



Estimation of Seismic Load Demand for a Wind Turbine in the Time Domain

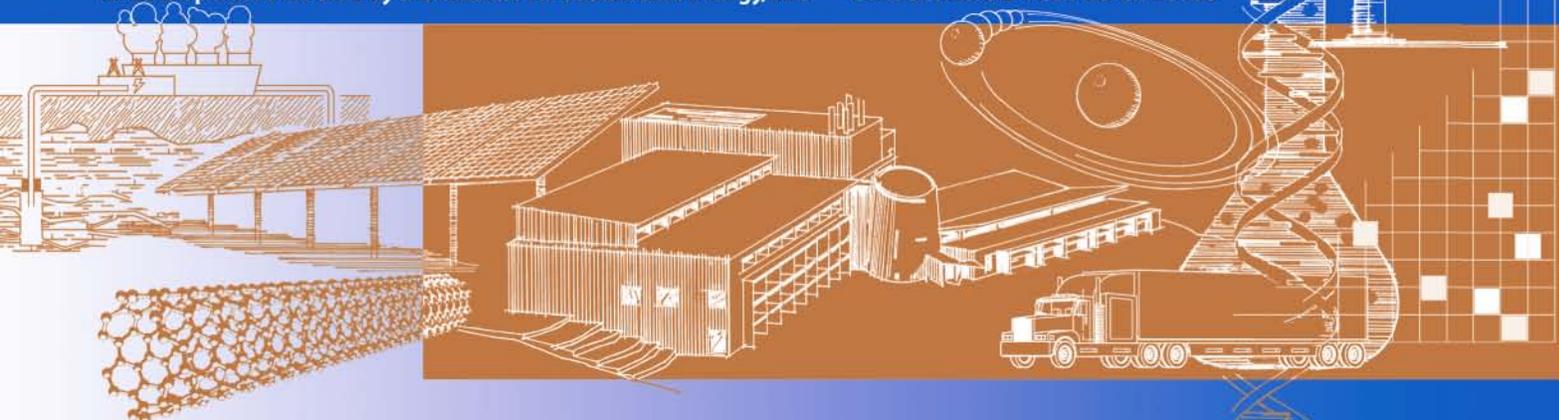
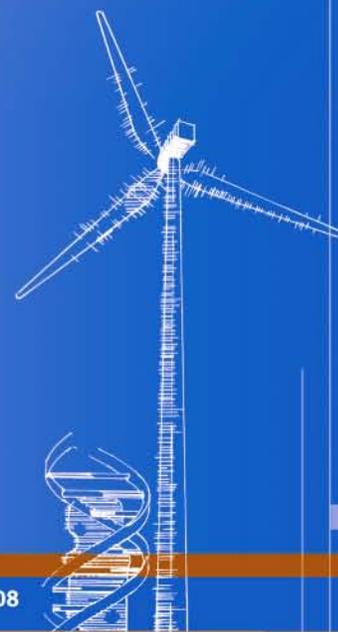
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I. Prowell, A. Elgamal, and C. Uang
University of California – San Diego

J. Jonkman
National Renewable Energy Laboratory

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Ian Prowell
University of California,
San Diego
iprowell@ucsd.edu

Ahmed Elgamal
University of California,
San Diego
elgamal@ucsd.edu

Jason Jonkman
National Renewable
Energy Laboratory
jason.jonkman@nrel.gov

Chia-Ming Uang
University of California,
San Diego
cmu@ucsd.edu

Abstract:

Turbines installed in seismically active regions such as the Pacific Rim or the Mediterranean must consider loads induced by base shaking from an earthquake. To account for this earthquake risk, current International Electrotechnical Commission (IEC) certification requirements provide a simplified method for calculating seismic loads which is intended to be conservative. Through the addition of capabilities, it is now possible to simulate earthquake loading of a wind turbine in conjunction other load sources such as wind and control system behavior using the FAST code. This paper presents a comparison of three earthquake loading scenarios of the National Renewable Energy Laboratory (NREL) offshore 5-MW baseline wind turbine: idling; continued operation through an earthquake; and an emergency shutdown initiated by an earthquake. Using a set of 22 earthquake records, simulations are conducted for each load case. A summary of the resulting tower moment demand is presented to assess the influence of operational state on the resulting structural demand.

Keywords: Earthquake loading; time domain simulation; extreme loads

1 Introduction

The amount of electricity produced from the wind has steadily grown [1] since its introduction in the 1980s [2] and with the introduction of AB 32 is poised to grow in California. Early turbines used many design variations, but the market has stabilized on the three-bladed upwind variable-speed variable-pitch turbine for commercial wind farms [2]. Each generation of turbines has increased in size from early commercial turbines with an 18 m rotor diameter to current turbines with rotors exceeding 100 m in diameter [3].

Of the loading sources considered for wind turbines, earthquakes receive relatively little attention, but are still included by regulating bodies for regions such as California [4, 5]. Despite being a non-linear dynamic system, combined earthquake and wind loads are often considered by superimposing independent simulations for wind and seismic loads. Early investigations [6, 7] mirror this approach by focusing on tower loading using models that lump the nacelle and rotor as a point mass when determining the seismic component of the response.

As turbines grew larger and more expensive [1], new technologies such as variable pitch and active control sometimes changed the design-driving considerations, with fatigue and turbulence becoming important considerations along with extreme events [3]. Through these active control techniques and intelligent design, modern turbines can be optimized to be lighter and more cost effective. For these lighter turbines, simulating earthquake and wind loads simultaneously in the time domain becomes desirable to reduce the uncertainty of the results.

This goal is apparent in the shift of simulation efforts to more refined approaches that consider wind and seismic loads simultaneously [8-11]. The standard load case of an emergency shutdown triggered by an earthquake [5] also motivates migration to models that include dynamics of the rotor. Recent modifications [12] to the FAST code [13], open-source software capable of modeling turbine dynamics, are used to conduct time-domain simulations that assess the implications of an earthquake on the structural demand of the NREL 5-MW baseline wind turbine [14].

2 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 [13]. For aerodynamic calculations, FAST employs the subroutines for HAWTs in the AeroDyn Code [15]. The FAST code uses a combined modal and multibody dynamics formulation to simulate a turbine's behavior in the time domain. The code solves the equations of motion using a standard multibody dynamics formulation 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 [16]. 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 displacement, velocity, or acceleration

time histories for each of the three translational axes. From the prescribed time histories, the corresponding displacement and velocity histories are calculated. At each time step, the forces required to achieve the desired time histories are calculated by simulating a damped oscillator attached at the base of the turbine. By setting the natural frequency of the damped oscillator at twice the highest frequency found in the input motion and using a damping of 65% of critical, a faithful reproduction of the desired time histories can be reproduced. This frequency must also be kept above twice the highest resonance in the turbine model. It is important to note that the simulation time step must be kept sufficiently small to produce stable results. In this investigation it was found that a time step of 0.002 seconds produced stable results for all simulations.

Implicit in the current implementation is the assumption that the foundation-soil system acts as a rigid block without rocking, but future improvements could remove this limitation. For stiff soil sites, foundation rocking is frequently neglected in earthquake engineering. Site specific conditions should be evaluated to ensure validity for a specific location. In conjunction with the prescribed time histories, 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 [5]. Conducting simulations 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.

3 Turbine Model

The National Wind Technology Center (NWTC) located at NREL has published specifications for a reference 5-MW turbine [14]. A summary of the turbine properties is presented in Table 1. This reference model is intended to serve as a standard model for conceptual studies of modern multi-megawatt turbines.

Type	Horizontal wind turbine
Power rating	5-MW
Rotor Configuration	3 blade upwind
Control	Variable speed, collective pitch
Drivetrain	High speed, multiple-stage gearbox
Hub Height	90 m
Cut-in Wind Speed	3 m/s
Rated Wind Speed	11.4 m/s
Cut-out Wind Speed	25 m/s
Rotor Speed Range	6.9 to 12.1 RPM
Rated Tip Speed	80 m/s
Rotor diameter	126 m
Tower height	87.6 m
Hub height	90 m
Mass of rotor	111,000 kg
Mass of nacelle	240,000 kg
Mass of tower	347,460 kg

Table 1: Main parameters of wind turbine

3.1 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. Being considerably stiffer than the other turbine components, the nacelle is modeled as a rigid body. The FAST code relies on external calculation of the tower and blade mode shapes and requires that they be described by a five-coefficient polynomial of the form $\phi(x) = a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6$. 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. Coefficients used for the model described here match those presented by NREL [14] based on an equivalent model constructed in ADAMS. The mode shapes, together with the stiffness distribution, are used to derive the generalized stiffness of the flexible bodies. With a Young's Modulus for steel of 210 GPa, the above simple model predicts natural frequencies as reported in Table 2 while parked. As previously noted for another turbine [10], many natural frequencies for the 5-MW reference turbine occur within the range of interest for earthquake loading and may be excited during an earthquake.

Mode Description	Freq. (Hz)
1 st Tower Fore-Aft	0.32
1 st Tower Side-to-Side	0.31
1 st Blade Asymmetric Flapwise Yaw	0.67
1 st Blade Asymmetric Flapwise Pitch	0.67
1 st Blade Collective Flap	0.70
1 st Blade Asymmetric Edgewise Pitch	1.08
1 st Blade Asymmetric Edgewise Yaw	1.09
2 nd Blade Asymmetric Flapwise Yaw	1.93
2 nd Blade Asymmetric Flapwise Pitch	1.92
2 nd Collective Flap	2.02
2 nd Tower Fore-Aft	2.90
2nd Tower Side-to-Side	2.93

Table 2: Model natural frequencies with a fixed base and parked rotor [14]

4 Numerical Modeling of Seismic Response

To obtain a better understanding of the influence of earthquake loads in comparison to the normal production case, simulations are conducted that subject the turbine to imposed acceleration time histories while idling, continuously operating, and in emergency shutdown scenarios. In each of these three load cases, the turbine is subjected to an 11.4 m/s wind field generated using TurbSim [17] with level B IEC turbulence intensity. The total simulation time for all simulations is 600 seconds. The first 400 seconds are used to allow initial transient behavior to diminish. Following this period the turbine is subjected to orthogonal horizontal acceleration time histories, one in line with and the other, normal to the wind. For the idling simulations, the blades were fully feathered, the generator was disabled, and the brake was not engaged. In the emergency shutdown simulations, shutdown of the turbine was triggered by a horizontal acceleration in the nacelle exceeding 1 m/s^2 . For all simulations, this level was not exceeded in the normal operation, but was exceeded shortly after the initiation of earthquake excitation. The emergency shutdown is achieved by feathering the turbine blades at the maximum rate of 8 degrees per second.

For the horizontal acceleration time histories a set of 22 earthquake records were used (Table 3). These earthquake records constitute the far field record set presented by the United States (US) Federal Emergency Management Agency (FEMA) [18]. To reduce variability in the recorded peak ground velocity, each of the two horizontal components from each earthquake were scaled by the factor presented in Table 3.

Following this normalization, the records were scaled by a factor of 1.3 to create a record set with a hazard for the considered turbine equivalent to that of a stiff soil site with a 1-second spectral response acceleration (S_1) of 0.132 g [19]. Under the 2006 International Building Code (IBC) [20], many locations in the western United States exceed this level. Being based on an event with a 2% probability of being exceeded in 50 years [19], the hazard is more conservative than the 10% probability of being exceeded in 50 years recommended by the IEC [5], but it is consistent with local building code requirements [20] in the US. A more in-depth analysis and extended information regarding this data set can be found in Appendix A of FEMA-P695 [18]. Figure 1 shows the input acceleration time history for the 1994 Northridge earthquake recorded at 14145 Mulholland Boulevard, Beverly Hills, CA, USA (ID 1) following scaling. In the example shown, the acceleration recorded at 9 degrees from north was oriented in line with the wind (X) and the component recorded at 279 degrees from north was oriented perpendicular to the wind (Y).

Each of the three load cases was simulated twice for each of the 22 earthquakes. Between the two simulations, the two horizontal components were rotated 90 degrees to reduce possible bias from the relative orientation of the wind and the earthquake excitation. In total, 132 simulations were conducted (44 simulations for each load case). Figure 2 shows the response acceleration at the nacelle for the input acceleration as shown in Figure 1. As mentioned earlier the earthquake motion starts at 400 seconds and in this simulation the emergency shutdown was triggered at 404 seconds when the nacelle acceleration exceeds 1 m/s^2 .

ID	Mag.	Year	Name	Scale Factor
1	6.7	1994	Northridge	0.65
2	6.7	1994	Northridge	0.83
3	7.1	1999	Duzce, Turkey	0.63
4	7.1	1999	Hector Mine	1.09
5	6.5	1979	Imperial Valley	1.31
6	6.5	1979	Imperial Valley	1.01
7	6.9	1995	Kobe, Japan	1.03
8	6.9	1995	Kobe, Japan	1.10
9	7.5	1999	Kocaeli, Turkey	0.69
10	7.5	1999	Kocaeli, Turkey	1.36
11	7.3	1992	Landers	0.99
12	7.3	1992	Landers	1.15
13	6.9	1989	Loma Prieta	1.09
14	6.9	1989	Loma Prieta	0.88
15	7.4	1990	Manjil, Iran	0.79
16	6.5	1987	Superstition Hills	0.87
17	6.5	1987	Superstition Hills	1.17
18	7.0	1992	Cape Mendocino	0.82
19	7.6	1999	Chi-Chi, Taiwan	0.41
20	7.6	1999	Chi-Chi, Taiwan	0.96
21	6.6	1971	San Fernando	2.10
22	6.5	1976	Friuli, Italy	1.44

Table 3: FEMA P-695 [18] Far Field Record Set Summary

5 Results of Simulations

Many design considerations exist for wind turbines [3, 7]. This paper presents a summary of the resulting tower moment demand for the simulations conducted, but the simulations provide information on many other demand parameters for seismic loading. A full analysis of tower moment demand under other load cases for the NREL 5-MW turbine is not attempted, but instead previous results are used [14, 21]. Based on extensive simulations, Fogle et al. [21] found that the maximum fore-aft tower-base bending moment was approximately 98 MN-m for normal operation of the NREL 5-MW turbine. In another study [14], a maximum moment of approximately 85 MN-m was observed. Using a load factor of 1.25 for normal operation and 1.2 for extrapolation to extreme loads, resulting in a total factor of 1.5, a range of 128 MN-m to 147 MN-m is required of the tower. For extreme turbulence simulations with a load factor of 1.35, it was found that the maximum moment demand was 153 MN-m [14].

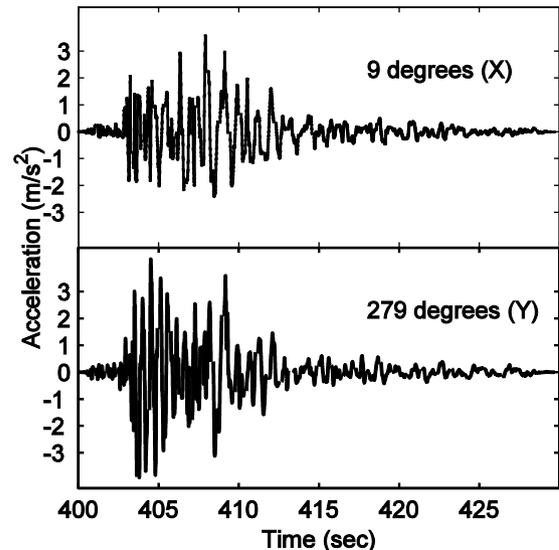


Figure 1: Sample Input Time History

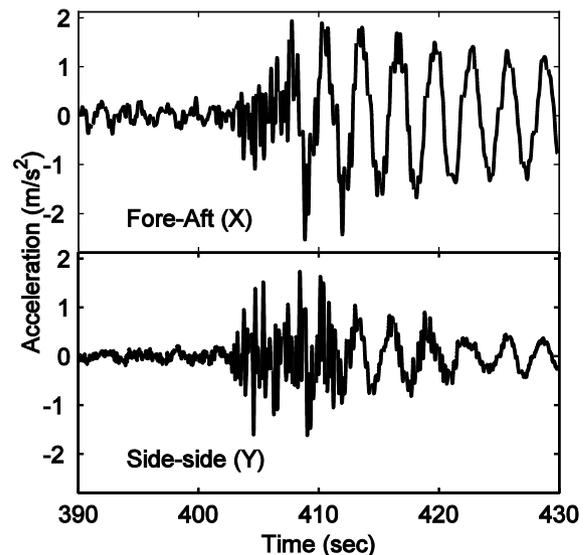


Figure 2: Sample Nacelle Response for Emergency Shutdown Simulation

Wind loading results in a maximum bending moment primarily oriented in line with the direction of the wind. Earthquake induced bending is not directly correlated with the wind direction, so the moments discussed here are presented as the maximum moment regardless of orientation. This is calculated as the square root of the sum of the squares of the tower fore-aft and side-side bending moments.

Using a partial safety factor of 1.0 [5], the mean, mean plus one standard deviation, and the maximum of the 44 simulations for each load case—idling, continued operation, and an earthquake induced emergency shutdown—are shown graphically in Figures 3 through 5. The mean of the moment demand at the base of the turbine tower for both operational load cases falls in the range expected for ultimate wind loading

alone. Again for the two operational cases, the mean plus one standard deviation is beyond the range anticipated from wind loading. These results show that tower bending from earthquake loading may be an important design consideration for the NREL 5-MW turbine and the maximum moment demand at the tower base may be controlled by earthquake loading for the level of seismic hazard considered here.

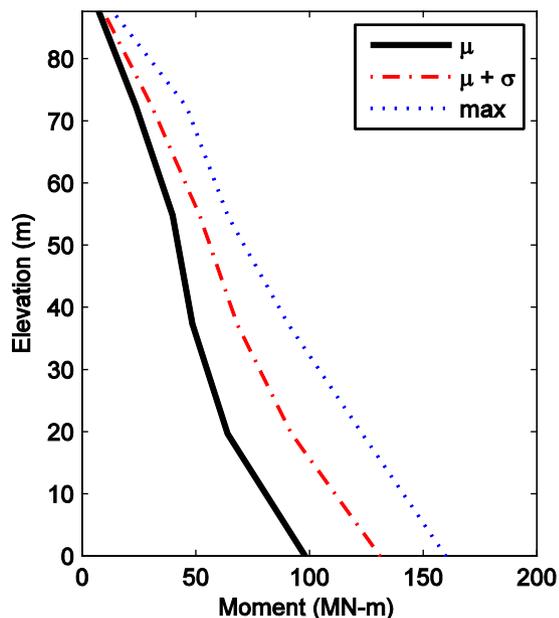


Figure 3: Resulting Tower Moment Demand for Idling Simulations

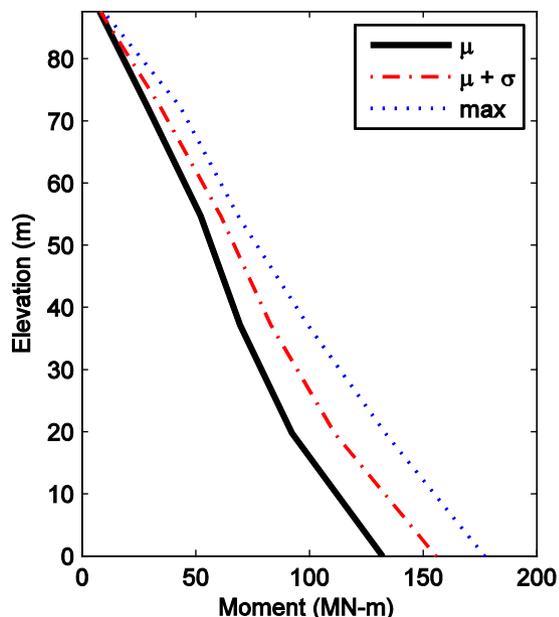


Figure 4: Resulting Tower Moment Demand for Running Simulations

A comparison of the three load cases shows a greater spread in the results for idling case in comparison to the running and emergency

shutdown scenarios. As others have suggested [9], this difference is attributable to the additional damping experienced by the turbine while operating. For the NREL 5-MW turbine, it is more important to consider earthquake loading while the turbine is running and show that a slight improvement in demand can be achieved by triggering an emergency shutdown upon the initiation of strong shaking in the nacelle. The reduction in tower moment demand is encouraging, given the anticipation that current control systems may initiate a shutdown in response to an earthquake.

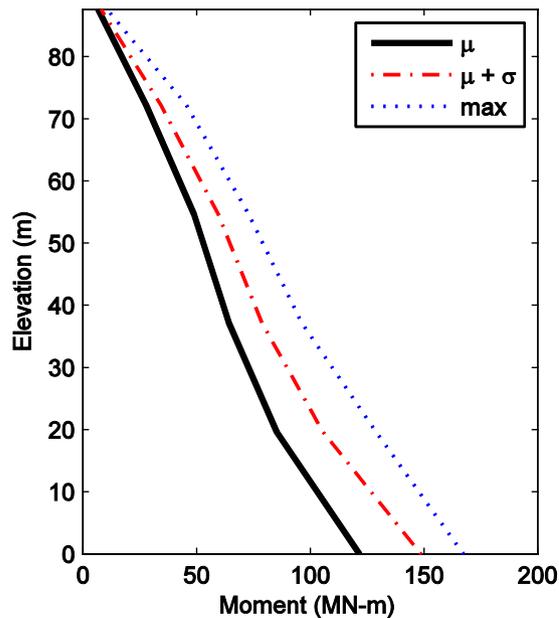


Figure 5: Resulting Tower Moment Demand for Emergency Shutdown Simulations

6 Conclusion

This paper presents recent modifications to the FAST code developed by researchers at UCSD in collaboration with NREL, which allow consideration of seismic loads for design of wind turbines. These modifications are used to investigate implications of different earthquake loading scenarios for the NREL 5-MW reference turbine. Based on the considered seismic hazard level, it appears to be important to consider earthquake loads for moment demand in the tower of the NREL 5-MW reference turbine. Practitioners and researchers familiar with the FAST code are now able to simulate scenarios where wind turbines are subjected to loads from wind, operational state, and base excitation simultaneously, directly in the time domain. As demonstrated here for tower moment demand, such simulations can provide valuable insight into other design considerations.

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.

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