NATIONAL RENEWABLE ENERGY LABORATORY

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Validation of Simplified Load Equations Through Loads Measurement and Modeling of a Small Horizontal-Axis Wind Turbine Tower

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Abstract

As part of an ongoing effort to improve the modeling and prediction of small wind turbine dynamics, the National Renewable Energy Laboratory (NREL) tested a small horizontal-axis wind turbine in the field at the National Wind Technology Center. The test turbine was a 2.1-kW downwind machine mounted on an 18-m multisection fiberglass composite tower. The tower was instrumented and monitored for approximately 6 months. The collected data were analyzed to assess the turbine and tower loads and further validate the simplified loads equations from the International Electrotechnical Commission (IEC) 61400-2 design standards. Field-measured loads were also compared to the output of an aeroelastic model of the turbine. Ultimate loads at the tower base were assessed using both the simplified design equations and the aeroelastic model output. The simplified design equations in IEC 61400-2 do not accurately model fatigue loads [1]. In this project, we compared fatigue loads as measured in the field, as predicted by the aeroelastic model, and as calculated using the simplified design equations.

Design Load Derivation Methods

1. Full-Scale Loads Measurements (Field)	2. Aeroelastic Modeling (FAST)	3. Simplified Loads Approach
• A 2.1-kW, free yaw, variable-speed, downwind machine • An 18-m multisection fiberglass composite tower • Meteorological data recorded at hub height [2]	• FAST v 7.02 utilized • Turbulent wind files with reference wind speeds of 2, 4…,24, 26 m/s • Turbulence intensity of 18% • Air density of 1.0 kg/m³ to match site conditions • Tower drag not modeled	• IEC 61400-2 design load cases (DLCs) A (fatigue), H, and I (ultimate loads) • Input parameters derived from the FAST model, preliminary test results, and turbine measurements • Simplified loads approach (SLA) load components used to determine the tower-base bending moment

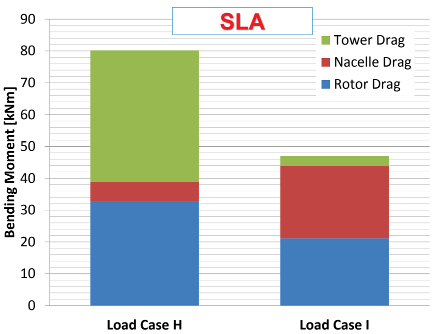

Figure 1. Component-drag contributions to the total combined tower-base bending moment for DLCs H and I

SLA DLCs for tower analysis:

- **IEC 61400-2 DLC H prescribes a wind speed of 59.5 m/s with a normally parked turbine**
- **IEC 61400-2 DLC I assumes an extreme wind speed of 42.5 m/s and maximum exposure (yaw mechanism failure), which for this turbine translates into a 'no-yaw-error' configuration**
- **DLC H develops the greatest bending moment ➔ tower design driver.**

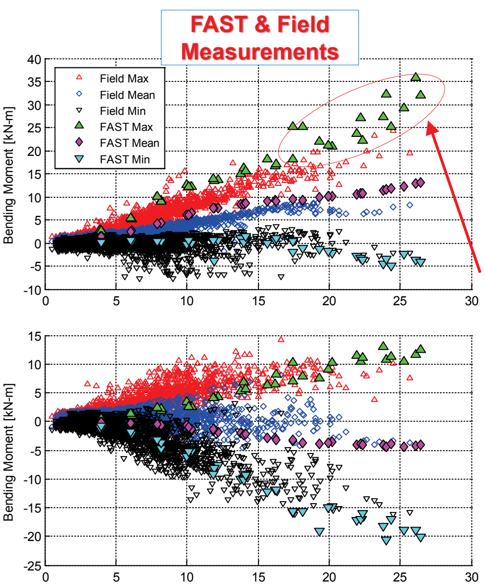

Figure 2. Ten-minute statistical comparison of the Field and FAST tower-base ultimate loads in the fore-aft (top) and side-to-side (bottom) directions

- **For the captured wind speeds shown in Figure 2, the FAST and field loads are within the load envelope of DLCs H and I (from Figure 1)**
- **Deviation between Field and FAST is likely a result of the actual turbine control system mitigating loads at high wind speeds (18 m/s and above)**

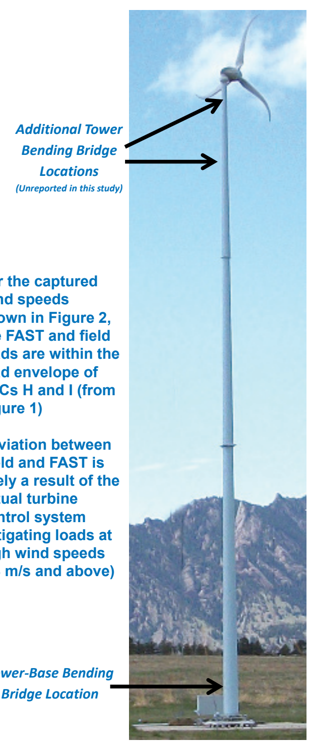

Figure 3. Test article used for full-scale loads measurement with identification of tower strain gage locations (Photo by Rick Damiani, NREL)

Loads extrapolation of the field-measured loads is required for a proper comparison with SLA results [3]—a future work item of this study.

Fatigue Loads Comparison

- **Damage equivalent loads (DELs) were calculated using three different S-N curves based on a Rayleigh distribution of wind speeds over a 20-year design lifetime (Figure 4)**
- **FAST DELs were consistently greater than the Field DELs**
- **SLA DELs were determined using IEC 61400-2 DLC A, which is based on the peak-to-peak rotor thrust load and the 20-yr number of cycles (NC) at rated rotor speed**
- **Significant effect of the material properties (S-N curve exponent, m):**

For steel (m=3), the SLA DEL is more conservative than the FAST DEL

For composites (m=10), the SLA DEL is less conservative than the FAST DEL

Figure 5 explains this effect: the SLA's DLC A assumes a large number of cycles (NSLA) associated with rated rpm for 20 years, at a low load range (SSLA). FAST-derived DELs account for a Rayleigh wind distribution, and therefore are associated with a higher load range (S_{FAST}) and lower number of cycles (N_{FAST}). When scaling to a common number of cycles (N_{20}), the value of m accounts for this artifact.

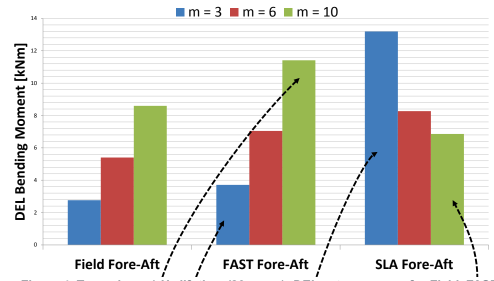

Figure 4. Tower-base 1-Hz lifetime (20 years); DELs at zero mean for Field, FAST, and SLA with S-N curves with inverse exponent values (m) of 3, 6, and 10

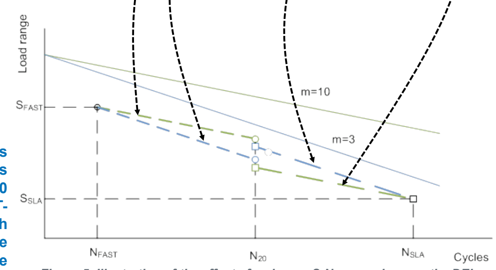

Figure 5. Illustration of the effect of a chosen S-N curve slope on the DEL for a high load range (S_{FAST}) at a low number of cycles (N_{FAST}) and vice versa (S_{SLA}, N_{SLA})

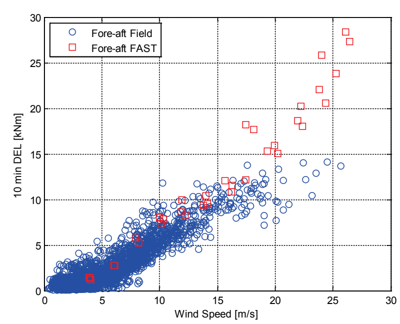

Figure 6. Short-term (10 minute) fore-aft tower-base bending moment DELs versus the mean wind speed for an S-N curve with m = 10

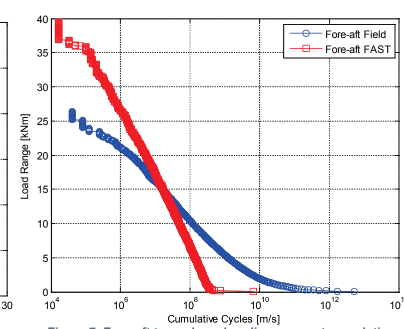

Figure 7. Fore-aft tower-base bending moment cumulative fatigue spectra comparison of field-measured loads and FAST predictions

Although the FAST and Field DELs are similar, Figures 6 and 7 demonstrate FAST's overprediction of high-range loads compared to the Field spectra. This outcome is consistent with the ultimate loads comparison.

The SLA DLC A yields a single fatigue load range value of 5.183 kNm, with a cycle count of 10.4e9.

Remarks

This study focused on tower-base bending moments of a horizontal-axis wind turbine to provide an indication of the overall performance of the load derivation methods. Notable outcomes include the following:

- *The SLA DELs showed large differences compared to the Field and FAST results because of a high dependence on the assumed S-N curve slope and the number of cycles. Thus, the SLA DEL is much higher for steel (m = 3 to 6) and lower for composites (m =10).*
- *Better agreement on the tower loads between the field measurements and FAST predictions under normal power production conditions was found for side-to-side than for fore-aft bending; this is likely caused by a lower fidelity turbine control model used in the FAST simulations.*
- *The fatigue spectra derived from the Field and FAST tower-base moments look quite different, with the FAST predictions showing more (fewer) cycles at large (small) amplitude load ranges than the Field predictions.*
- *We recommend that this study be repeated on wind turbines of different configurations and sizes, and that field load extrapolation be conducted.*

References

1. IEC 61400-2 ed 3.0 Wind turbines – Part 2: Small wind turbines, 2013-12.
2. IEC 61400-13 Wind turbine generator systems – Part 13: Measurement of mechanical loads, 2001-06.
3. IEC 61400-1 ed 3.1 Wind turbines – Part 1 : Design requirements, 2014-04.

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