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October 2010

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## ABSTRACT

Demand parameters for turbines, such as tower moment demand, are primarily driven by wind excitation and dynamics associated with operation. For that purpose, computational simulation platforms have been developed, such as FAST, maintained by the National Renewable Energy Laboratory (NREL). For seismically active regions, building codes also require the consideration of earthquake loading. Historically, it has been common to use simple building code approaches to estimate the structural demand from earthquake shaking, as an independent loading scenario. Currently, International Electrotechnical Commission (IEC) design requirements include the consideration of earthquake shaking while the turbine is operating. Numerical and analytical tools used to consider earthquake loads for buildings and other static civil structures are not well suited for modeling simultaneous wind and earthquake excitation in conjunction with operational dynamics. Through the addition of seismic loading capabilities to FAST, it is possible to simulate earthquake shaking in the time domain, which allows consideration of non-linear effects such as structural nonlinearities, aerodynamic hysteresis, control system influence, and transients. This paper presents a FAST model of a modern 900-kW wind turbine, which is calibrated based on field vibration measurements. With this calibrated model, both coupled and uncoupled simulations are conducted looking at the structural demand for the turbine tower. Response is compared under the conditions of normal operation and potential emergency shutdown due the earthquake induced vibrations. The results highlight the availability of a numerical tool for conducting such studies, and provide insights into the combined wind-earthquake loading mechanism.

## Introduction

Regulating bodies recently added requirements to consider seismically induced loads in conjunction with operational wind loads for certifying wind turbines (GL 2003; IEC 2005). This requirement is often fulfilled by superimposing the results from independently conducted simulations for the wind induced loads and the seismic loads. As turbines grow larger and become more expensive (Wiser and Bolinger 2009) simulating earthquake loads and wind loads simultaneously in the time domain becomes desirable to ensure that designs are not overly conservative.

Early investigations (Bazeos et al. 2002; Lavassas et al. 2003) of earthquake loading focused on tower loading using models that lump the nacelle and rotor as a point mass. These were incapable of considering the simultaneous combination of seismic and wind loads. Gradually, interest shifted from these simple models to more refined models that also consider loads for turbine components other than the tower (Ritschel et al. 2003; Witcher 2005; Haenler et al. 2006; Zhao and Maisser 2006). Migration to models that include dynamics of the rotor also is dictated by industry-standard load cases in situations such as an emergency shutdown triggered by an earthquake (IEC 2005). In addition to modeling techniques, researchers investigated effects such as soil-structure interaction through equivalent springs and dampers (Bazeos et al. 2002; Zhao and Maisser 2006). Each of these publications approaches modeling seismic loads for wind turbines differently.

This paper presents results from dynamic field measurements of a 900-kW turbine. Observed natural frequencies are reported from the experimental results and provide the basis for the development of a model for the FAST code. With this calibrated model, simulations investigate the implications of operational state on this class of turbine for a combination of operational wind loads and earthquake shaking.

## Turbine Description and FAST Model

A 900-kW turbine (Figure 1) installed at Oak Creek Energy Systems (OCES) near Mojave, California, USA was selected for in-situ measurements. This turbine is characteristic of units installed in the late 1990s (Wiser and Bolinger 2008). Salient properties of the turbine are reported in Table 1. Reports from OCES indicate that the soil profile under this particular turbine consists of an upper 2-meter layer of sandy materials underlain by dense, silty sands and clayey sands. The turbine foundation is a hollow cylindrical concrete shell, with a 3.5-meter outer diameter, that extends 9 meters below ground surface. Outer and inner corrugated metal shells 0.3 m apart filled in between with concrete to form a hollow cylinder. The inner shell is backfilled with soil. The turbine tower is attached to the foundation through un-bonded, post-tensioned bars that extend from the bottom of the foundation to the base of the tower.

The dynamic response of the turbine was recorded using a total of 81 channels in each of 3 orthogonal axes in 15 locations along the height of the tower, in 4 locations on the foundation, and in 8 locations on the surface of the surrounding soil. A variant of the Natural Excitation Technique (NExT) algorithm (James et al. 1992) called the Multiple Natural Excitation Technique (MNExT) was selected to process the recorded data. A summary of the average frequencies for the first two tower bending modes is shown in Table 2. In addition, vibration measurements were taken on one of the cantilevered blades while the rotor was resting horizontally on the ground. The observed first resonant frequencies are reported in Table 2. All of the tower and blade frequencies considered fall within the range of interest for earthquake loading of approximately 0 to 15 Hz.

PIX#17370

**Figure 1: Tested turbine**

**Table 1. Main parameters of wind turbine**

| **Type** | **Horizontal wind turbine** |
|---|---|
| Power rating | 900 kW |
| Rotor Configuration | 3 blade upwind |
| Control | Variable speed, fixed pitch |
| Rated Wind Speed | 11.4 m/s |
| Cut-out Wind Speed | 25 m/s |
| Rotor Speed Range | 14 to 22 RPM |
| Rotor diameter | 53.6 m |
| Tower height | 54 m |
| Hub height | 55 m |
| Mass of rotor | 16,000 kg |
| Mass of nacelle | 23,000 kg |
| Mass of tower | 65,000 kg |

These field measurements served as a basis for the development of a simple beam-column finite element model that was developed using the OpenSees code (Mazzoni et al. 2006) and the FAST code (Jonkman and Buhl 2005) to predict structural loads. Properties for equivalent beam elements were developed for the tower using engineering drawings and specifications (Table 1). Blade properties were arrived at by scaling reported values of stiffness and mass for the blades of the 1.5-MW turbine presented in the WindPACT Turbine Rotor Design Study (Malcolm and Hansen 2006) to create a blade whose first flap and edge resonances matched those measured in the field (Table 2). Using this OpenSees model, mode shapes were calculated as a basis for the FAST model. Because the second side-to-side and fore-aft tower modes contained a node near the top of the turbine, it was necessary to use a 7$^{th}$ order polynomial to describe mode shapes instead of the standard 6th order polynomial used by default in FAST (Jonkman and Buhl 2005). Following minor adjustments, it was found that the final FAST model produced natural frequency estimates (Table 3) that closely matched those observed experimentally (Table 2).

**Table 2: Summary of tower modes for a parked turbine and blade modes for a cantilevered blade (measured in the field)**

| Mode description | Frequency (Hz) |
|---|---|
| 1st tower side-to-side | 0.55 |
| 1st tower fore-aft | 0.56 |
| 1st blade flapwise | 0.99 |
| 1st blade edgewise | 1.80 |
| 2nd tower side-to-side | 3.95 |
| 2nd tower fore-aft | 3.96 |

**Table 3: Summary of tower and blade modes for a parked turbine (modeled in FAST)**

| Mode description | Frequency (Hz) |
|---|---|
| 1st tower fore-aft | 0.57 |
| 1st tower side-to-side | 0.57 |
| 1st blade flapwise-1 | 1.00 |
| 1st blade flapwise-2 | 1.01 |
| 1st blade flapwise-3 | 1.05 |
| 1st blade edgewise-1 | 1.69 |
| 1st blade edgewise-2 | 1.79 |
| 1st blade edgewise-3 | 1.83 |
| 2nd blade flapwise-1 | 2.98 |
| 2nd blade flapwise-2 | 3.08 |
| 2nd blade flapwise-3 | 3.13 |
| 2nd tower fore-aft | 3.96 |
| 2nd tower side-to-side | 3.97 |

## Numerical Simulations

To understand the implications of this approach to modeling a turbine subjected to an earthquake, simulations were conducted using the model described above. For all simulations a 10-minute-long wind field, with a mean speed of 12 m/s, was generated using TurbSim (Jonkman 2009) with level A IEC turbulence intensity. The simulations fall into two categories: independent simulations, in which only wind or earthquake loads are present, and coupled simulations, in which the two load sources were simulated simultaneously. The first 200 seconds of all results were discarded to eliminate the influence of initial transients. For simulations in which earthquake loads were present, the recorded ground motions of the 1940 El Centro earthquake (Figure 2) were used. The 1940 El Centro earthquake measured 6.9 according to the moment magnitude scale. For the two selected horizontal components recorded at Array Station 9 in El Centro, California, the peak ground acceleration was 3.4 $m/s^2$ in the north-south direction. The north-south component was aligned with the wind and the east-west component was imparted horizontally, perpendicular to the wind. In all earthquake simulations, the ground motion (Figure 2) started 400 seconds into the simulation and lasted approximately 55 seconds.

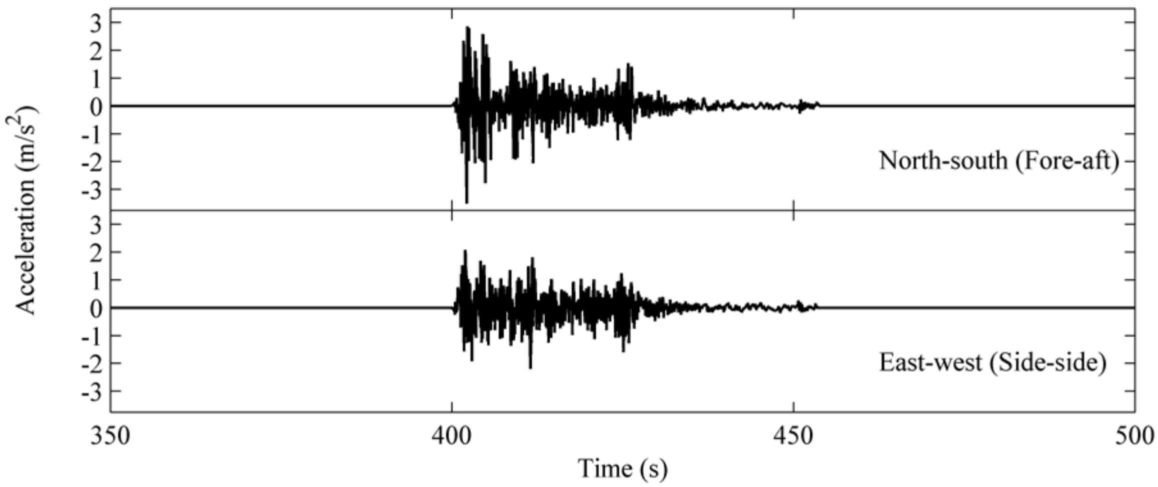


**Figure 2: Acceleration time history for 1940 El Centro earthquake**

Initial efforts have approached earthquake loading of wind turbines by simulating wind and earthquake loads independently and superimposing the results. This approach is advantageous because it allows the use of existing tools and techniques for both simulation sets. In most cases, these simulations are simple to conduct because of their familiarity.

The 900-kW turbine already introduced was simulated using FAST. Cases of parked, operating, and emergency shutdown, with and without the 1940 El Centro earthquake were simulated. In the parked simulation, the turbine was parked with the high-speed shaft brake engaged and the blade tip brakes deployed. In the operating and emergency shutdown simulations, a simple generator model was used in FAST to regulate the rotor speed at approximately 22 RPM. The emergency shutdown was initiated by deploying the tip brakes 401.28 seconds into the simulation followed 4 seconds later by the engagement of the high-speed shaft brake to bring the rotor to a full stop. An additional uncoupled simulation without wind and operational loads was considered to emulate a conventional finite element simulation that does not consider the aerodynamic interaction.

## Results and Discussion

By conducting the analysis using a turbine specific code, the FAST code, many parameters can be evaluated to assist in understanding the response of the turbine to possible load combinations. This paper focuses on bending moment demand at the base of the turbine tower for the simulations discussed. The predominant bending moment at the tower base is due to fore-aft bending of the tower for wind loading. In the earthquake loading simulation, there were bending moments in both directions due to the two horizontal components of the input motion (Figure 2). To allow direct comparison of demand in the various scenarios, a single moment value that is equal to the square root of the sum of the squares (SRSS) of the two horizontal moments is presented. Table 4 shows a comparison of the maximum moment demand for the simulations.

**Table 4: Base moment demand for simulations of coupled wind and earthquake loading**

| Load Case | Earthquake | Aerodynamics | Demand (MN-m) |
|---|---|---|---|
| Parked turbine | No | Yes | 2.3 |
| Operating turbine | No | Yes | 10.1 |
| Emergency shutdown | No | Yes | 10.1 |
| Parked turbine | Yes | No | 12.5 |
| Parked turbine | Yes | Yes | 9.8 |
| Operating turbine | Yes | Yes | 12.5 |
| Emergency shutdown | Yes | Yes | 10.2 |

The maximum demand was 12.5 MN-m for both the coupled operating turbine with earthquake simulation and the independent parked turbine with earthquake loading only simulation. A partial safety factor of 1.0 was applied to all demand parameters when independent simulations were combined for the earthquake simulation (IEC 2005). For the operating case, this led to a resulting moment demand of 22.6 MN-m in comparison to the 12.5 MN-m found in the coupled simulation. Such a difference in an estimate of demand would likely have design implications on the turbine. This raises questions about the accuracy and level of conservatism when conducting independent simulations.

A direct comparison of the moment demand in the simulations conducted for the parked turbine, when subjected to the El Centro earthquake considered with and without aerodynamics, shows the source of this difference (Figures 3 through 5). Little difference is seen in the side-side moment demand (Figure 3), but the fore-aft moment demand (Figure 4) clearly shows the influence of aerodynamic damping. When aerodynamics were not considered, the amplitude of the fore-aft moment demand continued to grow 20 seconds into the earthquake, whereas when aerodynamics were considered, the demand stopped growing 10 seconds after the onset of shaking. The combined demand (Figure 5) clearly shows that the increase in damping in consideration of aerodynamic loads resulted in a lower overall demand.

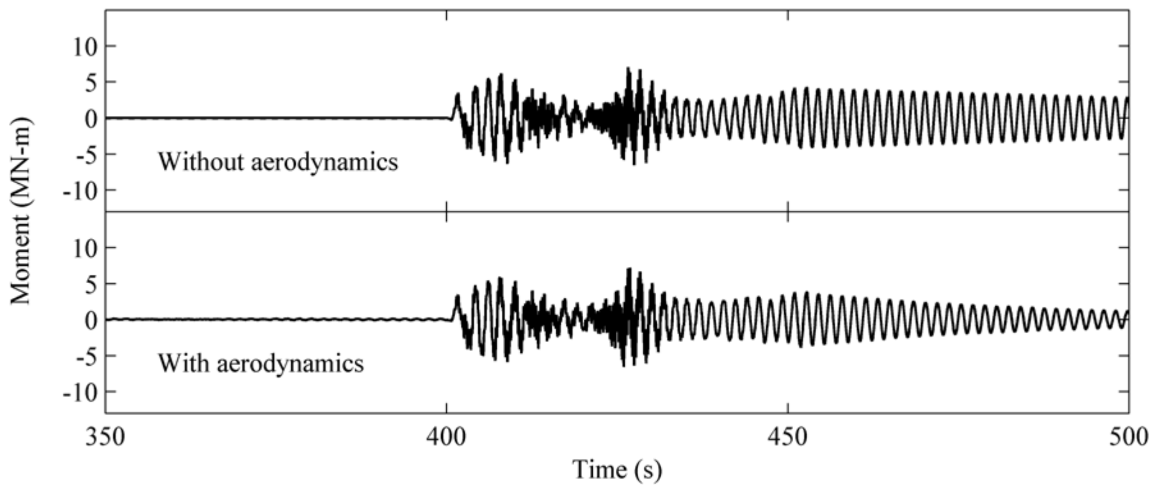


**Figure 3: Side-side moment demand at tower base for parked case**

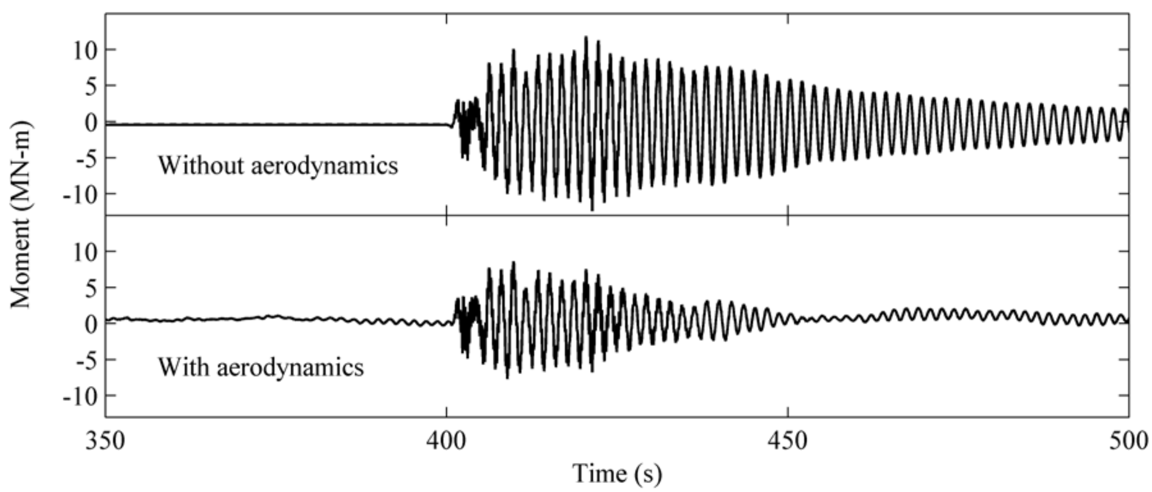


**Figure 4: Fore-aft moment demand at tower base for parked case**

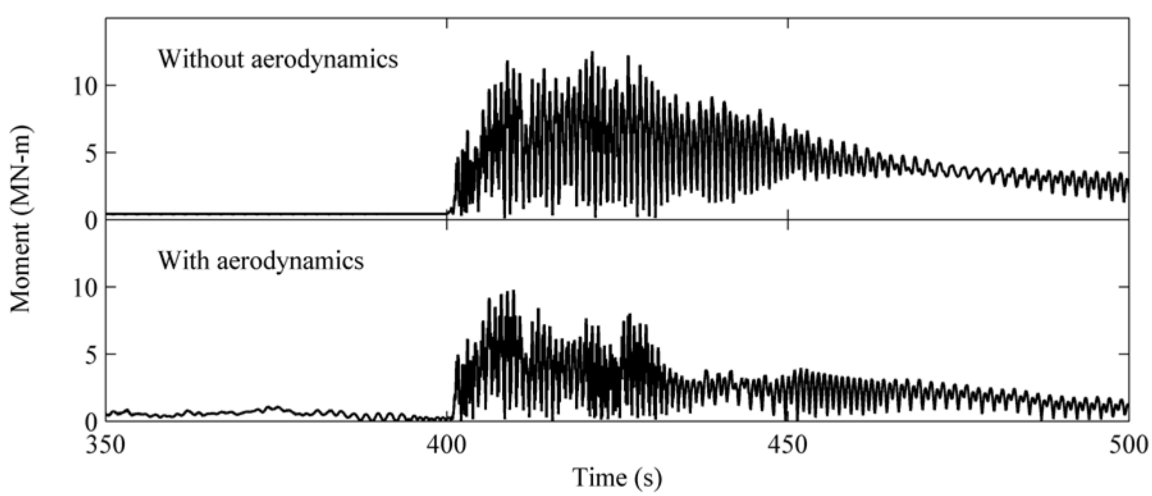


**Figure 5: SRSS moment demand at tower base for parked case**

## Conclusion

A model of a 900-kW turbine that matched field measurements for natural frequencies and mode shapes was built. Using this model and the FAST code, a set of simulations were conducted to investigate the differences between predictions of tower moment demands using uncoupled and coupled simulations. The results show a significant difference in demand depending on modeling approach. In the example shown, the supporting tower may have insufficient capacity based on independent simulations, but be suitable for the coupled simulation. Such implications could clearly affect the economic viability of wind energy in regions with a high seismic hazard.

For an actual site-specific assessment of design loads for turbines, many more simulations must be considered. Typically, many different wind fields must be simulated to achieve an appropriate level of confidence in derived design loads (Fogle et al. 2008). In a similar manner, a site-specific assessment should be conducted for earthquake loads to consider site characteristics in deriving a suite of selected ground motions (Conte and Zhang 2007). Simulations that consider these ground motions must be conducted to assess the implications relative to orientation of shaking and wind.

This work is part of a continuing effort at UCSD to reduce uncertainty associated with seismic design loads for wind turbines. Through National Science Foundation (NSF) funding, full scale experiments are currently being conducted to inform and refine modeling of wind turbines for earthquake induced loads. The modifications to FAST described here will be used to simulate and validate experimental results. Feedback from findings will be used to refine the capability of the FAST code to accurately incorporate base shaking as a load source for wind turbines.

## Acknowledgments

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## References

Bazeos, N., Hatzigeorgiou, G. D., Hondros, I. D., Karamaneas, H., Karabalis, D. L., and Beskos, D. E. (2002). "Static, seismic and stability analyses of a prototype wind turbine steel tower." Eng. Struct., 24(8), 1015-1025.

Conte, J. P., and Zhang, Y. (2007). "Performance Based Earthquake Engineering: Application to an Actual Bridge-Foundation-Ground System." 12th Italian National Conference on Earthquake Engineering, Pisa, Italy, 1-18.

Fogle, J., Agarwal, P., and Manuel, L. (2008). "Towards an Improved Understanding of Statistical Extrapolation for Wind Turbine Extreme Loads." Wind Energy, 11(6), 613-635.

GL (Germanischer Lloyd). (2003). Guidelines for the Certification of Wind Turbines. GL, Hamburg, Germany.

Haenler, M., Ritschel, U., and Warnke, I. (2006). "Systematic modelling of wind turbine dynamics and earthquake loads on wind turbines." European Wind Energy Conference and Exhibition, European Wind Energy Association, Athens, Greece, 1-6.

IEC (International Electrotechnical Commission). (2005). IEC 61400-1 ed.3: Wind Turbines - Part 1: Design Requirements. IEC, Geneva, Switzerland.

James, G. H., III, Carne, T. G., and Lauffer, J. P. (1992). "The Natural Excitation Technique (NExT) for Modal Parameter Extraction From Operating Wind Turbines." Rep. No. SAND92-1666, UC-261, Sandia National Laboratories, Albuquerque, New Mexico, USA.

Jonkman, B. J. (2009). "TurbSim User's Guide: Version 1.50." Rep. No. NREL/TP-500-46198, National Renewable Energy Laboratory, Golden, Colorado, USA.

Jonkman, J. M., and Buhl, M. L., Jr. (2005). "FAST User's Guide." Rep. No. NREL/EL-500-38230, NREL, Golden, Colorado, USA.

Lavassas, I., Nikolaidis, G., Zervas, P., Efthimiou, E., Doudoumis, I. N., and Baniotopoulos, C. C. (2003). "Analysis and design of the prototype of a steel 1-MW wind turbine tower." Eng. Struct., 25(8), 1097-1106.

Malcolm, D. J., and Hansen, A. C. (2006). "WindPACT Turbine Rotor Design Study." Rep. No. NREL/SR-500-32495, NREL, Golden, Colorado, USA.

Mazzoni, S., McKenna, F., and Fenves, G. L. (2006). "Open System for Earthquake Engineering Simulation User Manual." Pacific Earthquake Engineering Research Center, University of California, Berkeley, California, USA.

Ritschel, U., Warnke, I., Kirchner, J., and Meussen, B. (2003). "Wind Turbines and Earthquakes." 2nd World Wind Energy Conference, World Wind Energy Association, Cape Town, South Africa, 1-8.

Wiser, R., and Bolinger, M. (2009). "2008 Wind Technologies Market Report." Rep. No. NREL/TP-6A2-46026; DOE/GO-102009-2868, NREL, Golden, Colorado, USA.

Wiser, R., and Bolinger, M. (2008). "Annual Report on U.S. Wind Power Installation, Costs, and Performance Trends: 2007." Rep. No. DOE/GO-102008-2590, Department of Energy, Washington, District of Columbia, USA.

Witcher, D. (2005). "Seismic Analysis of Wind Turbines in the Time Domain." Wind Energy, 8(1), 81-91.

Zhao, X., and Maisser, P. (2006). "Seismic response analysis of wind turbine towers including soil-structure interaction." Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-Body Dynamics, 220(1), 53-61.

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