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Aeroelastic Modeling of Offshore Turbines and Support Structures in Hurricane-Prone Regions

R. Damiani*, Y. Guo*, W. Musial*, and D. Arora**
*National Renewable Energy Laboratory; **Alstom Power, Inc

Abstract

U.S. offshore wind turbines (OWTs) will likely have to contend with hurricanes and the associated loading conditions. Current industry standards do not account for these conditions in their design load cases (DLCs), thus a new approach is required to guarantee that the OWTs achieve an appropriate level of reliability. In this study, a sequentially coupled aero-hydro-servo-elastic modeling technique was used to study two proposed design approaches: 1) The ABS approach [1], and 2) The hazard curve or API approach [2]. The former employs [3] partial load factors (PSFs) and 100-yr return-period (RP) met-ocean events. The latter allows setting PSFs and RP to a prescribed level of system reliability. The 500-yr RP robustness check (appearing in [2] and [3] upcoming editions) is a good indicator of the target reliability for L2 structures [2,4]. Computer-aided engineering (CAE) tools such as the National Renewable Energy Laboratory's (NREL's) FAST and Bentley's SACS (offshore analysis and design software) can be efficiently coupled to simulate system loads under hurricane DLCs [5] and were used in this project to examine the two design approaches. For this task, we augmented the latest FAST version (v8) to include tower aerodynamic drag that cannot be ignored in hurricane DLCs. In this project, Alstom provided the Haliade 150, 6-MW turbine model that was simulated on a typical four-legged jacket for a mid-Atlantic site. FAST-calculated tower-base loads were fed to SACS at the interface level (transition piece); SACS added hydrodynamic and wind loads on the exposed substructure, and calculated mudline overturning moments, and member and joint utilization. Results show that CAE tools can be effectively used to achieve a well-balanced, safe OWT design.

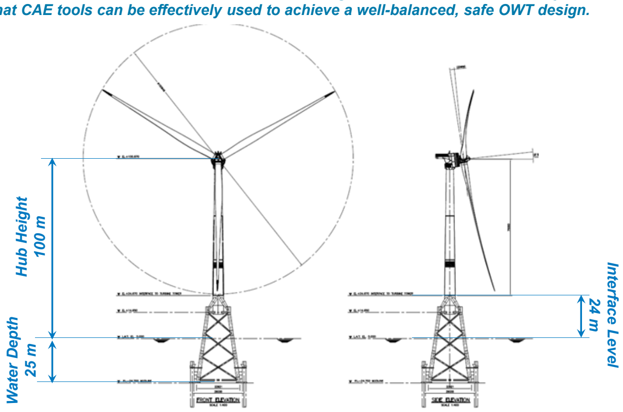

Figure 1. Offshore wind turbine (Alstom Haliade 150) and support structure configuration considered in this study

FAST v8 – Tower Drag Assessment

Tower-base shear dramatically increases when aerodynamic drag is included. Yaw-error effects need to be accounted for in hurricane ride-through strategies.

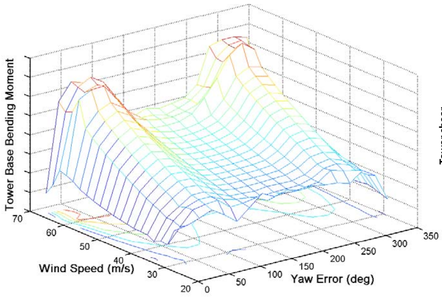

Figure 2. Tower-base bending moment as a function of wind speed and yaw error under parked conditions

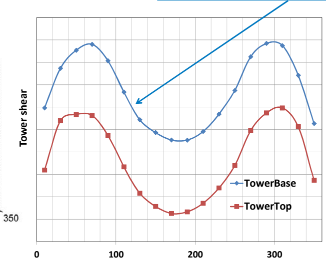

Figure 3. Tower-top and tower-base shear forces as a function of yaw error; difference is a result of the tower aerodynamic drag now included in FAST v8

FAST v8 – SACS Coupling

Tower-base loads calculated by FAST were applied at the substructure interface in SACS.

SACS model of the substructure

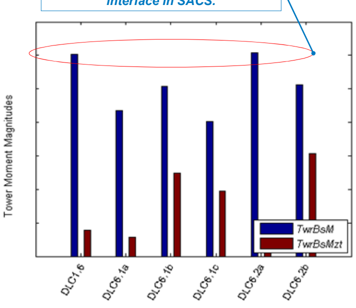

Figure 4. Tower-base bending moment (in blue) and torsion (in red) maxima for ultimate limit state (ULS) load cases as calculated by FAST. Note: both parked and operational DLCs produce tower-base load maxima.

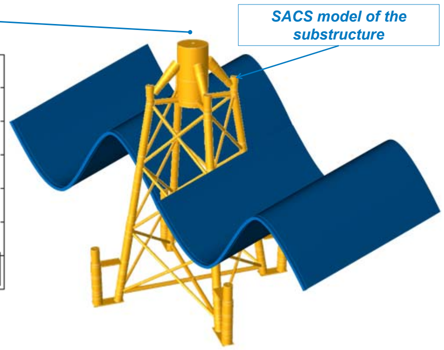

Figure 5. SACS adds substructure hydrodynamic loads and computes substructure overall overturning moment and stresses.

Hazard Curves: ABS/IEC/API Design Approach Comparison

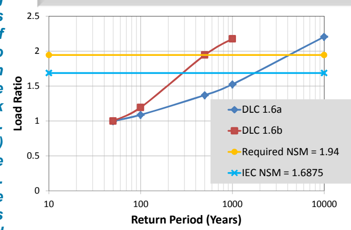

Figure 6. Hazard curves; DLC1.6 – normalized to 50 years (IEC); -15° wind-wave misalignment

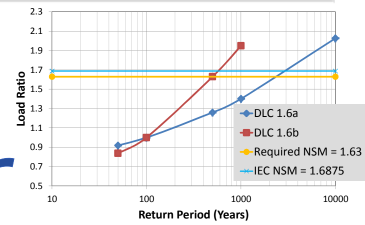

Figure 7. Hazard curves; DLC1.6 – normalized to 100 years (ABS); -15° wind-wave misalignment

Specifically devised controls may mitigate this requirement.

PSF→1.56 IEC NOT SUFFICIENT

PSF→1.35 ABS OK

*The hazard curve yields a 500-yr, required nominal safety margin (NSM = Soil Safety Factor (0.8) * PSF), thus the required PSF.*

PSF→1.45 ABS/IEC NOT SUFFICIENT

PSF→1.51 ABS/IEC NOT SUFFICIENT

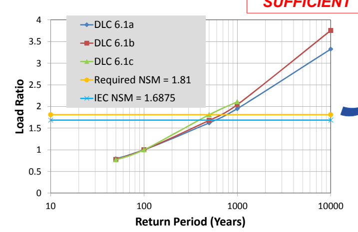

Figure 8. Hazard curves; DLC6.1 – normalized to 100 years (ABS); -15° wind-wave misalignment

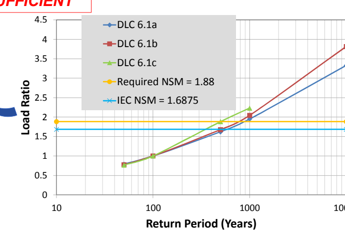

Figure 9. Hazard curves; DLC6.1 – normalized to 100 years (ABS); all wind-wave misalignments

FAST v8/SACS ULS Analysis of the Substructure

Structure designed per basic IEC requirements fails member API-code verification.

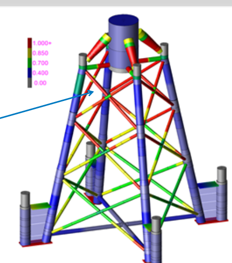

Figure 10. ULS analysis: member utilization according to API code checks (SACS output)

Conclusions

This study revealed how CAE tools can be used to assess the reliability of OWT systems in hurricane-prone waters, and thus achieve a well-balanced design, in which reliability levels and costs are optimized.

- *Tower drag is crucial when verifying the integrity of the substructure. Under parked DLCs, the tower and substructure drag account for two-thirds or more of the tower-base shear and cannot be ignored. As a result, the new FAST v8 Aerodyn module now includes tower aerodynamic drag.*
- *To assess the substructure, both operational and parked cases must be carefully investigated as they both produce peak loads at the interface with the tower. Additionally, yaw-error-induced loading needs to be assessed in hurricane ride-through strategies because tower-base shear can increase up to 4 times when the rotor is not aligned with the wind direction.*
- *Overload hazard in hurricane-prone waters may be significantly higher than in the North Sea. We produced hazard curves that show how IEC basic conditions (met-ocean RP events and basic PSFs) may not guarantee the ability to withstand a 500-yr RP event. Even the ABS approach may not suffice, and PSF values need to be revised for each DLC, though specifically devised controls may mitigate this requirement.*
- *A jacket that was designed with basic IEC requirements was shown to produce high utilization ratios that are not compatible with a safe design in hurricane-prone regions where PSF and met-ocean RP need to be increased.*

Acknowledgments

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