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FAST Simulation of Wind Turbine Seismic Response

Conference Paper
NREL/CP-500-46225
March 2010

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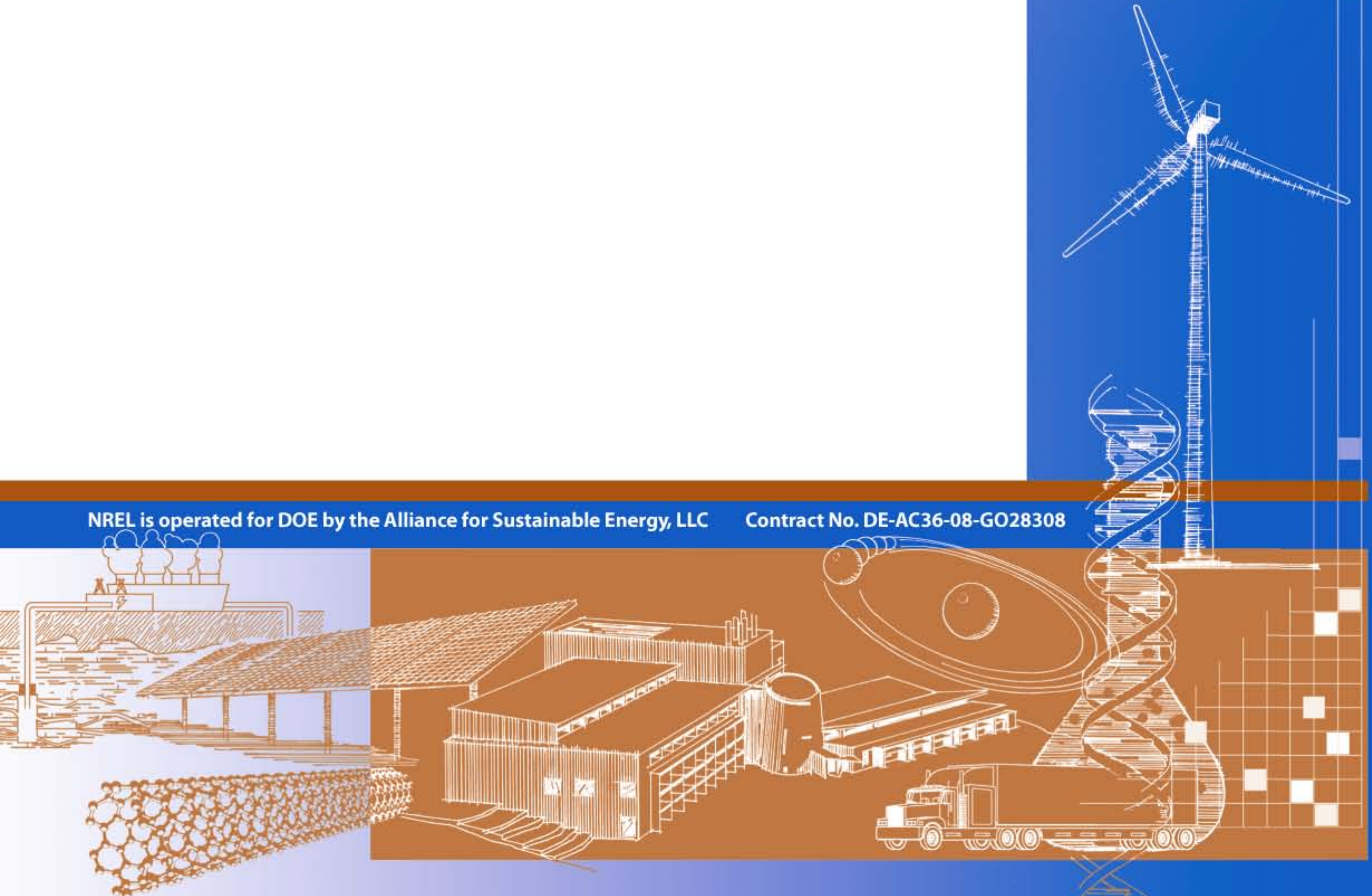
Presented at the 2009 Asian-Pacific Network of Centers for
Earthquake Engineering Research (ANCER) Workshop
Urbana-Champaign, Illinois
August 13–14, 2009



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ABSTRACT

Numerical modeling is an essential tool for predicting the seismic response of structures. Many mature computational tools, both commercial and public domain, are available for modeling stationary buildings and structures. Wind turbines are structures in motion, however, and as such are not easily modeled in these existing packages. FAST, an open source software tool maintained by the National Renewable Energy Laboratory (NREL), designed specifically to simulate turbine dynamics, overcomes this limitation. This paper discusses recent additions to FAST that allow a user to consider seismic loads in addition to existing robust capabilities for simulating wind and other load sources under the various states of wind turbine operation. For that purpose, researchers at the University of California San Diego (UCSD) first simulated seismic response for a small utility-scale wind turbine to a suite of earthquake motions using an experimentally validated OpenSees model. A comparable model built for FAST was subjected to the same earthquake recordings. Results from the two models validate this new capability in FAST.

Acknowledgments

The authors extend their gratitude to all the organizations, corporations, and individuals who contributed to this investigation, and who fund this research (National Science Foundation grant no. CMMI 0830422). Oak Creek Energy Systems (Hal Romanowitz and J. Edward Duggan) generously donated the 65-kW turbine for shake table testing and continues to assist in advancing this important area of research. The pilot phase of shake-table testing was conducted in collaboration with Professors José Restrepo and Marc Veletzos. In situ testing is progressing with the oversight of Dr. Robert Nigbor of the University of California Los Angeles. To facilitate this research, Dr. Paul Veers and the Sandia National Laboratories Wind Energy Technology Department gave summer internship support (Mr. Ian Prowell), guidance, and advice.

Introduction

Wind energy production continues to grow rapidly—almost 20 GW of capacity was built worldwide in 2007, and total production rapidly approached 100 GW (Wiser and Bolinger 2008). More so than with past installations, recent growth is expanding into some regions of high seismic hazard. In response to this trend, regulating bodies recently added some seismic requirements for certifying wind turbines (Germanischer Lloyd 2003; IEC 2005).

These updated certification guidelines led to an increased interest in considering related seismic loading. Early investigations (Bazeos et al. 2002; Lavassas et al. 2003) focused on tower loading using models that lump the nacelle and rotor as a point mass (Figure 1). 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 (Figure 1) is also dictated by industry standard load cases 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, and with the exception of Witcher (2005), none offers a publically available tool for analyzing wind turbines.

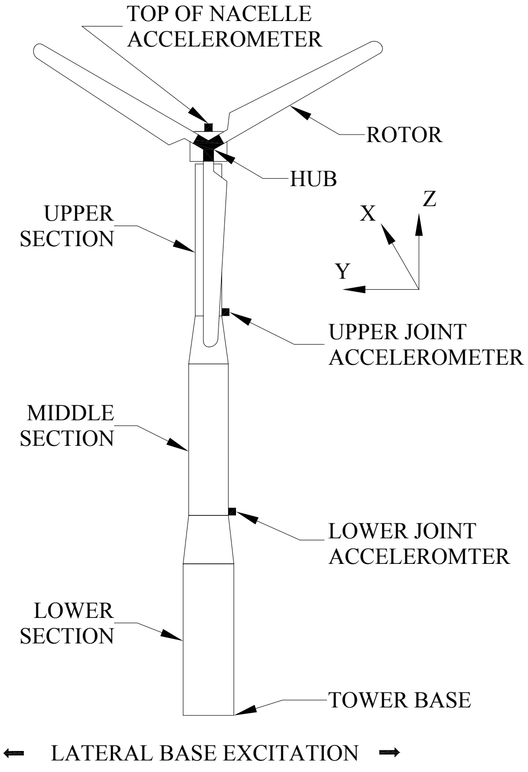


Figure 1. Wind turbine configuration and location of accelerometers

This paper details updates to the FAST (Jonkman and Buhl 2005) code, an open-source piece of software capable of modeling turbine dynamics that allow users to consider base excitation; it also discusses existing capabilities. A finite element code, OpenSees, was used to benchmark results obtained with the updated version of FAST. We compared simulations of an idling turbine subjected to base shaking from FAST to OpenSees simulations using an experimentally validated turbine model (Prowell et al. 2008).

Description of FAST

The FAST code is a package that models two- and three-bladed horizontal-axis wind turbines (HAWTs) under various conditions to predict extreme and fatigue loads (Jonkman and Buhl 2005). For aerodynamic calculations, FAST employs the subroutines for HAWTs in the AeroDyn Code (Laino and Hansen 2001). The FAST code uses a combined modal and multibody dynamics formulation to simulate a turbines dynamic behavior in the time domain. The code solves the equations of motion using standard multibody dynamics formulations with elements whose flexibility is determined by summing user-defined mode shapes. Wind Turbine designers and researchers throughout the world use the FAST code. Germanischer Lloyd Wind Energie evaluated the code and found it suitable for calculating onshore wind turbine loads for design and certification.

Of particular interest to this work are recent updates to FAST that allow modeling of an offshore turbine on a movable platform (Jonkman 2007). These updates are a mechanism to supply a force and moment to be applied at the tower base platform with six degrees of freedom at each time step for a time marching simulation. In earthquake engineering, a base acceleration time history is responsible for the resulting structural loads. The model configuration may prescribe acceleration time histories for each of the three translational axes (Figure 1). Using an artificially large mass for the platform, approximately 5,000 times the mass of the turbine, the force required to achieve the desired acceleration can be calculated by $F= ma$, where F is the required force, m is the total system mass (turbine and artificial platform mass), and a is the desired acceleration. This simple approach produces a faithful reproduction of the desired acceleration history, but implicitly assumes that the foundation and soil surrounding the turbine, modeled by the large artificial platform mass, act as a rigid block without rocking. This assumption is frequently used in earthquake engineering, but specific locations should be evaluated to ensure validity. In conjunction with the prescribed acceleration time history, all other loading mechanisms in the FAST code are still available. This allows time domain simulation of simultaneous earthquake and wind loads as well as the required simulation of an earthquake-induced emergency shutdown (IEC 2005). Conducting this calculation in the time domain allows a researcher to directly consider nonlinear effects such as structural nonlinearities, aerodynamic hysteresis, control system influence, and transients—all of which are important to wind turbine response.

Turbine Model

The models described here are based on a 65-kW Nordtank (Figure 2) wind turbine manufactured in Denmark. Many of these and similar turbines were installed during the 1980s in California. They are characterized by high reliability and simple operation in comparison to other turbines of a similar vintage (Hau 2006). These turbines are still in use in some areas, and many retired units have been reconditioned for sale on the second-hand market.

Figure 2. 65-kW Nordtank shake table test

A 65-kW turbine is near the lowest power rating used in 1980s-era utility-scale wind farms. Though no longer desirable for utility-scale applications, this size unit is still appropriate for distributed power applications. In comparison to modern megawatt-scale turbines, this unit is small, but it represents the most common turbine configuration, a thin-walled tubular steel tower topped with a nacelle that yaws to orient the rotor into the wind. Table 1 summarizes the turbine's engineering properties.

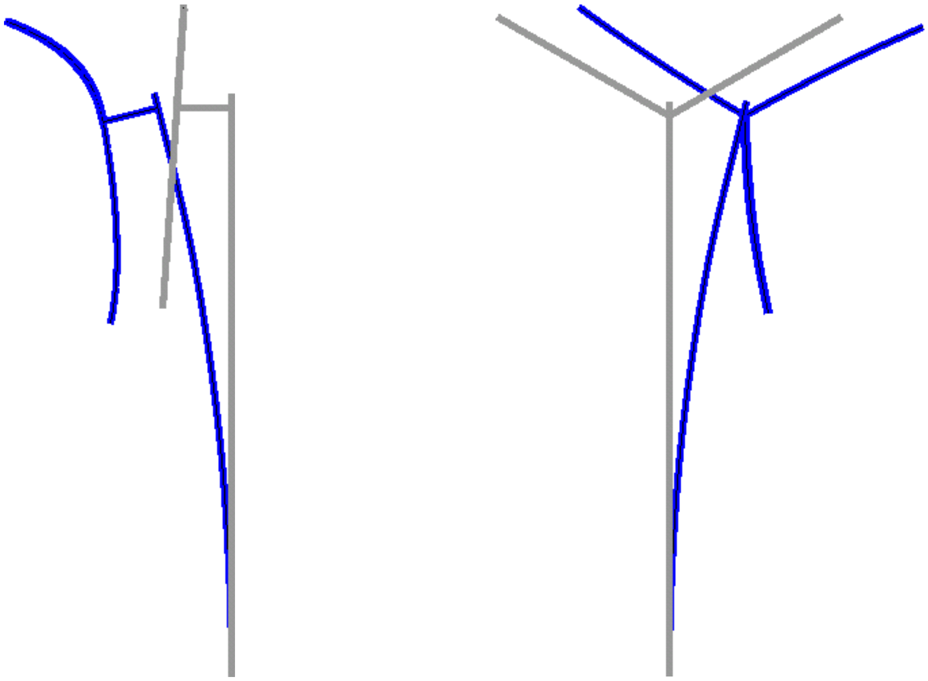
Table 1. Wind Turbine Properties

Property	Value
Rated power	65 kW
Speed regulation	Passive stall
Operational RPM range	45–55 rpm
Rated wind speed	33.8 km/h
Rotor diameter	16.0 m
Tower height	22 m
Lower section length	7.9 m
Lower section diameter	2.0 m
Middle section length	7.9 m
Middle section diameter	1.6 m
Top section length	6.0 m
Top section diameter	1.1 m
Tower wall thickness	5.314 mm
Rotor hub height	22.6 m
Tower mass	6400 kg
Nacelle mass	2400 kg
Rotor mass (with hub)	1900 kg

OpenSees Model

UCSD researchers developed a finite element (FE) model for OpenSees (Mazzoni et al. 2006) based on the engineering properties of the turbine (Table 1) to facilitate dynamic simulation of the turbine while idling. They divided the tower (Figure 1) into 30 beam-column elements with a flexural stiffness based on the cross section at the center of each element. Each blade was modeled using 12 beam-column elements to represent the mass and stiffness of the rotor (Figure 1). The nacelle was modeled with rigid elements to connect the top of the tower to the rotor. An added hinge condition allowed the free rotation of the rotor.

For an idling condition at zero rotational speed, the FE model predicted the first longitudinal (Figure 3a) and lateral (Figure 3b) bending modes at 1.7 Hz. It predicted the second bending modes at 10.5 Hz in the longitudinal direction and 10.9 Hz in the lateral direction. Full-scale shake table tests of an idling 65-kW Nordtank turbine validated this model configuration, which produces good agreement for the predicted and observed mode shapes and frequencies (Prowell et al. 2008). Based on the test results and industry guidelines (IEC 2005), structural damping was set to 1% for the first mode. Specified in the form of Rayleigh damping, a value of 3.5% used at 12 Hz better matched the recorded results.



(a) Longitudinal **(b) Lateral**

Figure 3. OpenSees model first bending modes (1.7 Hz)

FAST Model

As described earlier, the FAST code employs a combined multibody and modal dynamics formulation. A FAST model has five flexible bodies: tower, three blades, and drive shaft. As in the OpenSees model, the nacelle (Figure 1) is a rigid body. The mass and stiffness distribution derived for the FAST model matched that used in the OpenSees model as closely as possible. The FAST code relies on external calculation of mode shapes and requires that mode shapes be described by a five-coefficient polynomial of the form $\varphi(x) = a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6$. The coefficients must sum to a value of 1. Because the tower is assumed to have a cantilevered base, the code neglects the constant and linear coefficients. We calculated the coefficients used for the model described here by selecting polynomial coefficients that best approximated the first longitudinal and lateral modes (Figure 3) as well as the second longitudinal and lateral modes developed from the OpenSees model. The resulting FAST model predicted the first longitudinal and lateral bending modes at 1.7 Hz for the wind turbine idling at zero rotational speed. The predicted frequencies for the second bending modes are 10.4 Hz for the longitudinal mode and 10.9 Hz for the lateral mode. Table 2 summarizes the predicted tower bending natural frequencies for both models.

Table 2. Predicted Tower Bending Frequencies of Idling Turbine

Model	First Bending		Second Bending	
	Longitudinal	Lateral	Longitudinal	Lateral
OpenSees	1.7	1.7	10.5	10.9
FAST	1.7	1.7	10.4	10.9

Numerical Modeling of Seismic Response While Idling

We used the two turbine models to conduct base shaking simulations for three earthquakes recorded in California (Table 3). Because OpenSees cannot predict aerodynamics and other operational loads for a turbine, to accommodate direct comparison, both models have the wind turbine idling at zero rotational speed without aerodynamics during the simulations. Both horizontal components of the records simulated the turbine response for a fixed base condition. This assumption is suitable for the stiff soils found at many wind farms. Further consideration of soil structure interaction would be warranted for location with soft soils (Bazeos et al. 2002; Zhao and Maisser 2006). Figure 4 compares the calculated acceleration from OpenSees and FAST at the top of the nacelle for 1940 El Centro earthquake acceleration time history recorded at array station 9 in El Centro, California. The results for the other earthquake simulations also show the same high level of agreement observed for the El Centro earthquake simulation.

Table 3. Earthquake Data

Earthquake	Moment Magnitude	Station	PGA	Source Distance
1981 Westmorland	5.9 M_w	Fire Station	0.50 g	7.2 km
2000 Yountville	5.0 M_w	Fire Station No. 3	0.41 g	13.7 km
1940 El Centro	6.9 M_w	Array Station 9	0.35 g	12.2 km

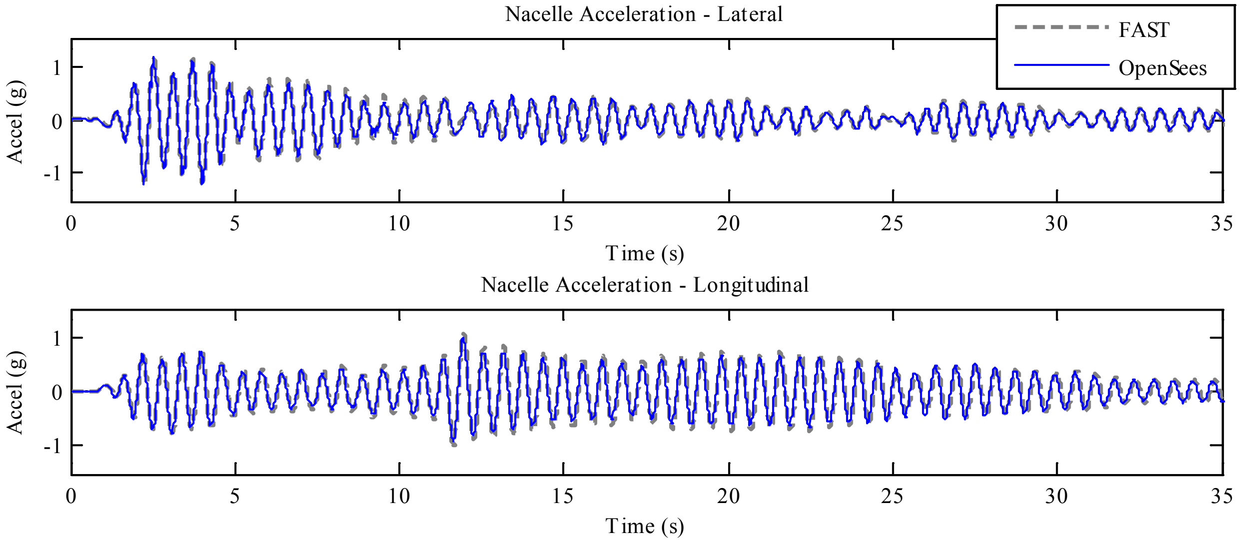
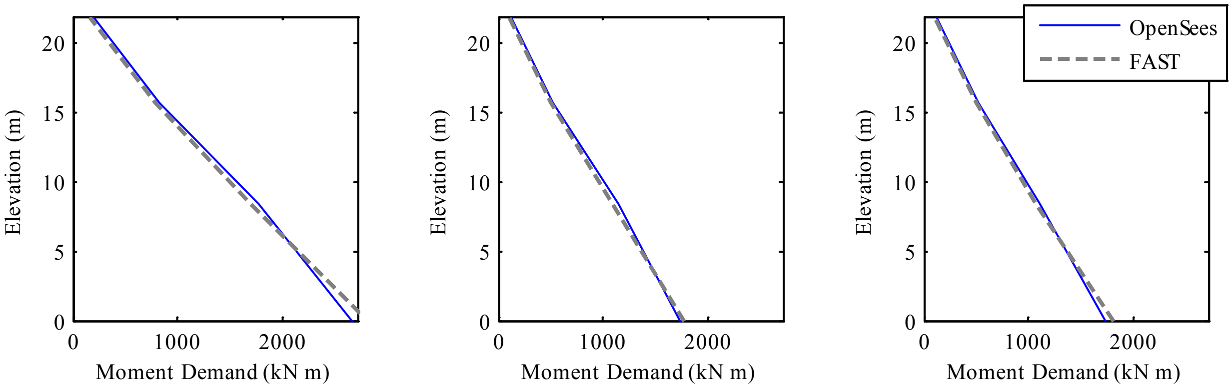


Figure 4. Comparison of nacelle acceleration for the 1940 El Centro earthquake

To investigate the possible implications of the two models on design loads, we calculated the maximum moment demand at the base, the lower joint, the upper joint, and the top of the tower (Figure 1). This maximum was taken from the square root of the sum of the squares (SRSS) of the horizontal tower moments at each time step. As with the acceleration time history, the moment demands calculated by the FAST and the OpenSees model showed good agreement (Figure 5).



a. Westmorland **b. Yountville** **c. El Centro**

Figure 5. Moment demand in turbine tower

Conclusions

This paper presents recent modifications developed by UCSD researchers to the FAST code that consider seismic loads for designing wind turbines. To validate these modifications, we compared results to those from a calibrated FE turbine model developed using OpenSees (Prowell et al. 2008). Both the acceleration time history and the tower moment demand show good agreement for both computational approaches. This development makes the FAST code the first open-source tool specific to wind energy for simulating seismic loading of wind turbines. This will enable practitioners and researchers throughout the world to simulate scenarios where wind turbines are subjected to loads from wind, operational state, and base excitation simultaneously in the time domain.

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 funding, researchers are conducting full-scale experiments 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.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
March 2010

2. REPORT TYPE
Conference paper

3. DATES COVERED *(From - To)*
August 13 - 14, 2009

4. TITLE AND SUBTITLE
FAST Simulation of Wind Turbine Seismic Response

5a. CONTRACT NUMBER
DE-AC36-08-GO28308

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
I. Prowell, A. Elgamal, and J. Jonkman

5d. PROJECT NUMBER
NREL/CP-500-46225

5e. TASK NUMBER
WER9-3530

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-500-46225

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
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U.S. Department of Commerce
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13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

This paper discusses recent additions to the computer simulation code FAST that allow a user to consider seismic loads in addition to existing robust capabilities for simulating wind and other load sources under the various states of wind turbine operation.

15. SUBJECT TERMS
wind turbine design codes; wind turbine simulation

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
Unclassified	Unclassified	Unclassified	UL	

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