Budget Period 2 Summary Report

Part 1

Hywind Maine Project

DE-FOA-0000410: U.S. Offshore Wind: Advanced Technology Demonstration Projects

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Public Report

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Public report

WP1-Design and Analysis: IEC Ultimate and Fatigue Load Assessment

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Acronyms

DLC	design load case
DEL	damage equivalent load
FAST	Fatigue, Aerodynamics, Structures, and Turbulence
FLS	fatigue limit state
IEC	International Electrotechnical Commission
metocean	meteorological and oceanographic
NREL	National Renewable Energy Laboratory
PSF	partial load safety factors
SOWFA	Simulator for On/Offshore Wind Farm Applications
STDEL	short-term design equivalent load
ULS	ultimate limit state

1 Introduction

This project was performed under the Work for Others—Funds in Agreement FIA-14-1793 between Statoil and the Alliance for Sustainable Energy, manager and operator of the National Renewable Energy Laboratory (NREL). To support the development of a 6-MW spar-mounted offshore wind turbine, Statoil funded NREL to perform tasks in the following three categories:

1. Design and analysis
2. Wake modeling
3. Concept resource assessment.

This summarizes the document reports on the design and analysis work package, which built a FAST [Jonkman & Buhl, 2005] computer model of the Hywind 6-MW floating wind turbine system and uses this tool to evaluate the performance of a set of design load cases (DLCs). The FAST model was also used in *Work Package 2: Wake Modeling*.

A more detailed publication of some of the main results is reported in [Burns et. al., 2015].

2 IEC Ultimate and Fatigue Load Assessment

In support of Statoil's Hywind 6-MW wind turbine project, which aims to develop a small array of 6-MW floating wind turbines, the National Renewable Energy Laboratory (NREL) performed a loads and fatigue analysis using the floating turbine simulation software FAST. For the effort, NREL built a model of a Hywind 6-MW turbine in FAST7 based on Statoil's generic 6-MW turbine and integrated Statoil's floater motion control algorithm. This FAST7 model was also used in the Simulator for On/Offshore Wind Farm Applications (SOWFA) wake modeling work, which is detailed in a parallel report titled *Work Package 2: Wake Modeling*. Based on the International Electrotechnical Commission's (IEC) standard 61400-3 Ed 1.0 on design requirements for offshore wind turbines, the following four suites of ultimate limit state (ULS) and fatigue limit state (FLS) design load cases (DLCs) were chosen:

- DLC Suite 1: Power production
- DLC Suite 2: Power production plus fault
- DLC Suite 6: Parked (still or idling)
- DLC Suite 7: Parked and fault conditions.[1]

This set of DLCs was used to investigate the system loads during normal power production for different combinations of wind conditions and partial load safety factors (PSF) (Table 1 in Appendix), and corresponding wave fields (Table 2 in Appendix). Ocean current was not included in the analysis.

For ULS, several sub-cases for each DLC suite, except DLC 7, were investigated, and these were developed considering different turbulence levels, storm events, gusts, and wind shear. This resulted in 11 DLCs that had 262 unique combinations for a total of 1571 simulations. For FLS, two additional DLCs were run for both floating and fixed platforms, which resulted in 486 simulations. No structural information was provided, so ULS analyses were limited to structural loads and platform motions—i.e., stresses and strains were not investigated. For the same reason, FLS results are presented in damage equivalent loads (DELs) instead of actual fatigue estimates. The DLC suites specified for transients (start-up and shutdown), and transport were not performed.

[1] DLC numbering is based on IEC 61400-3 Ed. 1.0.

The loads analysis considered the following:

- Mooring line tension (at the anchor and fairlead)
- Platform motion (roll, pitch, yaw, surge, and sway)
- Blade-root bending moments
- Tower loads at the base (shear force, bending moment, and yaw moment)
- Tower loads at the yaw bearing (bending and yaw moments).

The following three DLCs were identified as the limiting load cases (Figure 1):

- 1.6a: Power production, severe sea state, and normal turbulent winds
- 2.1: Power production plus fault
- 6.2a: Parked, 50-year event and loss of power.

All other DLCs had responses that were at least 20% lower with the exception of mooring loads (several DLCs) and the blade root bending moment (in DLC 1.4 only). DLCs 1.6a and 6.2a dominated the platform response and mooring loads, and DLCs 1.6a, 2.1, and 6.2a dominated the structural loads. DLCs 6.3a (1-Year Extreme Event) and 7.1a (1-Year Extreme Event Plus Fault) typically had some of the lowest values and were not design drivers for the Hywind 6-MW wind turbine system.

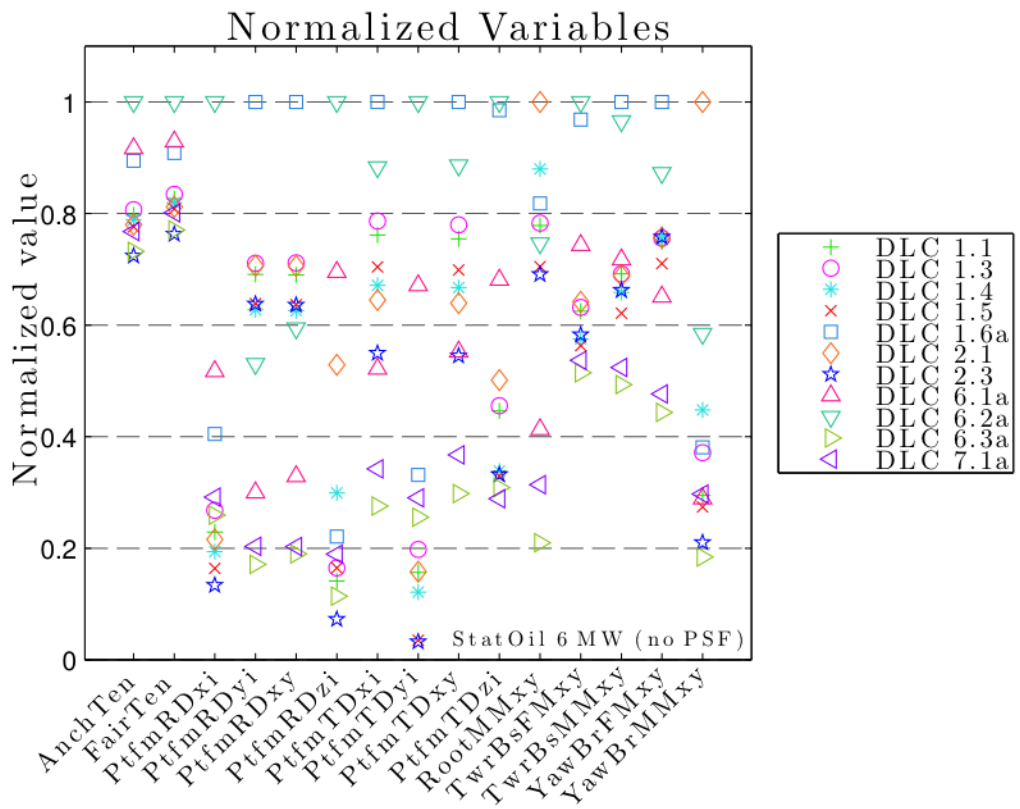

Figure 1. Summary plot of the maximum instantaneous absolute value for each design load case organized by variable. Partial Safety factors were not applied, and values in each column were normalized to a maximum of unity to facilitate side-by-side comparison.[2]

The FLS analysis was done using two DLCs:

- 1.2: Normal operating conditions
- 6.4: Parked (not operating) normal conditions.

The normalized DEL for each variable investigated is shown in Figure 2. Each normalized DEL is the weighted average of the largest DELs from each set of simulations with unique wind and wave parameters from DLCs 1.2 and 6.4. Contrary to Statoil's previous findings, tower base and tower top DELs for the floating system were typically less than those for the fixed system, and the blade-bending moment DELs were greater for the floating system. Calculating the DELs requires assumptions about the wind speed and wave field distributions, availability, and other quantities. Further investigation is needed to determine the cause of this discrepancy.

[2] The variables used in the figure are AnchTen: tension of mooring line at the anchor; FairTen: tension of the mooring line at the fairlead; PtfmRDxi: platform roll; PTfmRDyi: platform pitch; PTfmRDxyi: platform tilt; PTfmRDzi: platform yaw; PtfmTDx: platform surge; PtfmTDy: platform sway; PtfmTDxy: net platform displacement; RootMMxy: blade-root bending moment; TwrBsFMxy: tower shear force at base; TwrBsMMxy: tower base bending moment; YawBrFMxy: shear force at the yaw bearing ; and YawBrMMxy: bending moment at the yaw bearing.

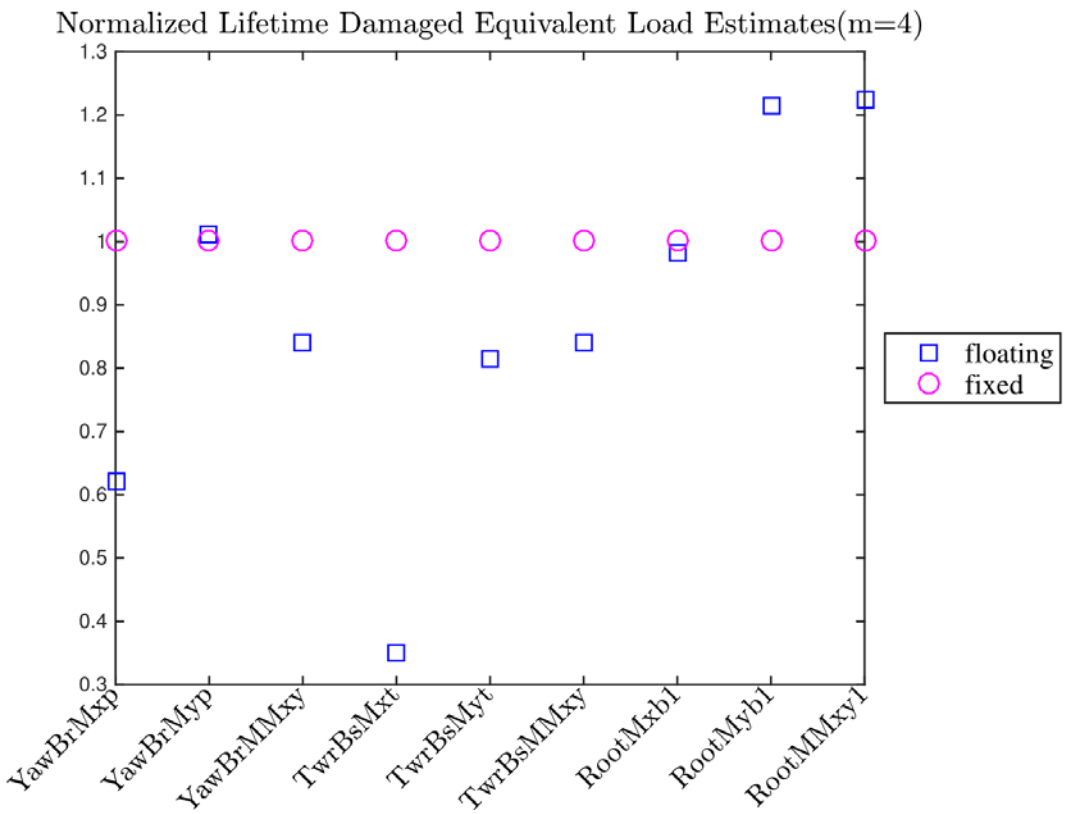

Figure 2. Summary plot of the design equivalent loads organized by variable for a fixed and floating 6-MW system. Values in each column were normalized by the fixed DEL to facilitate side-by-side comparison. For the floating system, DELs > 1 indicate higher fatigue than for the fixed cases, and DELs < 1 indicate lower fatigue than for the fixed cases.

3 Discussion and conclusion

The major findings and recommendations are:

1. Three DLCs were identified as the limiting load cases: 1.6a: Power production, severe sea state, and normal turbulent winds, 2.1: Power production plus fault, and 6.2a: Parked, 50-year event and loss of power.
2. Comparing the results from the ULS DLCs for a previous 3-MW design with the current 6-MW design analyzed by NREL, the DLCs that resulted in the largest loads were consistent; except that for the yaw bearing (nacelle) and tower loads for the 6-MW design, two additional DLCs were important: 1.6a and 6.2a.
3. Not including storm conditions may lead to the under prediction of fatigue loads, and thus; FLS analysis should include storm conditions to capture larger, less frequent loads. The present analysis considered only a range of wind speeds from 4 m/s to 34 m/s with corresponding sea state per IEC standards.
4. Sensitivity analysis should be performed on the spar system for turbulent wind regimes and for different wave fields to determine the contribution of the different metocean conditions to loads and platform motion. In particular, sensitivity to wave height and period should be performed.
5. Using only the wind speed probability density function to weight the fatigue loading likely overemphasizes the fatigue contributions from wind and underemphasizes contributions from waves. To calculate the DEL, a joint

wind-wave probability distribution should be used to account for the expected occurrence of both wind and waves. Considering only wind will bias the fatigue results.

6. During operation, the fore-aft heel (pitch) response due to wave traveling in the direction of the wind field is different than the side-to-side heel (roll) response for waves traveling normal to the wind direction. Hence, it is recommended to consider a range of wave directions, perhaps from 0 degrees to 90 degrees relative to the wind. Additionally a statistical approach can be used to extract the relative directional difference.
7. The DELs investigated are driven by waves and are sensitive to wave height and period, which are location specific. At the Boston site, the wave period was short and the wave heights were low when compared to other sites, which lowered the wave contribution to the DEL to significantly impact loads.
8. The yaw oscillations caused by the yaw misalignment of the nacelle relative to the wind should be investigated. In parallel, the impact of the artificial linear yaw stiffness model with non-bridle mooring lines should be compared to bridle mooring system.
9. The maximum load and motion values were determined from a single realization run rather than taking the mean of the maximums of multiple realizations per DLC. Future work will need to better quantify the extreme loads based on the extrapolation procedures recommended in IEC 61400-1.
10. The simulations are started near equilibrium position and platform orientation, the beginning 30 s – 60 s of each simulation are removed to eliminate startup transients based on previous floating work. This however should be revisited to see if longer transients are required.
11. DLCs for normal start-up and shut-down; emergency shut-down; and transportation, installation, and maintenance are not included, which will affect loads. It will be best to include these DLCs so the relative importance of all DLCs can be quantified. However, it requires detail procedural information from the turbine manufacture, transportation and installation contractors, and operator's maintenance schedule.

References

[Burns et. al., 2015], Burns, M., Driscoll, F., Sirnivas, S., Platt, A., Skaare, B., Nielsen, F.G., *Loads Analysis of a 6 MW Wind Turbine on a Floating Spar Platform*, NREL publication.

[Jonkman & Buhl, 2005], Jonkman, J. M., and Buhl, M. L., FAST User's Guide, NREL/EL-500-3823

Appendix

DLC		Wind Parameters				Wave Parameters				Turbine Yaw (°)	Simulations			PSF[a]	
		Turb Model	V (m/s)	Shear Exp	Turb Int	H_S	T_P	Dir (deg)	Γ		Dur (s)	# of Seeds	# of Sims	Ultimate/Material	Failure Consq
Power Production	1.1	NTM	4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24	0.14	NTM, Class C	Table 2		0	auto	0	600	6	198	1.5, 1	1
	1.2	NTM	4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24	0.14	NTM, Class C	Table 2		0	auto	0	600	6	198	1.1, 1.2	1.15, 1.30
	1.3	ETM	4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24	0.14	ETM, Class C	Table 2		0	auto	0	600	6	198	1.35, 1	1
	1.4	ECD	8.4, 10.4, 12.4	0.14	0	Table 2		0	auto	pos/neg gusts	60	2	18	1.35, 1	1
	1.5	EWS	4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24	EWS mode		Table 2		0	auto	0	60	4	132	1.35, 1	1
	1.6	NTM	4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24	0.14	NTM, Class C	8.64	12	0	auto	0	3,600	6	66	1.35, 1	1
Power Production Plus Fault	2.1	NTM	4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24	0.14	NTM, Class C	Table 2		0	auto	0	600	12	396	1.35, 1	1
	2.3	EOG	8.4, 12.4, 25	0.14	0	Table 2		0	auto	0	60	6	54	1.1, 1	1
Parked	6.1a	Turb. EWM	36.3	0.11	NTM, Class C	8.64	12	330,0,30	auto	352, 0, 8	3,600	6	6	1.35, 1	1
	6.2a	Turb. EWM	36.3	0.11	NTM, Class C	8.64	12	330,0,30	auto	0-360 (20 deg steps)	3,600	6	6	1.1, 1	1
	6.3a	Turb. EWM	24.7	0.11	NTM, Class C	5.12	9.5	330,0,30	auto	340, 0, 20	3,600	6	6	1.35, 1	1
	6.4	Turb. NTM	4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34	0.14	NTM, Class C	Table 2		0	auto	0	600	6	288	1.1, 1.2	1.15, 1.30
Parked Plus Fault	7.1a	Turb. EWM	24.7	0.11	NTM, Class C	5.12	9.5	330,0,30	auto	352, 0, 8	3,600	6	6	1.1, 1	1

Table 1. DLCs and the Operational, Meteorological, and Oceanographic Properties for Each Case.

Wind Speed (m/s)		H_S (m)	T_P (s)		
Minimum	Maximum	Average	Average	Minimum	Maximum
3	5	0.672	7.495	6.045	8.946
5	7	0.745	7.147	5.465	8.829
7	9	0.899	6.436	4.634	8.238
9	11	1.116	5.94	4.237	7.644
11	13	1.358	5.711	4.181	7.241
13	15	1.655	5.749	4.348	7.151
15	17	1.92	5.828	4.545	7.11
17	19	2.289	6.091	4.873	7.31
19	21	2.761	6.486	5.205	7.768
21	23	3.266	6.869	5.473	8.265
23	25	4.177	7.729	6.187	9.27
25	27	4.639	7.981	6.523	9.439
27	29	5.269	8.389	7.136	9.643
29	31	5.572	8.617	7.902	9.333
31	33	5.572	8.617	7.902	9.333
33	35	5.572	8.617	7.902	9.333

Table 2. Significant Wave Height and Period for Different Wind Speeds.