3-Hywind system.
Conclusion

Simulations were carried out over a wide range of met-ocean conditions and enabled us to show the importance of wind/wave misalignment when considering the whole range of met-ocean conditions. However, when considering our East Coast generic site, the importance of wind/wave misalignment decreases and the conservative case of using aligned wind and waves concurs most of the time. It should be noted that side-to-side loadings experience their highest loads with perpendicular wind and waves and this should be investigated for the different floating platforms as some platforms’ design can depend more on the side-to-side loads. The fatigue analysis show some dependence of the lifetime damage on the wind/wave misalignment, especially for side-to-side loadings. However, when considering our East Coast generic site and the different number of directions, it was concluded that the conservative case of aligned wind and waves give good estimate of the lifetime DELs and that the lifetime damage increase with the number of directions is due to how the lifetime damage is calculated in MLife and doesn’t prove any dependence of the lifetime damage on the wind/wave misalignment. Further studies will look further into the probability distributions used for the fatigue analysis results to validate or invalidate the results.

These analyses also enabled an evaluation of the OC3-Hywind design and the mooring lines failure should be investigated in similar concept for floating offshore platform in order to find a more appropriate length of mooring lines.

The cost of energy calculations, although many assumptions have been made and might not be very accurate, enabled an evaluation of the impact of considering different number of wind/wave misalignment on the LCOE. The conservative case of aligned wind and waves doesn’t seem accurate enough for the cost of energy and using at least four directions seem more appropriate.

Future work should include more seeds for each simulation, evaluate the impact of the 50 year return period chosen and if a 100 year or more return period should be used. Other platform designs and generic sites (Gulf of Mexico, West Coast) can also be investigated. Finally, this study was carried out by assuming a 0° wind direction and a 0° yaw, combinations of different wind and wave directions and yaw misalignment can be investigated to find the worst direction case. More precise site data could also be used especially wind direction measurement at hub height and not at buoy height, this could lead to an increase in the high misalignment probabilities and hence increase the design loads.
References


Stewart, G. (2013). To Be Published. (Papers on the met-ocean conditions and on the same loads analysis study with additional seeds)


Annex A

First series of representation of the failure of the second mooring line

Wave peak-spectral period in seconds

Wind/wave misalignment in degrees

Anchor angles in degrees

Significant wave height in meters
Second series of representation of the failure of the second mooring line