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May 2011 — August 2011

M.A. Asareh and I. Prowell
Missouri University of Science & Technology
Rolla, Missouri

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Introduction

As more wind farms are constructed in seismically active regions, earthquake loading increases in prominence for design and analysis of wind turbines. Early investigations of seismic load tended to simplify the rotor and nacelle as a lumped mass on top of the turbine tower [1, 2]. This simplification allowed the use of techniques developed for conventional civil structures, such as buildings, to be easily applied to wind turbines. However, interest is shifting to more detailed models that consider loads for turbine components other than the tower [3, 4]. These improved models offer three key capabilities in consideration of base shaking for turbines: 1) The inclusion of aerodynamics and turbine control; 2) The ability to consider component loads other than just tower loads; and 3) An improved representation of turbine response in higher modes by reducing modeling simplifications. Both experimental and numerical investigations have shown that, especially for large modern turbines, it is important to consider interaction between earthquake input, aerodynamics, and operational loads [3, 5, 6]. These investigations further show that consideration of higher mode activity may be necessary in the analysis of the seismic response of large modern turbines [5, 7, 8]. Since the FAST code already is capable of considering these factors, modifications were developed that allow simulation of base shaking [4]. This approach allows consideration of this additional load source within the FAST code, which is already familiar to many researchers and practitioners.

General Description

In the current implementation of the FAST code, earthquake excitation is defined as a motion time history applied at the tower base. Two options exist for defining motion — either user-provided input or synthetically generated time histories. Base-motion time histories can be applied in any combination of three directions, two horizontal and one vertical, specified in the inertial-frame coordinate system. The current implementation does not directly support consideration of base rocking, twisting, or soil-structure interaction. User-provided earthquake excitation can be supplied in terms of acceleration, velocity, or displacement. For synthetic time histories, artificial ground acceleration is generated based on user specified parameters. The force required to achieve the desired motion is calculated at run time for each time step using a damped oscillator model. Routines are provided to modify the user-provided or synthetically generated input to conform to a target response spectrum. Further, a simple procedure is available that can correct user-supplied motions to eliminate residual velocities and displacements (non-zero final values of velocity and/or displacement).

Model for Seismic Loading

Seismic loads created in a structure are the result of the base-motion that can be prescribed for FAST simulations as one of acceleration, velocity, or displacement. Using the provided base-motion, the other two time histories are numerically calculated so a consistent set of acceleration, velocity, and displacement records exist for each of the translational directions. To develop the required force time history to enforce the supplied base-motion time history, a damped oscillator is simulated at the base of the modeled wind turbine. Through this approach, the seismic forces required to achieve the earthquake input provided by the user are calculated at each time step. The oscillator stiffness, k , is calculated as:

$$k = m \cdot (2 \cdot \pi \cdot ActFreq)^2 \quad (1)$$

where m is the total mass of the turbine model, including the platform mass. It is recommended that the actuator frequency be approximately 10 times the highest frequency of the turbine model being excited. To obtain stable results, the time step of the simulation (DT) must be kept sufficiently small. As a general rule, the simulation time step should be at most $1/10^{\text{th}}$ the period of the actuator. By assuming a relatively large damping value, and maintaining a high stiffness, the damped actuator provides an efficient way to translate the specified motion into the required force time history. The actuator damping value can be specified as a percent of critical damping using the *ActDamp* variable. A value of 60 to 70 percent is recommended. The value of *ActDamp* is normalized to provide the damping coefficient, c , for the actuator model as:

$$c = 2 \cdot ActDamp \cdot m \cdot 2 \cdot \pi \cdot ActFreq \quad (2)$$

At each time step, the applied force for each translational direction is calculated as:

$$force = k \cdot (PtfmDisp - X) + c \cdot (PtfmVel - XD) \quad (3)$$

where: *PtfmDisp* is the desired displacement at the base of the tower; X is the realized displacement; *PtfmVel* is the desired velocity at the base of the tower; and XD is the realized velocity. The variables c and k are defined above. Further information detailing the theory associated with the motion of a damped oscillator is available in most fundamental dynamics textbooks [9]. With proper tuning of the time step and other model parameters, the difference between the desired and realized platform motion can be controlled to agree to any level of precision. Increased precision in reproduction of the desired platform motion will likely require increased computational time.

Distributed Files

The files packaged for conducting seismic simulations include the revisions to the FAST code and six simulation examples using the different features in the new seismic module. For seismic functionality, there is one additional source code file that replaces the *UserPtfmLd()* routine in the FAST code and all other files needed for compiling remain intact. All examples contain a new seismic configuration file that includes the variables and parameters needed to run the desired seismic analysis. Depending on the details of the desired analysis, the user provides additional input files for either the base-motion time history or the target response spectrum, which are read by defining a path in the seismic configuration file. The first three examples provide the user-defined motion, with different motion handling conditions. The next three use synthetically created motion, with different features described by name of each folder. A brief description of these files and their location is detailed in Table 1. Required files differ depending on the analysis and the selected analysis options. For this reason, different files are listed, as required for each of the examples of seismic simulations. The examples are based on the 5-MW NREL reference turbine [10] and evaluate different loading scenarios. The files that contain tower, blade, platform properties, and the AeroDyn input file, and also the FAST primary files specified for this turbine include the same information as is needed for the previous versions of FAST. Therefore, they are not included below.

Table 1. List of files available in deliverables

Modified Files for Compiling FAST	
File	Description
Source\UserPtfmLd_Seismic.f90	FORTRAN source file containing the logic of the seismic module and a replacement UserPtfmLd() routine for the FAST code
FAST.exe	A compiled version of the FAST v7.00.01a-bjj code, with support for seismic analysis and the GH Bladed DLL controller interface. This is suitable to execute the provided seismic examples.
rspm09.exe	The 2009 version of the RspMatch program [11]. This is used to adjust the elastic response spectra to match target spectra.
List of Files In the Example	
Examples\PtfmMotions*.*	Example base input acceleration files derived from the 1940 El Centro Earthquake. Each file contains two columns, the first column is time steps and the second column is the acceleration of motion given in m/s^2 . These files are used in simulations 1 through 3.
Examples\1_NRELOffshrBsline5MW_Onshore_udm_wo_baseline_wo_target*.*	<p>An example of a seismic simulation with a user-defined platform motion. The simulation runs without modifying the input motion. Aside from the platform motion files, the only additional file other than the standard 5-MW NREL turbine is NRELOffshrBsline5MW_Onshore_Seismic.dat. This file defines the details of the seismic simulation.</p> <p>The small acceleration spike in the X direction at the end of the input motion in this example illustrates that even with motions that are corrected for residual velocity and displacement, small numerical artifacts may occur. Simulation results should be checked for such artifacts.</p>
Examples\2_NRELOffshrBsline5MW_Onshore_udm_w_baseline_wo_target*.*	<p>An example of a seismic simulation with a user-defined platform motion. This simulation is the same as Example 1, but baseline correction is conducted on the input motion. This is accomplished by using "True" for the variable <i>BLineCorrection</i>. No additional files are required.</p> <p>Baseline correcting the motion from Example 1 removes the acceleration spike by making relatively small changes to the final portion of the input motion. These changes are unlikely to influence the extreme values from the simulation.</p>

Examples\3_NRELOffshrBsline5MW_Onshore_udm_w_baseline_w_target*.*	<p>An example of a seismic simulation with a user-defined platform motion. This simulation is the same as Example 2, but a target response spectrum is added for each of the horizontal base input motions. The input motion is modified to have a response spectrum that conforms to the specified response spectrum. To accomplish this, the variable <i>TgtResponse</i> is set to “True” and a value of “cms_T02.2_horiz.tgt” is used for the variables <i>TgtResFnX</i> and <i>TgtResFnY</i>. The format of this file and other variables important to a target response spectrum are documented later in the Target Response section. The executable for RspMatch must be in the model directory to be available for FAST to perform spectrum modification.</p>
Examples\4_NRELOffshrBsline5MW_Onshore_yn_wo_baseline_wo_target*.*	<p>An example of a seismic simulation with a synthetic platform motion. This example demonstrates the use of initial and final ramps to shape the synthetic motion. These ramps are specified through the variables <i>SynInitRampFnX</i> and <i>SynFinalRampFnX</i>, respectively, for motion in the X direction. For ramps in the Y and Z directions, the final letter of the variable is updated appropriately. Other variables important to a synthetically generated motion are documented in the Synthetic Motion section.</p> <p>It is important to note in this example that a synthetic motion will result in residual displacement and velocity, which creates a very large acceleration spike at the end of the base shaking. Example 5 solves this issue by adding baseline correction to the simulation.</p>
Examples\5_NRELOffshrBsline5MW_Onshore_yn_w_baseline_wo_target*.*	<p>An example of a seismic simulation with a synthetic platform motion. This simulation is the same as Example 4, but the baseline correction is conducted on the input motion. This is accomplished by using a value of “True” for <i>BLineCorrection</i>. No additional files are required.</p>
Examples\6_NRELOffshrBsline5MW_Onshore_yn_w_baseline_w_target*.*	<p>An example of a seismic simulation with a synthetic platform motion. This simulation is the same as Example 5, but a target response spectrum is added for each of the horizontal directions, as well as the vertical direction. In practice, it is unusual to use the same target response spectrum for both horizontal and vertical motion.</p>

Compiling FAST for Seismic Simulations

To compile the FAST code with support for seismic simulations, simply comment out the existing `UserPtfmLd()` subroutine located in *UserSubs.f90* and add *UserPtfmLd_Seismic.f90* to the list of files to be compiled. All other details for compilation are identical to the standard version of the FAST code, which is explained in the FAST User's Guide [12].

Conducting Seismic Simulations with FAST

To begin using the basic seismic capabilities of FAST, a seismic configuration file is required that defines the properties of the input motion provided by the user. The name of the seismic configuration file is derived from the primary FAST input file (*.fst*) with the “*.fst*” extension removed and “*_Seismic.dat*” added at the end. Seismic analysis is initiated by setting the value of *PtfmLdMod* to 1, which initiates the use of the custom user-defined routine for platform loading. The variables required in the seismic configuration file depend on the type of simulation to be conducted. Once a model is properly configured, execution is identical to that described in the FAST User's Guide.

Getting Started

The current routine is intended and developed for fixed, land-based wind turbines subjected to horizontal and vertical translation at the base of the turbine tower. Figure 1 illustrates the logical flow of the initialization of seismic portions in a FAST simulation. If desired, other loading conditions outside of those supported here may be achieved by custom development of the `UserPtfmLd()` subroutine in which the earthquake calculations are coded.

By setting *PtfmModel* to a value of 1 and choosing the appropriate value of *SeismicMode*, described below, the seismic loading routines are accessed from the `UserPtfmLd()` subroutine. The sections below provide the required detail for each logical grouping of variables used to control the behavior of seismic loading. The thick line in Figure 1 shows the commonly used path, which is appropriate when the provided motion requires no modification. In all cases (even if no corrections are made to the motion), it is suggested that the user capture and review the resulting motions by recording platform displacement, velocity, and acceleration (See Table 30 of the FAST User's Guide for required variables).

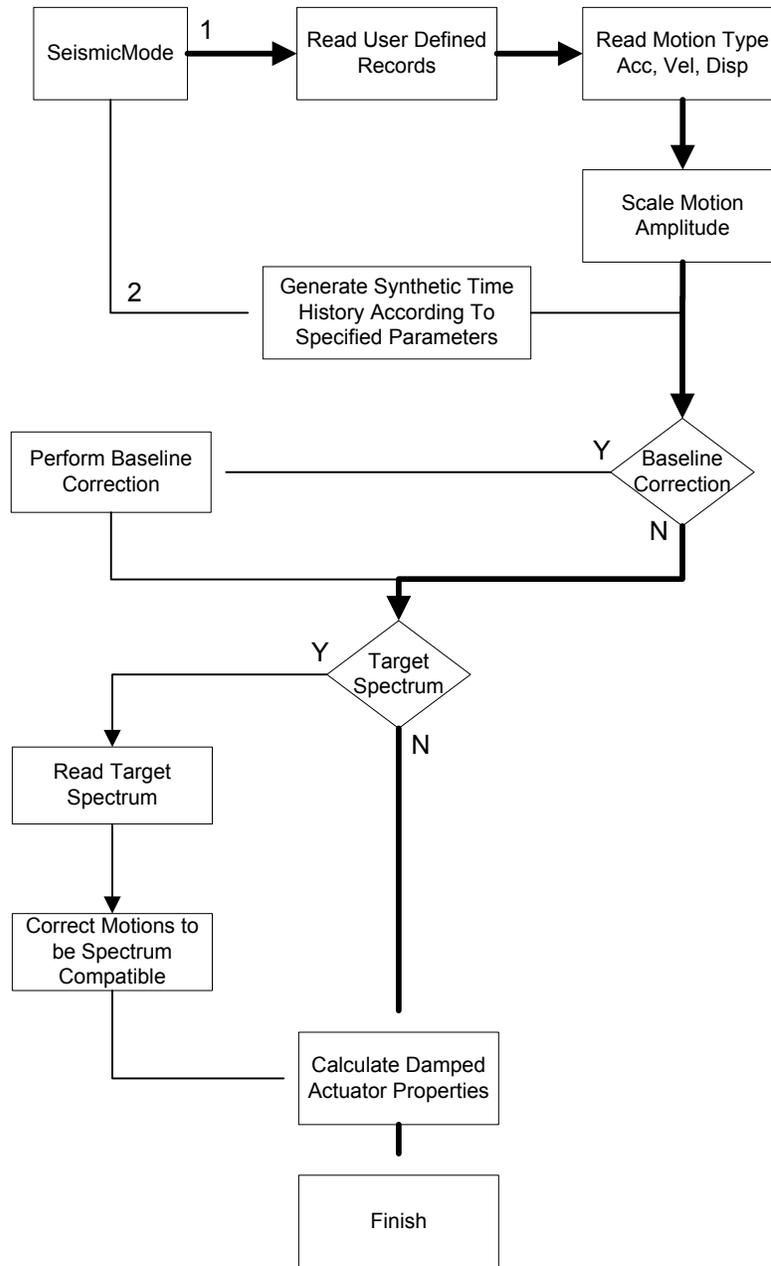


Figure 1. Flowchart for initialization of seismic shaking functionality

Input File

Seismic input parameters are located in a separate configuration file similar to the tower, platform, and other portions of the model. The configuration variables required for simulating a user-defined input motion are described below. Sample input files that demonstrate many of the features described here are available with each of the examples.

SeismicMode [1 or 2]

This switch determines if the user wants to provide a base-motion time history or prompts FAST to generate a synthetic time series. To perform a user-defined time history, a value of “1” is used for *SeismicMode*. A setting of “2” will result in a synthetically generated time history for each of the three loading directions. Other values are not valid and will result in aborting the execution of the simulation.

***PtfmXMotionFn*, *PtfmYMotionFn*, and *PtfmZMotionFn*: Platform X/Y/Z Motion Filename [Quoted String]**

These variables are the absolute or relative path of the files containing the base-motion time history data provided by the user. The user can specify any of the three files needed for the analysis. File names must contain fewer than 100 characters and be enclosed in double quotes. FAST will read these files, if the value of each parameter is not null. *PtfmXMotionFn*, *PtfmYMotionFn*, and *PtfmZMotionFn* contain motion information in the inertial-frame coordinate system X, Y, and Z direction, respectively. The values in these files should be given in two columns representing time and motion for each time step. To prevent loading for any direction, two quotation marks with no text should be specified (“”) in place of a file name and no motion will be applied in that direction. If a target response spectrum is used, the filename must contain fewer than 50 characters due to length limits in the RspMatch program.

***PtfmMotionType*: The Platform Motion Type [-]**

This switch will be used if *SeismicMode* is set to “1” and the ground motion is user-defined. This switch will describe the type of ground motion input by the user. Setting *PtfmMotionType* to “1” will mean that the ground motion type given by the user is in the form of acceleration. A setting of “2” or “3” will indicate that the data is input to FAST in velocity and displacement, respectively. Using other values for this switch will cause FAST to abort.

***PtfmMotionFactor*: Platform Motion Factor [-]**

This factor will be used if *SeismicMode* is set to “1” and ground motion is user-defined. This is a value for scaling the data contained in *PtfmXMotionFn*, *PtfmYMotionFn*, and *PtfmZMotionFn* and can be used to correct discrepancies in units between the input file(s) and those assumed by FAST. It is also useful for scaling the amplitude of the input motions. The FAST code assumes that input motions are specified in m, m/s, and m/s² for displacement, velocity, and acceleration, respectively. This factor is applied to all three specified directions.

***ActFreq*: Actuator Frequency [Hz]**

The frequency of the actuator used to calculate the base forces according to the input motion given to the program.

***ActDamp*: Actuator Damping [%]**

The damping ratio is assigned to the actuator to calculate the base forces. This variable is specified as a percent of the critical damping. A value of 60 to 70 percent is suggested.

***EqDelay*: Earthquake Delay [s]**

This is the time from the start of the simulation when the base shaking will start to be applied to the turbine.

Motions

Two types of motions are supported for application of base shaking in FAST: The first is explicitly provided by the user as acceleration, velocity, or displacement in each desired direction of shaking; and the second is a synthetically generated acceleration based on parameters given by the user. Both user-defined and synthetic motions can be adjusted to be compatible with a user-defined target spectrum.

To perform a seismic analysis on a wind turbine, the platform's translational degrees of freedom should be set to "True" in each direction of motion applied to the structure. For directions where motion is not applied, a value of "False" should be used for the platform degrees of freedom. These variables can be found in the FAST platform file. For example, if motion is to be applied in X, Y, and Z directions, a value of "True" must be used for *PtfmSgDOF*, *PtfmSwDOF*, and *PtfmHvDOF*. Without further modifications to the provided analysis routines, the platform's rotational degrees of freedom should be set to "False" at all times.

User-Specified Input Motion

A user-specified input motion is indicated by switching *SeismicMode* to "1" and defining the path of each input file using the three parameters *PtfmXMotionFn*, *PtfmYMotionFn*, and *PtfmZMotionFn*, which represent the user-specified motion in horizontal X axis, Y axis, and vertical Z axis of the inertial-frame coordinate system, respectively. Motion can be given in any time step according to the recorded data; the data will be interpolated in terms of the time step provided to the primary FAST input file by the program. If the user provides an input motion with residual drifts (non-zero final values) in displacement and velocity time histories, the baseline correction can be applied in the simulation by switching on *BLineCorrection* parameter in the seismic input file.

As mentioned earlier, it is recommended that the user review the resulting platform acceleration, velocity, and displacement in the following simulations to ensure expected behavior. These values can be obtained by recording the platform motion variables in the main FAST output file.

Synthetic Motions

In addition to a user-specified motion, generation of synthetic motion is supported by setting *SeismicMode* to 2. A full description of variables used by synthetic motion simulations is provided at the end of this section. Generation of the synthetic motion starts by creating a sequence of random numbers with a zero mean and a unit variance of the specified length (*SynDuration*). The generated motion is then scaled so that the resulting root-mean-square (RMS) amplitude matches the specified amplitude, for each direction.

To adjust the generated synthetic motion to more closely resemble an earthquake motion, which generally builds from low amplitude shaking to a period of strong motion and then decays again, an initial and final ramp may be specified for each direction. The ramps are applied by interpolating between specified time/amplitude pairs and then multiplied by the synthetic motion. This process results in a motion that more closely resembles observed earthquake time histories, but often modification of the response spectrum is desirable to adjust the frequency content of the synthetic motion [3, 7]. This can be achieved by specification of a target response spectrum to alter the frequency content of the synthetic time histories.

As always in seismic simulations, it is recommended that the resulting platform motion be recorded through capture of the appropriate variables in the main FAST output file. Further, without baseline correction, synthetically generated motions will most likely result in residual velocities and displacements.

***SynRandomSeedX1*, *SynRandomSeedX2*, *SynRandomSeedY1*,
SynRandomSeedY2, *SynRandomSeedZ1*, and *SynRandomSeedZ2*: Synthetic
Motion Random Seeds [-]**

These values are used if *SeismicMode* is set to “2.” They are seed numbers to generate random data that is consistent for synthetic motion between simulation runs. Valid values are between -2147483648 to 2147483647 (inclusive) for each seed.

***SynRMSAmpX*, *SynRMSAmpY*, and *SynRMSAmpZ*: Synthetic Motion RMS
Amplitude [m/s²]**

These values are used if *SeismicMode* is set to “2.” This variable is used to specify the RMS amplitude (m/s²) of the synthetically generated acceleration in each direction. The RMS amplitude is calculated prior to the application of initial and final ramps. Further, the final amplitude may be influenced by motion modification to conform to a target response spectrum. If no motion is desired in a particular direction, simply set the RMS amplitude for that direction to zero.

***SynDuration*: Synthetic Motion Duration [s]**

This value indicates the duration of the generated synthetic time history. To ensure analysis of the full synthetic motion, the total simulation length should be at least *SynDuration* + *EqDelay*.

***SynInitRampFnX*, *SynInitRampFnY*, and *SynInitRampFnZ*: Synthetic Motion Initial
Ramp Filename [-]**

This file contains time and amplitude pairs used to specify an initial ramp to be applied to the synthetically generated motion in each of the three possible loading directions. Each line consists of two floating point numbers separated by a space. The first number is the time in seconds. The second is the multiplication factor used to scale the motion. It is recommended that values monotonically increase from zero to one, but this is not enforced. For intermediate time values not specified, a scale factor is calculated through linearly interpolating between given values. If a ramp file name is omitted, no initial ramp is applied to the generated motion.

***SynFinalRampFnX*, *SynFinalRampFnY*, and *SynFinalRampFnZ*: Synthetic Motion
Final Ramp Filename [-]**

This file contains time and amplitude pairs used to specify a final ramp to be applied to the synthetically generated motion in each of the three possible directions. It is formatted as the *InitRampFn* file. It is recommended that values in this file monotonically decrease from one to zero, but such behavior is not enforced. The first time step in this file must be greater than the last time step in the initial ramp file. If a ramp file name is omitted, no final ramp is applied to the generated motion.

Motion Handling

This section explains how the specified user-defined or synthetic ground motions can be manipulated. There are two methods to deal with a ground motion in FAST. The first method of motion modification is the baseline correction, in which a ground motion that has residual drifts in velocity or displacement time history is adjusted to eliminate these artifacts. The second modification procedure is to adjust the motion to be compatible with a target response spectrum. Both user-defined and synthetic motion can be adjusted to conform within a desired tolerance of a target response spectrum. Though the method used for adjusting a motion to conform to a target spectrum will not create additional residual velocity or displacement, motions that

originally result in residual velocity or displacement should still be corrected. A brief description of each type of motion handling is in the following sections.

Baseline Correction

If the user provides an input motion or uses a synthetic motion that shows residual drifts in its displacement and velocity, baseline correction may be performed to remove these numerical artifacts. Baseline correction is performed by first numerically integrating the prescribed acceleration or velocity to get displacement. Next, a second-order polynomial is fit to the calculated displacement. The resulting polynomial is subtracted from the displacement time series to eliminate residual drifts in the displacement. Finally the velocity and acceleration time histories are updated using the corrected displacement time history by numerical differentiation.

***BLineCorrection*: Base Line Correction [T/F]**

This is a flag that controls the application of baseline correction to the input motions. When a value of “True” is used for *BLineCorrection*, motions are corrected for all of the three axes.

Target Spectrum

The response of an initial ground motion can be matched with a user-provided target response spectrum. Many approaches are available for matching the response of an initial time history to a desired response spectrum. The tapered cosine wavelet method implemented in the 2009 version of RspMatch (also known as RspMatch09), and documented in Atik and Abrahamson [11], is supported for use in the FAST code. This approach strategically adds a tapered cosine wavelet to the acceleration time history that has the effect of reducing the discrepancy between the actual and target response spectrum. This procedure has numerous advantages over previous approaches including: reducing computational expense; eliminating the need for additional baseline correction; and improving preservation of the non-stationary characteristics of the original motion. For more information about the process of spectral matching, the user can refer to Atik and Abrahamson [11]. Variables required for modification of the motion response spectrum are described below. Most of these variables are as described in the RspMatch documentation.

When using the target spectrum capabilities of FAST, the executable file of the RspMatch program must be copied into a folder contained in the search path for the executable file. This can be accomplished on most systems by copying the provided rspm09.exe file into the directory where the model is run. A second alternative is to include the directory where rspm09.exe is located into the system path.

***TgtResponse*: Target Response Spectrum [T/F]**

This flag indicates whether the user desires to match the time history with a target response spectrum. This flag is usually “True” when a synthetic motion is created (*SeismicMode* = 2).

***TgtResFnX*, *TgtResFnY*, and *TgtResFnZ*: Target Response Spectrum Filename [-]**

This is the absolute or relative path of the files containing a target response spectrum input by the user for each direction of loading. The format of this file is described in the target spectrum section below. If a null value is provided for any direction, no modification of the motions will be made in that direction. Due to length limitations in the RspMatch program, the path specified here should be less than 50 characters long.

If specified, it is important that the target spectrum match the desired amplitude because it will control not only spectral shape, but final amplitude measures, such as RMS amplitude and peak ground acceleration (PGA) for both user-specified and synthetic motion.

***nPass*: Number of Passes [-]**

This value is only used if *TgtResponse* is set to “True”, and FAST is required to match a time history with a response spectrum. This is an integer showing the number of adjustment passes that are required for different frequency ranges to make the synthetic motion match the target response spectrum. A default of “4” is acceptable for all cases.

***MaxIter*: Maximum Number of Iterations [-]**

This value is only used if *TgtResponse* is set to “True.” This is an integer showing the maximum number of iterations for spectral matching in each pass. A default number of 20 can be given to this value.

***Tol*: Tolerance [%]**

This value is only used if *TgtResponse* is set to “True.” This value is the tolerance for maximum deviation from the target spectrum. A value of 5% is typical, specified as 5 to maintain consistency with other percentage values in FAST. This differs from the *RspMatch* configuration file, where a tolerance of 5% is specified as 0.05.

***MaxFreq*: Maximum Frequency [Hz]**

This value is only used if *TgtResponse* is set to “True.” This value indicates the maximum frequency that spectral matching is performed.

***FreqMatch12*: Frequency Match 1 and 2 [Hz]**

This value is only used if *TgtResponse* is set to “True.” Two frequencies that clarify the frequency range for spectral matching are separated by commas. Spectral matching for a certain pass is performed for all frequencies between *FreqMatch1* and *FreqMatch2*.

Target Spectrum File Format

The required format for the target spectrum file is documented in the *RspMatch* user’s manual, which is distributed with the source code. A description of the format is reproduced in Table 2. Sample target spectrum files are provided in examples 3 and 6.

Table 2. Format required for the target response spectrum file

Line Number	Name	Description
1	<i>Title</i>	A title for the response spectrum. This has a maximum of 80 characters
2	<i>nPer, nDamp</i>	Two integers separated by space with the first indicating the number of data points in the target response spectrum and the second representing the number of damping values that the spectrum should match.
3	<i>Damp1, Damp2, ...</i>	A space delimited list of damping values that the spectrum is specified at.
4 through nPer + 3	<i>Freq, T1, T2, SA1, SA2 ..</i>	A space delimited array. The first value is the frequency at which the response spectrum is being specified. The second value is the time at which manipulation of the acceleration time history may begin relative to <i>EqDelay</i> parameter. It is recommended that this be set to zero. The third value is the time at which the acceleration time history may no longer be manipulated (again relative to <i>EqDelay</i>). It is recommended that this be set to a value larger than the length of the acceleration time history. The following values are pseudo-spectral acceleration (PSA), specified in m/s^2 , for each of the damping levels specified in line 3. The number of specified PSA levels should match the number of damping levels specified in line 3.

Discussion

This document discusses the mechanics of conducting a simulation using FAST when a wind turbine is subjected to an earthquake. Outside of the details discussed here, a large number of considerations exist for conducting a proper simulation. At a minimum, the user should be familiar with the seismic provisions specific to wind turbines developed by the International Electrotechnical Commission (IEC) [13] and also Germanischer Lloyd (GL) [14]. Further, users must consider locally applicable building codes. Many jurisdictions throughout the United States, and possibly other countries, require that wind turbines conform to seismic requirements set forth in the International Building Code [15]. A joint committee commissioned by the American Wind Energy Association (AWEA) and the American Society of Civil Engineers (ASCE) recently published recommended practices for design and permitting of large wind turbine support structures [16]. It provides initial guidance on calculating seismic loads for large wind turbines, considering industry guidelines in conjunction with applicable U.S. building codes.

Recommended Practices for Seismic Simulations

The following sections provide guidance regarding selection of parameters and other components of simulating seismic excitation of wind turbines.

Recommended Parameters

Time Step

Selection of the time step parameter is important in any form of simulation. It is generally acknowledged that, within the limits of machine precision, a smaller time step will yield more accurate results, while a larger time step allows simulations to run faster. Once the final base-motion time history is developed, all calculations associated with seismic loading in FAST occur at the time step (DT) specified in the main FAST configuration file. Seismic simulations require a time step smaller than that used for conventional simulations of the same turbine. Further, it is recommended that the time step be no larger than 1/10 the period of the actuator simulated at the turbine base. For input motions rich in high-frequency energy, a smaller time step may be required.

The current implementation of seismic loading in the FAST code supports interpolation of input time histories for base-motions. This feature is provided primarily for convenience and should be used with care. In general, it is suggested that this feature be used only when deciding on a final time step in a seismic simulation. Once a final time step is determined, the input time history should be re-sampled using more advanced routines to minimize the distortion.

Tower and Blade Damping Considerations

Assumptions regarding damping are critical to the resulting response of any civil structure. In the case of FAST, there are two places where damping values may significantly influence demand parameters for seismic simulations. The first location is in the tower definition file. The user is able to specify modal damping for first and second fore-aft and side-to-side modes of the turbine tower. The second location is in the blade definition file. The user is able to specify modal damping of the first and second flap modes, as well as the first edge mode. The values specified in these locations represent inherent damping in the turbine structure. Additional damping through aerodynamic interaction is inherently calculated by FAST, assuming the variable *CompAero* is set to “True” in the main configuration file. Considerations specific to seismic loading are not of significant importance when selecting other damping values not discussed in this document for turbine models in FAST.

There are varied opinions regarding the appropriate value to use for damping in seismic simulations. Many building codes suggest the use of a value of 5% of critical when determining the earthquake response of a structure. Conventional wisdom, with support from numerous experimental results, suggests that this value is high for actual damping in a wind turbine. Values around 1% of critical damping (not including aerodynamic damping) appear to be more realistic [17].

A code-to-code comparison of simulation results for a parked 65-kW turbine, using comparable models in the FAST code and the OpenSees code [18], suggests that to achieve approximately equal results (acceleration response and tower bending-moment demand) a value of 2% of critical damping is required for the first mode of the tower in the FAST code ($TwrFADmp(1)$ and $TwrSSDmp(1)$). Only 1% of critical damping is specified at the frequency of the first tower mode in the OpenSees code. Lacking information to calibrate damping levels or other specific guidance, it is suggested that a value of approximately 1% be used for modal damping in the FAST code ($TwrFADmp_i$ and $TwrSSDmp_i$).

Platform Mass

Another approach that may aid in providing stable results is to increase the mass of the turbine platform (*PtfmMass*). Increasing the platform mass may have stabilizing effects on the simulation results. A reasonable start for the platform mass value is approximately 10 times the total turbine mass.

Input Motions

Selection of input motions for simulation of seismic loading of any civil structure is critical. As with selection of wind fields, input motions are dependent on the intended site of installation for the turbine. Many jurisdictions have local requirements regarding the selection of motions. In the United States, most jurisdictions follow the IBC [15] requirements for motion selection. In most cases, the IBC refers to ASCE 7 [19] for details regarding the definition of seismic loads.

When conducting final simulations to determine the seismic demand for a turbine, a seismologist familiar with the specific location should be consulted to determine appropriate motions and scaling. As a starting point, a number of standard motion sets exist that can be used to evaluate seismic demand for a turbine. The Applied Technology Council's (ATC) report, FEMA-P695 [20], references a set of 22 far-field and 28 near-field events, which can serve as a preliminary set of motions for analysis. Each event in these sets contains two horizontal components. Another vetted and publically available data set of 100 motions is described by Mackie and Stojadinović [21] for more extensive investigations. In addition to containing two horizontal components for each event, this set also contains a vertical component (a total of three components).

In all cases of preliminary motion selection to final simulation, it is important to ensure that signal processing does not introduce undesirable artifacts, such as aliasing. If possible, it is recommended that analysts use original motions with minimal processing. If processing is required, such as re-sampling, scaling, or adjusting for spectrum compatibility, it is important that the resulting motion is verified. At a minimum, the time histories and elastic response spectra should be visibly compared to those from the original unprocessed motion. Differences should be minimal with deviations only due to scaling and adjustments for spectrum compatibility.

Post Simulation Verification

As with any numerical simulation, results of seismic excitation from the FAST code must be verified. Two main issues are most critical to verify in seismic simulations: the stability of the results and the reproduction quality of the base motion. For all simulations, the two horizontal and one vertical acceleration time histories should be verified.

In simulations in which the time step was too large or other numerical instabilities, the platform acceleration may rapidly oscillate over a large range (considerably larger than the desired motion). Results from any simulation with such an oscillation should be discarded. To resolve these oscillations, two approaches have shown improved simulation quality. First, a smaller simulation time step may resolve the stability issues. Second, increasing the earthquake delay (*EqDelay*) may improve result stability. As a general rule, earthquake motion should not start before large initial transients that are common in FAST simulations diminish (similar to how one should delay an IEC discrete wind gust). It is important to note that changing the earthquake delay may result in unintended consequences, such as changing the relative time of any emergency shutdown.

Once a simulation appears to be stable, it is important to verify the quality of the reproduced input time history. As suggested for verification of input motions following processing, the platform response time history must be compared to the intended time history. This should be done in both the time and frequency domains. One approach is a visual comparison of the intended and the realized motion. A more rigorous approach would be to verify the difference between the intended and realized motion to identify specific artifacts. If the accuracy of the realized motion time history is less than the desired level, increasing the frequency of the simulated actuator (*ActFreq*) may improve results. When increasing the actuator frequency, it is important to remember the time step also must be reduced to keep simulation results stable.

Preliminary Findings for 5-MW NREL Reference Turbine

To ensure that no changes were introduced, the code revisions documented here are verified with previous work done by Prowell et al. [22] on seismic analysis of the 5-MW reference wind turbine. This work contains analysis on the modeled wind turbine for idling, operational, and emergency shutdown during earthquake loading conditions. These loading conditions are chosen to show the effect of the combination of aerodynamics and seismic loading conditions. The previously mentioned suite of 22 far-field earthquake events described in FEMA-P695 [20] is considered for simulation. For each event, two simulations are executed that interchange the horizontal components to reduce bias due to relative orientation with wind direction. For each load condition, idling, operational, or emergency shutdown, a total of 44 scenarios are considered. In each of the three load cases, the turbine is subjected to a hub-height wind speed of 11.4 m/s with level B IEC turbulence intensity. A 600-second simulation time is considered with 0.002-second time steps. Earthquake shaking initiating at 400 seconds allows initial transient behavior to diminish. In the case of an emergency shutdown simulation, shutdown of the turbine is triggered by a horizontal acceleration in the nacelle exceeding 1 m/s^2 . The actuator frequency is set to 50 Hz and the actuator damping value is 65% of critical.

Selected results are presented for the 1987 El Centro earthquake to illustrate key features associated with each of the operational states considered. Figure 2 shows the platform acceleration time history in X and Y directions. The results from this figure can be used to check the adequacy in the initiation time and amplitude of the input acceleration. The earthquake motion started at 400 seconds in the simulation and ended at 440 seconds. The figure is shown from the start of earthquake shaking through five seconds after shaking ended. As observed in this figure, the results for previous findings with the new FAST code have identical values. The input acceleration time history shown in Figure 2 was the same for the three loading conditions. Figures 3 to 5 show the resulting tower moment demand, which is presented to assess the influence of different operational states on the resulting structural demand. Figure 3 shows the tower-base bending moment in the X and Y direction at the time of earthquake excitation in idling loading condition. The moment in idling condition is around zero at the start of the earthquake because no operational loads are involved before the earthquake's occurrence. At the end of the earthquake, the base moment attenuates gradually because of the low structural damping. Figure 4 shows the tower base moment in both directions ($TwrBsMxt$ and $TwrBsMyt$) for operational loading conditions during the earthquake. The base moment before the earthquake starts is significantly higher in comparison with the idling condition because of rotor thrust. A greater difference between the tower-base moment in idling and operational loads is observed in the Y direction because the wind is applied in the X direction in the simulation (the moment in the Y direction is due to forces in the X direction). The maximum moment between

idling and operational loading conditions occurs in the operational case because of the combination of operational loads and earthquake loads when the turbine is operating during seismic excitation. In both figures, the tower-base moment from previous work done by Prowell et al. [22] and the new FAST code are in agreement. For the emergency shutdown loading condition, the emergency shutdown is initiated at 409.416 seconds into the simulation (in this case, the ground motion is based on the assumption that the shutdown is triggered when horizontal acceleration in the nacelle exceeds 1 m/s^2). It takes about 14 seconds for the rotor speed to reach zero RPM. Figure 5 shows tower-base moment in the emergency shutdown condition. The results in this case also show a reasonable match. At the time of the emergency shutdown, the moment decreases rapidly and oscillates around zero once the emergency shutdown is initiated. The maximum moment in this case occurs around the time of the emergency shutdown. However, this value does not exceed the maximum moment value of the base moment in the operational loading condition. When comparing these three figures, it can be concluded that the difference in base moment for the described operational states of the considered motion appears mostly in the Y direction, which is perpendicular to the applied wind direction.

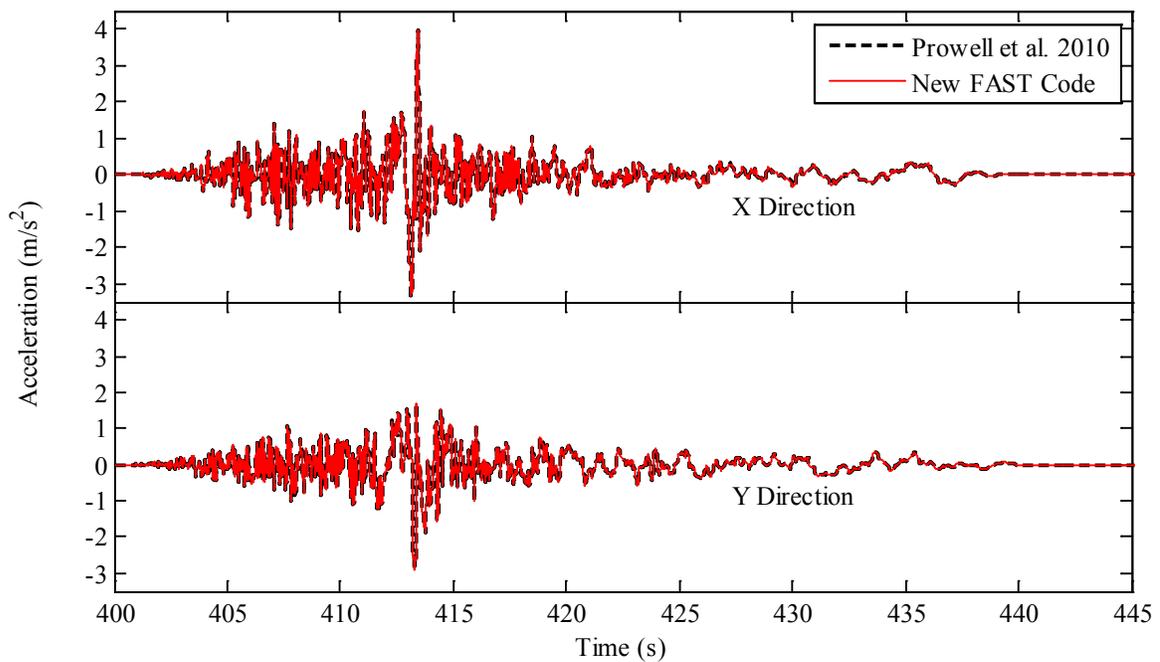


Figure 2. Platform inertial acceleration in idling, operational, and emergency shutdown loading conditions for X and Y directions (EI-Centro earthquake)

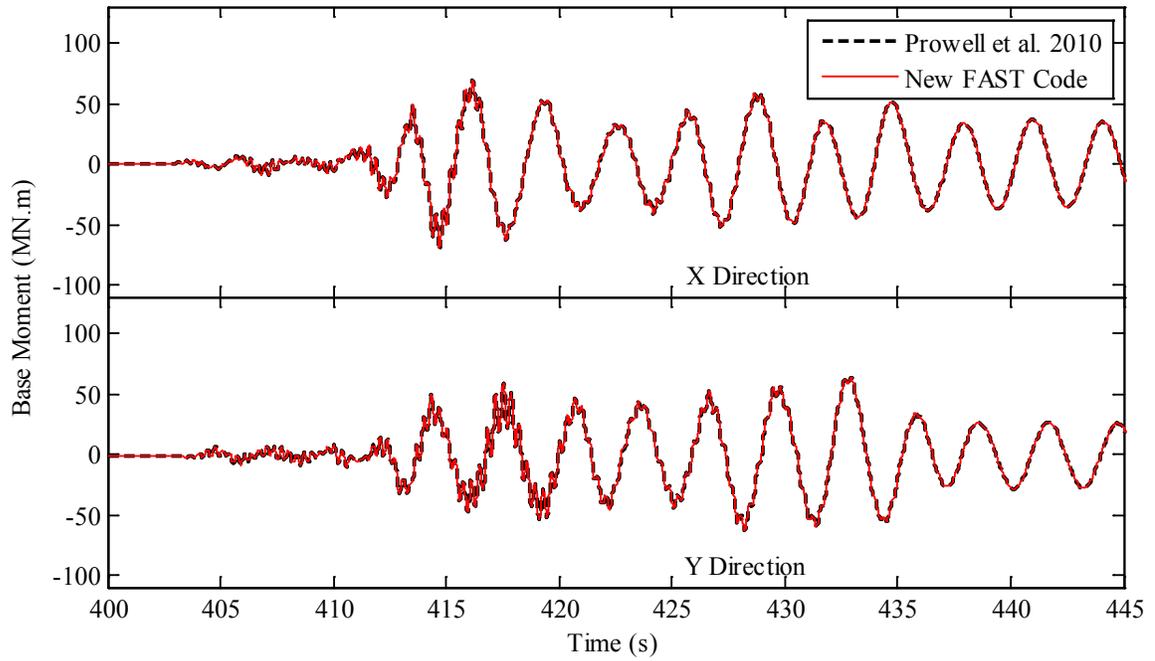


Figure 3. Tower-base moment in idling loading condition

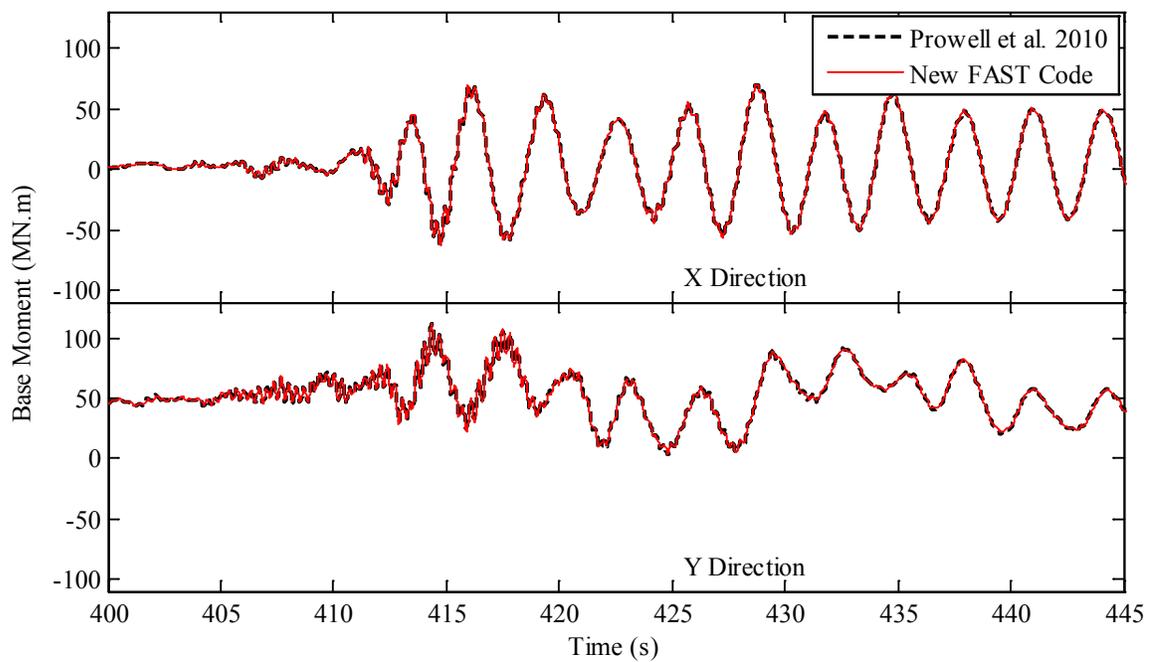


Figure 4. Tower-base moment for operational loading condition

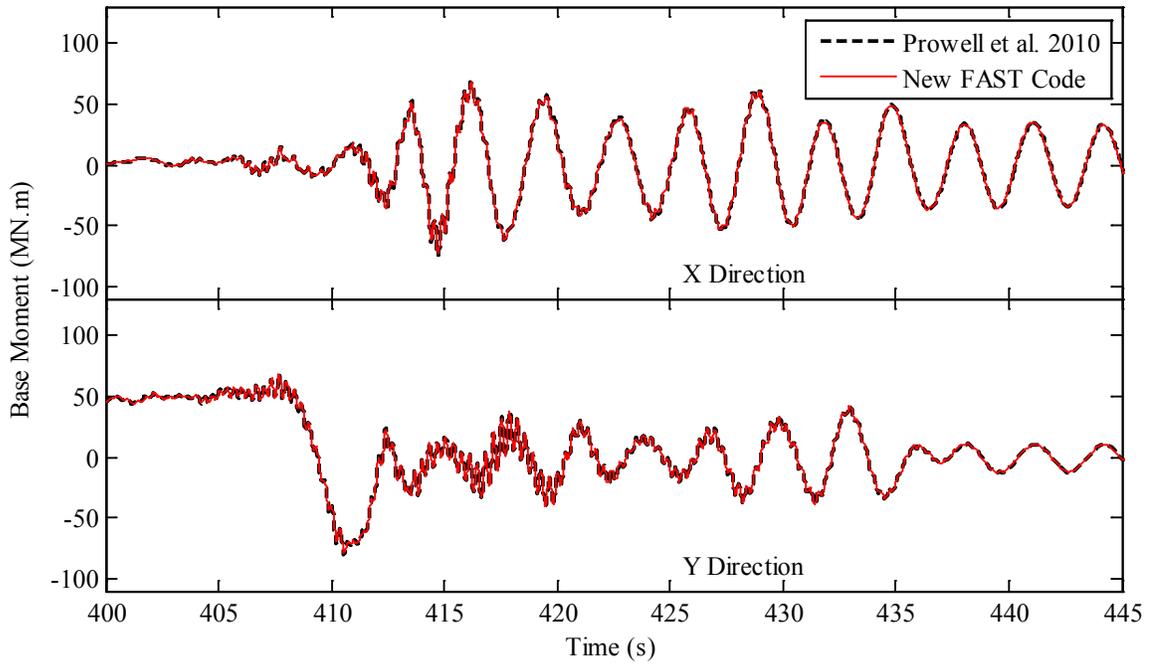


Figure 5. Tower-base moment for emergency shutdown loading condition

For an aggregate comparison, the results of all the seismic analyses are shown in the form of mean, mean plus one standard deviation, and the maximum magnitude of the tower bending moment, calculated as the square root of the sum of the squares (SRSS) value of moment in both directions, at five different elevations of the tower. Results are presented for idling, operational, and emergency shutdown loading conditions and are compared with results published earlier in Prowell et al.[22]. The dashed lines represent the results from the new FAST code and the solid lines belong to earlier findings.

In agreement with trends observed for the single motion presented above, the aggregate results show that, for the 5-MW NREL reference turbine, loads tend to be lower when the turbine is subjected to an earthquake in the idling condition. Loads are of a similar magnitude for the operational and emergency shutdown condition. However, in the considered scenarios, an emergency shutdown slightly reduces the base moment experienced by the tower. These results clearly show that the operational state influences the maximum tower-bending moment experienced by the turbine. This finding supports IEC and GL requirements that the operational state be considered in estimating extreme seismic loads for wind turbines.

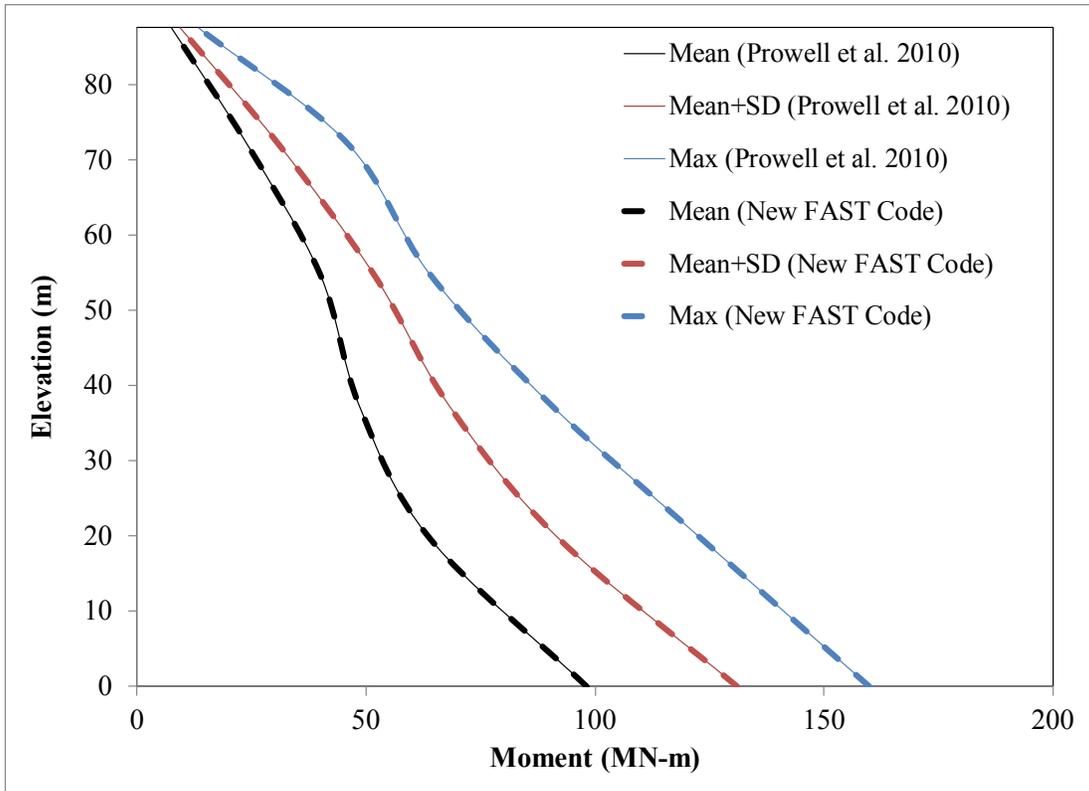


Figure 6. Mean, mean plus standard deviation, and maximum of the SRSS moment for the idling loading condition

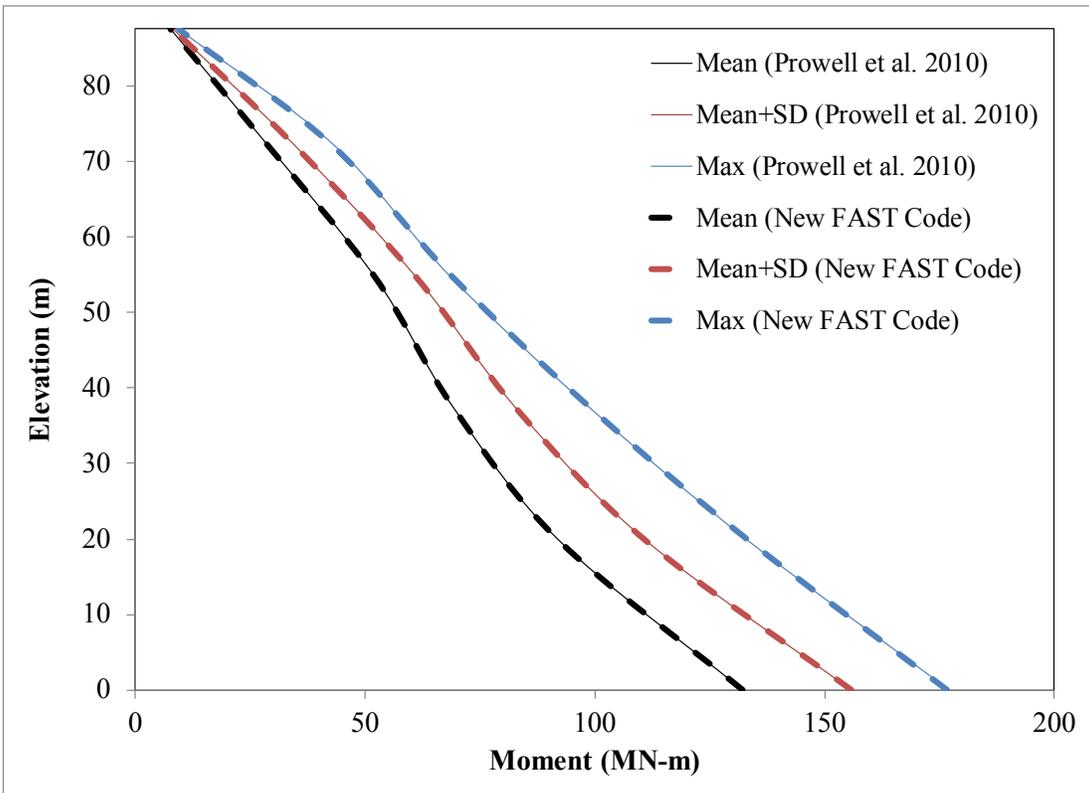


Figure 7. Mean, mean plus standard deviation, and maximum of the SRSS moment for the operational loading condition

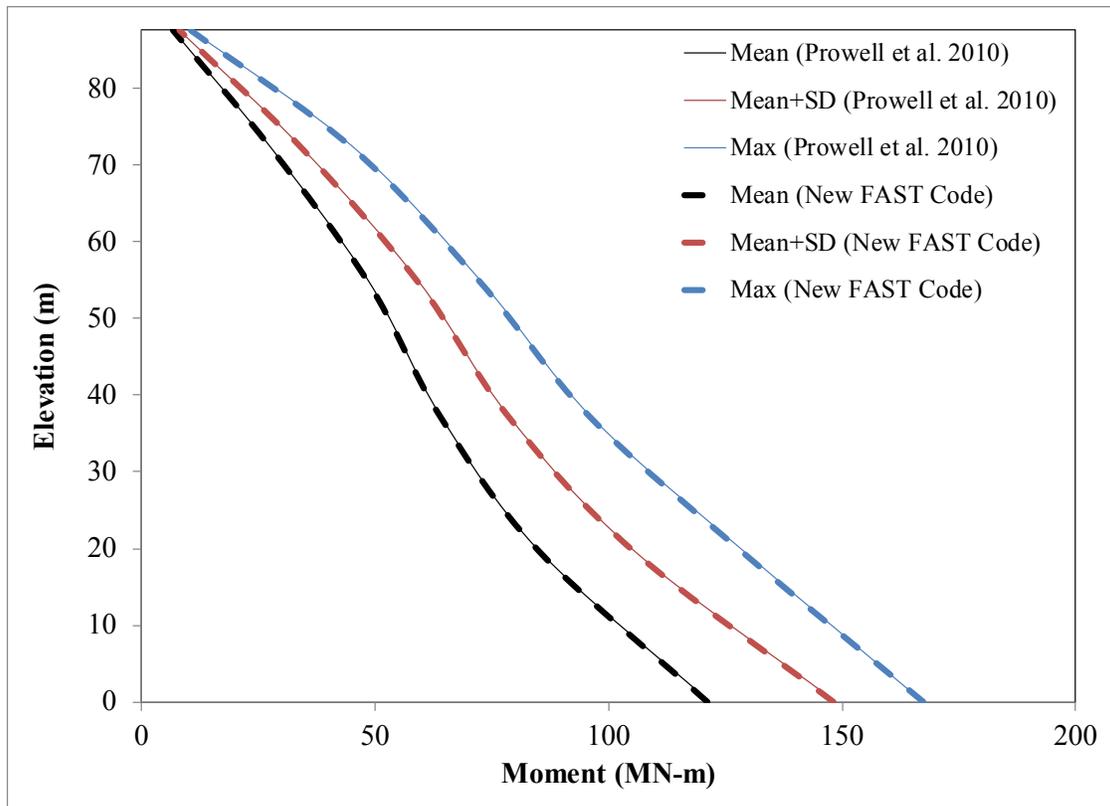


Figure 8. Mean, mean plus standard deviation, and maximum of the SRSS moment for the emergency shutdown loading condition

Limitations and Future Enhancements

As with most initial implementations of new software features, the current state of seismic loading in the FAST code has some inherent limitations. Inherent in the current code, it is assumed that the turbine base does not rotate about any of the three axes. This assumption is common in earthquake engineering and is a good first approximation for the seismic response of a structure. For wind turbines, this is particularly true considering numerous limitations on the foundation's flexibility imposed to minimize the effect on system operation and dynamic characteristics, such as the natural frequencies of the turbine when installed on a foundation. Consideration of base rotation is typically done for massive structures that do not have as stringent foundation requirements. However, consideration of base flexibility may offer advantages in optimization of turbine design, especially in foundation design, in which more detailed modeling may allow current constraints to be relaxed leading to more economical foundations. Additionally, as turbines grow larger and more massive, the influence of foundation and soil flexibility will become more pronounced. This is already evident in bottom-fixed offshore turbines where it is becoming more common to consider the influence of soil flexibility on the turbine's dynamic response.

A second recognized issue in the current implementation of seismic loading in the FAST code is associated with verification of motion quality. Currently, the user is required to verify that the achieved base motion is sufficiently accurate for the desired purposes. To accomplish this, a relatively small time step, smaller than equivalent simulations that do not have seismic loading, is required to maintain stable and accurate results. Future versions of seismic loading in the FAST code will likely automate the procedure for verification of motion quality. It is envisioned

that a warning similar to the current large deflection warning will be issued if reproduction quality of the prescribed motions deteriorates to unacceptable levels. In conjunction with automatic verification of motion quality, additional loading models, likely including a feedback loop, are being explored to improve stability and allow accurate simulations with a larger time step.

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