Budget Period 2 Summary Report

Part 2

Hywind Maine Project

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

August 15, 2015

Public Report

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)

Public report

WP2 - Wake Modeling

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Acronyms

BP1	Budget Period 1
BP2	Budget Period 2
CFD	Computational Fluid Dynamics
D	Rotor Diameter
DEL	Damage Equivalent Load
FAST	NREL's Aero-Elastic Code - Fatigue, Aerodynamics, Structures, and Turbulence
FLORIS	FLOw Redirection and Induction in Steady-state
IEC	International Electrotechnical Commission
LES	Large-Eddy Simulation
P	One blade rotational period
SOWFA	Simulator for Offshore Wind Farm Applications

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 study expands upon the work conducted in Budget Period 1 (BP1) to investigate the influence of the wake generated from an upstream turbine on a downstream turbine using Computational Fluid Dynamics (CFD) high-fidelity modeling tool. Simulator fOr Wind Farms Application (SOWFA) [1] is an NREL high fidelity modeling tool that couples OpenFOAM [2] CFD and NREL's Aero-Elastic code Fatigue, Aerodynamics, Structures, and Turbulence (FAST)[3]. In BP1 the configuration was based on Hywind-3MW at 140 m water depth in the Gulf of Maine; however this study for Budget Period 2 (BP2) the configuration investigated is based on Hywind-6MW at 220 m water depth off the coast of Boston. The objectives were to perform two-turbines One-Way Coupling (OWC), three-turbines Two-Way Coupling (TWC), and to investigate wind power plant optimization.

A more detailed publication of some of the main results is reported in [4].

2 Two-Turbines One-Way Coupling (OWC): SOWFA → FAST

This study investigates the impact of fatigue loads in relation to the various spacing and lateral offset positions for downstream turbines, which mimics partial and full waking scenarios for three different wind speeds: 8 m/s, 10.4 m/s and 15 m/s. In particular, 6D to 10D at 0.5D (1D = one diameter) increments downstream spacing with offsets lateral ranging from -1.5D to 1.5D with 0.5D increments, which resulted in a total of 189 cases. A simulation example of a cross-section of the wind field 7D downstream of the free-stream turbine is shown in Figure 1.

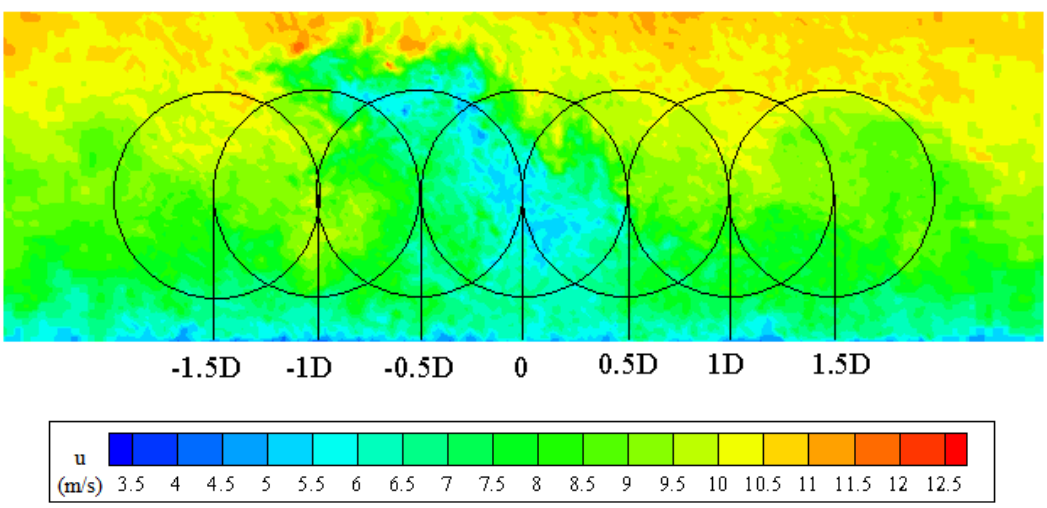

Figure 1. A cross-section of the wind field 7D downstream of the free-stream turbine at 8 m/s for lateral turbine positions: -1.5D to 1.5D in a typical wake field.

In general, partial wakes introduced the highest fatigue loads for the critical turbine and the floating platform components, including the mooring lines. The moments measured at the blade and the tower roots had elevated load signatures at offset positions of ±1.0D and ±0.5D, which decayed with respect to the downstream distance, although the decay rate was slow for the highest wind speed case, 15 m/s. The fore-aft damage equivalent loads, DELs, for the different wind speeds and locations are shown in Figure 2.

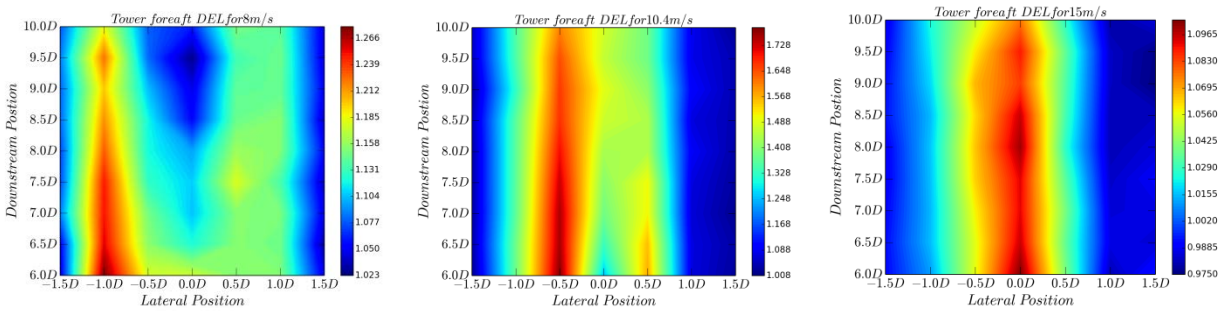

Figure 2. Fore-aft tower base moment DEL normalized to the upstream turbine

These components are primarily driven by the wake turbulence, which tended to diminish further downstream. However, the mooring fatigue loads persist beyond the 10D boundary that could be attributed to the slowly moving wake at its tail. At above rated wind speed where the meandering activity of the turbine wake is accentuated further downstream, the mooring line fatigue loads were worse at 8D-10D compared to upstream distance. Conversely, the power generation shown in Figure 3 yielded the expected result where the recovery was consistent with the wake diffusion for 8 m/s and 10.4 m/s case. At the wind speed of 15 m/s, the power was at rated condition regardless of the downstream turbine position because the waked flow was still higher than the above the rated wind speed.

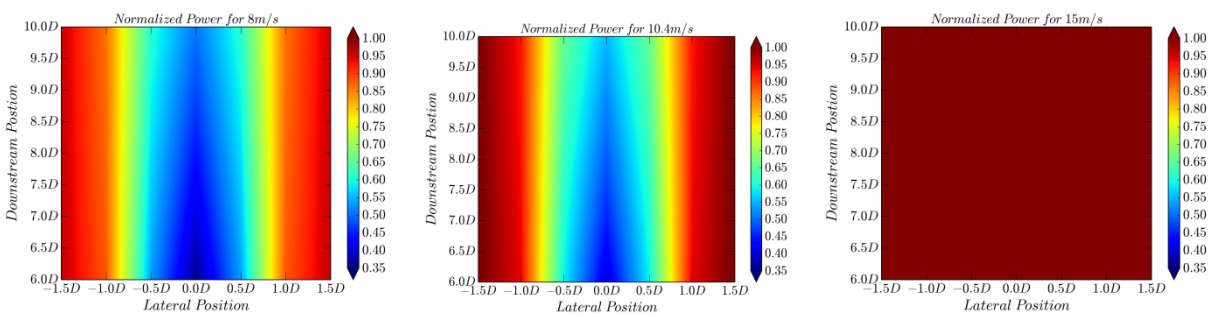

Figure 3: Power contour normalized to the upstream turbine

3 Three-Turbines Two Way Coupling (TWC) - SOWFA ↔ FAST

A series of simulations were performed with a 1 x 3 array of turbines spaced at 9D subjected to the same three inflows with a mean hub-height wind speed of 8 m/s, 10.4 m/s, and 15 m/s, along with five different wind directions of ±6.8°, ±3.4°, and 0°. This resulted in 15 different simulation conditions, but only 13 ran to completion. The 2 cases incomplete were the 15 m/s wind speed at +3.4° and -6.8° wind direction which was due to HPC system downtimes. Unlike in the previous set of simulations, two-way coupling is used where the CFD solver passes flow velocity to the blades which computed the structural and system dynamics via, FAST, which then computes and passes back to the CFD the aerodynamic force distribution along the blade. The two-way coupling is expensive, requiring 1600 computer cores over 6 days to yield roughly 2000 s of simulation data for each of the 13 cases. This set of cases is different than the

one-way coupled cases because there are multiple merged wakes. For example, Turbine 3 sees the merged wakes of both turbines 1 and 2 that forms in to a triple merged wake. Contours of instantaneous and mean normalized stream wise velocity in a horizontal plane at hub height are shown for the 10.4 m/s case in Figure 4.

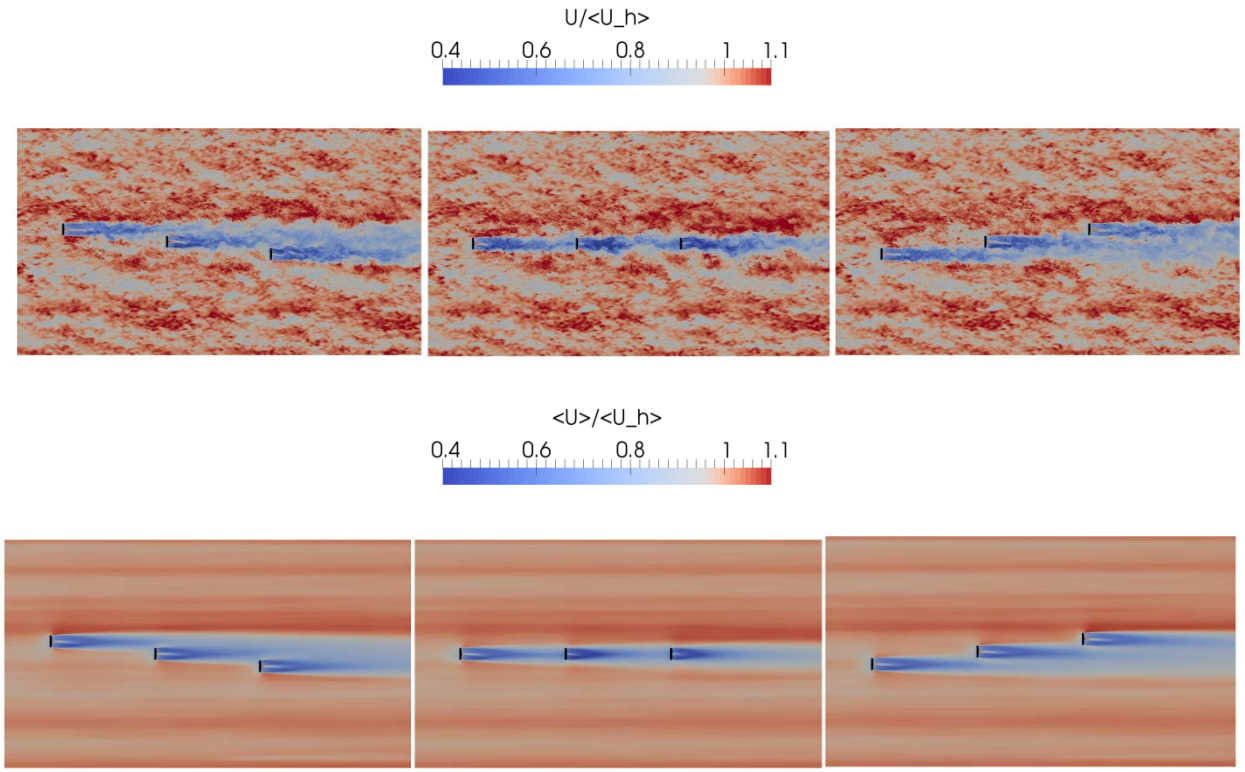

Figure 4: Contours of instantaneous (top) and mean (bottom) normalized streamwise velocity in a horizontal plane at hub height from the 10.4 m/s cases with the wind offset from the row -6.8° (left), 0° (middle), and +6.8° (right). The velocity is normalized by the mean hub height wind speed. The turbines are denoted by the black bars. The gray part of the contour scale corresponds to 95% of the undisturbed hub-height wind speed.

In general, as was seen with the one-way cases, partial waking produces the worst case scenario in terms of the loads, but direct waking is the worst for power production. For direct waking, turbines 2 and 3 operate at about 55% the power production of turbine 1. For partial waking, the loads on turbine 2 are significantly higher than those of turbine 1, and the loads on turbine 3 are somewhat higher than those of turbine 2. For example, as shown in figure 5, when examining the dynamic anchor tension on mooring line 1 for the -3.4° at 10.4 m/s winds, the damage equivalent load for turbine 2 is 400% that of turbine 1, and the damage equivalent load for turbine 3 is only 125% that of turbine 2.

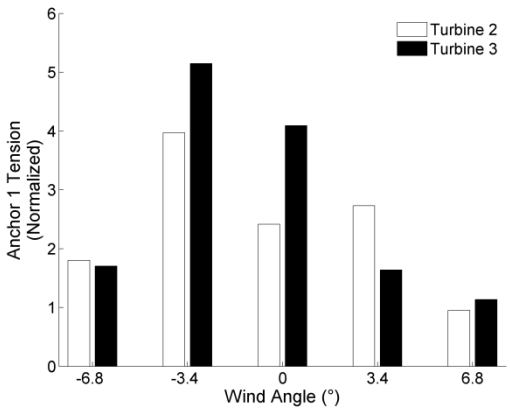

Figure 5: DELs of the dynamic tension in anchor 1 of turbines 2 and 3 normalized by the turbine 1 values for the 10.4 m/s cases.

There is reasonable overall agreement comparing the two-way coupled results to the one-way coupled results for the three wind speeds and for the row-aligned wind direction case with 9D spacing. The agreement of the mean loads is excellent, but the one-way coupled method predicts somewhat higher variances than does the two-way coupled method. This causes differences in damage equivalent loads of slightly above 30% for certain loads (but for other loads, the difference is less than 1%).

4 Wind Power Plant Optimization with FLORIS

The FLOw Redirection and Induction in Steady-state (FLORIS) model [5] was used to study optimized yaw setting of wind turbines in a wind power plant for improved energy production by redirecting the wake. It is a simplified model that is computationally efficient to perform wake redirection optimization at the plant level. The FLORIS model was shown to be reasonably accurate to calculate the yaw angles that yielded a significant total power improvement on the 1 x 3 SOWFA simulation setup, as shown in Figure 6.

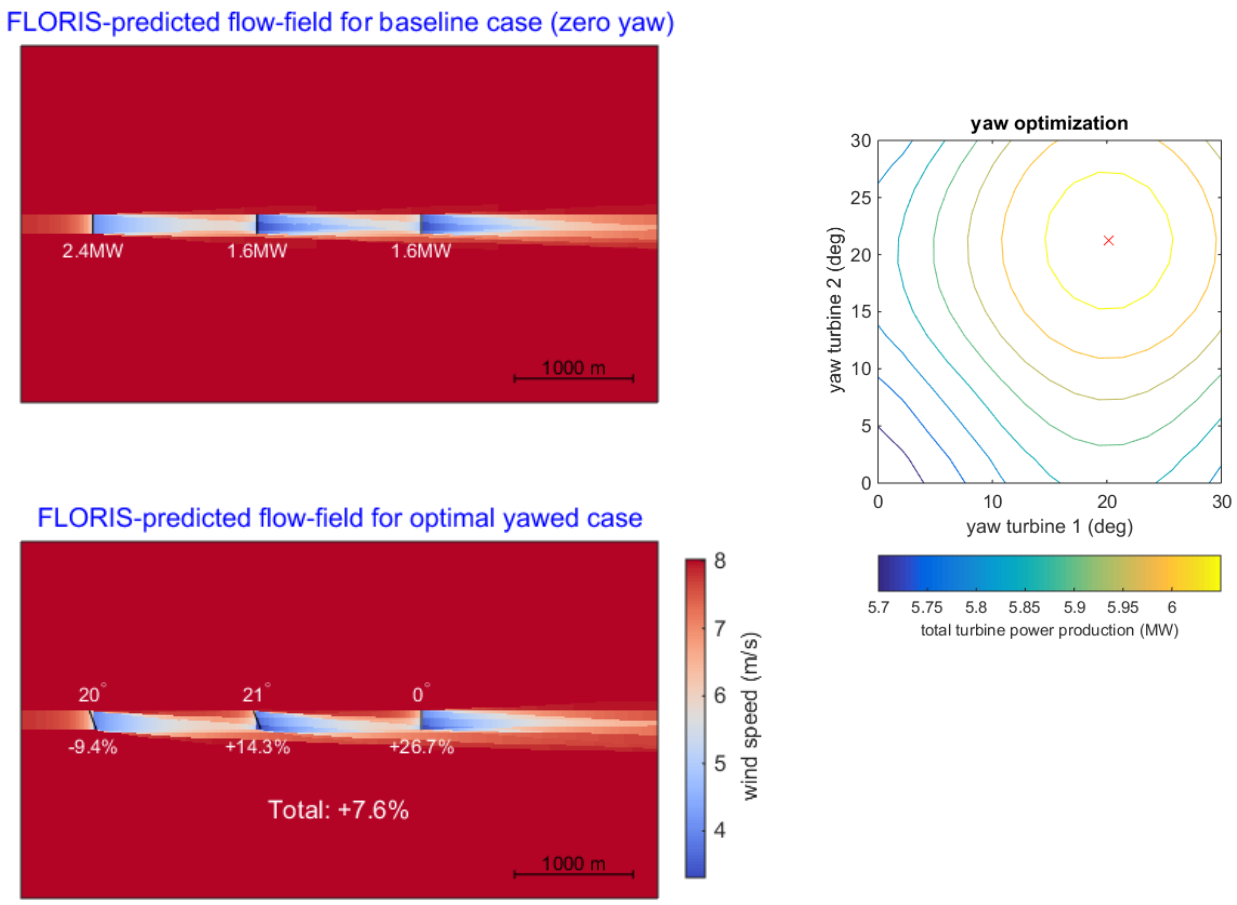

Figure 6: Optimization of yaw settings for the 1 x 3 setup. On the left the FLORIS-predicted flow-field, on the right a plot of how the FLORIS-predicted total power production of the setup depends on the yaw angles of the two front turbines, the red cross indicates the maximum.

The overall power production increased by 7.6% in the FLORIS model by yawing the first two turbines by 20° and 21° to redirect the wakes, compared to 5.7% predicted by a SOWFA 1 x 3 model simulation for those yaw angles that was run as a verification case. The FLORIS prediction error on total power production for the verification case with optimized yaw angles was 1.75%, which is small given its computational efficiency gained compared to SOWFA. By redirecting the wake the decrease in power production from the first turbine was 9.4% in FLORIS, however the increase in power production of the second and third turbines of 14.3% and 26.7 % respectively added to a total power production increase of 7.6%. When extending the wind power plant to a 10 x 10 grid array at 7D spacing, yaw control optimization yields a 2.35% increase in average power production in the FLORIS model, for a wind rose based on the Massachusetts site. Optimizing turbine layout did not significantly improve power production given the 7D spacing and the same wind rose.

References

[1] Simulator for Off/Onshore Wind Farm Applications, http://wind.nrel.gov/designcodes/simulators/sowfa

[2] OpenFOAM: OpenFOAM – The Open Source CFD Toolbox, User's Manual, Version 2.0.x, www.openfoam.org

[3] J. M. Jonkman and M. L. Buhl, "FAST User's Guide", NREL/EL-500-38230, (2005)

[4] Lee, S., Churchfield, M., Sirnivas, S., Moriarty, P., Nielsen, F.G., Skaare, B., and Byklum, E., *Coalescing Wind Turbine Wakes*, Wake Conference 2015, Visby, Sweden.

[5] Gebraad; Teeuwisse, F.W.; van Wingerden, J.W.; Fleming, P.A.; Ruben, S.D.; Marden, J.R.; Pao, L.Y. "Wind Plant Power Optimization Through Yaw Control Using a Parametric Model for Wake Effects: A CFD Simulation Study." Wind Energy, 2014.