

Innovation for Our Energy Future

Wind Turbine Control Design to Reduce Capital Costs

7 January 2009 – 31 August 2009

Phillip J. Darrow Colorado School of Mines Golden, Colorado Subcontract Report NREL/SR-500-46442 January 2010



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Abstract

Wind turbines installed in regions that sometimes have extreme conditions can experience both fatigue and extreme loading. These loads affect individual components of a wind turbine differently. Wind turbines currently have a design life of 20 years, which is achieved by building a turbine with robust components that can withstand the fatigue and extreme loads for the duration. Unfortunately, this approach increases the initial capital costs of a wind turbine because of the higher cost of the more robust components. Performing a full load case analysis and determining which components experience the largest design-driving loads allows design of advanced control algorithms that will enable turbines to be manufactured with less expensive components.

This report first discusses and identifies which wind turbine components can benefit from advanced control algorithms and also presents results from a preliminary loads case analysis using a baseline controller. Next, it describes the design, implementation, and simulation-based testing of an advanced controller to reduce loads on those components. The case-by-case loads analysis and advanced controller design will help guide future control research.

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List of Symbols

 u_{ref} - reference wind speed

- $I_{\rm ref}$ expected value of turbulence intensity at 15 m/s
- u_{in} cut-in wind speed
- u_{hub} wind speed at hub height
- u_{out} cut-out wind speed
- u_r rated wind speed
- τ commanded torque
- *k* torque constant
- ω undamped natural frequency
- ρ air density
- R rotor radius
- $C_{p,\max}$ maximum power coefficient
- λ tip speed ratio
- Δx state vector perturbation
- $\Delta \dot{x}$ time derivative of state vector perturbation
- $\Delta \ddot{x}$ time derivative of $\Delta \dot{x}$
- M_t tower mass coefficient associated with first fore-aft mode
- C_t tower damping coefficient associated with first fore-aft mode
- K_t tower stiffness coefficient associated with first fore-aft mode
- F_t pitch control input gain corresponding to first tower fore-aft mode
- $\Delta \theta$ blade pitch perturbation
- G gain in full state feedback law
- *u* wind speed
- u_0 wind speed set point for FAST linearization
- Ω_0 rotor speed set point for FAST linearization
- Θ_0 pitch angle set point for FAST linearization
- δ damping ratio
- Δx_1 state 1 perturbation for FSFB design
- Δx_2 state 2 perturbation for FSFB design
- Δx_3 state 3 perturbation for FSFB design
- A_c state matrix calculated in control synthesis routine
- $B_{\rm c}$ control input gain matrix calculated in control synthesis routine
- $C_{\rm c}$ output state matrix calculated in control synthesis routine

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1.0 Introduction

The demand for energy continues to climb: the U.S. Energy Information Administration estimates that electricity demand in this nation alone will grow by 39% between 2005 and 2030.¹ Today's supply of this energy primarily comes from nonrenewable sources—coal, natural gas, oil, and nuclear power. These sources are limited, however, and will be depleted. Using nonrenewable fossil fuels also leads to concerns about environmental degradation. Wind, a renewable and nonpolluting source of energy that can be tapped for electricity production around the world, is a prominent solution to this dilemma. The U.S. Department of Energy's 20% Wind Energy by 2030 sets the goal for wind power to supply 20% of America's electricity by 2030 and reduce emissions of carbon dioxide by 25%.¹

1.1 Background

Wind turbines will play an important role in the future of energy production. Evidence for this future importance can be seen in the current global demand for turbines. In the United States, the American Wind Energy Association (AWEA) reports, the number of wind installations increased by 50% in 2008 and should increase by 20% in 2009.² This increase in demand has helped greatly increase research efforts and funding for wind energy in recent years. Over a two-year span, funding for wind energy research increased from \$10 million to \$14 million.³

An important research topic is how to reduce initial capital costs, or the costs to purchase the wind turbine components, which can thus reduce the cost of the wind turbine. In general, these component costs are high because the components must be designed to both withstand extreme loads caused by turbulent wind fluctuations and have long fatigue lifetimes.

When wind turbines operate in extreme conditions, they can experience both fatigue and extreme loads. These loads affect separate components of a turbine differently. As defined by the International Electrotechnical Commission (IEC), a wind turbine must have a design life of 20 years.⁴ The current practice to achieve this goal is to build a turbine with robust, but very expensive, components that can withstand fatigue and extreme loads for this duration. The work presented here had two goals: increase understanding of which wind turbine components can benefit from advanced control algorithms by showing preliminary results from a load case analysis on the three-bladed Controls Advanced Research Turbine (CART3), and describe the development and simulation-based testing of advanced control algorithms to reduce loads on those components.

1.2 Previous Work

Numerous researchers have analyzed loads, including Wright and Balas.⁵ In their research, they designed controls to attenuate loads in the CART2, the two-bladed version of the CART3. They used disturbance accommodating control (DAC) to reduce loads by enhancing damping in several low-damped flexible modes of the turbine and to regulate

turbine speed in region III. Although they added active damping, they did not perform a rigorous loads analysis to ascertain which loads are the most important for capital cost reduction. The goal of the work described here is for the case-by-case loads analysis to guide future control research.

Jonkman also extensively analyzed loads. In his report titled *Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine*,⁶ he describes his full loads analysis of an offshore floating turbine to identify design driving events. His research, however, did not include designing an advanced controller to mitigate the design driving events. The research presented here performs a similar loads analysis of a land-based turbine and also designs advanced controls based on the results.

Smolka added sensors to monitor loading to a wind turbine to enable more advanced control techniques such as individual blade pitch.⁷ He explored the concept of an online monitoring system to adjust the controller in real time. His overall goal has been to identify and employ a load-monitoring concept that meets the demands of advanced controller design techniques. With the results of his research, specific components could be constantly monitored and adaptive controllers could be designed to use this information.

Barlas and Kuik focused on reducing rotor loading.⁸ Their research is based on the fact that lower costs for wind turbines is nearing a point where mechanical advances (less expensive components) are no longer going to be possible. Their goal is to reduce loads by technological advances for further cost reductions. They described smart rotor control techniques that successfully reduce rotor loading. The scope of their paper does not include an all-inclusive loads analysis, but it does illustrate the necessity for advanced controls and understanding design driving events.

Stol and colleagues presented an approach to use individual blade pitch control to reduce structural loads in the nonrotating turbine frame, such as the tower side-side bending moment.⁹ Most commercially installed wind turbine controllers use collective pitch when wind speeds are high. They described designing and implementing an individual pitch controller on the CART2 to verify controller performance for load attenuation. They compared individual pitch controller results to collective pitch controller results. Their results show the potential to reduce tower side-side fatigue damage in above-rated wind conditions by 70% (compared to collective pitch).

The goals of the research on simulations of load cases presented in this report include the following:

- Running a full loads case analysis using a simulation model of the CART3
- Identifying design driving events
- Designing advanced controllers to handle such events
- Quantitatively assessing the performance of the newly designed controllers.



Figure 1-1. CART3 research turbine at the National Wind Technology Center

The work described here differs from previous research in that the initial goal is to identify which events are most crucial for control design, thus enabling a more efficient and specific control design process.

1.3 Wind Turbine Description

This research used a simulation model of the CART3, a three-bladed, upwind, active-yaw wind turbine (Figure 1-1) with full-span, independent blade pitch and variable-speed capabilities. The CART3 has a power rating of 600 kW and is located at the National Renewable Energy Laboratory's (NREL) National Wind Technology Center near Golden, Colorado.

The CART3 model has three main components: the rotor, the tower, and the nacelle. The rotor includes the blades and their attachment point, called the hub, and is supported by a low-speed shaft fixed

inside the nacelle. The tower is a cantilever beam that can bend in two orthogonal directions and has a fixed plate at its top that supports a yaw bearing and nacelle. The yaw bearing allows the nacelle of the turbine to rotate as the wind direction varies. The nacelle houses the entire drive train assembly, including the generator, gearbox, and low-speed shaft. A high-speed shaft connects the generator to the gearbox.

The attachment points of the blades to the hub on the CART3 have three blade pitch actuators that allow each blade to be independently pitched. Each blade is modeled as a flexible beam with motion in the edgewise and flapwise directions, and can have varying properties along the length.

This research models the CART3 using NREL's design code FAST (Fatigue, Aerodynamics, Structures, and Turbulence, v6.10a-jmj).¹⁰ The FAST code can model both two- and three-bladed horizontal axis turbines. It combines modal and multibody formulations to model the dynamics of a wind turbine. Three-bladed turbines are allowed up to 24 degrees of freedom (DOF) to represent the turbine dynamics, including translation and rotational motions of the turbine foundation (6 DOF), longitudinal tower motion (2 DOF), lateral tower motion (2 DOF), nacelle yaw (1 DOF), generator azimuth angle (1 DOF), drive train torsion (1 DOF), blade flapwise tip motion (first mode; 3 DOF—one for each blade), blade flapwise tip motion (second mode; 3 DOF), blade edgewise tip displacement (first mode; 3 DOF), and rotor and tail-furl (2 DOF). FAST cannot model blade elastic twist deformations. Any combination of the allowable DOFs can be enabled during a simulation.

1.4 Report Organization

Section 2 covers the deterministic load cases (DLCs) as prescribed by the IEC that help identify design driving events. Section 3 presents results of selected simulations to select design-driving cases where advanced controllers have the potential to reduce loads. Section 4 discusses the advanced controller design and presents the results from the new controller. Section 5 gives the summary and conclusions. Appendices A and B contain the necessary simulation files. The body of this report contains only selected simulations report because of the sheer volume of results obtained; Appendices C and D contain the results.

2.0 Deterministic Load Cases

In the United States, the IEC rules on wind turbine certification . IEC document 61400-1 has a complete list of DLCs and also specifies design classes (I, II, and III) based on parameters such as average wind speed, turbulence intensity (A, B, or C, where A is the most turbulent), extreme wind speed V_{ref} , and the expected value of the turbulence intensity at 15 m/s I_{ref} (Table 2-1).⁴ These factors are the extreme conditions used to establish design conditions. For the complete list of IEC-specified DLCs, see reference [4].

This research used a subset of the IEC suite of DLCs in simulations with a model of the CART3 to determine extreme events. The load cases examined are 1, 2, 6, and 7, with the exception of 1.2 and 6.4, and Table 2-2 briefly describes these cases. Each DLC is simulated using the baseline controller described in Section 3.

Wind '	Ι	II	III	S	
V _{ref}	(m/s)	50	42.5	37.5	Values
А	$I_{\rm ref}(-)$	0.10	6		specified
В	$I_{\rm ref}(-)$	0.14			by the
С	$I_{\rm ref}(-)$	0.12	2		designer

Table 2-1. Basic Parameters for Classification

DLC				Control/Event
	Wind Mo	del	Wind Speed	-
1) Pow	er Product	ion		
1.1	NTM		$u_{in} < u_{hub} < u_{out}$	Normal operation
1.3	ETM		$u_{in} < u_{hub} < u_{out}$	Normal operation
	ECD			
1.4		ı	$u_{hub} = u_r, u_r \pm 2 m/s$	Normal operation: $\pm \Delta$ wind direction
1.5	EWS		$u_{in} < u_{hub} < u_{out}$	Normal operation: $\pm \Delta$ vertical & horizontal shear
2) Pow	er Product	ion w/	Occurrence of Fault	
2.1	NTM		$u_{hub} = u_r, u_{out}$	Pitch runaway → shutdown
2.3	EOG	U _{hu}	$u_{b} = u_{r}, u_{r} \pm 2 \text{ m/s}, u_{out}$	Loss of load → shutdown
6) Park	ed			
	EWM			
6.1a			$u_{hub} = 0.95^*V_{50}$	Yaw = 0°, ±8°
6.2a	EWM		$u_{hub} = 0.95^*V_{50}$	Loss of grid; –180° < yaw <180°
6.3a	EWM		$u_{hub} = 0.95 * V_1$	Yaw = 0°, ±20°
7) Park	ed w/ Occ	urrence	e of Fault	
7.1a	EWM		$u_{hub} = 0.95^*V_1$	Seized blade; yaw = 0°, 8°

Table 2-2. Description	of Selected DLCs.	Source: [4]

Notes: NTM = Normal Turbulence Model; ETM = Extreme Turbulence Model; ECD = Extreme Coherent Gust with Direction Change; EWS = Extreme Wind Shear; EOG = Extreme Operating Gust; EWM = Turbulent Extreme Wind Model.

The loads analysis tests the structural integrity of the CART3 wind turbine model by running a series of DLCs and observing the resulting structural loads. The outcome of each DLC helps determine the extreme events and fatigue that would normally occur over the lifetime of the turbine. The loads in the following components are simulated for each load case:

- Tower bending moments
 - Fore-aft (into and out of the wind)
 - Side-side (orthogonal to the wind)
- Blade bending moments
 - Edgewise (within the rotor plane)
 - Flapwise (out of the rotor plane)

- Low-speed shaft (LSS) torque
 - Minimum and maximum magnitude.

The full suite of DLCs covers events that drive turbine component design, including startup, shutdown, normal operating conditions, and parked events. The DLCs test external fault conditions such as loss of load (DLCs 2.3 and 6.2a), pitch runaway (DLC 2.1), and seized blade (DLC 7.1a).

The full set of IEC-prescribed DLCs includes cases that are not applicable to this research.⁴ DLCs 3.1, 3.2, 3.3, 4.1, 4.2, and 5.1 require a supervisory controller with logic for startup and shutdown procedures and are not considered here. DLC 8.1, which is also omitted, deals with transport, assembly, maintenance, and repair. Precedent for these omissions can be found in Jonkman for an offshore turbine.⁶ The work described here includes the remaining DLCs. These include the following design situations: 1.1–1.5 (with the exception of 1.2), power production; 2.1 and 2.3, power production with fault; 6.1–6.3, parked; and 7.1, parked with fault. Table 2-3 lists the wind models used by the DLCs.⁴

Table 2-3.	Wind	Condition	Model	Descriptions ⁻	Source:	[4]	
------------	------	-----------	-------	---------------------------	---------	-----	--

Wind Model	Description
NTM	This model consists of full-field three-component stochastic winds with a turbulence standard deviation given by the 90% quantile, based on the wind turbine turbulence category (B in this project) and increases with the given hub-height wind speed. The full-field turbulence is superimposed on a wind profile with a vertical power- law spear exponent of 0.14.
ETM	This model is similar to the NTM but consists of full-field three- component stochastic winds with a higher turbulence standard deviation, based on the wind-turbine class (IB in this project) and increases with the given hub-height wind speed. Like the NTM, the full-field turbulence is superimposed on a normal wind profile with a vertical power-law shear exponent of 0.14.
ECD	This deterministic-wind model consists of an unsheared gust superimposed on a uniform wind profile with a vertical power-law shear exponent of 0.14. The gust rises to 15 m/s over a 10-s period. Occurring concurrently, the wind direction changes inversely proportional to the given hub-height wind speed. Both positive and negative direction changes are considered.
EWS	This deterministic-wind model consists of a linear shear superimposed on a uniform wind profile with a vertical power-law shear exponent of 0.14. Over a 12-s transient, the shear rises to a maximum, then decreases again before disappearing. Its magnitude depends on the wind turbine turbulence category (B in this project) and increases with the given hub-height wind speed. Positive and negative vertical and horizontal shears are considered independently.
EOG	This deterministic-wind model consists of an unsheared gust superimposed on a uniform wind profile with a vertical power-law shear exponent of 0.14. Over a 10.5-s transient, the gust first dips, rises to a maximum, then dips again before disappearing. Its magnitude depends on the wind-turbine class (IB in this project) and increases with the given hub-height wind speed.
EWM	This model consists of full-field three-component stochastic winds with a turbulence standard deviation of 0.11 times the 10-min average wind speed at hub height, plus 0.2 m/s for 1-h-long simulations. The full-field turbulence is superimposed on a wind profile with a vertical power-law shear exponent of 0.11.

The selected DLCs were simulated using NREL's design code FAST,¹⁰ with AeroDyn and a previously developed CART3 model. All simulations were run with the following DOFs enabled: two flapwise bending modes per blade (six total), one edgewise bending mode per blade (three total), the drive train rotational-flexibility DOF, the variable generator speed, the first and second tower fore-aft bending modes, and the first and second tower side-to-side bending modes, for a total of 15 DOFs. Figure 2-1 illustrates the enabled DOFs. (The remaining nine DOFs were excluded because they were not applicable to the CART3 land-based turbine.)



Figure 2-1. Enabled DOFs for CART3 wind turbine model

The DLCs require different wind conditions. The second column in Table 2-2 describes the required wind conditions for each case. Some of the DLCs require continuous turbulent wind and others require discrete wind conditions. Discrete wind models characterize extreme events that are not well-represented in the turbulent wind cases, including a 50-year extreme gust profile, a wind shear change, and a wind direction change. These cases contain time-dependent magnitudes so that the transient response of the turbine can be observed. The DLCs that require turbulent wind are 1.1, 1.3, 1.6, 2.1, 6.1–6.3, and 7.1. The DLCs that require discrete wind conditions are 1.4, 1.5, and 2.3. The Perl script GenTurb.pl created the turbulent wind input files and the NREL design code IECWind created the discrete wind files. Both GenTurb and IECWind require the same input parameters: rated, cut-out, and cut-in wind speeds, and the number of seeds to generate for each file. Figure 3 defines these speed parameters, and Section 3 describes the control regions II, II¹/₂ and III.

The NREL design code RunIEC applied each DLC to the FAST model.¹¹ RunIEC is a Perl script written by Buhl to automate the DLC simulation process. This script requires the turbine parameters, the desired DLCs to run, the location of the wind files, and the number of seeds for each DLC. The design code then simulates all selected DLCs and creates the desired output files.



Figure 2-2. Regions of operation

3.0 Baseline Controller

3.1 Controller Description

Like most variable-speed, pitch-regulated turbines, the CART3 uses different control schemes depending on the region of operation (Figure 2-2). In region II, where input wind speed is below rated speed, blade pitch is held constant and generator torque is controlled by commanding a demanded torque τ to maximize energy capture. Region II is the variable speed region for a variable-speed turbine. In region III, where wind speed is above rated speed, generator torque is held constant and blade-pitch control maintains rated power and rotor speed by shedding excess aerodynamic power. This pitch control tries to maintain rotor speed to a desired set-point (41.7 revolutions per minute [rpm] for the CART3). The torque control curve shown in Figure 2-2 also includes region II¹/₂, which is sometimes necessary to produce a continuous torque control curve. In this region, generator torque varies linearly with generator speed. For the CART3, the slope of this region represents an induction generator with a 5% slip. Region II¹/₂ is defined between 94% and 99.6% of rated speed, with the upper limit chosen to reduce switching between the region II¹/₂ and region III controllers. This region enables operation at rated torque when rated generator speed is achieved.

In regions II–III, the demanded torque τ is given by

$$\tau(\omega) = \begin{cases} k\omega^2, & \text{Region II} \\ \tau_1 + \frac{\tau_{rated} - \tau_1}{\omega_{rated} - \omega_1} (\omega - \omega_1), & \text{Region II} \frac{1}{2}, \\ \tau_{rated} & \text{Region III} \end{cases}$$
(3-1)

where ω is the generator speed. The torque constant k is given by

$$k = \frac{1}{2} \rho \pi R^5 \frac{C_{p,\max}}{\lambda_*^3},$$
 (3-2)

where $C_{p,max}$ is the maximum power coefficient, ρ is the air density, R is the blade radius, and λ_* is the optimal tip speed ratio (TSR). TSR, defined as λ , is the ratio of the linear speed of the blade tip to the wind speed,

$$\lambda = \frac{\omega R}{u}$$

and λ_* is the TSR at which $C_{p,max}$ occurs.¹⁵ It is generally agreed that variable-speed turbines have a single $C_{p,max}$ and corresponding λ_* .

In region III the baseline controller is a proportional-integral-derivative (PID) controller that commands blade pitch angle to limit rotor speed and aerodynamic power. The CART3 has a baseline proportional integral/integrated derivative (PI/ID) controller, described by Johnson and colleagues.¹² The main difference between the PI/ID controller and a PID controller is that the discrete-time integrated derivative term is not equivalent to a proportional term as it would be if the PI/ID controller were implemented in continuous time. Like the generator torque controller, the PI/ID pitch controller is implemented in a DLL subroutine that is linked to the FAST model.¹⁰ The PI/ID controller is given by:

$$q_{k} = \frac{1}{T} (\psi_{k} - \psi_{k-1}), \qquad (3-3)$$

$$r_k = (1 - e^{-4T})q_k + e^{-4T}q_{k-1}, \qquad (3-4)$$

$$\tilde{r}_k = r_k - r_k^{\bullet} \tag{3-5}$$

$$\Delta \beta_k = \max[1.4, \Delta \beta_{k-1} + k_i T \tilde{r}_k + k_d (\tilde{r}_k - \tilde{r}_{k-1})], \qquad (3-6)$$

and
$$\beta_k = \max[1.4, \Delta \beta_k + k_p \tilde{r}_k],$$
 (3-7)

In (3-3)-(3-7), the subscript $_k$ denotes the discrete time step, q is the discretized calculated rotor speed, T is the time period of the discrete filter, ψ is the rotor azimuth position, r is the filtered rotor speed, r^* is the desired rotor speed, \tilde{r} is the error between the actual and desired rotor speed, $\Delta\beta$ is the change in pitch from one time period to the next, β is the pitch angle, and k_p , k_i , and k_d are the proportional, integral, and derivative gains, respectively. The "max" function in (3-6)-(3-7) allows the controller to run throughout all three operating regions, saturating the pitch angle to a value of 1.4° when not in Region III.

Testing the baseline controller operation involved prototyping it in Matlab/Simulink. The control scheme in Equations 3-1 through 3-7 was implemented in a Simulink model and verified for proper operation. Figure 3-1 shows the overall realization, where the CART3 model is contained in the block labeled FAST model.



Figure 3-1. Simulation model for the CART3 baseline controller

Figure 3-2 expands the torque control block torque controller, which illustrates the three different regions of operation and the corresponding commanded torque. The pitch controller, shown in Figure 3-3, uses a Matlab M file (Appendix A.1) to compute the commanded pitch given by Equations 3-3 through 3-7.



Figure 3-2. Simulink torque control block for CART3 baseline controller



Figure 3-3. Simulink pitch control block for CART3 baseline controller

Figure 3-4 shows the outputs from a simulation run using the baseline controller (Equations 3-3 through 3-7). The input (wind speed) is in the top subplot of Figure 3-4. The rotor speed (second subplot) and generator torque (third subplot) both increase with wind speed until rated speed is reached. The commanded torque follows the equations until rated speed is reached. When rated speed is reached at 350 s, the blade pitch control (last subplot) becomes active.





3.2 Results

The codes Crunch¹³ and MCrunch¹⁴ processed all data from the DLC runs. Crunch is a command line program that can read in multiple files and calculated statistical quantities such as extreme events, statistics, fatigue, rain-flow counts, and other items of interest. For this research, Crunch read in all the data from the current DLC and found extreme events. MCrunch, a Matlab interface for Crunch, is useful for visualizing results.

The first goal was to identify the extreme events within the DLC results. Crunch processed each DLC separately because the classification of a design-driving event varied from one DLC to another. Each of the tables contains information about blade moments, shaft torque, and tower moments. More specifically, each extreme-event table includes

- the extreme minimum and maximum loads for each measured parameter,
- the name of the file in which the extreme load can be found,
- the wind speed during the event,
- the time at which the event occurred, and
- the corresponding values of the other observed parameters.

Tables 3-1 through 3-3 are example extreme-event tables from DLC 1.1. Appendix C contains the remaining 30 tables. Once the extreme event tables were generated, MCrunch was used to plot the time-series information surrounding each event. These time-series plots provide additional insight regarding the extreme-event information.

Parameter	Туре	File	RootMxb1	RootMyb1	Time	WindVxi
			(kNm)	(kNm)	(s)	(m/s)
RootMxb1	Minimum	DLC1.1_0021_09.0V0_S01.out	-1.66E+02	2.32E+02	3.62E+02	1.10E+01
RootMxb1	Maximum	DLC1.1_0031_11.0V0_S01.out	2.49E+02	5.88E+02	4.54E+02	1.35E+01
RootMyb1	Minimum	DLC1.1_0036_12.0V0_S01.out	9.52E+01	2.01E+01	2.01E+02	1.01E+01
RootMyb1	Maximum	DLC1.1_0031_11.0V0_S01.out	1.63E+02	6.04E+02	2.31E+02	1.13E+01

 Table 3-1. Extreme Events for Blade 1 Root Moments: DLC 1.1

Note: Similar tables exist for blades 2 and 3. kNm = kilo-Newton-meter.

Table 3-2.	Extreme	Events f	for the	Tower	Moments:	DLC 1.1
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Parameter	Туре	File	TwHt1Mlxt	TwHt1Mlyt	TwrBsMxt	Time	WindVxi
			(kNm)	(kNm)	(kNm)	(s)	(m/s)
TwHt1MIxt	Minimum	DLC1.1_0031_11.0V0_S01.out	-1.48E+02	2.51E+03	-2.41E+02	1.45E+02	1.26E+01
TwHt1MIxt	Maximum	DLC1.1_0006_06.0V0_S01.out	3.86E+02	2.70E+03	4.67E+02	2.52E+02	1.38E+01
TwHt1Mlyt	Minimum	DLC1.1_0001_05.0V0_S01.out	2.69E+01	9.96E+02	1.86E+01	3.08E+01	1.25E+01
TwHt1Mlyt	Maximum	DLC1.1_0026_10.0V0_S01.out	1.84E+02	3.98E+03	1.92E+02	2.91E+02	1.45E+01
TwrBsMxt	Minimum	DLC1.1_0031_11.0V0_S01.out	-1.48E+02	2.51E+03	-2.41E+02	1.45E+02	1.26E+01
TwrBsMxt	Maximum	DLC1.1_0006_06.0V0_S01.out	3.84E+02	2.69E+03	4.67E+02	2.52E+02	1.38E+01

			-		
Parameter	Туре	File	LSShftTq	Time	WindVxi
			(kNm)	(S)	(m/s)
LSShftTq	Minimum	DLC1.1_0011_07.0V0_S01.out	3.56E+01	3.01E+01	1.25E+01
LSShftTq	Maximum	DLC1.1_0021_09.0V0_S01.out	1.78E+02	4.66E+02	1.44E+01

Table 3-3. Extreme Events for the Shaft Torque: DLC 1.1

In Tables 3-1 through 3-3, the blade-root moments Mxb1, Myb1, and Mzb1 refer to the internal moments about the x, y, and z axes of blade 1. Figure 3-5 illustrates this coordinate system, which is fixed in the hub and rotates with the blade. The x-axis points downwind. The y-axis is in the plane of rotation and the z-axis is pointed along the line from the hub to the tip of the blade (see reference [10] for a complete description of this coordinate system.) Mxb1 refers to the edgewise bending moment, Myb1 refers to the flapwise bending moment, and Mzb1 refers to the pitching moment.



Source: Reference [10].

Figure 3-5. Blade coordinate system for the FAST CART3 model

For the tower moments, Mxt refers to the side-to-side bending moment at the base of the tower, Mlxt refers to the side-to-side bending moment several meters above the tower base, and Mlyt (also refered to as MLyt) refers to fore-aft bending moment several meters above the tower base. Figure 3-6 illustrates this coordinate system. Table 3-3 is for the

shaft torque and contains only one parameter, LSShftTq, which refers to the torque in the low-speed shaft.



Source: Reference [10].



3.2.1 DLC 1.3 Baseline Controller Results

The first case presented here is DLC 1.3, which uses the extreme turbulence model. This DLC caused large values for the blade's out-of-plane bending moments. Figure 3-7 shows the input wind speed to the CART3 model, which varies from about 3 to 38 m/s, with standard deviations ranging from 5 to 10 m/s determined by the turbine class (Table 2-1) and a seed-dependent vertical power-law shear. This shear is the difference in windspeed between the highest point and the lowest point of the turbine blade's swept

area.





Figure 3-8 illustrates the bending moments for blade 1. The out-of-plane blade bending moment, Myb1, has the largest magnitudes during the time segments of 200–300 s and 400–500 s. These time segments coincide with large wind-speed fluctuations. The inplane bending moment is cyclic at roughly constant amplitude because of the periodic gravitational loads on the blades. Both moments contribute to the overall fatigue and ultimate loads of the wind turbine components.



Figure 3-8. Blade 1 root bending moments for DLC 1.3: baseline controller (Note: Different colors represent different seeds.)

Figure 3-9 shows the shaft torque from simulations using DLC 1.3. The shaft torque exhibits its extreme values during the time segments of 50-150 s, 200-300 s, and 400-500 s.





Figure 3-9. LSS torque for DLC 1.3: baseline controller (Note: Different colors represent different seeds.)

Figure 3-10 illustrates the tower bending moments. The Mlyt, or fore-aft bending moment, shows large bending moments during times of large turbulence fluctuations, which illustrates the first tower mode being excited because of these turbulent wind conditions.



Time Series Plots of Tower Moments

Figure 3-10. Tower bending moments for DLC 1.3: baseline controller

Table 3-4 summarizes the extreme events that were recorded for DLC 1.3. These values are used later to quantitatively assess performance improvements achieved by using the advanced controller. All the output tables in this work contain the same parameters; these are defined as follows:

Blade X Root Bending Moment = $\sqrt{\text{RootMybX}^2 + \text{RootMxbX}^2}$

where RootMybX and RootMxbX are the blade bending moments for blade X.

Tower Bending Moment = $\sqrt{\text{TwrHt1MLxt}^2 + \text{TwrHt1MLyt}^2}$

where TwrHt1MLxt and TwrHt1MLyt are the tower bending moments.

LSS Torque = the minimum and maximum low-speed shaft torque magnitudes

LSS Torque Spread = the spread between the maximum and minimum LSS torque values

Parameter	Туре	Value	
		(kNm)	
Blade 1 Root Bending Moment	Mag	1038	
Blade 2 Root Bending Moment	Mag	1067	
Blade 3 Root Bending Moment	Mag	1065	
Tower Bending Moment	Mag	4740	
LSS Torque	Min	-63.84	
LSS Torque	Max	415.90	
LSS Torque Spread (Max-Min)		479.74	
Note: INm - Irila Newton motors			

Table 3-4. Baseline Controller Results: DLC 1.3

Note: kNm = kilo-Newton-meters.

3.2.2 DLC 1.4 Baseline Controller Results

The next case is DLC 1.4; it is a discrete case characterized by the combination of an extreme coherent wind gust and a wind direction change. The turbine controller does not contain yaw control, so as the wind changes direction, the turbine experiences loading because of yaw misalignment. The wind changes from 0°, directly aligned with the turbine, to between 43° and 60° depending on the seed over a 10-s period starting at t = 40 s. The gust begins at 40 s, reaching its peak at about 45 s, and then decreases to a steady value. Figure 3-11 shows the wind speed for DLC 1.4.





Figure 3-11. Wind speed for DLC 1.4: baseline controller

Figure 3-12 illustrates the bending moments for blade 1. The out-of-plane bending moment (Myb1) oscillates with relatively small amplitude until about 44 s. After that point, the yaw misalignment becomes apparent and the oscillations become larger in amplitude and less smooth. The in-plane bending moment also exhibits an increase in oscillation amplitudes when the yaw misalignment occurs.

Time Series Plots of Blade 1 Moments



Figure 3-12. Blade 1 root bending moments for DLC 1.4: baseline controller

Figure 3-13 shows the low-speed shaft torque for DLC 1.4. Its value remains nearly constant until the wind speed begins to increase at 40 s. After that point, the low-speed shaft torque begins to rise until it reaches a peak of about 200 kNm. The decay that follows is caused by the decrease in wind speed after the peak of the gust. The yaw misalignment causes the undesirable excitation of the LSS torque at 50 s.

Time Series Plots of Shaft Torque



Figure 3-13. LSS shaft torque for DLC 1.4: baseline controller (Note: Different colors represent different seeds.)

Figure 3-14 contains the tower moments. The first 40 s show normal operation because of the constant wind speed and direction. At 40 s the fore-aft (MLyt, middle subplot) tower moment begins to increase because of the increase in wind speed. The effect of change in wind direction on the side-side (MLxt) moments appears at about 45 s, as shown in the top subplot. By 55 s the mean value of each side-side moment decreases by approximately 250 kNm because of the change in alignment of the wind direction with the wind turbine tower.





Figure 3-14. Tower bending moments for DLC 1.4: baseline controller

Table 3-5 summarizes the extreme events recorded for DLC 1.4

Parameter	Туре	Value	
		(kNm)	
Blade 1 Root Bending Moment	Mag	1005	
Blade 2 Root Bending Moment	Mag	1003	
Blade 3 Root Bending Moment	Mag	1009	
Tower Bending Moment	Mag	3062	
LSS Torque	Min	136.60	
LSS Torque	Max	272.60	
LSS Torque Spread (Max–Min)	-	136.00	

Table 3-5. H	Baseline	Controller	Results:	DLC 1	1.4
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3.2.3 DLC 2.3 Baseline Controller Results

The next set of results are from DLC 2.3, which combines a significant wind event, an EOG, and an internal electrical system fault. The timing of the two events is intended to achieve the worst possible loading on the turbine. Specifically, each wind file contains an extreme gust that begins at about 40 s, and in each simulation the generator torque fails at a seed-dependent time near 45 s. Figure 3-15 shows the input wind speed versus time,
and shows only three curves because of overlapping data. Figure 3-16 shows an example of the loss of generator torque at 45 s.



Time Series Plots of Wind Speeds





Time Series Plots of Generator Torque

Figure 3-16. Loss of generator torque for DLC 2.3: baseline controller

Figure 3-17 shows the blade bending moments. At about 45 s, the out-of-plane bending moments, Myb1, increases because of the increase in wind speed. Then the generator torque is set to zero at a time that coincides with the peak of the gust, which varies with each seed. This seed dependency is not shown in the plots for this DLC because the operating conditions that caused extreme events occurred at the same time. This loss of load causes the value of the blade out-of-plane moment to increase initially, then to decay as the turbine adjusts to operating in a powerless state. The baseline controller given by Equations 3-1 through 3-7 is not designed for a case such as loss of generator torque.



Figure 3-17. Blade 1 root bending moments for DLC 2.3: baseline controller

Figure 3-18 shows the shaft torque for DLC 2.3. The baseline controller successfully maintains a reasonable shaft torque during the wind gust at 45 s. Once the generator torque is set to zero, however, the LSS torque drops abruptly to about -180 kNm and then settles with initially high amplitude oscillations to zero. The excitation of the CART3 drive train, which has a very small amount of damping, causes these oscillations.

Time Series Plots of Shaft Torque



Figure 3-18. LSS torque for DLC 2.3: baseline controller (Note: Different colors represent different seeds.)

Figure 3-19 shows the tower moments resulting from the DLC 2.3 simulation. During the wind event between 40 and 50 s, the tower fore-aft bending moment (MLyt) increases slightly in magnitude. Also, the wind gust creates a ringing oscillation that is amplified by the loss of generator torque at t = 45 s. The tower modes are excited by the sudden loss of generator torque caused by the large resulting loads in the drive train, apparent in the low-speed shaft torque (Figure 3-18). After the loss of generator torque at about 45 s, depending on seed, the tower side-side (MLxt) bending moments mean value shifts to near zero and exhibits oscillatory behavior.





Figure 3-19. Tower bending moments for DLC 2.3: baseline controller

Table 3-6 summarizes the extreme events recorded for DLC 1.4.

Table 3-6. Baseline Controller Results: DLC 1.4					
Parameter	Туре	Value			
		(kNm)			
Blade 1 Root Bending Moment	Mag	516.60			
Blade 2 Root Bending Moment	Mag	546.00			
Blade 3 Root Bending Moment	Mag	553.10			
Tower Bending Moment	Mag	5642			
LSS Torque	Min	-208.70			
LSS Torque	Max	231.80			
LSS Torque Spread (Max-Min)	-	440.50			

3.2.4 DLC 6.3 Baseline Controller Results

The last DLC presented is 6.3a, which uses the EWM wind model. The wind turbine is parked and the extreme wind is combined with a yaw misalignment of $+30^{\circ}$. Figure 3-20 contains the time-series wind speed and Figure 3-21 shows the blade 1 root bending

moments. Note that the Myb1, the out-of-plane moments, have loads proportional to the magnitude of the wind speed curve. The wind speed tracking in Figure 3-21 illustrates that when the wind turbine is parked, the out-of-plane blade moments follow the same form as the wind speed magnitude.



Time Series Plots of Wind Speeds

Figure 3-20. Wind speed for DLC 6.3a: baseline controller



Figure 3-21. Blade 1 root bending moments for DLC 6.3a: baseline controller (Note: Different colors represent different seeds.)

Figure 3-22 shows the shaft torque output from the DLC 6.3a simulation. The low-speed shaft still experiences small amounts of torque because the turbine is parked and is experiencing external forces from the wind's interaction with the blades, but the magnitudes of the torque are much smaller than in the operation cases (e.g., Figure 3-13 and the first 15 s of Figure 3-18).

Time Series Plots of Shaft Torque



Figure 3-22. LSS torque for DLC 6.3a: baseline controller

Figure 3-23 shows the resulting tower moments. The initial tower fore-aft moment, Mlyt, has large oscillations because wind is applied to the tower at t = 0. The tower is parked and the tower is assumed to have zero loads before t = 0. In other DLC cases the turbine is assumed to be running at t = 0, so the turbine has initial operating conditions such as rotor speed and blade pitch defined. After the initial transient, the tower moment oscillations decay. The tower moments then increase again when the wind speeds are high.



Figure 3-23. Tower bending moments for DLC 6.3a: baseline controller

Table 3-7 summarizes the extreme events recorded for DLC 6.3.

	· Dasenne Control	iter Results: DEC 0.5
Parameter	Туре	Value
		(kNm)
Blade 1 Root Bending Moment	Mag	523.50
Blade 2 Root Bending Moment	Mag	524.50
Blade 3 Root Bending Moment	Mag	461.60
Tower Bending Moment	Mag	3335
LSS Torque	Min	-58.63
LSS Torque	Max	56.07
LSS Torque Spread (Max-Min)	_	114.70

Table 5-7. Dasenne Controller Results. DLC 0.5	Table 3-7.	Baseline	Controller	Results:	DLC 6.3
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4.0 Advanced Controller

An advanced controller could reduce turbine component loading, which would ideally reduce initial capital costs for new turbines under construction or increase lifetimes of existing turbines. Determining which components would most benefit from advanced control techniques required analyzing the baseline results. The obvious candidates included all 1.x and 2.x DLC cases because they all assume the turbine is in power production mode (not parked operation).

Analyzing the output plots and extreme event tables in Section 3 and Appendix C revealed that the drive train and tower showed the most need for load reduction. The tower exhibited large oscillatory loads, especially apparent in DLC 1.3 (Figure 3-10). The drive train's need of advanced control was evident from the loading on the LSS torque, which exhibited a ringing response to changes in wind speed (see Figure 3-13 for DLC 1.4). Wind turbine drive trains are a known concern in the industry, with gear box failure rates higher than predicted.

Jonkman's⁶ work confirms the selection of DLCs 1.3 and 1.4 as design-driving simulations for focusing advanced controller design. He found that DLC 1.3 drives all the extreme moments in the base of the tower and DLC 1.4 drives most of the extreme root bending moments in the blades. This section describes the advanced controller design and shows simulation results, comparing the simulation outputs to the baseline controller case. Each of the individually designed controllers follows the same structure as in Wright,¹⁵ and Wright and Fingersh.¹⁶

4.1 Controller Design

To reduce moments in the tower and the drive train, two controllers were designed independently before being combined into the master advanced controller which will be called the Drive Train/Tower (DTT) Damping Controller. The first controller, designed to damp tower moments, uses tower velocity feedback to augment the commanded pitch angle. The second controller reduces drive train torsion using full state feedback (FSFB) to augment commanded torque.

4.1.2 Active Tower Damping

An active tower-damping controller augments the PID baseline pitch controller with a feedback loop to damp the tower fore-aft motion. The new feedback loop is added onto the commanded collective pitch component of the baseline controller. The tower can be approximated by a linear modal representation. The dominant tower motion is characterized by the tower first fore-aft mode. The equation of motion is

$$M_t \Delta \ddot{x} + C_t \Delta \dot{x} + K_t \Delta x = F_t \Delta \theta , \qquad (4-1)$$

where

• Δx , $\Delta \dot{x}$, $\Delta \ddot{x}$ are the perturbed tower fore-aft deflection, velocity, and acceleration in the first bending mode

- M_t , C_t , K_t are the first bending mode modal mass, damping, and stiffness coefficients
- $\Delta \theta$ and F_t are the perturbed pitch input and input gain.

Next, the perturbed pitch input $\Delta \theta$ is set proportional to tower velocity by adding a gain term *G* to add active tower damping:

 $\Delta \theta = G \Delta \dot{x}$

Changing the value of G adjusts the amount of tower damping. Thus Equation 4-1 becomes

$$M_{t}\Delta \ddot{x} + C_{t}\Delta \dot{x} + K_{t}\Delta x = F_{t}G\Delta \dot{x}.$$
(4-2)

Taking the Laplace transform of Equation 4-2 and rearranging it gives

$$\Delta x(s)[M_t s^2 + (C_t - F_t G)s + K_t] = 0.$$
(4-3)

The characteristic equation of Equation 4-3 is

$$M_t s^2 + (C_t - F_t G)s + K_t = 0$$

which can be rewritten as

$$s^2 + 2\delta\omega s + \omega^2 = 0 \tag{4-4}$$

where $2\delta\omega = \frac{C_t - F_t G}{M_t}$ and $\omega^2 = \frac{K_t}{M_t}$. The roots of the characteristic equation (Equation 4-4) are

$$s_{1,2} = -\delta\omega \pm \omega\sqrt{\delta^2 - 1}$$

The active tower-damping controller was tested in simulation using the CART3, linearized about the following operating point: $u_0 = 18$ m/s, $\Omega_0 = 41.7$ rpm, and $\Theta_0 = 12.7^\circ$, where u_0 is the wind speed, Ω_0 is the rotor speed, and Θ_0 is the blade pitch angle. Appendix B contains the FAST input file for this linearization. (The Aerodyn input file is on page B-7; the file containing the FAST linearization parameters is on page B-8.) Only the tower fore-aft mode is switched on during the linearization. Table 4-1 summarizes the linearization results.

Table 4-1. FAST Linearization Results for the CART3 Wind Turbine

Parameter	Value	
M_{τ}	55890 kg	
C_{t}	14096 kg/s	
K_t	1682000 kg/s ²	
F_t	–587620 kg-m/s ²	
Undamped natural frequency, $\boldsymbol{\omega}$	5.48 rad/s	

The natural damping ratio, δ , is determined by setting G = 0 in

$$G = \frac{C_t - 2M_t \delta \omega}{F_t},\tag{4-5}$$

which yields $\delta = 0.022965$. In general, the value for δ can be varied to add damping. For example, setting $\delta = 1$ in a characteristic equation of the form in Equation 4-4 results in critical damping; however, doing so could result in a feedback loop with a large gain and poses the risk of causing instabilities in other tower modes such as the first side-side mode. To tune the gain *G*, multiple values of δ were tested starting near the natural damping ratio of $\delta = 0.022965$. Figure 4-1 shows these results. At t = 40 s a step change in wind speed is applied to observe the transient response. From these data the optimal value for *G* is 0.2 because of its low oscillations and fast transient response time. Values of *G* greater than 0.4 were also tested but could not be simulated because of resulting instabilities in the closed-loop CART3 turbine plus controller system.

Effects of Tower Damping Gains



Figure 4-1. Effects of tower-damping gains on the tower fore-aft bending moment

Figure 4-2 illustrates the Simulink implementation of the gain calculated in Equation 3-7. Figure 4-2 illustrates the inside of the Simulink block labeled conventional discrete PID in Figure 3-1, replacing the system shown in Figure 3-3 with the tower fore-aft velocity gain augmentation.



Figure 4-2. Tower velocity feedback gain to reduce tower loading

4.1.3 Drive Train Damping Controller

In region III, the baseline controller (Equations 3-1 through 3-7) maintains constant rated torque and uses the collective blade pitch to regulate speed. In the DTT Damping controller, this constant generator torque (Equation 3-1) is augmented by a small signal in region III to add damping to the drive train torsion mode. Because the turbine is operating in region III, the generator torque must still remain nearly constant, but small perturbations are allowed to damp the drive train torsion actively.

Designing the drive train damper controller requires finding a linearized model of the CART3 that corresponds to the control objectives. The FAST input file used in this linearization is the same as the one in Appendix B except that the tower fore-aft mode DOF is switched off and the generator DOF is switched on The CART3 is again linearized about the operating point: $u_0 = 18 \text{ m/s}$, $\Omega_0 = 41.7 \text{ rpm}$, $\Theta_0 = 12.7^\circ$. The file containing the FAST linearization parameters is the same as on page B-8 except the Trim Case is set to 2 for generator torque and the CntrlInpt is set to 3 for generator torque.

This research used FSFB to realize this drive train damper controller. The generator torque feedback law is formed based on the states shown in Table 4-2.

State	Description	Units
Δx_1	Perturbed drive train torsional deflection	kNm
Δx_2	Perturbed generator rotational speed	m/s
Δx_3	Perturbed drive train torsional velocity	m/s ²

Table 4-2. FSFB States for Drive Train Damper Controller

Matlab analyzed the resulting linearization and produced azimuth averaged state-space matrices. An eigenanalysis of the averaged A matrix AvgAMat shows the open-loop poles at $s_{1,2} = -0.012 \pm 16.62i$ and $s_3 = -0.19$. The pole pair $s_{1,2}$ corresponds to the first drive train torsion mode, and the pole at s_3 corresponds to the generator speed state. The goal of the drive train damping controller is to move the real part of the complex pole pair $s_{1,2}$ farther to the left, thus increasing damping of the first drive train torsion mode (Figure 4-3).



Figure 4-3. Pole locations of open loop turbine operation

Appendices A.2 and A.4 list the Matlab scripts run_turbine.m and LQR_design_GenTorque.m used to design this controller. The first part of the LQR_design_GenTorque.m script reads the state-space matrices produced by the FAST linearization and forms azimuth-averaged matrices. Next, the script calls Eigenanalysis.m (Appendix A.4) to form the matrices A_c , B_{c} , and C_c for the LQR routines. The overall matrix equation is given by

$$\Delta \dot{x} = A_c \Delta x + B_c \Delta u$$
$$\Delta y = C_c \Delta x$$

where

$$A_{c} = \begin{bmatrix} 0 & 0 & 1 \\ 245.30 & -4.390583e - 09 & -1.792588e - 08 \\ -276.40 & -0.216346 & -0.21635 \end{bmatrix}$$

$$B_{c} = \begin{bmatrix} 0 \\ 0.0011 \\ -0.0011 \end{bmatrix}$$

$$C_{c} = \begin{bmatrix} 0 & 412.20000000000 & 0 \end{bmatrix}$$
(4-6)

and

- Δx is the state vector
- Δu is the control input vector.

Each matrix corresponds to the states in Table 4-2.

The generator azimuth state, which is initially included in the eigenanalysis, is eliminated because the generator speed state is retained for this controller. After creating the azimuth-averaged matrices and checking for controllability, the script uses the calculated A_c and B_c matrices to perform an LQR pole placement. The LQR routine uses weights chosen by the user to calculate the corresponding pole locations and state gains. Deciding which weights to use involved first choosing values for *R* and *Q* and then simulating the CART3 model against a step wind input. The resulting LSS shaft loads were compared after each iteration until reasonable shaft loads were obtained. After this tuning was complete, the gains chosen were R = 1 and

$$Q = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 4000000 \end{bmatrix}.$$

These weights correspond to the control gain vector

$$G = \begin{bmatrix} 48.0719 & 0.33506 & -1978.006 \end{bmatrix}$$
(4-7)

The closed loop pole locations that correspond to the chosen *R* and *Q* are at $s_{1,2} = -1.12 \pm 16.62i$ and $s_3 = -0.19$. Because the real part of the drive train torsion damping before the LQR design was Re $\{s_{1,2}\} = -0.012$ and the imaginary part Im $\{s_{1,2}\} = \pm 16.62i$ is unchanged, the new complex pole location corresponds to a significant increase in damping (Figure 4-4).



Figure 4-4. Closed loop pole locations after adding active tower damping gain

The control gain vector G is then implemented in FSFB for active drive train torsion damping. Figure 4-5 shows the added FSFB block labeled drive-damper controller, and Figure 4-6 shows the internal workings of the drive-damper box, both of which are just a portion of the overall Simulink model in Figure 3-1.



Figure 4-5. Simulink drive train FSFB implementation



Figure 4-6. Drive-damper controller block structure

4.2 Implementation and Modification

After the design of both the drive train (Equation 4-7) and tower damping (Equation 4-6) portions of the DTT Damping controller, they were each tested individually to observe their effects on the CART3 load responses. Each was compared to the operation of the baseline controller (Equations 3-1 through 3-7) using the same wind input. These test runs used the same wind file, the NTM (Normal Turbulence Model). It is important to clarify that these test runs used a simple NTM wind file created specifically for the controller verification and tuning, which should not be confused with the full set of DLC load case runs performed for the baseline controller. This wind file was re-created for a shorter duration (200 s) and was used specifically to implement and verify the advanced controller components. The wind file contains mainly region III wind speeds, which was appropriate because the advanced controllers were designed for region III operation. The results in this section should not be confused with the results in the baseline results section. The quantitative comparison of the baseline and combined advanced controllers follows the discussion of implementing the advanced controller components. The loads from the two components and the combined DTT controller are described and compared to the baseline controller case.

4.2.1 Active Tower Damping Controller

The active tower damping controller was the first to be implemented and tested with the NTM wind input. Table 4-3 and Figure 4-7 show the resulting increase or decrease in turbine loading (relative to the baseline controller). Because it is not always obvious whether a positive or negative percent change is better or worse, the final column of the table gives that information. Percentages of less than 3% are not considered statistically significant and are indicated with a dash in the final column.

Parameter	Baseline (kNm)	Tower Damping	Difference (%)	Better or Worse?
		(kNm)		
Blade 1 Root Bending Moment	788.90	838.92	6.34	Worse
Blade 2 Root Bending Moment	904.10	841.17	-6.96	Better
Blade 3 Root Bending Moment	942.80	1023.6	8.57	Worse
Tower Bending Moment	3199.00	2560.16	-19.97	Better
LSS Torque (Min)	72.00	-22.56	-131.33	Worse
LSS Torque (Max)	385.80	433.07	20.70	Worse
LSS Torque Spread (Max- Min)	313.80	455.63	31.12	Worse

Table 4-3. Active Tower Damping Controller Results



Figure 4-7. Active tower damping controller verification results

The addition of the tower damping controller (Equation 4-6) is apparent because of the reduction of 20% in the tower bending moment magnitude from 3199 kNm in the baseline to 2560 kNm for the tower damping controller. The blade bending moments exhibited both increased and decreased loads, ranging from a decrease of -6.96% to an increase of 8.57%.

With the shaft torque, one metric of interest is the difference between the minimum and maximum values (the spread). The spread gives a more meaningful value than just the minimum or maximum for the amount of loading experienced. The spread in shaft torque, which had a baseline value of 313.80 kNm, increased to 455.63 kNm with the active tower damping controller. The drive train damping controller (Equation 4-7), designed to add damping to the drive train, should alleviate this somewhat but not to the extent desired for the overall advanced controller. One main goal of the overall advanced controller is to reduce turbine loading, whereas with this increase in drive train loading, the end result would be a negligible improvement in drive train loading performance. Because of this increase in loads, it was necessary to examine the cause of the drive train excitation before implementing the drive train damping controller (Equation 4-7). Some troubleshooting revealed that the drive train was excited by the tower-damping controller (Equation 4-6) because of the high frequency content of the commanded pitch signal. Thus, a second-order low pass filter was added to the commanded pitch controller. The first natural frequency of the drive train torsion was determined in a FAST linearization to be 16.62 rad/s, or 2.64 Hz. This frequency was then the basis for calculating the cutoff frequency for the low-pass filter (LPF), resulting in a filtered computed pitch angle, as shown in Figure 4-8.



Figure 4-8. Second-order LPF for commanded pitch angle

Table 4-4 and Figure 4-9 show the results from the active tower damping controller with the added low-pass filter on the pitch control signal.

Parameter	Baseline	With LPF	Difference	
	(kNm)	(kNm)	(%)	Better or Worse?
Blade 1 Root Bending Moment	788.90	757.70	-3.95	Better
Blade 2 Root Bending Moment	904.10	870.90	-3.67	Better
Blade 3 Root Bending Moment	942.80	912.90	-3.17	Better
Tower Bending Moment	3199.00	2484.02	-22.35	Better
LSS Torque (min)	72.00	75.28	4.56	Better
LSS Torque (max)	385.80	371.78	-3.56	Better
LSS Torque Spread (Max-Min)	313.80	296.50	5.8	Better

Table 4-4. Active Tower Damping Controller Results with LPF Added



Figure 4-9. Active tower damping controller with LPF verification results

As shown in Table 4-4, the spread in the shaft loading decreased from 313.80 kNm to 296.50 kNm after adding the LPF. The tower loading, which improved by 20% in the original active tower damping test, further improves to a 22.35% reduction. Adding the LPF to the tower damping controller (Equation 4-6) will enable the drive train damping controller (Equation 4-7) to more significantly improve drive train loads.

4.2.2 Drive Train Damping Controller

The next step involved implementing and testing drive train damping controller. Testing used the same wind file described in Section 4.2.1. Table 4-5 and Figure 4-10 show the resulting loads, along with the corresponding change in turbine loading.

Parameter	Baseline	Drive Train	Difference	Better or
	(kNm)	(kNm)	(%)	Worse?
Blade 1 Root Bending Moment	788.90	757.70	-3.95	Better
Blade 2 Root Bending Moment	904.10	870.90	-3.67	Better
Blade 3 Root Bending Moment	942.80	912.90	-3.17	-
Tower Bending Moment	3199.00	3182.00	-0.53	_
LSS Torque (min)	72.00	149.00	106.94	Better
LSS Torque (max)	385.80	314.00	-18.61	Better
LSS Torque Spread (Max-Min)	313.80	165.00	-47.42	Better

Table 4-5. Drive Train Damping Controller Results



Figure 4-10. Drive train damping controller verification results

The increase in minimum LSS torque, decrease in maximum LSS torque, and decrease in LSS torque spread make clear the drive train damping. The baseline value for the LSS torque spread of 313.80 kNm decreased to 165 kNm, a 47% decrease, meaning that torque excursions were less extreme and torque was less variable during operation. The blade bending moments and the tower bending moment did not exhibit any significant changes.

4.2.3 Drive Train/Tower Damping Controller

The two controllers were combined to form the drive train/tower (DTT) damping controller. This DTT damping controller was simulated using the same NTM wind file and then compared to the baseline results. Table 4-6 gives the results.

Table 1.6 Combined (DTT) Controller Desults

Table 4-0. Combined (D11) Controller Results						
Parameter	Baseline	DTT Damping	Difference	Better or		
	(kNm)	(kNm)	(%)	Worse?		
Blade 1 Root Bending Moment	788.90	793.10	0.53	_		
Blade 2 Root Bending Moment	904.10	835.70	-7.57	Better		
Blade 3 Root Bending Moment	942.80	908.90	-3.60	Better		
Tower Bending Moment	3199	2340	-26.85	Better		
LSS Torque (min)	72.00	148.00	105.56	Better		
LSS Torque (max)	385.80	322.30	-16.46	Better		
LSS Torque Spread (Max-Min)	313.80	174.30	-44.46	Better		

The advanced DTT controller performed very well for the NTM wind input file. The blade 2 and blade 3 root bending moments improved by 7.5% and 3.6%, respectively, and the blade 1 root bending moment did not have a statistically significant change. With the combined advanced controller, the shaft torque spread showed a 44.46% improvement. The tower bending moments also improved greatly. The baseline value for the tower magnitude of 3199 k·Nm decreased to 2340 kNm, a 26.85% improvement. Figure 4-11 shows the performance for the baseline controller (Equations 3-1–3-7), active tower damping controller (Equation 4-6), drive train damping controller (Equation 4-7), and DTT damping controller (Equations 4-6 and 4-7).



Figure 4-11. Comparison of DTT damping controller components to the operation of the baseline controller

4.3 DLC Results for DTT Damping Controller

All data from the advanced DLC runs were processed using the same method as the baseline controller. As in Section 3, Crunch read in all the data from the each DLC and find extreme events; it created 30 tables for the advanced (DTT) controller results. Each table contains the same output parameters as the baseline results (Table 3-1 through Table 3-3), including blade moments, shaft torque, and tower moments. MCrunch was used for visualizing results. The coordinate system for the advanced controller results is the same as that shown in Figure 3-5 and Figure 3-6. Because of space concerns, this chapter presents only the DLCs presented in Section 3. Appendix D has the complete set of results.

4.3.1 DLC 1.3 DTT Damping Controller Results

DLC 1.3 uses the ETM as described in Table 2-3. Figure 4-12 shows the input wind speed for this DLC, which varies from about 3 to 38 m/s, with a standard deviation determined by the turbine class. (Note: The wind speed plots for the DTT damping controller will not necessarily match the corresponding plots from the baseline controller. The wind speed plots are generated based on the files that caused extreme events, which vary between controllers.)



Figure 4-12. Wind speed for DLC 1.3: DTT damping controller

Figure 4-13 shows the resulting blade bending moments for the DTT damping controller from DLC 1.3. The flapwise bending moment (Myb1) achieves its largest magnitudes during the same time segments as the baseline controller because the wind has large fluctuations in each set of simulations. The DTT damping controller damps the oscillatory behavior of the flapwise motion compared to the baseline results, which can be seen by comparing the red line from the advanced results to the red line on the baseline results . The edgewise moment (Mxb1) is almost identical to the baseline results because it is predominantly driven by the periodic gravitational loads on the blades owing to the cyclic motion of the turbine.



Figure 4-13. Blade 1 root bending moments for DLC 1.3: DTT damping controller (Note: Different colors represent different seeds.)

Figure 4-14 illustrates the shaft torque from simulations using DLC 1.3. The shaft torque shows purely cyclic behavior, caused by the turbulent wind conditions and the rotational nature of the turbine.

Time Series Plots of Shaft Torque



Figure 4-14. LSS torque for DLC 1.3: DTT damping controller

Figure 4-15 contains the tower bending moments from DLC 1.3 with the DTT damping controller. All three subplots exhibit an excitation at about t = 150 s, caused by the frequency content of the wind conditions. The turbulence contains energy at frequencies sufficient to cause significant tower excitation. Both the baseline (Figure 3-9) and DTT damping controllers show this tower excitation.



Figure 4-15. Tower bending moments for DLC 1.3: DTT damping controller

Table 4-7 summarizes the extreme events, along with quantitative comparisons, for the baseline and DTT damping controllers; the table contains values specific to the operating conditions for this DLC. Table 4-7 also indicates whether the DTT damping controller results are better or worse than the baseline case. Figure 4-16 is a visual comparison of the results from the two controllers. For this DLC, using the DTT damping controller improves the tower bending, LSS torque maximum, and LSS torque spread compared to the baseline case.

Parameter	Baseline	DTT	Difference	Better or
	(kNm)	Damping (kNm)	(%)	Worse?
Blade 1 Root Bending Moment	1038	1082	4.24	_
Blade 2 Root Bending Moment	1067	1123	5.25	_
Blade 3 Root Bending Moment	1065	1121	5.26	-
Tower Bending Moment	4740	4333	-8.59	Better
LSS Torque (min)	63.84	-36.29	-43.15	Worse
LSS Torque (max)	415.90	306.50	-26.15	Better
LSS Torque Spread (Max-Min)	479.74	342.79	-28.55	Better

Table 4-7. Comparison of Results: DLC 1.3



Figure 4-16. Comparison of controllers for DLC 1.3

4.3.2 DLC 1.4 DTT Damping Controller Results

The DLC presented here is 1.4, a discrete case that combines an extreme coherent gust combined with a wind direction change. As with the baseline controller, the DTT damping controller does not contain yaw control, so the turbine will experience additional loading because of yaw misalignment. The wind changes from 0°, directly

aligned with the turbine, to between 43° and 60° depending on the simulation seed over a 10-s period starting at t = 40 s. The gust begins at 40 s, reaching its peak at about 45 s, and then decreases to a steady value. Figure 4-17 shows the wind speed for this DLC.



Time Series Plots of Wind Speeds

Figure 4-17. Wind speed for DLC 1.4: DTT damping controller

Figure 4-18 shows the blade root bending moments that caused extreme load cases. The flapwise (Myb1) bending moment maintains a fairly constant value until the gust event at approximately 43 s, when the value increased to about 480 kNm. At about t = 48 s, the wind begins to change directions and the Myb1 moment exhibits an oscillatory behavior with a peak-to-peak value of approximately 620 kNm. The baseline controller exhibited the same form, but its peak-to-peak value was somewhat worse at 700 kNm.

Time Series Plots of Blade 1 Moments



Figure 4-18. Blade 1 root bending moments for DLC 1.4: DTT damping controller

Figure 4-19 shows the LSS torque for the DTT damping controller from DLC 1.4. The gust in the wind profile caused the peak at about 45 s. At t = 48 s the wind begins to change directions and the LSS becomes oscillatory. The DTT damping controller reduces the oscillation magnitudes within 5 s compared to the baseline controller, which does not reduce oscillation magnitudes.

Time Series Plots of Shaft Torque



Figure 4-19. LSS torque for DLC 1.4: DTT damping controller

Figure 4-20 shows the tower bending moments from DLC 1.4. The first 40 s correspond to a constant wind speed with 0° yaw misalignment. At t = 40 s the fore-aft (MLyt) tower moment responds to the gust in wind speed just like the baseline controller does. At t = 48 s when the yaw misalignment begins, the DTT damping controller reduces the resulting loads compared to the baseline (Figure 3-14). The baseline results show a mean increase in tower moments, whereas the DTT damping controller shows a decrease in mean values after the gust.



Figure 4-20. Tower bending moments for DLC 1.4: DTT damping controller

Table 4-8 summarizes the extreme events and quantitative comparisons for DLC 1.4 for the baseline and DTT damping controllers. All of the observed parameters for DLC 1.4 were similar for the DTT damping and baseline controllers with two exceptions. The tower bending moment reduced by 6.79% and the LSS torque reduced by 6.69% with the DTT damping controller. Figure 4-21 is a visual comparison of the results from the two controllers.

r r r r r r r r r r r r r r r r r r r								
Parameter	Baseline	DTT Damping	Difference	Better or Worse?				
	(kNm)	(kNm)	(%)					
Blade 1 Root Bending Moment	1005	1008	0.30	_				
Blade 2 Root Bending Moment	1003	1022	1.89	_				
Blade 3 Root Bending Moment	1009	1002	-0.69	-				
Tower Bending Moment	3062	2854	-6.79	Better				
LSS Torque	136.60	139.70	2.27	_				
LSS Torque	272.60	266.60	-2.20	-				
LSS Torque Spread (Max-Min)	136.00	126.90	-6.69	Better				

Table 4-8. Comparison of Results: DLC 1.4



Figure 4-21. Comparison of controllers for DLC 1.4

4.3.3 DLC 2.3 DTT Damping Controller Results

DLC 2.3 combines two significant events, an extreme operating gust and an internal electrical system fault. The loss of generator torque simulates the fault at a time designated by each simulation seed but usually near t = 45 s. Because neither the baseline controller nor the DTT damping controller contains logic for such an event, all useful data for controller design purposes are obtained from the transient response at the time of the generator loss, after which neither controller has any effect on the turbine loading. Figure 4-22 shows the wind plots for the DTT damping controller extreme cases. The loss of generator torque is the same as in Figure 3-16 for the baseline controller and occurs at t = 45 s.

Time Series Plots of Wind Speeds



Figure 4-22. Wind speed for DLC 2.3: DTT damping controller

Figure 4-23 shows the resulting blade loads. At about 40 s the flapwise (Myb1) bending moment increases because of the wind gust until about 45 s, when the generator torque is lost. This loss of generator torque causes a short-term increase in the flapwise bending moment.



Figure 4-23. Blade 1 root bending moments for DLC 2.3: DTT damping controller (Note: Different colors represent different seeds.)

Figure 4-24 shows the resulting shaft loads from DLC 2.3. Any useful data for loads resulting from controller design for comparing the DTT damping controller's operation to that of the baseline are obtained before the loss of generator torque because neither controller has any logic for an electrical fault.



Time Series Plots of Shaft Torque

Figure 4-24. LSS torque for DLC 2.3 (Note: Different colors represent different seeds.)

Figure 4-25 contains the last set of plots for DLC 2.3. During the wind gust, the tower fore-aft (MLyt) moment increases by approximately 400 kNm, which is less than the baseline case of approximately 500 kNm (Figure 3-13).



Figure 4-25. Tower bending moments for DLC 2.3: DTT damping controller

Table 4-9 summarizes the extreme events and quantitative comparisons for the baseline and DTT damping controllers for DLC 2.3. All of the observed parameters were similar for the DTT damping and baseline controllers except for the tower bending moment, which was reduced by 9.16%. Figure 4-26 is a visual comparison of the results from the two controllers.

Tuble 19. Comparison of Results, DEC 20							
Baseline	DTT Damping	Difference (%)	Better or				
(kNm)	(KNM)		Worse?				
516.60	516.00	-0.12	_				
546.00	545.10	-0.16	_				
553.10	549.40	-0.67	_				
5642	5125	-9.16	Better				
-208.70	-200.10	-4.12	Worse				
231.80	223.40	-3.62	Better				
440.50	423.50	-3.86	Better				
	Baseline (kNm) 516.60 546.00 553.10 5642 -208.70 231.80 440.50	Baseline (kNm) DTT Damping (kNm) 516.60 516.00 546.00 545.10 553.10 549.40 5642 5125 -208.70 -200.10 231.80 223.40 440.50 423.50	Baseline (kNm) DTT Damping (kNm) Difference (%) 516.60 516.00 -0.12 546.00 545.10 -0.16 553.10 549.40 -0.67 5642 5125 -9.16 -208.70 -200.10 -4.12 231.80 223.40 -3.62 440.50 423.50 -3.86				

Table 4-9. Comparison of Results: DLC 2.3



Figure 4-26. Comparison of controllers for DLC 2.3

4.3.4 DLC 6.3 DTT Damping Results

DLC 6.3a is the last set of results included here; the remaining DLCs appear in Appendix D. DLC 6.3a uses the EWM wind model (Table 2-3). During this DLC, the wind turbine is parked and the EWM is combined with a +30° yaw misalignment. As mentioned previously, neither the baseline controller nor the DTT damping controller contains logic for parked, or electrical loss, cases. This DLC was included to verify that the operation of the baseline and DTT damping controllers was identical. Because the resulting plots are all identical to the outputs of the baseline controller (Figure 3-20 through Figure 3-22), they are not included here.

Table 4-10 summarizes the extreme events, along with quantitative comparisons, for the baseline and DTT damping controllers. All of the observed parameters for DLC 6.3 were the same for the DTT damping and baseline controllers. Figure 4-27 shows a visual comparison of the results from the two controllers, emphasizing that the two do not differ in the DLC 6.3a case.
Parameter	Baseline	DTT	Difference	Better or
	(kNm)	Damping (kNm)	(%)	Worse?
Blade 1 Root Bending Moment	523.50	523.50	0	_
Blade 2 Root Bending Moment	524.50	524.50	0	_
Blade 3 Root Bending Moment	461.60	461.60	0	_
Tower Bending Moment	3335	3335	0	_
LSS Torque (min)	-58.63	-58.63	0	_
LSS Torque (max)	56.07	56.07	0	_
LSS Torque Spread (Max-Min)	114.70	114.70	0	_

Table 4-10. Comparison of Results: DLC 6.3



Figure 4-27. Comparison of controllers for DLC 6.3

5.0 Summary and Conclusions

The research for this project constituted successfully completing a full set of DLC simulations with the CART3 wind turbine model with both baseline and advanced controllers. FAST simulated the CART3 model using the operating conditions necessary for each DLC, as prescribed by the IEC. Each simulation involved observing the same output parameters: tower bending moments, blade bending moments, and the low-speed shaft torque. This report presents a representative set of results in a time-series format and in bar graphs illustrating extreme values. Because of space considerations, the body of this report contains only results from DLC 1.3, 1.4, 2.3, and 6.3.

With the results from the full set of DLCs (i.e., including those not presented in the report body), an all-inclusive loads analysis found the design-driving events . First, the baseline results helped determine which components would benefit from advanced controls design; this required analyzing tabular output data of the resulting loads on the turbine components and observing which parts exhibited larger oscillatory behavior or large extreme loads. The selected components were the tower and the drive train. The next step involved processing the results to find all the design-driving events for the tower and drive train for each DLC. Lastly, each event was analyzed in greater depth to better understand what factors caused it.

With the important events and components determined, advanced controllers were developed and tested individually for each turbine component to mitigate loads and reduce the magnitude of the extreme events. To reduce tower loading, an active tower damping controller was designed by using tower fore-aft velocity feedback to augment the commanded pitch. To reduce drive train loads, a FSFB controller was designed that augmented the commanded torque. Once each controller was successfully designed they were combined into the DTT damping controller. Each of the individually designed controllers follows the same structure as in Wright et al.^{15,16}

Once developed, the DTT damping controller simulated the full set of DLC runs. Comparing the results from the DTT damping controller to the results from the baseline controller determined the amount of increase or decrease in turbine loading. The four DLCs in sections 3 and 4 allow for a quantitative load comparisons between the two controllers. For DLC 1.3, the LSS torque, which showed the largest improvement compared to the baseline case, had a spread reduction of 28.55% and the tower bending moment showed a magnitude reduction of 8.6%. For DLC 1.4, the shaft torque spread also exhibited the largest improvement, 7%, whereas the tower loading remained nearly identical to the baseline results. DLC 2.3 exhibited nearly identical extreme events for both the DTT damping and baseline controllers, with the exception of the tower loading, which showed a 9.16% reduction. The results for the two controllers are similar because DLC 2.3 encounters an electrical fault at t = 45 s, which drives the loads, and neither controller has logic to handle such a situation. DLC 6.3, which is a parked simulation, verifies the assumption that the resulting loads should be identical for both controllers.

The results from this research have shown the potential to reduce the capital cost or increase the lifetime of a wind turbine through advanced controller design during normal

operation for design driving events. Both the DLCs that assume normal operation, DLCs 1.3 and 1.4, showed substantial improvements, between 7% and 29%, using the advanced (DTT) controller. Now that the DTT damping controller has been designed, the next step would be to apply it to the actual wind turbine and then work on fine-tuning because the model cannot accurately portray every aspect of the physical turbine. Another step would be to design advanced controllers specific to blade load reductions as well as developing advanced controls for the other load cases such as startup, shutdown, and the various fault conditions.

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Appendix A: MATLAB Control Design Scripts

A.1 MATLAB Script for PID Control: ("PID_ctrl.m")

```
function out = PID ctrl(psi,RotSpeed Rt)
% current CART pitch controller - essentially discrete-time PI control
% with a low-pass filter to calculate speed from azimuth
global pitchinc dspeed old psi old speed old
speedset = RotSpeed Rt*pi/30; % rotor speed set point
if isempty(pitchinc)
psi old = 0;
 speed old = speedset;
 pitchinc = 0;
 dspeed old = 0;
end
pitchmin = 1.4; % lower limit on pitch [deg]
dt = 0.004; % time step at 100 Hz
GBRatio = 43.16496;
Kp = 0.5236*GBRatio;
Ki = 0.2618 \times GBRatio;
Kd = 0*GBRatio;
% \text{ Kp} = 30;
% Ki = 15;
% \text{ Kd} = 30;
%Ki = 0;
%Kd = 0;
% calculate LSS speed from psi (actually psi + epsilon) by
% numerical differentiation and filtering (K = 4, Tc = 0.25)
speed = (psi - psi old)/dt; % derivative
alpha = 1 - \exp(-4 \cdot dt);
speed = alpha*speed + (1-alpha)*speed old; % filtered
```

```
dspeed = speed - speedset;
pitchinc = pitchinc + Kd*(dspeed - dspeed old) + Ki*dt*dspeed;
%pitchinc = pitchinc + Ki*dt*dspeed;
if pitchinc < pitchmin</pre>
pitchinc = pitchmin;
end
pitchout = pitchinc + Kp*dspeed;
%pitchout = pitchinc + (Kp+Kd) *dspeed;
if pitchout < pitchmin</pre>
pitchout = pitchmin;
end
pitchout = pitchout*pi/180; % convert to rad
% above is equivalent to the following PI implementation:
% pitchinc = pitchinc + Ki*dt*dspeed;
% pitchout = pitchinc + (Kp+Kd)*dspeed;
dspeed old = dspeed;
psi old = psi;
speed old = speed;
out = [pitchout];
```

A.2 MATLAB Script for CART3 Simulations: ("run_turbine.m")

```
%% Matlab Initialization
close all
clear all
clc
tic
cd('0:\CART3_FAST_Model\')
%% Read FAST input file and set run time
input_fast = char('CART3_Matlab.fst');
input_fast_lin = char('CART3_Linear_Gentq');
% input_fast_lin = char('CART3_Linear');
Read_FAST_Input
```

```
TMin = 30; % - Simulation start time Turb: 30, Gust: 20
TMax = 450; % - Simulation End Time Turb: 600, Gust: 60
```

```
%% Define Region 2 and 2.5 Torque Control
```

```
GenSpeed_Op = 1800; % - Optimal Generator Speed (HSS)
RotSpeed_Op = 41.7; % - Optimal Rotor Speed (LSS)
Gen_Eff = 0.989898; % - Generator Efficiency
GenSpeed_Rt = GenSpeed_Op*Gen_Eff; % - Rated Generator Speed (HSS)
% (Used in pitch control block)
GBRatio = GenSpeed_Op/RotSpeed_Op; % - Gearbox ratio (-)
RotSpeed_Rt = 41.7;% GenSpeed_Rt/GBRatio; % - Rated rotor speed (LSS)
GB_Eff = 0.93; % - Gearbox efficiency
Rated Tg = 3581.0281; % - Rated Generator Torque
```

```
radius = 20; % - Blade radius (m)
rho = 0.98; % - Air density (kg/m^3)
lamda_op = 6.6; % - Optimal TSR
Cpmax = 0.4633; % - Optimal Cp
```

```
% Calulation of K in Region 2
```

K = 0.5*rho*pi*radius^5*Cpmax/lamda_op^3; VS Rgn2K = GB Eff*K*(1/(GBRatio)^3)*(pi/30)^2;

```
% Calculate slope for Region 2.5
w = 20:0.01:43;
w = w*GBRatio;
```

```
for i=1:size(w,2)
  t(1,i) = VS_Rgn2K*w(1,i).^2;
end
```

a = find(t <= Rated_Tq-600); % Find indicie for lower bound on torque
maxvals = t(a); % Extract values from torque array
maxval = max(maxvals); % Extract max value (lower bound)</pre>

```
ind = find(t == maxval); % Get index of lower torque bound
t1 = t(ind); % Extract torque value t1
w1 = w(ind); % Extract w value w1
```

%% Setup Region 3 Pitch Control & Run the Simulink Model (NOT USED)

```
% Tower dampening setup
Tower Gain=0.2; % Gain for tower dampening
```

% LPF Parameters

wc = 16.5; % was 16.5
num = [1];
den = [1/wc^2 2/wc 1];
%show_bode

```
%Drive train dampening setup
R=1;
Q=[2 0 0;
0 2 0;
0 0 4000000];
LQR_design_GenTorque % Matlab script for Shaft torque dampening
```

```
%sim CART3_Baseline_Controller.mdl
sim CART3_Advanced_Controller.mdl
```

%% Extract Data from Outlist

get_data

```
%% Plot Results
xmin = 30; % Define time plotting axis
xmax = TMax;
ind1 = find(tout == xmin); % Index for time vector corresponding to xmin
ind2 = find(tout == xmax); % Index for time vector corresponding to xmax
figure
subplot(3,1,1)
plot(tout, WindSpeed);
xlabel('Time')
ylabel('Wind Speed (m/s)')
axis([40 TMax 10 40])
subplot(3,1,2)
plot(tout, BldPitch1)
```

```
xlabel('Time');
ylabel('Blade Pitch Angle (deg)');
axis([40 TMax 12 30])
```

```
subplot(3,1,3)
plot(tout,GenTq*1000)
xlabel('Time')
ylabel('Generator Torque (N*m)')
```

A.3 MATLAB Script to Read FAST Input Parameters: ("Read_FAST_Input.m")

```
% This script reads FAST *.fst files and creates Matlab workspace variables
% required to run the FAST s-function in Simulink.
input len=size(input fast,2); % the S-function needs this parameter
fid=fopen(input fast);
if (fid == -1)
disp(['Input file: ',input fast,' could not be opened.']);
return
end
for i=1:2;
temp char=fgetl(fid); % first two lines
end
FTitle=fgetl(fid); % input file description
disp(FTitle)
for i=1:5;
temp char=fgetl(fid); % through AnalMode
end
% read simulation parameters
NumBl=fscanf(fid,'%i',[1 1]); temp char=fgetl(fid); % the S-function needs this parameter
TMax = fscanf(fid, '%g', [1 1]); temp char = fgetl (fid); % can be used in Simulation Parameters menu
DT = fscanf(fid, '%g', [1 1]); temp char = fgetl (fid); % can be used in Simulation Parameters menu
for i=1:57;
temp char = fget1 (fid); % Turbine control through feature switches
end
```

```
OoPDefl = fscanf (fid, '%g', [1 1]); temp char = fgetl (fid);
IPDefl = fscanf (fid, '%g', [1 1]); temp char = fgetl (fid);
TeetDefl = fscanf (fid, '%g', [1 1]); temp char = fgetl (fid);
Azimuth = fscanf (fid, '%g', [1 1]); temp char = fgetl (fid);
RotSpeed = fscanf (fid, '%g', [1 1]); temp char = fgetl (fid);
NacYaw = fscanf (fid, '%g', [1 1]); temp char = fgetl (fid);
TTDspFA = fscanf (fid, '%g', [1 1]); temp char = fgetl (fid);
TTDspSS = fscanf (fid, '%g', [1 1]); temp char = fgetl (fid);
% read AzimB1Up
for i=1:18;
temp char = fget1 (fid); % Turbine configuration through cone angles
end
AzimB1Up = fscanf (fid, '%g', [1 1]); temp char = fgetl (fid); % Azimuth when Blade 1 is up
for i=1:35;
temp char = fgetl (fid); % Mass and inertia to beginning of Platform Model
end
% if we have a platform model, read initial platform displacements
PtfmModel = fscanf (fid, '%g', [1 1]); temp char = fgetl (fid);
if ((PtfmModel == 1) | (PtfmModel == 2) | (PtfmModel == 3))
temp char = fgetl (fid);
i=2;n=1;
while temp char(i) ~='"'
PtfmFile(n) = temp char(i);
i=i+1;
n=n+1;
end
fid2=fopen(PtfmFile);
if (fid2 == -1)
disp(['Platform file: ',PtfmFile,' could not be opened.']);
return
end
for i=1:11;
temp char = fgetl (fid2); % first 11 lines of PtfmFile
end
PtfmSurge = fscanf (fid2, '%g', [1 1]); temp char = fgetl (fid2); % Initial platform surge
PtfmSway = fscanf (fid2, '%g', [1 1]); temp char = fgetl (fid2); % Initial platform sway
PtfmHeave = fscanf (fid2, '%g', [1 1]); temp char = fgetl (fid2); % Initial platform heave
PtfmRoll = fscanf (fid2, '%g', [1 1]); temp char = fgetl (fid2); % Initial platform roll
```

% read initial conditions

```
PtfmPitch = fscanf (fid2, '%g', [1 1]); temp char = fgetl (fid2); % Initial platform pitch
PtfmYaw = fscanf (fid2, '%g', [1 1]); temp char = fgetl (fid2); % Initial platform yaw
status = fclose(fid2);
else
temp char = fgetl(fid); % read PtfmFile line
end
for i=1:8;
temp char = fgetl (fid); % Nacelle-Yaw to beginning of Furling
end
% if furling, read initial rotor and tail furl values
Furling = fgetl (fid);
if ((Furling(1) == 't') | (Furling(1) == 'T'))
temp char = fgetl (fid);
i=2;n=1;
while temp char(i) ~='"'
FurlFile(n) = temp char(i);
i=i+1;
n=n+1;
end
fid2=fopen(FurlFile);
if (fid2 == -1)
disp(['Furling file: ',FurlFile,' could not be opened.']);
return
end
for i=1:7;
temp char = fgetl (fid2); % first 7 lines of FurlFile
end
RotFurl = fscanf (fid2, '%g', [1 1]); temp char = fgetl (fid2); % Initial rotor furl
TailFurl = fscanf (fid2, '%g', [1 1]); temp char = fgetl (fid2); % Initial tail furl
status = fclose(fid2);
else
temp char = fgetl(fid); % read FurlFile line
end
for i=1:41;
temp char = fgetl (fid); % Rotor-Teeter to beginning of OutList
end
% read output list
k=1;n=1;i=2;
```

```
temp char = fgetl (fid);
while temp char(1) ~= 'E' % the first character should always be " or blank line
while temp char(i) ~= '"'
if temp char(i) == ' '
i=i+1;
else
temp(n)=temp_char(i);
n=n+1;
i=i+1;
end
if (temp char(i) == ',')
OutList(k, 1) = cellstr(temp);
k=k+1;
n=1;
i=i+1;
clear temp;
end
end
OutList(k,1)=cellstr(temp);
k=k+1;
n=1;
i=2;
clear temp;
clear temp char;
temp char = fgetl(fid);
if (isempty(temp char))
temp char = fgetl(fid);
end
end
NumOuts = k-1; % the S-function needs this parameter
status=fclose(fid);
% Set number of DOF's
if (NumBl == 2)
NDOF = 22;
elseif (NumBl == 3 )
NDOF = 24;
else
disp ('NumBl must be 2 or 3')
end
```

```
% Set DOF indices
DOF Sg = 1; % DOF index for platform surge.
DOF Sw = 2; % DOF index for platform sway.
DOF Hv = 3; % DOF index for platform heave.
DOF R = 4; % DOF index for platform roll.
DOF P = 5; % DOF index for platform pitch.
DOF Y = 6; \% DOF index for platform yaw.
DOF TFA1 = 7; % DOF index for 1st tower fore-aft mode.
DOF TSS1 = 8; % DOF index for 1st tower side-to-side mode.
DOF TFA2 = 9; % DOF index for 2nd tower fore-aft mode.
DOF TSS2 = 10; % DOF index for 2nd tower side-to-side mode.
DOF Yaw = 11; % DOF index for nacelle-yaw.
DOF RFrl = 12; % DOF index for rotor-furl.
DOF GeAz = 13; % DOF index for the generator azimuth.
DOF DrTr = 14; % DOF index for drivetrain rotational-flexibility.
DOF TFrl = 15; % DOF index for tail-furl.
for k = 1:NumBl % Loop through all blades
DOF BF(k,1) = 16 + 3*(k-1); % 1st blade flap mode--DOFs 16, 19, and 22 for blade 1, 2, and 3, respectively
DOF BE(k,1) = 17 + 3*(k-1); % 1st blade edge mode--DOFs 17, 20, and 23 for blade 1, 2, and 3, respectively
DOF BF(k,2) = 18 + 3*(k-1); % 2nd blade flap mode--DOFs 18, 21, and 24 for blade 1, 2, and 3, respectively
end % k - All blades
DOF Teet = 22; % DOF index for rotor-teeter.
% Create initial condition arrays in rad, rad/s
q init (1:NDOF) = 0;
qdot init(1:NDOF)=0;
% Set all initial conditions except initial blade and tower displacements, which are very complicated equations.
if (NumBl == 2)
q init(DOF Teet)=TeetDefl*pi/180;
end
if ((Furling(1) == 't') | (Furling(1) == 'T'))
q init(DOF RFrl) = RotFurl*pi/180;
q init(DOF TFrl) = TailFurl*pi/180;
end
if ((PtfmModel == 1) | (PtfmModel == 2) | (PtfmModel == 3))
q init(DOF Sg ) = PtfmSurge;
q init(DOF Sw ) = PtfmSway;
q init(DOF Hv ) = PtfmHeave;
```

```
q_init(DOF_R ) = PtfmRoll*pi/180;
q_init(DOF_P ) = PtfmPitch*pi/180;
q_init(DOF_Y ) = PtfmYaw*pi/180;
end
q_init(DOF_Yaw )=NacYaw*pi/180;
Azim_Initial = rem(Azimuth - AzimBlUp + 270.0 + 360.0, 360); % Internal position of blade 1.
q_init(DOF_GeAz)=Azim_Initial*pi/180;
qdot_init(DOF_GeAz)=RotSpeed*pi/30;
Initialized = 1; % Tells S-function if this script ran prior to simulation. 0 = no.
clear temp_char fid status temp k n i
clear AzimBlUp Azim_Initial FTitle
clear PtfmModel PtfmFile PtfmSurge PtfmSway PtfmHeave PtfmRoll PtfmPitch PtfmYaw
clear Furling FurlFile RotFurl TailFurl fid2
```

clear OoPDefl IPDefl TeetDefl Azimuth RotSpeed NacYaw TTDspFA TTDspSS

A.4 MATLAB Script for Control Design in Section 4.1.3: ("LQR_design_GenTorque.m")

```
%-----%
% LQR_design.m: Control design using LQR
% Requires FAST linerization first (.lin file required)
% Uses torque control inputs
%
% Phillip J Darrow (Original code: Alan Wright)
% 04/2009
%------%
clear az_prev counter AMat BMat CMat
disp('Performing a time-invariant LQR design');
%% Initialization
%disp('Current Process: Initialization ');
%Read the FAST linearization file (*.lin) containing the SS model data
Read_linfile;
az = [0 : 2*pi/NAzimStep : 2*pi]; %Vector of azimuth angles
omega_op = Avgxop(az_statenum + NActvDOF);
```

```
% Initialize global variables for 'azimuth unwind' function
global az prev counter
az prev = 0;
counter = 0;
%% Form SS Matrices / Plant Model
disp('Current Process: Forming SS Matrices / Plant Model ')
% 3 States:
% -- Drive train torsional deflection
% -- Generator Speed
% -- Drive train torsional velocity
Amod = [0 \ 0 \ 1;
AvgAMat(3,2) AvgAMat(3,3) AvgAMat(3,4);
AvgAMat(4,2) AvgAMat(4,3) AvgAMat(4,4)];
EigValues = eig(Amod);
disp(' ');
disp(' The Eigenvalues of the A matrix are: ');
disp(EigValues)
NStates = size(Amod, 1);
Bmod = [AvgBMat(2,1);
AvgBMat(3,1);
AvgBMat(4,1)];
Cmod = [AvgCMat(1,2) AvgCMat(1,3) AvgCMat(1,4)];
A c = Amod;
B c = Bmod;
C^{-}c = Cmod;
D c = AvgDMat;
[nump, denp] = ss2tf(A_c, B_c, C_c, D_c);
%% Full State Feedback Design
disp('Current Process: Full State Feedback Design ')
% Check controllabillity
```

```
rnk = rank(ctrb(A_c,B_c), 0); % Rank with tol = 0
if rnk == size(A_c,1)
disp('Plant is controllable');
else
disp([ 'Plant is UNcontrollable, rank = ', num2str(rnk), ' < ', num2str(size(A_c,1))]);
error(' Cannot continue!');
end
% LQR design using pitch and torque
% R=1 % Uncomment for stand alone
% Q=[0.01 0 0; % operation of this script.
% 0 0.001 0; % These values currently defined
% 0 0 160000] % in run_turbine.m
[K,S,E] = lqr(A_c, B_c, Q, R);
E
Gx = K</pre>
```

A.5 MATLAB Script to Perform Eigenanalysis in Section 4.1.3: ("Eigenanalysis.m")

```
% Eigenanalysis.m
% Written by J. Jonkman, NREL
% Last update: 08/09/2006
% Compatible with FAST linear output (.lin) files generated using FAST v6.02a-jmj.
% This m-file is used to read in the data written to A FAST linear output
% (.lin) file, compute the state matrix, [A], at each of the equally-spaced
% azimuth steps and their azimuth-average, along with their eigenvalues and
% eigenvectors.
format short q;
% Input data:
% If RootName does not currently exist, prompt the user which file to read in:
if ( ~ exist('RootName') )
ClearRootName = true;
disp( ' ' );
disp( ' ENTER:' );
disp('-----');
```

```
disp( ' Name of FAST linearization output file to process' );
 disp( ' (omit the .lin extension when entering the name) ' );
 disp( '<-----' );
RootName = [ input(' < ','s') ]; % FAST (.lin) filename</pre>
else
ClearRootName = false;
end
%RootName = char('CART3 Linear');
FASTLinName = [ RootName, '.lin']; % FAST (.lin) filename
% ------ Read in the matrices from the file, FASTLinName ------
% Open the FAST linear file:
FileID = fopen( FASTLinName, 'r');
% Abort if file is not found:
if (FileID == -1)
disp( ['FAST linearization output file "', FASTLinName, '" not found. Aborting.'] );
clear ClearRootName RootName FASTLinName FileID;
return;
end
% Tell the user what is running:
disp( ' ' );
disp( ['Running Eigenanalysis.m using "', FASTLinName, '"'] );
disp( 'Please wait...' );
% Read in (and ignore) the first portion of the file:
for Row = 1:10
line = fgetl( FileID );
end
% Read in the azimuth-average rotor speed, the steady state period of solution,
% then ignore the next three lines:
line = fgetl( FileID );
RotSpeed = str2num( line(55:68) ); % in (rad/s)
line = fgetl( FileID );
if ( RotSpeed > 0 )
Period = str2num( line(55:68) ); % in (sec)
else
 clear Period;
```

```
end
line = fgetl( FileID );
line = fgetl( FileID );
line = fgetl( FileID );
% Read in the number of equally spaced azimuth steps, the model order, the
% number of active (enabled) DOFs, the number of control inputs, the
% number of wind input disturbances, and the number of output measurements,
% then ignore the next four lines:
line = fgetl( FileID );
NAzimStep = str2num( line(55:58) );
line = fgetl( FileID );
MdlOrder = str2num( line(55:58) );
line = fgetl( FileID );
NActvDOF = str2num( line(55:58) );
line = fgetl( FileID );
NInputs = str2num( line(55:58) );
line = fgetl( FileID );
NDisturbs = str2num( line(55:58) );
line = fgetl( FileID );
NumOuts = str2num( line(55:58) );
line = fgetl( FileID );
% Define the number of states:
N = 2 \times NActvDOF; % the number of states in the linearized model {x}
% Initialize the matrices before reading them in:
DescStates = cell ( NActvDOF ,1 );
Azimuth = zeros( NAzimStep,1 );
xdop = zeros(N ,NAzimStep);
xop = zeros(N ,NAzimStep);
AMat = zeros(N , N , NAzimStep);
if ( NInputs > 0 )
DescCntrlInpt = cell ( NInputs ,1 );
BMat = zeros(N ,NInputs ,NAzimStep);
else
 clear DescCntrlInpt BMat;
end
if ( NDisturbs > 0 )
```

```
DescDisturbnc = cell ( NDisturbs,1 );
BdMat = zeros(N, NDisturbs, NAzimStep);
else
 clear DescDisturbnc BdMat;
end
if (NumOuts > 0)
DescOutput = cell (NumOuts ,1 );
OutName = cell (NumOuts ,1 );
yop = zeros(NumOuts , NAzimStep);
 CMat = zeros(NumOuts , N , NAzimStep);
if ( NInputs > 0 )
 DMat = zeros(NumOuts , NInputs , NAzimStep);
 else
 clear DMat;
end
 if ( NDisturbs > 0 )
 DdMat = zeros(NumOuts , NDisturbs, NAzimStep);
 else
clear DdMat;
end
else
clear DescOutput OutName yop CMat DMat DdMat;
end
if ( MdlOrder == 2 )
 qd2op = zeros(NActvDOF, NAzimStep);
 qdop = zeros(NActvDOF ,NAzimStep);
 qop = zeros(NActvDOF, NAzimStep);
MassMat = zeros(NActvDOF, NActvDOF, NAzimStep);
 DampMat = zeros(NActvDOF, NActvDOF, NAzimStep);
 StffMat = zeros(NActvDOF, NActvDOF, NAzimStep);
if ( NInputs > 0 )
 FMat = zeros(NActvDOF,NInputs ,NAzimStep);
 else
 clear FMat;
end
 if ( NDisturbs > 0 )
 FdMat = zeros(NActvDOF, NDisturbs, NAzimStep);
 else
 clear FdMat;
 end
 if (NumOuts > 0)
VelCMat = zeros(NumOuts ,NActvDOF ,NAzimStep);
```

```
DspCMat = zeros(NumOuts ,NActvDOF ,NAzimStep);
 else
clear VelCMat DspCMat;
end
else
clear qd2op qdop qop MassMat DampMat StffMat FMat FdMat VelCMat DspCMat;
end
% Read in the description of the model states, control inputs, input wind
% disturbances, and output measurements:
if ( MdlOrder == 1 )
for Row = 1:NActvDOF
DescStates {Row} = strtrim( fgetl( FileID ) );
end
line = fgetl( FileID );
else % ( MdlOrder == 2 )
for Row = 1:NActvDOF
DescStates {Row} = strtrim( fgetl( FileID ) );
end
end
line = fgetl( FileID );
if ( NInputs > 0 )
for Row = 1:NInputs
DescCntrlInpt{Row} = strtrim( fgetl( FileID ) );
end
else
line = fgetl( FileID );
end
line = fgetl( FileID );
if ( NDisturbs > 0 )
for Row = 1:NDisturbs
DescDisturbnc{Row} = strtrim( fgetl( FileID ) );
end
else
line = fgetl( FileID );
end
```

```
line = fgetl( FileID );
if ( NumOuts > 0 )
for Row = 1:NumOuts
DescOutput {Row} = strtrim( fgetl( FileID ) );
EqlCol = min(strfind(DescOutput{Row}, '=')) + 1; % find the index following the index of the first instance of string
1 = 1
OutName {Row} = strtok(DescOutput{Row})(EqlCol:length(DescOutput{Row})));
end
else
line = fgetl( FileID );
end
line = fgetl( FileID );
% Loop through all azimuth steps:
for L = 1:NAzimStep
% Read in the azimuth step and reference azimuth angle from the azimuth title,
% then ignore the two column headers:
line = fgetl( FileID );
Azimuth(L) = str2num(line(21:26)); % in (deg)
AzimB1Up = str2num( line(60:65) ); % in (deg)
line = fgetl( FileID );
line = fgetl( FileID );
% Read in the vectors and matrices:
if (MdlOrder == 1)
for Row = 1:N
line = fgetl( FileID );
xdop(Row,L) = str2num(line(1:10));
 xop (Row, L) = str2num( line(14:23) );
for Col = 1:N
 AMat (Row,Col,L) = str2num( line(( 27 + 11*( Col - 1 ) ):( 36 + 11*( Col - 1 ) )) );
 end
```

```
for Col = 1:NInputs
 BMat (Row,Col,L) = str2num( line(( 27 + 2 + 11*( N + Col - 1 ) ):( 36 + 2 + 11*( N + Col - 1 ) )) );
end
if ( NInputs > 0 ) % control inputs exist
for Col = 1:NDisturbs
BdMat (Row, Col, L) = str2num( line(( 27 + 4 + 11*( NInputs + N + Col - 1 ) ):( 36 + 4 + 11*( NInputs + N + Col - 1 ) ))
);
end
else % no control inputs selected
for Col = 1:NDisturbs
 BdMat (Row, Col,L) = str2num( line(( 27 + 2 + 11*( N + Col - 1 ) ):( 36 + 2 + 11*( N + Col - 1 ) )) );
 end
 end
 end
if (NumOuts > 0)
line = fgetl( FileID ); % ignore the header
line = fgetl( FileID ); % for the output
line = fgetl( FileID ); % matrices
for Row = 1:NumOuts
line = fgetl( FileID );
yop (Row, L) = str2num(line(1:10));
for Col = 1:N
 CMat (Row, Col, L) = str2num( line(( 27 + 11*( Col - 1 ) ):( 36 + 11*( Col - 1 ) )) );
 end
for Col = 1:NInputs
 DMat (Row,Col,L) = str2num( line(( 27 + 2 + 11*( N + Col - 1 ) ):( 36 + 2 + 11*( N + Col - 1 ) )) );
end
if ( NInputs > 0 ) % control inputs exist
for Col = 1:NDisturbs
 DdMat(Row,Col,L) = str2num( line(( 27 + 4 + 11*( NInputs + N + Col - 1 ) ):( 36 + 4 + 11*( NInputs + N + Col - 1 ) ))
);
end
else % no control inputs selected
for Col = 1:NDisturbs
 DdMat(Row,Col,L) = str2num( line(( 27 + 2 + 11*( N + Col - 1 ) ):( 36 + 2 + 11*( N + Col - 1 ) )) );
 end
 end
 end
```

end

```
else % ( MdlOrder == 2 )
for Row = 1:NActvDOF
line = fgetl( FileID );
qd2op(Row,L) = str2num(line(1:10));
qdop (Row, L) = str2num(line(14:23));
qop (Row, L) = str2num(line(27:36));
for Col = 1:NActvDOF
MassMat (Row,Col,L) = str2num( line(( 40 + 11*( Col - 1 ) ):( 49 + 11*( Col - 1 ) )) );
DampMat (Row, Col, L) = str2num( line(( 40 + 2 + 11*( NActvDOF + Col - 1 ) ):( 49 + 2 + 11*( NActvDOF + Col - 1 ) )) );
StffMat (Row, Col, L) = str2num( line(( 40 + 4 + 11*( 2*NActvDOF + Col - 1 ) ):( 49 + 4 + 11*( 2*NActvDOF + Col - 1 ) ))
);
end
for Col = 1:NInputs
FMat (Row, Col, L) = str2num( line(( 40 + 6 + 11*( 3*NActvDOF + Col - 1 ) ):( 49 + 6 + 11*( 3*NActvDOF + Col - 1 ) )) );
end
if ( NInputs > 0 ) % control inputs exist
for Col = 1:NDisturbs
FdMat (Row, Col, L) = str2num( line(( 40 + 8 + 11*( NInputs + 3*NActvDOF + Col - 1 ) ):( 49 + 8 + 11*( NInputs +
3*NActvDOF + Col - 1 ) )) );
end
else % no control inputs selected
for Col = 1:NDisturbs
FdMat (Row, Col, L) = str2num( line(( 40 + 6 + 11*( 3*NActvDOF + Col - 1 ) ):( 49 + 6 + 11*( 3*NActvDOF + Col - 1 ) ))
);
end
end
end
if (NumOuts > 0)
line = fgetl( FileID ); % ignore the header
line = fgetl( FileID ); % for the output
line = fgetl( FileID ); % matrices
for Row = 1:NumOuts
line = fgetl( FileID );
yop (Row,L) = str2num( line( 1:10) );
```

```
for Col = 1:NActvDOF
VelCMat (Row,Col,L) = str2num( line(( 40 + 2 + 11*( NActvDOF + Col - 1 ) ):( 49 + 2 + 11*( NActvDOF + Col - 1 ) )) );
DspCMat (Row, Col,L) = str2num( line(( 40 + 4 + 11*( 2*NActvDOF + Col - 1 ) ):( 49 + 4 + 11*( 2*NActvDOF + Col - 1 ) ))
);
end
for Col = 1:NInputs
DMat (Row, Col, L) = str2num( line(( 40 + 6 + 11*( 3*NActvDOF + Col - 1 ) ):( 49 + 6 + 11*( 3*NActvDOF + Col - 1 ) )) );
end
if ( NInputs > 0 ) % control inputs exist
for Col = 1:NDisturbs
DdMat(Row,Col,L) = str2num( line(( 40 + 8 + 11*( NInputs + 3*NActvDOF + Col - 1 ) ):( 49 + 8 + 11*( NInputs +
3*NActvDOF + Col - 1 ) )) );
end
else % no control inputs selected
for Col = 1:NDisturbs
DdMat(Row,Col,L) = str2num( line(( 40 + 6 + 11*( 3*NActvDOF + Col - 1 ) ):( 49 + 6 + 11*( 3*NActvDOF + Col - 1 ) )) );
end
end
end
end
end
% Ignore the blank lines:
line = fgetl( FileID );
line = fgetl( FileID );
end
% Close the FAST linear file:
fclose( FileID );
% ----- Assemble a 1st order model from the 2nd order model ------
% ------ Azimuth average the matrices ------
if ( MdlOrder == 2 )
 Form the [A], [B], and [Bd] matrices (so that {xdot} = [A]{x} + [B]{u} +
% [Bd]{ud}) at each azimuth step using the 2nd order state matrices:
% Also, form the 1st order [C] matrix using [VelC] and [DspC]:
```

```
for L = 1:NAzimStep
xdop ( 1:N , L ) = [ qdop( 1:NActvDOF, L ); qd2op( 1:NActvDOF, L ) ];
xop ( 1:N , L ) = [ qop( 1:NActvDOF, L ); qdop( 1:NActvDOF, L ) ];
AMat ( 1:NActvDOF , ( NActvDOF + 1 ):N, L ) = eye(NActvDOF);
AMat ( ( NActvDOF + 1 ):N, 1:NActvDOF , L ) = -inv(MassMat(:,:,L))*StffMat(:,:,L);
AMat ( ( NActvDOF + 1 ):N, ( NActvDOF + 1 ):N, L ) = -inv(MassMat(:,:,L))*DampMat(:,:,L);
if ( NInputs > 0 )
BMat ( ( NActvDOF + 1 ):N, 1:NInputs , L ) = inv(MassMat(:,:,L))*FMat (:,:,L);
end
if ( NDisturbs > 0 )
BdMat( ( NActvDOF + 1 ):N, 1:NDisturbs , L ) = inv(MassMat(:,:,L))*FdMat (:,:,L);
end
if (NumOuts > 0)
CMat ( 1:NumOuts , 1:N , L ) = [ DspCMat(1:NumOuts,1:NActvDOF,L), VelCMat(1:NumOuts,1:NActvDOF,L) ];
end
end
% Find the azimuth-averaged linearized 2nd order state matrices:
Avgqd2op = zeros(NActvDOF, 1); %
Avgqdop = zeros(NActvDOF, 1); %
Avggop = zeros(NActvDOF, 1); %
AvgMassMat = zeros(NActvDOF, NActvDOF); %
AvgDampMat = zeros (NActvDOF, NActvDOF ); %
AvgStffMat = zeros(NActvDOF, NActvDOF); % first initialize to zero
if ( NInputs > 0 )
AvgFMat = zeros(NActvDOF,NInputs); %
else
clear AvgFMat;
end
if ( NDisturbs > 0 )
AvgFdMat = zeros(NActvDOF, NDisturbs); %
else
clear AvgFdMat;
end
if (NumOuts > 0)
AvgVelCMat = zeros(NumOuts ,NActvDOF ); %
AvgDspCMat = zeros(NumOuts ,NActvDOF ); %
else
clear AvgVelCMat AvgDspCMat;
end
for L = 1:NAzimStep
Avgqd2op (: ) = Avgqd2op (: ) + qd2op (: ,L)/NAzimStep;
```

```
Avgqdop (: ) = Avgqdop (: ) + qdop (: ,L)/NAzimStep;
Avgqop (: ) = Avgqop (: ) + qop (: ,L)/NAzimStep;
AvgMassMat (:,:) = AvgMassMat(:,:) + MassMat(:,:,L)/NAzimStep;
AvgDampMat (:,:) = AvgDampMat(:,:) + DampMat(:,:,L)/NAzimStep;
AvgStffMat (:,:) = AvgStffMat(:,:) + StffMat(:,:,L)/NAzimStep;
if ( NInputs > 0 )
AvgFMat (:,:) = AvgFMat (:,:) + FMat (:,:,L)/NAzimStep;
end
if ( NDisturbs > 0 )
AvgFdMat (:,:) = AvgFdMat (:,:) + FdMat (:,:,L)/NAzimStep;
end
if ( NumOuts > 0 )
AvgVelCMat(:,:) = AvgVelCMat(:,:) + VelCMat(:,:,L)/NAzimStep;
AvgDspCMat(:,:) = AvgDspCMat(:,:) + DspCMat(:,:,L)/NAzimStep;
end
end
else
clear Avgqd2op Avgqdop Avgqop Avgqos AvgDassMat AvgDampMat AvgStffMat AvgFMat AvgFdMat AvgVelCMat AvgDspCMat;
end
% Find the azimuth-averaged linearized 1st order state matrices:
Avgxdop = zeros(N,1); %
Avgxop = zeros(N,1); %
AvgAMat = zeros(N , N ); %
if ( NInputs > 0 )
AvgBMat = zeros(N, NInputs); % first initialize to zero
else
clear AvgBMat;
end
if ( NDisturbs > 0 )
AvgBdMat = zeros(N ,NDisturbs); %
else
clear AvgBdMat;
end
if (NumOuts > 0)
Avgyop = zeros (NumOuts , 1 ); %
AvgCMat = zeros(NumOuts , N ); %
if ( NInputs > 0 )
AvgDMat = zeros(NumOuts , NInputs ); %
else
```

clear AvgDMat;

```
if ( NDisturbs > 0 )
AvgDdMat = zeros(NumOuts , NDisturbs ); %
else
clear AvgDdMat;
end
else
clear Avgyop AvgCMat AvgDMat AvgDdMat;
end
for L = 1:NAzimStep
Avgxdop (: ) = Avgxdop (: ) + xdop (: ,L)/NAzimStep;
Avgxop (: ) = Avgxop (: ) + xop (: ,L)/NAzimStep;
AvgAMat (:,:) = AvgAMat (:,:) + AMat (:,:,L)/NAzimStep;
if (NInputs > 0)
AvgBMat (:,:) = AvgBMat (:,:) + BMat (:,:,L)/NAzimStep;
end
if ( NDisturbs > 0 )
AvgBdMat (:,:) = AvgBdMat(:,:) + BdMat(:,:,L)/NAzimStep;
end
if ( NumOuts > 0 )
Avgyop (: ) = Avgyop (: ) + yop (: ,L)/NAzimStep;
AvgCMat (:,:) = AvgCMat (:,:) + CMat (:,:,L)/NAzimStep;
if ( NInputs > 0 )
AvgDMat (:,:) = AvgDMat (:,:) + DMat (:,:,L)/NAzimStep;
end
if ( NDisturbs > 0 )
AvgDdMat(:,:) = AvgDdMat(:,:) + DdMat(:,:,L)/NAzimStep;
end
end
end
% ------ Find multi-blade coordinate (MBC) transformation indices ----
% Find the number of, and indices for, state triplets in the rotating
% frame:
NRotTripletStates = 0; % first initialize to zero
if ( exist('RotTripletIndicesStates') )
clear RotTripletIndicesStates; % start from scratch if necessary
end
for I = 1:NActvDOF % loop through all active (enabled) DOFs
BldCol = strfind(DescStates{I}, 'blade'); % find the starting index of the string 'blade'
```

end

```
if ( ~isempty(BldCol) ) % true if the DescStates{I} contains the string 'blade'
EqlCol = min(strfind(DescStates{I},'=')) + 1; % find the index following the index of the first instance of string '='
[K, OK] = str2num(DescStates{I}(BldCol+6)); % save the blade number for the initial blade
if (OK && isreal(K)) % true if the 2nd character after the string 'blade' is a real number (i.e., a blade number)
Tmp = zeros(1,3); % first initialize to zero
Tmp( 1,K) = I; % save the index for the initial blade
for J = (I+1):NActvDOF % loop through all remaining active (enabled) DOFs
if ( ( length(DescStates{J}) >= BldCol ) && ( strcmpi(DescStates{J}(EqlCol:BldCol),DescStates{I}(EqlCol:BldCol)) ) %
true if we have the same state from a different blade
K = str2num(DescStates{J}(BldCol+6)); % save the blade numbers for the remaining blades
Tmp(1,K) = J; % save the indices for the remaining blades
end
end % J - all remaining active (enabled) DOFs
if (all(Tmp)) % true if all the elements of Tmp are nonzero; thus, we found a triplet of rotating indices
NRotTripletStates = NRotTripletStates + 1; % this is the number of state triplets in the rotating frame
RotTripletIndicesStates(NRotTripletStates,:) = Tmp; % these are the indices for state triplets in the rotating frame
end
end
end
end % I - all active (enabled) DOFs
% Find the number of, and indices for, control input triplets in the
% rotating frame:
NRotTripletCntrlInpt = 0; % first initialize to zero
if ( exist('RotTripletIndicesCntrlInpt') )
clear RotTripletIndicesCntrlInpt; % start from scratch if necessary
end
for I = 1:NInputs % loop through all control inputs
BldCol = strfind(DescCntrlInpt{I},'blade'); % find the starting index of the string 'blade'
if ( ~isempty(BldCol) ) % true if the DescCntrlInpt{I} contains the string 'blade'
EqlCol = min(strfind(DescCntrlInpt{I},'=')) + 1; % find the index following the index of the first instance of string
1 = 1
[K, OK] = str2num(DescCntrlInpt{I}(BldCol+6)); % save the blade number for the initial blade
if (OK && isreal(K)) % true if the 2nd character after the string 'blade' is a real number (i.e., a blade number)
Tmp = zeros(1,3); % first initialize to zero
Tmp( 1,K) = I; % save the index for the initial blade
for J = (I+1):NInputs % loop through all remaining control inputs
if ( ( length(DescCntrlInpt{J}) >= BldCol ) && (
strcmpi(DescCntrlInpt{J}(EqlCol:BldCol),DescCntrlInpt{I}(EqlCol:BldCol)) ) % true if we have the same control input
from a different blade
K = str2num(DescCntrlInpt{J}(BldCol+6)); % save the blade numbers for the remaining blades
Tmp(1,K) = J; % save the indices for the remaining blades
```

```
end
end % J - all remaining active control inputs
if (all(Tmp)) % true if all the elements of Tmp are nonzero; thus, we found a triplet of rotating indices
NRotTripletCntrlInpt = NRotTripletCntrlInpt + 1; % this is the number of control input triplets in the rotating frame
RotTripletIndicesCntrlInpt(NRotTripletCntrlInpt,:) = Tmp; % these are the indices for control input triplets in the
rotating frame
end
end
end
end % I - all control inputs
% Find the number of, and indices for, output measurement triplets in the
% rotating frame:
NRotTripletOutput = 0; % first initialize to zero
if ( exist('RotTripletIndicesOutput') )
clear RotTripletIndicesOutput; % start from scratch if necessary
end
for I = 1:NumOuts % loop through all output measurements
[K, OK] = str2num(OutName{I}(length(OutName{I}))); % save the blade number for the initial blade
if ( OK && isreal(K) ) % true if the last character of string OutName{I}' is a real number (i.e., a blade number)
Tmp = zeros(1,3); % first initialize to zero
Tmp(1,K) = I; \% save the index for the initial blade
for J = (I+1):NumOuts % loop through all remaining output measurements
if ( ( length(OutName{J}) == length(OutName{I}) ) && ( strcmpi(OutName{J}(1:length(OutName{J})))
1),OutName{I}(1:length(OutName{I})-1)) ) ) % true if we have the same output measurement from a different blade
K = str2num(OutName{J}(length(OutName{J}))); % save the blade numbers for the remaining blades
Tmp(1,K) = J; % save the indices for the remaining blades
end
end % J - all remaining active output measurements
if (all(Tmp)) % true if all the elements of Tmp are nonzero; thus, we found a triplet of rotating indices
NRotTripletOutput = NRotTripletOutput + 1; % this is the number of output measurement triplets in the rotating frame
RotTripletIndicesOutput (NRotTripletOutput,:) = Tmp; % these are the indices for output measurement triplets in the
rotating frame
end
end
end % I - all output measurements
% ------ Perfrom an eigenanalysis -----
% Find the eigenvalues and eigenvectors at each azimuth step:
```

```
Eigenvectors = zeros(N, N, NAzimStep);
```

```
Eigenvalues = zeros(N,N,NAzimStep);
for L = 1:NAzimStep
[Eigenvectors(1:N,1:N,L), Eigenvalues(1:N,1:N,L)] = eig(AMat(1:N,1:N,L));
%JASON: EigenvaluesHz (1:N,1 ,L) = diag( Eigenvalues(1:N,1:N,L)/(2*pi) ); % frequencies in Hz (instead of rad/sec) and
in a column vector
end
%JASON:
%JASON:% Find the eigenvalues and eigenvectors at each azimuth step (w/o damping):
%JASON:for L = 1:NAzimStep
%JASON: AMatNoDamp(1:N,1:N,L) = AMat(1:N,1:N,L);
%JASON: AMatNoDamp( ( NActvDOF + 1 ):N, ( NActvDOF + 1 ):N, L ) = zeros(NActvDOF, NActvDOF);
%JASON:
%JASON: EigenvectorsNoDamp (1:N,1:N,L) = zeros(N,N);
%JASON: EigenvaluesNoDamp (1:N,1:N,L) = zeros(N,N);
%JASON: [ EigenvectorsNoDamp(1:N,1:N,L), EigenvaluesNoDamp(1:N,1:N,L) ] = eig( AMatNoDamp(1:N,1:N,L) );
%JASON: EigenvaluesHzNoDamp (1:N,1, L) = diag( EigenvaluesNoDamp(1:N,1:N,L)/(2*pi) ); % frequencies in Hz (instead of
rad/sec) and in a column vector
%JASON end
% Find the azimuth-averaged eigenvalues and eigenvectors:
[ AvgEigenvectors, AvgEigenvalues ] = eig( AvgAMat );
%JASON:AvgEigenvaluesHz (1:N,1 ) = diag( AvgEigenvalues(1:N,1:N)/(2*pi) ); % frequencies in Hz (instead of rad/sec) and
in a column vector
%JASON:
%JASON:% Find the azimuth-averaged eigenvalues and eigenvectors (w/o damping):
%JASON:AvgAMatNoDamp(1:N,1:N) = AvgAMat(1:N,1:N);
%JASON:AvgAMatNoDamp( ( NActvDOF + 1 ):N, ( NActvDOF + 1 ):N ) = zeros(NActvDOF,NActvDOF);
%JASON:
%JASON:AvgEigenvectorsNoDamp (1:N,1:N) = zeros(N,N);
%JASON:AvgEigenvaluesNoDamp (1:N,1:N) = zeros(N,N);
%JASON: [ AvgEigenvectorsNoDamp(1:N,1:N), AvgEigenvaluesNoDamp(1:N,1:N) ] = eig( AvgAMatNoDamp(1:N,1:N) );
%JASON:AvgEigenvaluesHzNoDamp (1:N,1 ) = diag( AvgEigenvaluesNoDamp(1:N,1:N)/(2*pi) ); % frequencies in Hz (instead of
rad/sec) and in a column vector
% ------ Convert to engineering units ------
% Find the natural frequencies, damped frequencies, and damping ratios for
% the azimuth-averaged state matrix:
AvgDampedFrequency = zeros(NActvDOF, 1); %
AvgDampedFrequencyHz = zeros(NActvDOF, 1); %
AvgNaturalFrequency = zeros(NActvDOF, 1); %
```

```
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```

```
AvgNaturalFrequencyHz = zeros(NActvDOF, 1); % first initialize to zero
AvgDampingRatio = zeros(NActvDOF, 1); %
AvgModeShapeMagnitude = zeros(NActvDOF,NActvDOF); %
AvgModeShapePhaseDeg = zeros(NActvDOF, NActvDOF); %
for I = 1:NActvDOF
Real1 = real(AvgEigenvalues(2*I-1,2*I-1));
Real2 = real(AvgEigenvalues(2*I,2*I));
Imag1 = imag(AvgEigenvalues(2*I-1,2*I-1));
Imag2 = imag(AvgEigenvalues(2*I,2*I));
AvgDampedFrequency (I) = Imag1;
AvgDampedFrequencyHz (I) = AvgDampedFrequency (I)/(2*pi); % frequencies in Hz (instead of rad/sec)
AvgNaturalFrequency (I) = sgrt( Real1*Real2 - Imag1*Imag2 );
AvgNaturalFrequencyHz(I) = AvgNaturalFrequency(I)/(2*pi); % frequencies in Hz (instead of rad/sec)
if ( AvgNaturalFrequency(I) ~= 0 )
AvgDampingRatio (I) = -( Real1 + Real2 )/( 2*AvgNaturalFrequency(I) );
end
[ Tmp, L ] = max(abs(AvgEigenvectors(:,2*I-1)));
if ( L > NActvDOF )
AvgModeShapeMagnitude(:,I) = abs (AvgEigenvectors(NActvDOF+1:1:N, 2*I-1));
AvgModeShapePhaseDeg (:,I) = angle(AvgEigenvectors(NActvDOF+1:1:N, 2*I-1))*180/pi;
else
AvgModeShapeMagnitude(:,I) = abs (AvgEigenvectors( 1:1:NActvDOF,2*I-1));
AvgModeShapePhaseDeg (:,I) = angle(AvgEigenvectors( 1:1:NActvDOF, 2*I-1))*180/pi;
end
end
% ------ Clear some unneeded variables -----
% Clear some unneeded variables:
if ( ClearRootName )
clear RootName;
end
clear ClearRootName FASTLinName FileID line Row Col BldCol EqlCol I J K L Tmp OK OutName Real1 Real2 Imaq1 Imaq2 ans;
% ------ We're finished -----
```

```
% Tell the user that we are finished:
disp('');
```

disp('Eigenanalysis.m completed '); disp('Type "who" to list available variables');

Appendix B. FAST Simulation Files for the CART3

B.1 FAST Input File for MATLAB Simulations ("CART3_Matlab.fst")

------ FAST INPUT FILE -----FAST Model: CART 3-blades, Operating Point #1, with Region 2.5 Compatible with FAST v6.02c. ----- SIMULATION CONTROL ------False Echo - Echo input data to "echo.out" (flag) 1 ADAMSPrep - ADAMS preprocessor mode {1: Run FAST, 2: use FAST as a preprocessor to create an ADAMS model, 3: do both} (switch) 1 AnalMode - Analysis mode {1: Run a time-marching simulation, 2: create a periodic linearized model} (switch) 3 NumBl - Number of blades (-) 9999 TMax - Total run time (s) NOTE: Set to 9999 for Matlab, defined in runturbine.m DT - Integration time step (s) 0.004 ----- TURBINE CONTROL ------0 YCMode - Yaw control mode {0: none, 1: user-defined from routine UserYawCont, 2: user-defined from Simulink} (switch) 9999.9 TYCOn - Time to enable active yaw control (s) [unused when YCMode=0] 2 PCMode - Pitch control mode {0: none, 1: user-defined from routine PitchCntrl, 2: user-defined from Simulink} (switch) 0. TPCOn - Time to enable active pitch control (s) [unused when PCMode=0] 3 VSContrl - Variable-speed control mode {0: none, 1: simple VS, 2: user-defined from routine UserVSCont, 3: user-defined from Simulink} (switch) 1781.9791 VS RtGnSp - Rated generator speed for simple variable-speed generator control (HSS side) (rpm) [used only when VSContrl=1] 3581.0281 VS RtTq - Rated generator torque/constant generator torque in Region 3 for simple variable-speed generator control (HSS side) (Nm) [used only when VSContrl=1] 0.000981 VS Rgn2K - Generator torque constant in Region 2 for simple variable-speed generator control (HSS side) (N-m/rpm^2) [used only when VSContrl=1] 5.000000000 VS_SIPc - Rated generator slip percentage in Region 2 1/2 for simple variable-speed generator control (%) [used only when VSContrl=1] 1 GenModel - Generator model {1: simple, 2: Thevenin, 3: user-defined from routine UserGen} (switch) [used only when VSContrl=0] True GenTiStr - Method to start the generator {T: timed using TimGenOn, F: generator speed using SpdGenOn} (flag) True GenTiStp - Method to stop the generator $\{T: timed using TimGenOf, F: when generator power = 0\}$ (flag) 0.0 SpdGenOn - Generator speed to turn on the generator for a startup (HSS speed) (rpm) [used only when GenTiStr=False] 0.0 TimGenOn - Time to turn on the generator for a startup (s) [used only when GenTiStr=True] 9999.9 TimGenOf - Time to turn off the generator (s) [used only when GenTiStp=True] 1 HSSBrMode - HSS brake model {1: simple, 2: user-defined from routine UserHSSBr} (switch) 9999.9 THSSBrDp - Time to initiate deployment of the HSS brake (s) 9999.9 TiDynBrk - Time to initiate deployment of the dynamic generator brake [CURRENTLY IGNORED] (s) 9999.9 TTpBrDp1 - Time to initiate deployment of tip brake 1 (s) 9999.9 TTpBrDp2 - Time to initiate deployment of tip brake 2 (s) 9999.9 TTpBrDp3 - Time to initiate deployment of tip brake 3 (s) [unused for 2 blades] 9999.9 TBDepISp1 - Deployment-initiation speed for the tip brake on blade 1 (rpm) 9999.9 TBDepISp2 - Deployment-initiation speed for the tip brake on blade 2 (rpm) 9999.9 TBDepISp3 - Deployment-initiation speed for the tip brake on blade 3 (rpm) [unused for 2 blades] 9999.9 TYawManS - Time to start override yaw maneuver and end standard yaw control (s) 9999.9 TYawManE - Yaw rate (in absolute value) at which override yaw maneuver heads toward final yaw angle (deg/s) 0.0 NacYawF - Final yaw angle for yaw maneuvers (degrees) 9999.9 TPitManS1 - Time to start override pitch maneuver for blade 1 and end standard pitch control (s) 9999.9 TPitManS2 - Time to start override pitch maneuver for blade 2 and end standard pitch control (s) 9999.9 TPitManS3 - Time to start override pitch maneuver for blade 3 and end standard pitch control (s) [unused for 2 blades] 9999.9 TPitManE1 - Time at which override pitch maneuver for blade 1 reaches final pitch (s) 9999.9 TPitManE2 - Time at which override pitch maneuver for blade 2 reaches final pitch (s) 9999.9 TPitManE3 - Time at which override pitch maneuver for blade 3 reaches final pitch (s) [unused for 2 blades] 12.7 BlPitch1 - Blade 1 initial pitch (degrees) 12.7 BlPitch2 - Blade 2 initial pitch (degrees) 12.7 BlPitch3 - Blade 3 initial pitch (degrees) [unused for 2 blades] 90.0 BlPitchF1 - Blade 1 final pitch for pitch maneuvers (degrees) 90.0 BlPitchF2 - Blade 2 final pitch for pitch maneuvers (degrees) 90.0 BlPitchF3 - Blade 3 final pitch for pitch maneuvers (degrees) [unused for 2 blades] ----- ENVIRONMENTAL CONDITIONS -----9.80665 Gravity - Gravitational acceleration (m/s^2) ----- FEATURE FLAGS True FlapDOF1 - First flapwise blade mode DOF (flag) True FlapDOF2 - Second flapwise blade mode DOF (flag) True EdgeDOF - First edgewise blade mode DOF (flag) False TeetDOF - Rotor-teeter DOF (flag) [unused for 3 blades]

True DrTrDOF - Drivetrain rotational-flexibility DOF (flag) True GenDOF - Generator DOF (flag) False YawDOF - Yaw DOF (flag) True TwFADOF1 - First fore-aft tower bending-mode DOF (flag) True TwFADOF2 - Second fore-aft tower bending-mode DOF (flag) True TwSSDOF1 - First side-to-side tower bending-mode DOF (flag) True TwSSDOF2 - Second side-to-side tower bending-mode DOF (flag) True CompAero - Compute aerodynamic forces (flag) False CompNoise - Compute aerodynamic noise (flag) ---- INITIAL CONDITIONS ---0.0 OoPDefl - Initial out-of-plane blade-tip displacement, (meters) 0.0 IPDefl - Initial in-plane blade-tip deflection, (meters) 0.0 TeetDefl - Initial or fixed teeter angle (degrees) [unused for 3 blades] 0.0 Azimuth - Initial azimuth angle for blade 1 (degrees) 41.7 RotSpeed - Initial or fixed rotor speed (rpm) -0.0 NacYaw - Initial or fixed nacelle-yaw angle (degrees) 0.0 TTDspFA - Initial fore-aft tower-top displacement (meters) 0.0 TTDspSS - Initial side-to-side tower-top displacement (meters) ----- TURBINE CONFIGURATION -----20.0000000 TipRad - The distance from the rotor apex to the blade tip (meters) 0.8191500 HubRad - The distance from the rotor apex to the blade root (meters) 1.0000000 PSpnEIN - Number of the innermost blade element which is still part of the pitchable portion of the blade for partial-span pitch control [1 to BldNodes] [CURRENTLY IGNORED] (-) 0.0000000 UndSling - Undersling length [distance from teeter pin to the rotor apex] (meters) [unused for 3 blades] 0.0000000 HubCM - Distance from rotor apex to hub mass [positive downwind] (meters) -4 2570400 OverHang - Distance from yaw axis to rotor apex [3 blades] or teeter pin [2 blades] (meters) -0.4020000 NacCMxn - Downwind distance from the tower-top to the nacelle CM (meters) 0.0000000 NacCMyn - Lateral distance from the tower-top to the nacelle CM (meters) 1.7340000 NacCMzn - Vertical distance from the tower-top to the nacelle CM (meters) 34.8615000 TowerHt - Height of tower above ground level [onshore] or MSL [offshore] (meters) 1.7340000 Twr2Shft - Vertical distance from the tower-top to the rotor shaft (meters) 0.0000000 TwrRBHt - Tower rigid base height (meters) -4.0000000 ShftTilt - Rotor shaft tilt angle (degrees) 0.0000000 Delta3 - Delta-3 angle for teetering rotors (degrees) [unused for 3 blades] 0.0000000 PreCone1 - Blade 1 cone angle (degrees) 0.0000000 PreCone2 - Blade 2 cone angle (degrees) 0.0000000 PreCone3 - Blade 3 cone angle (degrees) [unused for 2 blades] 0.0000000 AzimB1Up - Azimuth value to use for I/O when blade 1 points up (degrees) ----- MASS AND INERTIA -----0.0 YawBrMass - Yaw bearing mass (kg) 23884.1 NacMass - Nacelle mass (kg) 6552. HubMass - Hub mass (kg) 0. TipMass1 - Tip-brake mass, blade 1 (kg) 0. TipMass2 - Tip-brake mass, blade 2 (kg) 0. TipMass3 - Tip-brake mass, blade 3 (kg) [unused for 2 blades] 36590. NacYIner - Nacelle inertia about yaw axis (kg m^2) 34.4 GenIner - Generator inertia about HSS (kg m²) 3899.7 HubIner - Hub inertia about rotor axis [3 blades] or teeter axis [2 blades] (kg m^2) ----- DRIVETRAIN ----98.0 GBoxEff - Gearbox efficiency (%) 93.0 GenEff - Generator efficiency [ignored by the Thevenin and user-defined generator models] (%) 43.16496 GBRatio - Gearbox ratio (-) False GBRevers - Gearbox reversal {T: if rotor and generator rotate in opposite directions} (flag) 8686.4 HSSBrTqF - Fully deployed HSS-brake torque (N-m) 1.0 HSSBrDT - Time for HSS-brake to reach full deployment once initiated (sec) [used only when HSSBrMode=1] DynBrkFi - File containing a mech-gen-torque vs HSS-speed curve for a dynamic brake [CURRENTLY IGNORED] (quoted string) 1.6043e7 DTTorSpr - Drivetrain torsional spring (N-m/rad) 0.000e0 DTTorDmp - Drivetrain torsional damper (N-m/s) -- SIMPLE INDUCTION GENERATOR -0.1 SIG SIPc - Rated generator slip percentage (%) [used only when VSContrl=0 and GenModel=1] 1800 SIG SySp - Synchronous (zero-torque) generator speed (rpm) [used only when VSContrl=0 and GenModel=1] 3580 SIG_RtTq - Rated torque (N-m) [used only when VSContrl=0 and GenModel=1] 2 SIG PORt - Pull-out ratio (Tpullout/Trated) (-) [used only when VSContrl=0 and GenModel=1] ----- THEVENIN-EQUIVALENT INDUCTION GENERATOR ------0.0 TEC Freq - Line frequency [50 or 60] (Hz) [used only when VSContrl=0 and GenModel=2] 0 TEC_NPol - Number of poles [even integer > 0] (-) [used only when VSContrl=0 and GenModel=2] 0.00 TEC SRes - Stator resistance (ohms) [used only when VSContrl=0 and GenModel=2] 0.00 TEC_RRes - Rotor resistance (ohms) [used only when VSContrl=0 and GenModel=2] 0.0 TEC_VLL - Line-to-line RMS voltage (volts) [used only when VSContrl=0 and GenModel=2] 0.0 TEC_SLR - Stator leakage reactance (ohms) [used only when VSContrl=0 and GenModel=2]

0.0 TEC RLR - Rotor leakage reactance (ohms) [used only when VSContrl=0 and GenModel=2] 0.0 TEC_MR - Magnetizing reactance (ohms) [used only when VSContrl=0 and GenModel=2] ----- PLATFORM MODEL -----0 PtfmModel - Platform model {0: none, 1: onshore, 2: fixed bottom offshore, 3: floating offshore} (switch) PtfmFile - Name of file containing platform properties (quoted string) [unused when PtfmModel=0] ----- TOWER ------17 TwrNodes - Number of tower nodes used for analysis (-) "CART Tower.dat" TwrFile - Name of file containing tower properties (quoted string) ----- NACELLE-YAW -----0.0 YawSpr - Nacelle-yaw spring constant (N-m/rad) 0.0 YawDamp - Nacelle-yaw damping constant (N-m/rad/s) 0.0 YawNeut - Neutral yaw position--yaw spring force is zero at this yaw (degrees) ----- FURLING ------False Furling - Read in additional model properties for furling turbine (flag) "dummy" FurlFile - Name of file containing furling properties (quoted string) [unused when Furling=False] ------ ROTOR-TEETER ------0 TeetMod - Rotor-teeter spring/damper model {0: none, 1: standard, 2: user-defined from routine UserTeet} (switch) [unused for 3 blades] 0.0 TeetDmpP - Rotor-teeter damper position (degrees) [used only for 2 blades and when TeetMod=1] 0.0 TeetDmp - Rotor-teeter damping constant (N-m/rad/s) [used only for 2 blades and when TeetMod=1] 0.0 TeetCDmp - Rotor-teeter rate-independent Coulomb-damping moment (N-m) [used only for 2 blades and when TeetMod=1] 0.0 TeetSStP - Rotor-teeter soft-stop position (degrees) [used only for 2 blades and when TeetMod=1] 0.0 TeetHStP - Rotor-teeter hard-stop position (degrees) [used only for 2 blades and when TeetMod=1] 0.0 TeetSSSp - Rotor-teeter soft-stop linear-spring constant (N-m/rad) [used only for 2 blades and when TeetMod=1] 0.0 TeetHSSp - Rotor-teeter hard-stop linear-spring constant (N-m/rad) [used only for 2 blades and when TeetMod=1] ----- TIP-BRAKE ---0.0 TBDrConN - Tip-brake drag constant during normal operation, Cd*Area (m^2) 0.0 TBDrConD - Tip-brake drag constant during fully-deployed operation, Cd*Area (m^2) 0.0 TpBrDT - Time for tip-brake to reach full deployment once released (sec) ---- BLADE ---"CART3 Blades.dat" BldFile1 - Name of file containing properties for blade 1 (quoted string) "CART3 Blades.dat" BldFile2 - Name of file containing properties for blade 2 (quoted string) "CART3_Blades.dat" BldFile3 - Name of file containing properties for blade 3 (quoted string) [unused for 2 blades] ----- AERODYN -----"CART3 AD Matlab.ipt" ADFile - Name of file containing AeroDyn input parameters (quoted string) ----- NOISE -----"dummy" NoiseFile - Name of file containing aerodynamic noise input parameters (quoted string) [used only when CompNoise=True] ----- ADAMS -----"dummy" ADAMSFile - Name of file containing ADAMS-specific input parameters (quoted string) [unused when ADAMSPrep=1] ----- LINEARIZATION CONTROL ------"dummy" LinFile - Name of file containing FAST linearazation parameters (quoted string) [unused when AnalMode=1] ----- OUTPUT ------True SumPrint - Print summary data to "<RootName>.fsm" (flag) True TabDelim - Generate a tab-delimited tabular output file. (flag) "ES10.3E2" OutFmt - Format used for tabular output except time. Resulting field should be 10 characters. (quoted string) [not checked for validity!] 30.00000000 TStart - Time to begin tabular output (s) 5.00000000 DecFact - Decimation factor for tabular output {1: output every time step} (-) 1.000000000 SttsTime - Amount of time between screen status messages (sec) 3.052000000 NcIMUxn - Downwind distance from the tower-top to the nacelle IMU (meters) 0.000000000 NcIMUyn - Lateral distance from the tower-top to the nacelle IMU (meters) 0.489000000 NcIMUzn - Vertical distance from the tower-top to the nacelle IMU (meters) 1.113000000 ShftGagL - Distance from rotor apex [3 blades] or teeter pin [2 blades] to shaft strain gages [positive for upwind rotors] (meters) 1.000000000 NTwGages - Number of tower nodes that have strain gages for output [0 to 5] (-) 5.000000000 TwrGagNd - List of tower nodes that have strain gages [1 to TwrNodes] (-) [unused if NTwGages=0] 0.000000000 NBIGages - Number of blade nodes that have strain gages for output [0 to 5] (-) 3,5,7 BldGagNd - List of blade nodes that have strain gages [1 to BldNodes] (-) [unused if NBlGages=0] OutList - The next line(s) contains a list of output parameters. See OutList.txt for a listing of available output channels, (-) "Azimuth,LSSGagP" - Rotor and Gen Azimuth Angles "WindVxi" - Hub height windspeed "LSSGagV,HSShftV,RotSpeed" "LSSGagAxa,HSShftA " - Low-speed shaft vel. and generator vel. "BldPitch1,BldPitch2,BldPitch3" - Blade 1 and 2 pitch angles "YawBrTDxt, YawBrTDyt" - Tower-top fore-aft and side-side displ "TwHt1MLxt,TwHt1MLyt" "TipDxb1,TipDxb2" "TipDxc1, TipDyc1" - Blade 1 tip out-plane (flapwise) and in-plane defl (edgewise) "TipDxc2, TipDyc2" - Blade 2 tip out-plane (flapwise) and in-plane defl (edgewise) "TipDxc3, TipDyc3" - Blade 3 tip out-plane (flapwise) and in-plane defl (edgewise) "RotTorq,LSShftTq,HSShftTq" - Rotor and shaft torque "GenTq,RotThrust" - Generator torque and rotor thrust

Seneration torque and rotor infast
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"RotPwr,GenPwr,HSShftPwr" - rotor power
"TipSpdRat,RotCp"
"YawBrTAyp"
"YawBrTAxp"
"YawBrTDyp"
"LSSTipPxa"
"YawBrMzn"
"NcIMUTVvs"
"RootMyb1"
"RootMyb2"
"RootMyb3"
"RootMxb1"
"RootMxb2"
"RootMxb3"
"RootFxb1"
"RootFxc1"
"LSSTipAxa"
"HSShftA"
"TwrBsMxt"
"YawBrFyp"
"YawBrMxp"
"LSShftFys
"LSShftFxa"
"LSSTipMys"
END of FAST input file (the word "END" must appear in the first 3 columns of this last line).
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B.2 FAST Input File for Command Line Simulations ("CART3.fst")

_____ ------ FAST INPUT FILE ------FAST Model: CART 3-blades, Operating Point #1, with Region 2.5 Compatible with FAST v6.10a ----- SIMULATION CONTROL ------True Echo - Echo input data to "echo.out" (flag) 1 ADAMSPrep - ADAMS preprocessor mode {1: Run FAST, 2: use FAST as a preprocessor to create an ADAMS model, 3: do both} (switch) 1 AnalMode - Analysis mode {1: Run a time-marching simulation, 2: create a periodic linearized model} (switch) 3 NumBl - Number of blades (-) 400 TMax - Total run time (s) NOTE: Set to 8000 for Matlab, defined in runturbine.m DT - Integration time step (s) 0.004 ----- TURBINE CONTROL -0 YCMode - Yaw control mode {0: none, 1: user-defined from routine UserYawCont, 2: user-defined from Simulink} (switch) 9999.9 TYCOn - Time to enable active yaw control (s) [unused when YCMode=0] 1 PCMode - Pitch control mode {0: none, 1: user-defined from routine PitchCntrl, 2: user-defined from Simulink} (switch) 0. TPCOn - Time to enable active pitch control (s) [unused when PCMode=0] 2 VSContrl - Variable-speed control mode {0: none, 1: simple VS, 2: user-defined from routine UserVSCont, 3: user-defined from Simulink} (switch) 1781.9791 VS RtGnSp - Rated generator speed for simple variable-speed generator control (HSS side) (rpm) [used only when VSContrl=1] 3581.0281 VS RtTq - Rated generator torque/constant generator torque in Region 3 for simple variable-speed generator control (HSS side) (Nm) [used only when VSContrl=1] 0.000981 VS Rgn2K - Generator torque constant in Region 2 for simple variable-speed generator control (HSS side) (N-m/rpm^2) [used only when VSContrl=1] 5.000000000 VS_SIPc - Rated generator slip percentage in Region 2 1/2 for simple variable-speed generator control (%) [used only when VSContrl=11 1 GenModel - Generator model {1: simple, 2: Thevenin, 3: user-defined from routine UserGen} (switch) [used only when VSContrl=0] True GenTiStr - Method to start the generator {T: timed using TimGenOn, F: generator speed using SpdGenOn} (flag) True GenTiStp - Method to stop the generator {T: timed using TimGenOf, F: when generator power = 0} (flag) 0.0 SpdGenOn - Generator speed to turn on the generator for a startup (HSS speed) (rpm) [used only when GenTiStr=False] 0.0 TimGenOn - Time to turn on the generator for a startup (s) [used only when GenTiStr=True] 9999.9 TimGenOf - Time to turn off the generator (s) [used only when GenTiStp=True] 1 HSSBrMode - HSS brake model {1: simple, 2: user-defined from routine UserHSSBr} (switch) 9999.9 THSSBrDp - Time to initiate deployment of the HSS brake (s) 9999.9 TiDynBrk - Time to initiate deployment of the dynamic generator brake [CURRENTLY IGNORED] (s) 9999.9 TTpBrDp1 - Time to initiate deployment of tip brake 1 (s) 9999.9 TTpBrDp2 - Time to initiate deployment of tip brake 2 (s) 9999.9 TTpBrDp3 - Time to initiate deployment of tip brake 3 (s) [unused for 2 blades] 9999.9 TBDepISp1 - Deployment-initiation speed for the tip brake on blade 1 (rpm) 9999.9 TBDepISp2 - Deployment-initiation speed for the tip brake on blade 2 (rpm)

9999.9 TBDepISp3 - Deployment-initiation speed for the tip brake on blade 3 (rpm) [unused for 2 blades] 9999.9 TYawManS - Time to start override yaw maneuver and end standard yaw control (s) 9999.9 YawManRat - Yaw rate (in absolute value) at which override yaw maneuver heads toward final yaw angle (deg/s) 0.0 NacYawF - Final yaw angle for yaw maneuvers (degrees) 9999.9 TPitManS1 - Time to start override pitch maneuver for blade 1 and end standard pitch control (s) 9999.9 TPitManS2 - Time to start override pitch maneuver for blade 2 and end standard pitch control (s) 9999.9 TPitManS3 - Time to start override pitch maneuver for blade 3 and end standard pitch control (s) [unused for 2 blades] 18 PitManRat1 - Pitch rate (in absolute value) at which override pitch maneuver for blade 1 heads toward final pitch (deg/s) 18 PitManRat2 - Pitch rate (in absolute value) at which override pitch maneuver for blade 2 heads toward final pitch (deg/s) 18 PitManRat3 - Pitch rate (in absolute value) at which override pitch maneuver for blade 3 heads toward final pitch (deg/s) [unused for 2 blades] 12.7 BlPitch1 - Blade 1 initial pitch (degrees) 12.7 BlPitch2 - Blade 2 initial pitch (degrees) 12.7 BlPitch3 - Blade 3 initial pitch (degrees) [unused for 2 blades] 90.0 BlPitchF1 - Blade 1 final pitch for pitch maneuvers (degrees) 90.0 BlPitchF2 - Blade 2 final pitch for pitch maneuvers (degrees) 90.0 BlPitchF3 - Blade 3 final pitch for pitch maneuvers (degrees) [unused for 2 blades] ----- ENVIRONMENTAL CONDITIONS ------9.80665 Gravity - Gravitational acceleration (m/s^2) ----- FEATURE FLAGS -----True FlapDOF1 - First flapwise blade mode DOF (flag) True FlapDOF2 - Second flapwise blade mode DOF (flag) True EdgeDOF - First edgewise blade mode DOF (flag) False TeetDOF - Rotor-teeter DOF (flag) [unused for 3 blades] True DrTrDOF - Drivetrain rotational-flexibility DOF (flag) True GenDOF - Generator DOF (flag) False YawDOF - Yaw DOF (flag) True TwFADOF1 - First fore-aft tower bending-mode DOF (flag) True TwFADOF2 - Second fore-aft tower bending-mode DOF (flag) True TwSSDOF1 - First side-to-side tower bending-mode DOF (flag) True TwSSDOF2 - Second side-to-side tower bending-mode DOF (flag) True CompAero - Compute aerodynamic forces (flag) False CompNoise - Compute aerodynamic noise (flag) ----- INITIAL CONDITIONS ------0.0 OoPDefl - Initial out-of-plane blade-tip displacement, (meters) 0.0 IPDefl - Initial in-plane blade-tip deflection, (meters) 0.0 TeetDefl - Initial or fixed teeter angle (degrees) [unused for 3 blades] 0.0 Azimuth - Initial azimuth angle for blade 1 (degrees) 41.7 RotSpeed - Initial or fixed rotor speed (rpm) -0.0 NacYaw - Initial or fixed nacelle-vaw angle (degrees) 0.0 TTDspFA - Initial fore-aft tower-top displacement (meters) 0.0 TTDspSS - Initial side-to-side tower-top displacement (meters) ----- TURBINE CONFIGURATION ------20.0000000 TipRad - The distance from the rotor apex to the blade tip (meters) 0.8191500 HubRad - The distance from the rotor apex to the blade root (meters) 1.0000000 PSpnEIN - Number of the innermost blade element which is still part of the pitchable portion of the blade for partial-span pitch control [1 to BIdNodes] [CURRENTLY IGNORED] (-) 0.0000000 UndSling - Undersling length [distance from teeter pin to the rotor apex] (meters) [unused for 3 blades] 0.0000000 HubCM - Distance from rotor apex to hub mass [positive downwind] (meters) OverHang - Distance from yaw axis to rotor apex [3 blades] or teeter pin [2 blades] (meters) -4.2570400 -0.4020000 NacCMxn - Downwind distance from the tower-top to the nacelle CM (meters) 0.0000000 NacCMyn - Lateral distance from the tower-top to the nacelle CM (meters) 1.7340000 NacCMzn - Vertical distance from the tower-top to the nacelle CM (meters) 34.8615000 TowerHt - Height of tower above ground level [onshore] or MSL [offshore] (meters) 1.7340000 Twr2Shft - Vertical distance from the tower-top to the rotor shaft (meters) 0.0000000 TwrRBHt - Tower rigid base height (meters) -4.0000000 ShftTilt - Rotor shaft tilt angle (degrees) 0.0000000 Delta3 - Delta-3 angle for teetering rotors (degrees) [unused for 3 blades] 0.0000000 PreCone1 - Blade 1 cone angle (degrees) 0.0000000 PreCone2 - Blade 2 cone angle (degrees) 0.0000000 PreCone3 - Blade 3 cone angle (degrees) [unused for 2 blades] 0.0000000 AzimB1Up - Azimuth value to use for I/O when blade 1 points up (degrees) ----- MASS AND INERTIA -0.0 YawBrMass - Yaw bearing mass (kg) 23884.1 NacMass - Nacelle mass (kg) 6552. HubMass - Hub mass (kg) 0. TipMass1 - Tip-brake mass, blade 1 (kg) 0. TipMass2 - Tip-brake mass, blade 2 (kg) 0. TipMass3 - Tip-brake mass, blade 3 (kg) [unused for 2 blades] 36590. NacYIner - Nacelle inertia about yaw axis (kg m²) 34.4 GenIner - Generator inertia about HSS (kg m²)

3899.7 HubIner - Hub inertia about rotor axis [3 blades] or teeter axis [2 blades] (kg m^2) ----- DRIVETRAIN ------98.0 GBoxEff - Gearbox efficiency (%) 93.0 GenEff - Generator efficiency [ignored by the Thevenin and user-defined generator models] (%) 43.16496 GBRatio - Gearbox ratio (-) False GBRevers - Gearbox reversal {T: if rotor and generator rotate in opposite directions} (flag) 8686.4 HSSBrTqF - Fully deployed HSS-brake torque (N-m) 1.0 HSSBrDT - Time for HSS-brake to reach full deployment once initiated (sec) [used only when HSSBrMode=1] DynBrkFi - File containing a mech-gen-torque vs HSS-speed curve for a dynamic brake [CURRENTLY IGNORED] (quoted string) 1.6043e7 DTTorSpr - Drivetrain torsional spring (N-m/rad) 0.000e0 DTTorDmp - Drivetrain torsional damper (N-m/s) ------ SIMPLE INDUCTION GENERATOR ------0.1 SIG_SIPc - Rated generator slip percentage (%) [used only when VSContrl=0 and GenModel=1] 1800 SIG SySp - Synchronous (zero-torque) generator speed (rpm) [used only when VSContrl=0 and GenModel=1] 3580 SIG RtTq - Rated torque (N-m) [used only when VSContrl=0 and GenModel=1] 2 SIG PORt - Pull-out ratio (Tpullout/Trated) (-) [used only when VSContrl=0 and GenModel=1] ------ THEVENIN-EQUIVALENT INDUCTION GENERATOR -------0.0 TEC Freq - Line frequency [50 or 60] (Hz) [used only when VSContrl=0 and GenModel=2] 0 TEC_NPol - Number of poles [even integer > 0] (-) [used only when VSContrl=0 and GenModel=2] 0.00 TEC SRes - Stator resistance (ohms) [used only when VSContrl=0 and GenModel=2] 0.00 TEC RRes - Rotor resistance (ohms) [used only when VSContrl=0 and GenModel=2] 0.0 TEC_VLL - Line-to-line RMS voltage (volts) [used only when VSContrl=0 and GenModel=2] 0.0 TEC_SLR - Stator leakage reactance (ohms) [used only when VSContrl=0 and GenModel=2] 0.0 TEC RLR - Rotor leakage reactance (ohms) [used only when VSContrl=0 and GenModel=2] 0.0 TEC_MR - Magnetizing reactance (ohms) [used only when VSContrl=0 and GenModel=2] ----- PLATFORM MODEL ------0 PtfmModel - Platform model {0: none, 1: onshore, 2: fixed bottom offshore, 3: floating offshore} (switch) PtfmFile - Name of file containing platform properties (quoted string) [unused when PtfmModel=0] ----- TOWER -----17 TwrNodes - Number of tower nodes used for analysis (-) "CART_Tower.dat" TwrFile - Name of file containing tower properties (quoted string) ------ NACELLE-YAW ------0.0 YawSpr - Nacelle-yaw spring constant (N-m/rad) 0.0 YawDamp - Nacelle-yaw damping constant (N-m/rad/s) 0.0 YawNeut - Neutral yaw position--yaw spring force is zero at this yaw (degrees) ----- FURLING ------False Furling - Read in additional model properties for furling turbine (flag) "dummy" FurlFile - Name of file containing furling properties (quoted string) [unused when Furling=False] ------ ROTOR-TEETER ------0 TeetMod - Rotor-teeter spring/damper model {0: none, 1: standard, 2: user-defined from routine UserTeet} (switch) [unused for 3 blades] 0.0 TeetDmpP - Rotor-teeter damper position (degrees) [used only for 2 blades and when TeetMod=1] 0.0 TeetDmp - Rotor-teeter damping constant (N-m/rad/s) [used only for 2 blades and when TeetMod=1] 0.0 TeetCDmp - Rotor-teeter rate-independent Coulomb-damping moment (N-m) [used only for 2 blades and when TeetMod=1] 0.0 TeetSStP - Rotor-teeter soft-stop position (degrees) [used only for 2 blades and when TeetMod=1] 0.0 TeetHStP - Rotor-teeter hard-stop position (degrees) [used only for 2 blades and when TeetMod=1] 0.0 TeetSSSp - Rotor-teeter soft-stop linear-spring constant (N-m/rad) [used only for 2 blades and when TeetMod=1] 0.0 TeetHSSp - Rotor-teeter hard-stop linear-spring constant (N-m/rad) [used only for 2 blades and when TeetMod=1] ----- TIP-BRAKE -----0.0 TBDrConN - Tip-brake drag constant during normal operation, Cd*Area (m^2) 0.0 TBDrConD - Tip-brake drag constant during fully-deployed operation, Cd*Area (m^2) 0.0 TpBrDT - Time for tip-brake to reach full deployment once released (sec) ----- BLADE ---"/CART3 FAST Model/CART3 Blades.dat" BldFile1 - Name of file containing properties for blade 1 (quoted string) "/CART3 FAST Model/CART3 Blades.dat" BldFile2 - Name of file containing properties for blade 2 (quoted string) "/CART3 FAST Model/CART3 Blades.dat" BldFile3 - Name of file containing properties for blade 3 (quoted string) [unused for 2 blades] ----- AERODYN ------"/CART3 FAST Model/CART3 AD.ipt" ADFile - Name of file containing AeroDyn input parameters (quoted string) ----- NOISE -----"dummy" NoiseFile - Name of file containing aerodynamic noise input parameters (quoted string) [used only when CompNoise=True] ----- ADAMS -----"dummy" ADAMSFile - Name of file containing ADAMS-specific input parameters (quoted string) [unused when ADAMSPrep=1] ----- LINEARIZATION CONTROL ------"dummy" LinFile - Name of file containing FAST linearazation parameters (quoted string) [unused when AnalMode=1] ----- OUTPUT ------True SumPrint - Print summary data to "<RootName>.fsm" (flag) True TabDelim - Generate a tab-delimited tabular output file. (flag) "ES10.3E2" OutFmt - Format used for tabular output except time. Resulting field should be 10 characters. (quoted string) [not checked for validity!]

30.00000000 TStart - Time to begin tabular output (s)

5.00000000 DecFact - Decimation factor for tabular output {1: output every time step} (-)

1.000000000 SttsTime - Amount of time between screen status messages (sec) 3.052000000 NcIMUxn - Downwind distance from the tower-top to the nacelle IMU (meters) 0.000000000 NcIMUyn - Lateral distance from the tower-top to the nacelle IMU (meters) 0.489000000 NcIMUzn - Vertical distance from the tower-top to the nacelle IMU (meters) 1.113000000 ShftGagL - Distance from rotor apex [3 blades] or teeter pin [2 blades] to shaft strain gages [positive for upwind rotors] (meters) 1.000000000 NTwGages - Number of tower nodes that have strain gages for output [0 to 5] (-) 5.000000000 TwrGagNd - List of tower nodes that have strain gages 1 to TwrNodes] (-) [unused if NTwGages=0] 0.000000000 NBIGages - Number of blade nodes that have strain gages for output [0 to 5] (-) 3,5,7 BldGagNd - List of blade nodes that have strain gages [1 to BldNodes] (-) [unused if NBlGages=0] OutList - The next line(s) contains a list of output parameters. See OutList.txt for a listing of available output channels, (-) "Azimuth,LSSGagP" - Rotor and Gen Azimuth Angles "WindVxi" - Hub height windspeed "LSSGagV,HSShftV,RotSpeed" "LSSGagAxa,HSShftA " - Low-speed shaft vel. and generator vel. "BldPitch1,BldPitch2,BldPitch3" - Blade 1 and 2 pitch angles "YawBrTDxt, YawBrTDyt" - Tower-top fore-aft and side-side displ "TwHt1MLxt,TwHt1MLyt" "TipDxb1,TipDxb2" "TipDxc1, TipDyc1" - Blade 1 tip out-plane (flapwise) and in-plane defl (edgewise) "TipDxc2, TipDyc2" - Blade 2 tip out-plane (flapwise) and in-plane defl (edgewise) "TipDxc3, TipDyc3" - Blade 3 tip out-plane (flapwise) and in-plane defl (edgewise) "RotTorq,LSShftTq,HSShftTq" - Rotor and shaft torque "GenTq,RotThrust" - Generator torque and rotor thrust "RotPwr,GenPwr,HSShftPwr" - rotor power "TipSpdRat,RotCp" "YawBrTAyp" "YawBrTAxp" "YawBrTDyp" "LSSTipPxa" "YawBrMzn" "NcIMUTVys" "RootMyb1" "RootMvb2" "RootMyb3" "RootMxb1" "RootMxb2" "RootMxb3" "RootFxb1" "RootFxc1" "LSSTipAxa" "HSShftA" "TwrBsMxt" "YawBrFyp" "YawBrMxp" "LSShftFvs" "LSShftFxa" "LSSTipMvs" END of FAST input file (the word "END" must appear in the first 3 columns of this last line).

B.3 Aerodyn Input File for the CART3 ("CART3_AD.ipt")

CART 3-blade aerodynamic parameters for FAST. AeroDyn ver. 12.58. SI SysUnits - System of units for used for input and output [must be SI for FAST] (unquoted string) BEDDOES StallMod - Dynamic stall included [BEDDOES or STEADY] (unquoted string) NO_CM UseCm - Use aerodynamic pitching moment model? [USE_CM or NO_CM] (unquoted string) EQUIL InfModel - Inflow model [DYNIN or EQUIL] (unquoted string) WAKE IndModel - Induction-factor model [NONE or WAKE or SWIRL] (unquoted string) 0.001 AToler - Induction-factor tolerance (convergence criteria) (-) PRANDtl TLModel - Tip-loss model (EQUIL only) [PRANDtl, GTECH, or NONE] (unquoted string) NONE HLModel - Hub-loss model (EQUIL only) [PRANDtl or NONE] (unquoted string) "MatlabWind\CART3_2ETM_600s_25.0V0_S05.wnd" WindFile - Name of file containing wind data (quoted string) 36.5955 HH - Wind reference (hub) height [TowerHt+Twr2Shft+OverHang*SIN(ShftTilt)] (m) 0.0 TwrShad - Tower-shadow velocity deficit (-) 1.0 ShadHWid - Tower-shadow nalf width (m) 0.0 T_Shad_Refpt - Tower-shadow reference point (m)

0.9975 Rho - Air density (kg/m^3) 1.75e-5 KinVisc - Kinematic air viscosity [CURRENTLY IGNORED] (m²/sec) 0.004 DTAero - Time interval for aerodynamic calculations (sec) 14 NumFoil - Number of airfoil files (-) "\CART3 FAST Model\AeroData\c3 01-02 circle AD12.dat" FoilNm - Names of the airfoil files [NumFoil lines] (quoted strings) "\CART3 FAST Model\AeroData\c3 03 2cir+1s818 AD12.dat" "\CART3 FAST Model\AeroData\c3 04 1cir+2s818 AD12.dat" "\CART3_FAST_Model\AeroData\c3_05_s818 AD12.dat" "\CART3 FAST Model\AeroData\c3 06 6s818+1s816 AD12.dat" "\CART3 FAST Model\AeroData\c3 07 5s818+2s816 AD12.dat" "\CART3_FAST_Model\AeroData\c3_08_4s818+3s816_AD12.dat" "\CART3_FAST_Model\AeroData\c3_09_3s818+4s816_AD12.dat" "\CART3_FAST_Model\AeroData\c3_10_2s818+5s816_AD12.dat" "\CART3_FAST_Model\AeroData\c3_11_1s818+6s816_AD12.dat" "\CART3 FAST Model\AeroData\c3 12-13 s816 AD12.dat" "\CART3_FAST_Model\AeroData\c3_14_2s816+1s817_AD12.dat" "\CART3_FAST_Model\AeroData\c3_15_1s816+2s817_AD12.dat" "\CART3 FAST Model\AeroData\c3 16-20 s817 AD12.dat" 17 BldNodes - Number of blade nodes used for analysis (-) RNodes AeroTwst DRNodes Chord NFoil PrnElm 1.2987 21.000 0.959 1.359 1 NOPRINT 2.2577 21.000 0.959 1.359 1 NOPRINT 3.6963 18.053 1.918 1.725 2 NOPRINT 5.6144 14.470 1.918 2.228 4 NOPRINT 7.5324 10.095 1.918 2.191 6 NOPRINT 9.4505 7.077 1.918 2.079 7 NOPRINT 11.3686 4.971 1.918 1.939 9 NOPRINT 13.2867 3.468 1.918 1.775 11 NOPRINT 15.2048 2.298 1.918 1.590 11 NOPRINT 16.6434 1.624 0.959 1.441 12 NOPRINT 17.6024 1.215 0.959 1.337 13 NOPRINT 18.2737 0.958 0.384 1.260 14 NOPRINT 18.6573 0.820 0.384 1.216 14 NOPRINT 19.0410 0.687 0.384 1.171 14 NOPRINT 19.4246 0.554 0.384 1.126 14 NOPRINT 19.7123 0.461 0.192 1.091 14 NOPRINT 19.9041 0.402 0.192 1.067 14 NOPRINT

ReNum

B.4 FAST Linearization File for the CART3 ("CART3_lin.dat")

----- FAST LINEARIZATION CONTROL FILE -----

CART linearization input properties.

----- PERIODIC STEADY STATE SOLUTION ------

True CalcStdy - Calculate periodic steady state condition (False: linearize about zero) (switch)

2 TrimCase - Trim case {1: find nacelle yaw, 2: find generator torque, 3: find collective blade pitch} (switch) [used only when CalcStdy=True and GenDOF=True]

0.00001 VelTol - Convergence tolerance for the 2-norm of velocities in the periodic steady state calculation (rad/s) [used only when CalcStdy=True]

----- MODEL LINEARIZATION -----

24 NAzimStep - Number of equally-spaced azimuth steps in periodic linearized model (-)

1 MdlOrder - Order of output linearized model {1: 1st order A, B, Bd, C, D, Dd; 2: 2nd order M, C, K, F, Fd, VelC, DspC, D, Dd} (switch)

------ INPUTS AND DISTURBANCES ------

1 NInputs - Number of control inputs [0 (none) or 1 to 4+NumBl] (-)

3 CntrlInpt - CntrlInpt - List of control inputs [1 to NInputs] {1: nacelle yaw angle, 2: nacelle yaw rate, 3: generator torque, 4: collective blade pitch, 5: individual pitch of blade 1, 6: individual pitch of blade 2, 7: individual pitch of blade 3 [unavailable for 2-bladed turbines]} (-) [unused if NInputs=0]

^{0.0001} DispTol - Convergence tolerance for the 2-norm of displacements in the periodic steady state calculation (rad) [used only when CalcStdy=True]

¹ NDisturbs - Number of wind disturbances [0 (none) or 1 to 7] (-)

1 Disturbne - List of input wind disturbances [1 to NDisturbs] {1: horizontal hub-height wind speed, 2: horizontal wind direction, 3: vertical wind speed, 4: horizontal wind shear, 5: vertical power law wind shear, 6: linear vertical wind shear, 7: horizontal hub-height wind gust} (-) [unused if NDisturbs=0]

Appendix C: Baseline Controller Results

C.1 Extreme Events Tables

DLC 1.1

Extreme events for Blade Moments:

Parameter TypeRootMxb1 RootMxb2 RootMxb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxiFile (kN*m) (kN*m)

RootMxb1 Minimum DLC1.1_0063_25.0V0_S03.out -3.385E+02 2.388E+02 1.851E+02 5.310E+02 3.120E+00 4.311E+02 4.143E+02 5.623E+02 4.311E+02 5.792E+02 3.053E+01 RootMxb1 Maximum DLC1.1_0059_23.0V0_S05.out 3.851E+02 1.403E+02 -5.241E+00 -2.646E+02 -1.197E+02 -2.703E+02 4.098E+02 2.647E+02 2.956E+02 6.186E+01 2.388E+01 RootMyb1 Minimum DLC1.1_0064_25.0V0_S04.out 1.129E+02 -5.418E+02 -1.158E+02 1.118E+02 1.925E+02 2.092E+02 5.534E+02 1.610E+02 2.843E+02 2.495E+01 RootMyb1 Maximum DLC1.1_0064_25.0V0_S06.out 1.049E+02 1.032E+03 2.307E+02 5.989E+02 -2.032E+02 5.288E+02 1.037E+03 6.418E+02 5.665E+02 2.921E+02 1.708E+01 RootMxb2 Minimum DLC1.1_0066_25.0V0_S06.out 1.049E+02 1.032E+03 2.307E+02 5.989E+02 -2.032E+02 6.319E+02 2.194E+02 3.419E+02 6.805E+02 3.960E+02 2.808E+01 RootMxb2 Maximum DLC1.1_0066_25.0V0_S06.out -1.441E+02 -2.177E+02 4.114E+02 -3.81E+01 -5.252E+02 6.319E+02 2.610E+02 4.132E+02 3.088E+02 2.807E+01 RootMyb2 Minimum DLC1.1_0063_25.0V0_S06.out -1.441E+02 -2.177E+02 4.114E+02 -3.81E+01 -3.243E+02 5.029E+02 6.258E+02 1.578E+02 2.807E+01 RootMyb2 Maximum DLC1.1_0063_25.0V0_S03.out -1.516E+02 5.784E+02 3.006E+02 9.732E+02 3.55E+01 4.509E+02 5.980E+02 1.019E+03 4.523E+02 2.730E+01 2.730E+01 RootMxb3 Minimum DLC1.1_0064_25.0V0_S03.out -1.516E+02 5.784E+02 -0.000E+02 -8.907E+01 3.742E+02 3.457E+02 3.382E+02 3.712E+02 3.708E+01 3.090E+01 RootMxb3 Maximum DLC1.1_0064_25.0V0_S04.out -1.253E+01 -4.288E+02 -1.000E+02 -8.907E+01 3.742E+02 3.042E+02 4.290E+02 1.339E+02 4.823E+02 2.177E+02 2.746E+01 RootMxb3 Maximum DLC1.1_0064_25.0V0_S04.out -1.253E+01 -4.288E+02 -1.000E+02 -8.907E+01 3.742E+02 3.042E+02 3.852E+02 1.339E+02 4.823E+02 2.177E+02 2.746E+01 RootMyb3 Minimum DLC1.1_0064_25.0V0_S04.out -2.560E+01 -8.472E+01 2.736E+02 -5.503E+02 4.290E+02 1.339E+02 4.823E+02 2.177E+02 2.746E+01 RootMyb3 Maximum DLC1.1_0064_25.0V0_S04.out -2.560E+01 -8.472E+01 2.736E+02 -5.503E+02 5.503E+02 1.230E+02 1.001E+03 3.656E+02 1.266E+01 RootMyb3 Maximum DLC1.1_0064_25.0V0_S04.out -3.938E+00 6.309E+02 2.567E+02 6.589E+02 -2.352E+01 3.642E

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC1.1_0064_25.0V0_S04.out -1.131E+03 3.888E+02 1.196E+03 7.576E+01 2.716E+01 TwHt1Mlxt Maximum DLC1.1_0064_25.0V0_S04.out 1.984E+03 1.477E+03 2.474E+03 7.642E+01 2.806E+01 TwHt1Mlyt Minimum DLC1.1_0006_05.0V0_S06.out -4.394E+01 -3.099E+03 3.099E+03 6.260E+02 6.733E+00 TwHt1Mlyt Maximum DLC1.1_0029_13.0V0_S05.out 3.453E+02 3.820E+03 3.836E+03 2.759E+02 1.421E+01 Tower Mag Maximum DLC1.1_0029_13.0V0_S05.out 3.453E+02 3.820E+03 3.836E+03 2.759E+02 1.421E+01

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC1.1_0012_07.0V0_S06.out -2.908E+01 3.583E+02 7.886E+00 LSShftTq Maximum DLC1.1_0064_25.0V0_S04.out 4.227E+02 3.274E+02 2.693E+01

DLC 1.3

Extreme events for Blade Moments:

Parameter Type File

RootMxb1 RootMyb1 RootMxb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) kN*m kN*m kN*m (sec) (m/sec)

RootMxb1 Minimum DLC1.3_0065_25.0V0_S05.out -3.654E+02 -2.608E+02 1.719E+02 5.227E+02 1.855E+02 7.358E+01 4.490E+02 5.502E+02 1.995E+02 5.303E+02 3.076E+01 RootMxb1 Maximum DLC1.3_0066_25.0V0_S06.out 4.130E+02 1.886E+02 2.996E+01 -2.248E+02 -1.552E+02 -4.267E+02 4.540E+02 2.268E+02 4.541E+02 4.877E+02 2.902E+01 RootMyb1 Minimum DLC1.3_0012_25.0V0_S02.out 9.134E+01 -6.565E+02 -5.396E+01 2.907E+02 2.228E+02 -2.238E+01 6.628E+02 2.956E+02 2.239E+02 2.594E+02 3.122E+01 RootMyb1 Maximum DLC1.3_0019_11.0V0_S01.out 3.043E+02 9.924E+02 -1.096E+02 5.393E+02 -3.090E+01 2.410E+02 1.038E+03 5.504E+02 2.429E+02 4.232E+02 1.464E+01 RootMxb2 Minimum DLC1.3_0066_25.0V0_S06.out 2.124E+02 5.463E+02 -3.722E+02 6.205E+01 1.692E+01 5.523E+02 5.862E+02 3.773E+02 5.255E+02 6.059E+02 2.760E+01 RootMxb2 Minimum DLC1.3_0035_15.0V0_S05.out -8.799E+01 7.272E+02 3.740E+02 9.661E+01 3.993E+02 7.325E+02 9.213E+02 4.108E+02 2.271E+02 1.282E+01 RootMyb2 Minimum DLC1.3_0058_23.0V0_S04.out 2.821E+02 5.011E+02 6.592E+01 -6.241E+02 -1.693E+02 1.527E+02 5.751E+02 6.276E+02 2.2080E+02 3.007E+02 2.735E+01 RootMyb2 Maximum DLC1.3_0019_11.0V0_S01.out -5.935E+01 3.622E+02 3.193E+02 1.018E+03 -1.017E+02 5.465E+02 3.670E+02 1.067E+03 5.559E+02 4.227E+02 1.324E+01 RootMxb3 Minimum DLC1.3_0066_25.0V0_S06.out -6.014E+01 -2.033E+02 -8.544E+01 -2.911E+02 3.729E+02 1.046E+02 2.120E+02 3.033E+02 3.873E+02 4.882E+02 3.170E+01 RootMxb3 Minimum DLC1.3_0066_25.0V0_S06.out -6.014E+01 -2.033E+02 -8.544E+01 -2.911E+02 3.729E+02 1.046E+02 2.120E+02 3.033E+02 3.873E+02 4.882E+02 3.170E+01 RootMyb3 Minimum DLC1.3_0066_25.0V0_S06.out -6.014E+01 -2.033E+02 -8.544E+01 -2.911E+02 3.729E+02 1.046E+02 2.120E+02 3.303E+02 3.808E+02 1.452E+01 RootMyb3 Minimum DLC1.3_0019_11.0V0_S01.out

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC1.3_0001_05.0V0_S01.out -1.505E+03 -4.491E+02 1.571E+03 2.952E+02 6.278E+00 TwHt1Mlxt Maximum DLC1.3_0061_25.0V0_S01.out 2.242E+03 8.851E+02 2.411E+03 8.220E+01 2.441E+01 TwHt1Mlyt Minimum DLC1.3_0004_05.0V0_S04.out -5.031E+02 -4.713E+03 4.740E+03 1.517E+02 8.740E+00 TwHt1Mlyt Maximum DLC1.3_0045_19.0V0_S03.out 4.824E+02 4.189E+03 4.217E+03 4.633E+02 1.438E+01 Tower Mag Maximum DLC1.3_0004_05.0V0_S04.out -5.031E+02 -4.713E+03 4.740E+03 1.517E+02 8.740E+00

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC1.3_0008_07.0V0_S02.out -6.384E+01 2.095E+02 7.063E+00 LSShftTq Maximum DLC1.3_0064_25.0V0_S04.out 4.159E+02 5.772E+02 3.255E+01

DLC 1.4

Extreme events for Blade Moments:

Parameter Type FileRootMxb1 RootMxb1 RootMxb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi
(kN*m) (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) (kN*m)

RootMxb1 Minimum DLC1.4 0019 ECD-R-20.out -1.993E+02 3.843E+02 1.175E+02 5.948E+02 1.160E+02 4.944E+02 4.329E+02 6.063E+02 5.078E+02 4.472E+01 1.611E+01 RootMxb1 Maximum DLC1.4 0019 ECD-R-20.out 3.660E+02 8.645E+02 -9.416E+01 2.680E+02 -1.166E+02 2.163E+02 9.388E+02 2.840E+02 2.457E+02 5.418E+01 1.219E+01 RootMyb1 Minimum DLC1.4 0013 ECD+R+20.out -7.970E+01 -2.106E+02 -3.945E+01 3.582E+02 1.980E+02 2.688E+02 2.252E+02 3.603E+02 3.339E+02 4.806E+01 2.157E+01 RootMyb1 Maximum DLC1.4 0019 ECD-R-20.out 3.262E+02 9.511E+02 -2.218E+01 3.108E+02 -1.762E+02 9.883E+01 1.005E+03 3.116E+02 2.020E+02 5.116E+01 1.219E+01 RootMxb2 Minimum DLC1.4 0019 ECD-R-20.out 1.320E+02 2.769E+02 -2.007E+02 1.172E+02 1.840E+02 8.386E+02 3.067E+02 2.325E+02 8.586E+02 5.150E+01 1.219E+01 RootMxb2 Maximum DLC1.4 0019 ECD-R-20.out -1.144E+02 1.863E+02 3.663E+02 8.674E+02 -7.590E+01 2.889E+02 2.186E+02 9.415E+02 2.987E+02 5.806E+01 1.219E+01 RootMyb2 Minimum DLC1.4 0013 ECD+R+20.out 1.997E+02 2.570E+02 -7.201E+01 -2.124E+02 -4.764E+01 3.486E+02 3.255E+02 2.242E+02 3.518E+02 4.758E+01 2.177E+01 RootMyb2 Maximum DLC1.4 0019 ECD-R-20.out -1.867E+02 1.158E+02 3.177E+02 9.513E+02 3.008E+00 3.575E+02 2.197E+02 1.003E+03 3.575E+02 5.066E+01 1.219E+01 RootMxb3 Minimum DLC1.4 0019 ECD-R-20.out 5.519E+01 4.325E+02 1.526E+02 4.469E+02 -1.910E+02 3.029E+02 4.360E+02 4.722E+02 3.581E+02 4.514E+01 1.627E+01 RootMxb3 Maximum DLC1.4 0019 ECD-R-20.out -7.768E+01 2.905E+02 -1.109E+02 1.953E+02 3.704E+02 8.637E+02 3.007E+02 2.246E+02 9.398E+02 5.466E+01 1.219E+01 RootMvb3 Minimum DLC1.4 0013 ECD+R+20.out -4.257E+01 3.702E+02 1.958E+02 2.719E+02 -7.812E+01 -2.037E+02 3.726E+02 3.350E+02 2.182E+02 4.854E+01 2.137E+01 RootMyb3 Maximum DLC1.4 0019 ECD-R-20.out 4.177E+00 3.082E+02 -1.586E+02 1.354E+02 3.187E+02 9.481E+02 3.082E+02 2.086E+02 1.000E+03 5.310E+01 1.219E+01 RootB1Mag Minimum DLC1.4 0007 ECD+R.out 7.707E+00 2.091E+00 -1.314E+02 2.375E+02 1.837E+02 2.722E+02 7.986E+00 2.714E+02 3.284E+02 4.518E+01 1.888E+01 RootB1Mag Maximum DLC1.4 0019 ECD-R-20.out 3.262E+02 9.511E+02 -2.218E+01 3.108E+02 -1.762E+02 9.883E+01 1.005E+03 3.116E+02 2.020E+02 5.116E+01 1.219E+01 RootB2Mag Minimum DLC1.4 0013 ECD+R+20.out 1.824E+02 2.824E+02 -3.580E+00 1.361E+00 -1.294E+02 2.265E+02 3.362E+02 3.830E+00 2.609E+02 4.466E+01 2.076E+01 RootB2Mag Maximum DLC1.4 0019 ECD-R-20.out -1.867E+02 1.158E+02 3.177E+02 9.513E+02 3.008E+00 3.575E+02 2.197E+02 1.003E+03 3.575E+02 5.066E+01 1.219E+01 RootB3Mag Minimum DLC1.4 0007 ECD+R.out -1.275E+02 3.529E+02 1.843E+02 3.214E+02 6.392E+00 -9.164E-01 3.752E+02 3.705E+02 6.458E+00 4.848E+01 1.765E+01 RootB3Mag Maximum DLC1.4 0019 ECD-R-20.out -2.527E+01 2.780E+02 -1.542E+02 1.540E+02 3.471E+02 9.472E+02 2.791E+02 2.179E+02 1.009E+03 5.020E+01 1.219E+01

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC1.4_0031_ECD-R+20.out -3.924E+02 -5.143E+01 3.958E+02 4.858E+01 2.135E+01 TwHt1Mlxt Maximum DLC1.4_0013_ECD+R+20.out 9.144E+02 7.405E+02 1.177E+03 4.920E+01 2.113E+01 TwHt1Mlyt Minimum DLC1.4_0031_ECD-R+20.out 1.905E+01 -2.207E+02 2.215E+02 4.790E+01 2.164E+01 TwHt1Mlyt Maximum DLC1.4_0019_ECD-R+20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Minimum DLC1.4_0031_ECD-R+20.out 2.835E+00 -6.295E+00 6.904E+00 4.710E+01 2.191E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 1.231E+02 3.059E+03 3.062E+03 4.396E+01 1.546E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.000E+00 4.556E+00 4.55

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC1.4_0019_ECD-R-20.out 1.366E+02 4.996E+01 1.219E+01 LSShftTq Maximum DLC1.4_0001_ECD+R-20.out 2.726E+02 4.414E+01 1.565E+01

DLC 1.5

Extreme events for Blade Moments:

Parameter Type File	RootMxb1 RootMyb1	RootMxb2 RootM kN*m) (kN*m) (kl	yb2 RootMxb3 F N*m) (kN*m) (k	lootMyb3 RootB N*m) (kN*m) kN	1Mag RootB2Mag N*m kN*m kN*m	RootB3Mag Time V (sec) (m/sec)	VindVxi	
RootMxb1 Minimum DLC1.5_0	055_EWSH-09.0.out -1	.916E+02 1.093E+	02 1.267E+02 3.	321E+02 1.329E	+02 3.096E+02 2.2	205E+02 3.555E+02	3.369E+02 4.518E+	-01 9.000E+00
RootMxb1 Maximum DLC1.5_0 RootMyb1 Minimum DLC1.5_0	103_EWSH-13.0.out 3. 253 EWSV+25.0.out -6	086E+02 7.229E+ 5.577E+00 -3.393E	02 -6.454E+01 3 E+02 -8.651E+01	.239E+02 -8.060 3.220E+02 1.87	E+01 3.646E+02 7 0E+02 2.915E+02	2.860E+02 3.302E+02 3.393E+02 3.334E+0	2 3.734E+02 4.566E 02 3.463E+02 4.650	E+01 1.300E+01 E+01 2.500E+01
RootMyb1 Maximum DLC1.5_0	103_EWSH-13.0.out 3.	073E+02 7.236E+	02 -4.672E+01 3	.407E+02 -9.711	E+01 3.465E+02 7	.861E+02 3.439E+02	2 3.599E+02 4.564E	+01 1.300E+01
RootMxb2 Minimum DLC1.5_0 RootMxb2 Maximum DLC1.5_0	103 EWSH-07.0.out 1. 103 EWSH-13.0.out -8	179E+02 2.040E+0 3.755E+01 3.599E+)2 -1.918E+02 5. ⊦02 3.074E+02 7	863E+01 1.172E .224E+02 -5.728	+02 2.230E+02 2 E+01 3.293E+02 3	356E+02 2.006E+02 .704E+02 7.851E+02	2.520E+02 4.6/0E- 2 3.342E+02 4.662E	-01 7.000E+00 E+01 1.300E+01
RootMyb2 Minimum DLC1.5_0	253_EWSV+25.0.out 1	.855E+02 2.992E+	02 -6.669E+00 -3	3.465E+02 -8.58	3E+01 3.239E+02	3.520E+02 3.466E+0	2 3.350E+02 4.602	E+01 2.500E+01
RootMyb2 Maximum DLC1.5_0 RootMxb3 Minimum DLC1.5_0	103_EWSH-13.0.out -8	432E+02 3.455E+(HO2 3.074E+02 7	.224E+02 -5.728)20E+02 -1.916E	E+01 3.293E+02 3 +02 1.054E+02 3.	740E+02 7.851E+02 740E+02 3.247E+02	2 3.342E+02 4.662E 2.186E+02 4.588E+	-01 9.000E+00
RootMxb3 Maximum DLC1.5_0	103_EWSH-13.0.out -6	5.041E+01 3.247E+	+02 -8.531E+01 3	3.587E+02 3.087	E+02 7.247E+02 3	.302E+02 3.687E+02	2 7.877E+02 4.614E	+01 1.300E+01
RootMyb3 Maximum DLC1.5_0	103_EWSV+25.0.out -4	1.277E+01 3.421E+	+02 1.8/3E+02 2 +02 -1.012E+02 3	.996E+02 - 7.668 8.407E+02 3.070	E+00 -3.371E+02 E+02 7.248E+02 3	5.282E+02 5.554E+0	2 7.871E+02 4.612E	E+01 2.500E+01
RootB1Mag Maximum DLC1.5 RootB2Mag Maximum DLC1.5	0103_EWSH-13.0.out	3.073E+02 7.236E	+02 -4.672E+01	3.407E+02 -9.71	1E+01 3.465E+02 8E+01 3 293E+02	7.861E+02 3.439E+	02 3.599E+02 4.564	E+01 1.300E+01
RootB3Mag Maximum DLC1.5_	0103_EWSH-13.0.out	-6.041E+01 3.247I	E+02 -8.531E+01	3.587E+02 3.08	7E+02 7.247E+02	3.302E+02 3.687E+	02 7.877E+02 4.614	E+01 1.300E+01

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC1.5_0211_EWSV-21.0.out -3.299E+02 1.955E+02 3.835E+02 4.638E+01 2.100E+01 TwHt1Mlxt Maximum DLC1.5_0229_EWSV+23.0.out 9.927E+02 7.440E+02 1.241E+03 4.586E+01 2.300E+01 TwHt1Mlyt Minimum DLC1.5_0013_EWSV+05.0.out 1.585E+02 -9.944E+02 1.007E+03 5.148E+01 5.000E+00 TwHt1Mlyt Maximum DLC1.5_0109_EWSV+13.0.out 3.032E+02 2.693E+03 2.710E+03 4.536E+01 1.300E+01 Tower Mag Maximum DLC1.5_0109_EWSV+13.0.out 5.636E+02 2.691E+03 2.749E+03 4.576E+01 1.300E+01

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC1.5_0001_EWSH+05.0.out 2.527E+01 3.044E+01 5.000E+00 LSShftTq Maximum DLC1.5 0109 EWSV+13.0.out 2.171E+02 4.508E+01 1.300E+01

DLC 2.1

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMxb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*

RootMxb1 Minimum DLC2.1_0009_25.0V0_S03.out -2.815E+02 9.364E+01 1.192E+02 4.721E+02 1.245E+02 1.389E+02 2.966E+02 4.869E+02 1.865E+02 3.674E+01 2.652E+01 RootMxb1 Maximum DLC2.1_0008_25.0V0_S02.out 6.465E+02 9.258E+02 1.481E+01 -3.850E+02 3.154E+01 -3.132E+02 1.129E+03 3.853E+02 3.148E+02 6.196E+01 2.920E+01 RootMyb1 Minimum DLC2.1_0007_25.0V0_S01.out -1.339E+02 -4.132E+02 1.613E+02 1.733E+02 1.285E+02 2.140E+02 4.344E+02 2.368E+02 2.496E+02 4.392E+01 3.128E+01 RootMyb1 Maximum DLC2.1_0008_25.0V0_S02.out 5.640E+02 1.200E+03 1.647E+02 -3.406E+02 1.055E+02 -6.202E+02 1.326E+03 3.783E+02 6.291E+02 6.162E+01 3.064E+01 RootMxb2 Minimum DLC2.1_0008_25.0V0_S02.out 5.640E+02 1.200E+03 3.97E+02 -2.438E+04 2.439E+01 2.415E+02 4.101E+02 2.870E+02 2.555E+02 3.754E+01 2.943E+01 RootMxb2 Maximum DLC2.1_0008_25.0V0_S02.out 1.611E+02 3.772E+02 -2.838E+04 2.4319E+01 8.338E+01 2.415E+02 1.052E+03 6.747E+02 5.955E+02 6.118E+01 3.097E+01 RootMxb2 Minimum DLC2.1_0007_25.0V0_S01.out 2.214E+02 1.032E+03 1.855E+02 -7.063E+02 2.815E+02 -5.021E+02 1.055E+03 7.303E+02 5.756E+02 6.108E+01 3.097E+01 RootMyb2 Maximum DLC2.1_0004_13.5V0_S04.out -1.085E+02 4.707E+02 4.000E+01 7.750E+02 2.238E+02 5.189E+02 4.831E+02 7.761E+02 5.652E+02 5.702E+01 1.377E+01 RootMxb3 Minimum DLC2.1_0008_25.0V0_S02.out 6.670E+01 3.039E+02 2.233E+02 2.068E+02 -3.195E+02 9.742E+01 3.111E+02 3.044E+02 3.341E+02 3.708E+01 3.090E+01 RootMxb3 Maximum DLC2.1_0007_25.0V0_S01.out 2.523E+02 7.698E+02 2.076E+02 -5.774E+02 4.331E+02 -3.710E+02 8.101E+02 6.136E+02 5.702E+02 6.114E+01 2.634E+01 RootMxb3 Minimum DLC2.1_0007_25.0V0_S06.out 1.833E+02 6.303E+02 1.870E+02 5.509E+02 5.939E+01 8.416E+02 4.6564E+02 6.096E+02 8.635E+02 6.098E+01 2.244E+01 RootMyb3 Maximum DLC2.1_0007_25.0V0_S06.out 1.833E+02 6.303E+02 1.870E+02 5.509E+02 5.939E+01 8.416E+02 4.6564E+02 6.096E+02 8.635E+02 6.602E+01 3.064E+01 RootMyb3 Maximum DLC2.1_0008_25.0V0_S02.out 5.640E+02 1.200E+03 1.647E+02 -5.802E+02 4.035E+02 -7.634E+02 6.564E+02 6.096E+02 8.635E+02 6.602E+01 3.064E+01 RootB1Mag Maximum DLC2.1_

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC2.1_0008_25.0V0_S02.out -5.449E+03 -9.688E+03 1.111E+04 6.240E+01 2.946E+01 TwHt1Mlxt Maximum DLC2.1_0010_25.0V0_S04.out 4.749E+03 6.496E+03 8.047E+03 6.176E+01 2.505E+01 TwHt1Mlyt Minimum DLC2.1_0008_25.0V0_S02.out -5.380E+03 -9.809E+03 1.119E+04 6.236E+01 2.944E+01 TwHt1Mlyt Maximum DLC2.1_0008_25.0V0_S02.out 3.947E+03 8.316E+03 9.205E+03 6.298E+01 2.852E+01 Tower Mag Maximum DLC2.1_0008_25.0V0_S02.out -5.380E+03 -9.809E+03 1.119E+04 6.236E+01 2.944E+01 TwHt1Mlyt Maximum DLC2.1_0008_25.0V0_S02.out 3.947E+03 8.316E+03 9.205E+03 6.298E+01 2.852E+01 Tower Mag Maximum DLC2.1_0008_25.0V0_S02.out -5.380E+03 -9.809E+03 1.119E+04 6.236E+01 2.944E+01 TwHt1Mlyt Maximum DLC2.1_0008_25.0V0_S02.out -5.380E+03 -9.809E+03 1.119E+04 6.236E+01 2.944E+01 TwHt1Mlyt Maximum DLC2.1_0008_25.0V0_S02.out -5.380E+03 -9.809E+03 1.119E+04 6.236E+01 2.944E+01 TwH1Mlyt Maximum DLC2.1_0008_25.0V0_S02.0Ut -5.380E+03 -9.809E+03 1.119E+04 6.236E+01 2.944E+01 TWH1ML20008_25.0V0_S02.0Ut -5.380E+03 -9.809E+03 1.119E+04 6.236E+01 2.944E+01 2.944E

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC2.1_0012_25.0V0_S06.out -2.118E+02 6.258E+01 2.916E+01 LSShftTq Maximum DLC2.1_0007_25.0V0_S01.out 3.540E+02 6.032E+01 2.359E+01

DLC 2.3

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMxb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*

RootMxb1 Minimum DLC2.3_0004_EOGR-20_S04.out -2.064E+02 2.495E+02 4.632E+01 2.896E+02 -1.309E+01 2.308E+02 3.238E+02 2.932E+02 2.312E+02 4.648E+01 1.316E+01 RootMxb1 Maximum DLC2.3_0014_EOGO_S02.out 3.402E+02 -2.160E+02 1.964E+02 -3.210E+02 1.224E+02 -4.219E+02 4.030E+02 3.763E+02 4.393E+02 4.320E+01 2.371E+01 RootMyb1 Minimum DLC2.3_0009_EOGR+20_S03.out 7.944E+01 -5.040E+02 3.169E+02 -3.045E+02 2.280E+02 -3.210E+02 5.102E+02 4.395E+02 3.937E+02 4.564E+01 2.022E+01 RootMyb1 Maximum DLC2.3_0004_EOGR-20_S04.out 3.903E+01 5.091E+02 1.654E+02 4.925E+02 -1.022E+02 4.714E+02 5.106E+02 5.195E+02 4.2328E+02 4.532E+01 1.569E+01 RootMxb2 Minimum DLC2.3_0005_EOGR-20_S05.out 3.260E+00 8.437E+01 -2.180E+02 1.082E+02 3.975E+01 1.533E+02 8.443E+01 2.438E+02 4.898E+01 1.070E+01 RootMxb2 Minimum DLC2.3_0012_EOGR+20_S06.out 1.731E+02 -4.296E+02 3.538E+02 -4.159E+02 1.022E+02 -4.388E+02 4.631E+02 5.460E+02 4.505E+02 5.162E+01 1.550E+01 RootMyb2 Minimum DLC2.3_0004_EOGR-20_S04.out 2.549E+02 -4.374E+02 1.880E+02 5.079E+02 -2.057E+01 4.588E+02 4.988E+02 5.415E+02 4.593E+02 4.738E+01 1.060E+01 RootMyb2 Maximum DLC2.3_0004_EOGR-20_S04.out -6.507E+01 4.946E+02 1.880E+02 5.079E+02 -2.057E+01 4.588E+02 4.988E+02 5.415E+02 4.593E+02 4.534E+01 1.567E+01 RootMxb3 Minimum DLC2.3_0007_EOGR+20_S01.out -3.914E+01 2.092E+02 4.125E+01 1.530E+02 -2.171E+02 1.196E+02 2.128E+02 1.585E+02 2.479E+02 4.020E+01 1.550E+01 RootMxb3 Maximum DLC2.3_0009_EOGR+20_S03.out 1.314E+02 -4.275E+02 1.850E+02 -4.037E+02 -4.102E+02 -4.102E+02 4.441E+02 5.530E+02 4.534E+01 2.057E+01 RootMyb3 Minimum DLC2.3_0004_EOGR-20_S04.out 2.305E+02 -3.900E+02 3.182E+02 -2.355E+02 5.768E+01 -5.071E+02 4.530E+02 3.959E+02 5.104E+01 4.550E+01 RootMyb3 Minimum DLC2.3_0004_EOGR-20_S04.out 3.05E+02 -3.900E+02 4.835E+02 -1.125E+02 4.732E+02 5.059E+02 4.556E+01 4.568E+01 RootMyb3 Maximum DLC2.3_0004_EOGR-20_S04.out 1.34E+02 -4.275E+02 4.835E+02 -1.125E+02 4.732E+02 5.122E+02 5.059E+02 4.550E+01 1.550E+01 RootMyb3 Maximum DLC2.3_0004_EOGR-20_S04.out 1.382E+02 -3.398E+02 -4.037E+02 -4.102E+

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC2.3_0012_EOGR+20_S06.out -5.582E+02 -2.886E+03 2.940E+03 5.208E+01 1.550E+01 TwHt1Mlxt Maximum DLC2.3_0013_EOGO_S01.out 5.683E+02 3.892E+02 6.888E+02 4.014E+01 2.500E+01 TwHt1Mlyt Minimum DLC2.3_0010_EOGR+20_S04.out 5.335E+00 -5.642E+03 5.642E+03 4.724E+01 1.477E+01 TwHt1Mlyt Maximum DLC2.3_0004_EOGR-20_S04.out 9.254E+01 2.655E+03 2.657E+03 4.542E+01 1.565E+01 Tower Mag Maximum DLC2.3_0010_EOGR+20_S04.out 5.335E+00 -5.642E+03 5.642E+03 4.724E+01 1.477E+01

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC2.3_0016_EOGO_S04.out -2.087E+02 4.688E+01 2.563E+01 LSShftTq Maximum DLC2.3_0004_EOGR-20_S04.out 2.318E+02 4.574E+01 1.523E+01

DLC 6.1

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMxb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*

RootMxb1 Minimum DLC6.1a_0010_40.4V0_352ny_S04.out -7.792E+01 -3.143E+02 -9.901E+00 1.465E+02 4.217E+01 1.963E+02 3.238E+02 1.468E+02 2.008E+02 5.980E+02 4.317E+01 RootMxb1 Maximum DLC6.1a_0007_40.4V0_352ny_S03.out 1.034E+02 4.243E+02 -4.678E+00 -3.333E+02 -2.849E+01 -7.808E+01 4.367E+02 3.333E+02 8.312E+01 3.874E+01 5.007E+01 RootMyb1 Minimum DLC6.1a_0018_40.4V0_008ny_S06.out 8.239E+01 -4.975E+02 5.765E+01 3.251E+02 -1.457E+01 1.465E+02 4.975E+02 3.302E+02 1.472E+02 4.163E+02 4.807E+01 RootMyb1 Maximum DLC6.1a_0007_40.4V0_352ny_S03.out 8.720E+01 5.522E+02 -7.131E+00 -2.237E+02 -2.913E+00 -3.213E+02 5.590E+02 2.238E+02 3.213E+02 2.860E+02 5.285E+01 RootMxb2 Minimum DLC6.1a_0005_40.4V0_000ny_S02.out -2.169E+01 -3.974E+01 -6.889E+01 2.094E+01 -3.278E+01 1.590E+01 4.528E+01 7.200E+01 3.643E+01 3.643E+01 5.068E+01 RootMxb2 Minimum DLC6.1a_0013_40.4V0_08ny_S01.out -1.848E+01 -3.371E+02 1.099E+02 3.557E+02 -6.439E+00 2.789E+01 3.376E+02 3.723E+02 2.862E+01 1.142E+02 5.143E+01 RootMyb2 Minimum DLC6.1a_0012_40.4V0_08ny_S01.out -2.668E+01 -2.338E+02 6.728E+01 5.404E+02 -4.837E+00 -3.025E+02 1.547E+02 5.246E+02 3.026E+02 7.294E+01 4.772E+01 RootMxb3 Minimum DLC6.1a_0007_40.4V0_08ny_S01.out -2.668E+01 -2.338E+02 6.728E+01 5.404E+02 -4.837E+00 -3.025E+02 1.342E+02 3.026E+02 7.294E+01 4.772E+01 RootMxb3 Minimum DLC6.1a_0003_40.4V0_08ny_S01.out -1.027E+01 -1.340E+02 -1.844E+01 -3.528E+02 1.140E+02 4.990E+02 1.344E+02 3.532E+02 5.946E+02 5.992E+01 RootMxb3 Maximum DLC6.1a_0003_40.4V0_08ny_S01.out -1.027E+01 -1.340E+02 -1.844E+01 -3.528E+02 1.140E+02 4.990E+02 1.344E+02 3.532E+02 5.138E+02 6.285E+02 4.845E+01 RootMyb3 Minimum DLC6.1a_0003_40.4V0_08ny_S01.out -1.027E+01 -1.849E+02 -1.974E+01 -3.528E+02 1.140E+02 4.990E+02 1.344E+02 3.532E+02 5.118E+02 6.285E+02 4.845E+01 RootMyb3 Maximum DLC6.1a_0003_40.4V0_08ny_S01.out 1.524E-01 -1.899E+02 -1.974E+01 -3.409E+02 2.913E+00 -3.213E+02 3.532E+02 3.213E+02 5.299E+02 5.241E+01 RootMyb3 Maximum DLC6.1a_0003_40.4V0_08ny_S03.out 8.720E+01 5.522E+02 -1.974E+01 -3.409E+02 2.913E+00 -3.21

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC6.1a_0007_40.4V0_352ny_S03.out -4.049E+03 -4.143E+02 4.070E+03 2.849E+02 5.251E+01 TwHt1Mlxt Maximum DLC6.1a_0009_40.4V0_008ny_S03.out 3.282E+03 -5.636E+02 3.330E+03 8.844E+01 5.075E+01 TwHt1Mlyt Minimum DLC6.1a_0006_40.4V0_008ny_S02.out 4.062E+02 -2.207E+03 2.244E+03 3.754E+01 3.820E+01 TwHt1Mlyt Maximum DLC6.1a_0006_40.4V0_008ny_S02.out 1.521E+03 1.238E+03 1.961E+03 3.586E+01 5.155E+01 Tower Mag Maximum DLC6.1a_0007_40.4V0_352ny_S03.out -4.049E+03 -4.143E+02 4.070E+03 2.849E+02 5.251E+01

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC6.1a_0007_40.4V0_352ny_S03.out -9.692E+01 3.609E+02 4.979E+01 LSShftTq Maximum DLC6.1a_0007_40.4V0_352ny_S03.out 9.707E+01 3.607E+02 4.785E+01

DLC 6.2

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMyb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) kN*m kN*m kN*m (sec) (m/sec)

RootMxb1 Minimum DLC6.2a_0011_40.4V0_040ny_S01.out -1.752E+02 -7.992E+02 7.742E+01 2.577E+02 6.750E+01 5.347E+02 8.182E+02 2.691E+02 5.390E+02 4.820E+02 4.604E+01 RootMxb1 Maximum DLC6.2a_0046_40.4V0_020ny_S03.out 2.290E+02 8.821E+02 -1.844E+01 -1.812E+02 -3.440E+00 -6.751E+02 9.113E+02 1.821E+02 6.751E+02 5.943E+02 5.501E+01 RootMyb1 Minimum DLC6.2a_0041_40.4V0_280ny_S03.out -1.289E+02 -9.412E+02 -1.105E+01 2.642E+02 5.412E+01 6.552E+02 9.500E+02 2.644E+02 6.574E+02 5.970E+02 5.126E+01 RootMyb1 Maximum DLC6.2a_0085_40.4V0_080ny_S05.out 6.547E+01 9.014E+02 -1.085E+02 -6.982E+02 -1.704E+01 -2.018E+02 9.038E+02 7.066E+02 2.025E+02 1.417E+02 5.613E+01 RootMxb2 Minimum DLC6.2a_0047_40.4V0_060ny_S01.out 3.344E+01 6.608E+02 -1.805E+02 -7.017E+02 -6.684E+00 1.928E+01 6.617E+02 7.246E+02 2.040E+01 1.140E+02 5.090E+01 RootMxb2 Maximum DLC6.2a_0047_40.4V0_040ny_S03.out -4.394E+01 -5.405E+02 1.890E+02 7.663E+02 -1.586E+01 -1.931E+02 5.432E+02 7.892E+02 1.937E+02 2.851E+02 5.106E+01 RootMyb2 Minimum DLC6.2a_0047_40.4V0_040ny_S03.out -7.482E+00 3.945E+02 -1.721E+02 -7.817E+02 1.039E+02 3.974E+02 3.945E+02 8.004E+02 4.108E+02 3.235E+02 5.425E+01 RootMyb2 Maximum DLC6.2a_0047_40.4V0_040ny_S03.out -5.490E+01 -5.115E+02 1.393E+02 8.031E+02 -4.952E+01 -2.611E+02 5.145E+02 8.151E+02 2.657E+02 2.860E+02 5.315E+01 RootMxb3 Minimum DLC6.2a_0047_40.4V0_040ny_S03.out -5.490E+01 -5.115E+02 2.935E+01 4.396E+02 -1.661E+02 -6.993E+02 2.446E+02 4.396E+02 7.187E+02 3.810E+02 5.087E+01 RootMxb3 Maximum DLC6.2a_0029_40.4V0_040ny_S03.out -5.490E+01 -5.318E+02 2.935E+01 -5.088E+02 2.119E+02 6.723E+02 2.006E+02 5.097E+02 7.482E+01 4.988E+01 RootMyb3 Minimum DLC6.2a_0029_40.4V0_040ny_S03.out -7.772E+01 -3.949E+02 -2.939E+01 -5.088E+02 2.119E+02 6.723E+02 2.446E+02 4.954E+02 7.462E+02 4.867E+01 RootMyb3 Maximum DLC6.2a_0044_40.4V0_040ny_S03.out -7.772E+01 -3.494E+02 -2.937E+02 4.371E+02 1.655E+02 8.243E+02 3.579E+02 4.372E+02 8.414E+02 1.396E+02 4.977E+01 RootMyb3 Maximum DLC6.2a_0044_40.4V0_040ny_S03.out -7.772E+01 -3.494E+02 -5.975E+00 -4.371E+0

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC6.2a_0008_40.4V0_340ny_S01.out -4.522E+03 7.086E+02 4.578E+03 1.137E+02 5.110E+01 TwHt1Mlxt Maximum DLC6.2a_0065_40.4V0_040ny_S04.out 6.001E+03 1.084E+02 6.002E+03 1.571E+02 5.677E+01 TwHt1Mlyt Minimum DLC6.2a_0011_40.4V0_040ny_S01.out 1.660E+03 -2.693E+03 3.164E+03 3.054E+01 3.876E+01 TwHt1Mlyt Maximum DLC6.2a_0013_40.4V0_080ny_S01.out 7.482E+02 5.805E+03 5.853E+03 1.139E+02 4.945E+01 Tower Mag Maximum DLC6.2a_0065_40.4V0_040ny_S04.out 6.001E+03 1.084E+02 6.002E+03 1.571E+02 5.677E+01

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC6.2a_0053_40.4V0_160ny_S03.out -9.990E+01 3.302E+01 4.738E+01 LSShftTq Maximum DLC6.2a_0028_40.4V0_020ny_S02.out 1.042E+02 5.539E+02 5.370E+01

DLC 6.3

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMyb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) kN*m kN*m kN*m (sec) (m/sec)

RootMxb1 Minimum DLC6.3a_0002_32.3V0_000ny_S01.out -5.202E+01 2.612E+01 -2.248E+01 3.745E+01 -2.261E+01 -4.321E+01 5.821E+01 4.368E+01 4.877E+01 6.253E+02 3.991E+01 RootMxb1 Maximum DLC6.3a_0009_32.3V0_020ny_S03.out 1.274E+02 5.077E+02 -2.398E+01 -4.803E+01 -5.983E+00 -4.594E+02 5.235E+02 5.368E+01 4.594E+02 5.941E+02 4.478E+01 RootMyb1 Minimum DLC6.3a_0009_32.3V0_020ny_S03.out 1.274E+02 5.077E+02 -2.398E+01 -4.803E+01 -5.983E+00 -4.594E+02 5.235E+02 5.368E+01 4.594E+02 5.941E+02 4.478E+01 RootMxb2 Minimum DLC6.3a_0009_32.3V0_020ny_S03.out 1.274E+02 5.077E+02 -2.398E+01 -4.803E+01 -5.983E+00 -4.594E+02 5.235E+02 5.368E+01 4.594E+02 5.941E+02 4.478E+01 RootMxb2 Minimum DLC6.3a_0012_32.3V0_020ny_S03.out 1.274E+02 5.077E+02 -2.398E+01 -4.803E+01 -5.983E+00 6.781E+01 2.209E+02 2.806E+02 6.826E+01 3.566E+01 3.955E+01 RootMxb2 Maximum DLC6.3a_0015_32.3V0_020ny_S05.out -2.796E+00 -3.606E+02 1.111E+02 4.086E+02 -1.409E+01 -3.559E+01 3.606E+02 4.235E+02 3.826E+01 3.556E+01 RootMyb2 Minimum DLC6.3a_0012_32.3V0_020ny_S05.out -2.246E+01 -2.693E+01 -9.778E+00 -4.309E+02 1.141E+02 4.320E+02 3.507E+01 4.310E+02 4.468E+02 7.534E+01 4.166E+01 RootMyb2 Maximum DLC6.3a_0007_32.3V0_340ny_S03.out -4.034E+01 -1.754E+02 7.880E+01 5.185E+02 -1.928E+01 -3.414E+02 1.799E+02 5.245E+02 3.420E+02 5.956E+02 3.960E+01 RootMxb3 Minimum DLC6.3a_0013_32.3V0_020ny_S03.out -2.061E+01 -3.985E+01 4.482E+01 2.913E+02 4.478E+01 -2.743E+02 4.487E+01 2.948E+02 2.785E+02 5.178E+02 3.638E+01 RootMxb3 Maximum DLC6.3a_0012_32.3V0_020ny_S03.out -1.426E+01 -2.624E+01 -6.002E+00 -3.398E+02 1.407E+00 3.841E+02 2.987E+01 3.398E+02 4.090E+02 7.444E+01 4.057E+01 RootMyb3 Minimum DLC6.3a_0012_32.3V0_020ny_S03.out 1.272E+02 5.058E+02 -2.141E+01 -4.929E+01 -8.047E+00 4.616E+02 5.216E+02 5.374E+01 4.616E+02 5.941E+02 4.460E+01 RootMyb3 Maximum DLC6.3a_0009_32.3V0_020ny_S03.out 1.272E+02 5.058E+02 -2.141E+01 -4.929E+01 -3.414E+02 1.799E+02 5.25E+02 3.40E+02 5.95E+02 3.40E+01 4.270E+01 RootB1Mag Maximum DLC6.3a_0009_32.3V0_020ny_S03.out 1.272E+02 5.058E+02 -2.141E+01 -

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC6.3a_0007_32.3V0_340ny_S03.out -3.055E+03 -6.309E+02 3.120E+03 6.510E+01 4.009E+01 TwHt1Mlxt Maximum DLC6.3a_0015_32.3V0_020ny_S05.out 3.266E+03 -2.724E+02 3.277E+03 4.983E+02 3.680E+01 TwHt1Mlyt Minimum DLC6.3a_0006_32.3V0_020ny_S02.out 9.974E+02 -2.352E+03 2.554E+03 3.056E+01 3.062E+01 TwHt1Mlyt Maximum DLC6.3a_0006_32.3V0_020ny_S02.out 1.692E+03 1.267E+03 2.113E+03 3.344E+01 3.813E+01 Tower Mag Maximum DLC6.3a_0009 32.3V0_020ny_S03.out 3.127E+03 -1.160E+03 3.335E+03 8.220E+01 3.698E+01

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC6.3a_0017_32.3V0_000ny_S06.out -5.863E+01 5.482E+02 3.675E+01 LSShftTq Maximum DLC6.3a_0017_32.3V0_000ny_S06.out 5.607E+01 5.476E+02 3.216E+01

DLC 7.1

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMyb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) kN*m kN*m kN*m (sec) (m/sec)

RootMxb1 Minimum DLC7.1a_0009_32.3V0_008ny_S03.out -1.762E+02 3.172E+02 3.548E+01 2.466E+02 -2.288E+00 -6.145E+01 3.629E+02 2.492E+02 6.149E+01 2.987E+02 3.521E+01 RootMxb1 Maximum DLC7.1a_0014_32.3V0_0352ny_S02.out 2.343E+02 4.651E+02 3.828E+00 6.287E+00 1.951E+00 -2.529E+02 5.208E+02 7.360E+00 2.529E+02 5.542E+02 4.364E+01 RootMyb1 Minimum DLC7.1a_0014_32.3V0_000ny_S05.out 3.775E+01 1.327E+02 -1.470E+01 -1.103E+02 -1.499E+01 7.765E+01 1.379E+02 1.113E+02 7.908E+01 4.035E+02 2.678E+01 RootMyb1 Maximum DLC7.1a_0007_32.3V0_352ny_S03.out 1.827E+02 6.812E+02 1.642E+00 6.619E+01 -1.005E+01 -2.456E+02 7.053E+02 6.621E+01 2.458E+02 2.855E+02 4.252E+01 RootMxb2 Minimum DLC7.1a_0003_32.3V0_008ny_S01.out -1.108E+02 3.582E+02 -4.111E+01 7.765E+01 -1.672E+01 3.187E+01 3.749E+02 8.786E+01 3.599E+01 3.118E+01 2.876E+01 RootMxb2 Minimum DLC7.1a_0003_32.3V0_008ny_S01.out -1.456E+02 3.781E+02 3.983E+01 2.011E+02 -2.289E+00 -2.725E+01 4.052E+02 2.050E+02 2.734E+01 5.440E+02 3.600E+01 RootMyb2 Minimum DLC7.1a_0013_32.3V0_008ny_S01.out -1.252E+02 4.946E+02 3.455E+01 1.768E+02 -9.912E+00 9.515E+01 3.36E+02 1.775E+02 9.566E+01 6.372E+01 3.223E+01 RootMxb3 Minimum DLC7.1a_0004_32.3V0_038ny_S01.out -1.252E+02 4.946E+02 3.455E+01 2.934E+02 -6.942E-01 -1.449E+02 5.102E+02 2.954E+02 1.449E+02 4.818E+02 3.624E+01 RootMxb3 Minimum DLC7.1a_0004_32.3V0_352ny_S02.out 1.782E+02 4.681E+02 -8.691E+00 4.104E+01 -5.374E+01 -2.160E+02 5.008E+02 4.195E+01 2.226E+02 5.318E+02 4.244E+01 RootMxb3 Maximum DLC7.1a_0004_32.3V0_352ny_S02.out 1.912E+02 4.638E+02 2.531E+01 4.102E+01 3.433E+01 -2.154E+02 5.016E+02 4.820E+01 2.181E+02 3.827E+01 RootMyb3 Minimum DLC7.1a_0004_32.3V0_352ny_S05.out 1.902E+02 5.318E+02 4.693E+00 -3.405E+01 -7.037E+00 1.464E+02 3.602E+02 3.437E+01 2.181E+02 3.827E+01 RootMyb3 Minimum DLC7.1a_0004_32.3V0_000ny_S05.out 1.902E+02 5.378E+02 4.292E+01 -7.037E+00 1.464E+02 5.016E+02 4.820E+01 2.181E+02 3.827E+01 RootMyb3 Maximum DLC7.1a_0004_32.3V0_000ny_S05.out 1.250E+02 3.378E+02 4.693E+00 -3.405E+01 -7.037E+00 1.464E+02 3.602E+02 3.43

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC7.1a_0007_32.3V0_352ny_S03.out -1.964E+03 -1.602E+02 1.970E+03 2.824E+02 3.561E+01 TwHt1Mlxt Maximum DLC7.1a_0018_32.3V0_008ny_S06.out 1.622E+03 -6.564E+01 1.624E+03 4.678E+02 3.792E+01 TwHt1Mlyt Minimum DLC7.1a_0003_32.3V0_008ny_S01.out 6.735E+02 -1.339E+03 1.499E+03 5.948E+02 3.104E+01 TwHt1Mlyt Maximum DLC7.1a_0004_32.3V0_352ny_S02.out -7.411E+02 1.983E+03 2.117E+03 5.295E+02 4.228E+01 Tower Mag Maximum DLC7.1a_0004_32.3V0_352ny_S02.out -7.611E+02 1.983E+03 2.124E+03 5.295E+02 4.214E+01

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC7.1a_0003_32.3V0_008ny_S01.out -4.477E+01 1.112E+02 4.306E+01 LSShftTq Maximum DLC7.1a_0006_32.3V0_008ny_S02.out 5.195E+01 6.007E+02 3.620E+01

C.2 Time Series Plots

DLC 1.1







C-13







DLC 1.3







Time Series Plots of Blade 3 Moments



Time Series Plots of Shaft Torque







DLC 1.4

















Time Series Plots of Shaft Torque







DLC 1.5



Time Series Plots of Wind Speeds

(Note: This DLC uses the EWS wind model, which is not illustrated in the figure above.)



Time Series Plots of Blade 1 Moments









Time Series Plots of Shaft Torque







DLC 2.1







Time Series Plots of Blade 2 Moments



Time Series Plots of Blade 3 Moments



Time Series Plots of Shaft Torque







DLC 2.3

Time Series Plots of Wind Speeds







Time Series Plots of Blade 2 Moments







Time Series Plots of Shaft Torque








Time Series Plots of Wind Speeds









Time Series Plots of Shaft Torque









Time Series Plots of Wind Speeds







Time Series Plots of Blade 3 Moments











Time Series Plots of Wind Speeds











Time Series Plots of Shaft Torque







DLC 7.1















Appendix D: DTT Damping Controller Results

D.1 Extreme Events Tables

DLC 1.1

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMxb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*

RootMxb1 Minimum DLC1.1_0063_25.0V0_S03.out -3.834E+02 3.020E+02 1.191E+02 6.051E+02 -2.769E+01 6.371E+02 4.880E+02 6.167E+02 6.377E+02 5.792E+02 3.067E+01 RootMxb1 Maximum DLC1.1_0058_23.0V0_S04.out 3.984E+02 -1.256E+02 -8.906E+01 -2.200E+02 -7.432E+00 -1.366E+01 4.177E+02 2.374E+02 1.555E+01 6.196E+01 2.527E+01 RootMyb1 Minimum DLC1.1_0054_21.0V0_S06.out 9.469E+01 -6.120E+02 -5.363E+00 -5.597E+01 2.817E+02 2.631E+02 6.193E+02 5.622E+01 3.855E+02 1.760E+02 2.740E+01 RootMxb2 Minimum DLC1.1_0054_21.0V0_S06.out 9.896E+01 1.083E+03 2.217E+02 6.677E+02 -2.223E+02 5.848E+02 1.088E+03 7.035E+02 6.257E+02 2.921E+02 1.708E+01 RootMxb2 Minimum DLC1.1_0055_23.0V0_S02.out 1.011E+02 4.813E+02 -3.876E+02 1.139E+02 1.237E+02 6.724E+02 4.918E+02 4.040E+02 6.837E+02 1.485E+02 2.362E+01 RootMxb2 Minimum DLC1.1_0054_25.0V0_S01.out 9.200E+01 -1.707E+02 4.097E+02 -1.353E+02 -2.241E+01 -3.862E+02 1.939E+02 4.314E+02 3.869E+02 1.165E+02 2.939E+01 RootMxb2 Minimum DLC1.1_0054_25.0V0_S03.out -1.398E+02 6.246E+02 3.115E+02 1.006E+03 2.335E+01 4.922E+02 6.401E+02 1.053E+03 4.927E+02 2.854E+01 RootMxb3 Minimum DLC1.1_0054_25.0V0_S06.out 1.352E+02 7.556E+02 7.243E+01 5.293E+02 -3.822E+02 2.572E+01 7.675E+02 5.343E+02 3.831E+02 3.954E+02 2.483E+01 RootMxb3 Minimum DLC1.1_0055_23.0V0_S06.out 1.352E+02 7.556E+02 7.243E+01 -1.801E+02 3.957E+02 -2.034E+02 3.302E+02 1.860E+02 4.449E+02 1.171E+02 2.932E+01 RootMxb3 Maximum DLC1.1_0055_23.0V0_S01.out 3.906E+01 -3.279E+02 3.235E+02 -3.822E+02 2.572E+01 7.675E+02 5.343E+02 3.831E+02 3.954E+02 2.483E+01 RootMxb3 Maximum DLC1.1_0055_23.0V0_S04.out -2.260E+01 7.086E+02 3.235E+02 6.750E+00 1.953E+02 -2.034E+02 3.302E+02 1.860E+02 4.449E+02 1.171E+02 2.942E+01 RootMyb3 Minimum DLC1.1_0054_21.0V0_S04.out -2.260E+01 7.086E+02 3.235E+02 6.750E+00 1.953E+02 -6.549E+02 1.976E+02 3.236E+02 6.257E+02 2.922E+01 RootMyb3 Maximum DLC1.1_0054_21.0V0_S04.out -2.260E+01 7.086E+02 3.217E+02 6.677E+02 -2.233E+02 5.848E+02 1.062E+03 7.030E+02 7.871E+02 1.066E+03 3.655E+02 1.276E+01 RootB1Mag Maximum DLC1.1_0024_17.0V0

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC1.1_0006_05.0V0_S06.out -1.314E+03 -5.012E+02 1.407E+03 2.827E+02 6.749E+00 TwHt1Mlxt Maximum DLC1.1_0064_25.0V0_S04.out 1.944E+03 1.120E+03 2.244E+03 7.644E+01 2.847E+01 TwHt1Mlyt Minimum DLC1.1_0002_05.0V0_S02.out -4.266E+02 -1.900E+03 1.948E+03 5.986E+01 4.049E+00 TwHt1Mlyt Maximum DLC1.1_0054_21.0V0_S06.out 4.317E+02 3.636E+03 3.662E+03 2.918E+02 1.517E+01 Tower Mag Maximum DLC1.1_0054_21.0V0_S06.out 4.317E+02 3.636E+03 3.662E+03 2.918E+02 1.517E+01

Extreme events for Shaft Torque:

LSShftTq Time WindVxi

Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC1.1_0002_05.0V0_S02.out -1.565E+01 6.396E+01 1.583E+00 LSShftTq Maximum DLC1.1_0065_25.0V0_S05.out 3.400E+02 4.733E+02 2.581E+01

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMxb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*

RootMxb1 Minimum DLC1.3_0066_25.0V0_S06.out -4.269E+02 4.308E+02 1.049E+02 5.782E+02 5.000E+01 1.415E+02 6.065E+02 5.876E+02 1.501E+02 4.870E+02 2.765E+01 RootMxb1 Maximum DLC1.3_0066_25.0V0_S06.out 4.629E+02 8.346E+01 1.357E+02 -3.268E+02 -9.875E+01 -5.122E+02 4.704E+02 3.539E+02 5.216E+02 4.877E+02 2.940E+01 RootMyb1 Minimum DLC1.3_0042_25.0V0_S04.out 6.299E+01 -7.451E+02 1.271E+02 1.615E+02 2.685E+02 -9.694E+01 7.477E+02 2.055E+02 2.855E+02 5.717E+02 3.059E+01 RootMyb1 Maximum DLC1.3_0042_17.0V0_S06.out 1.2963E+02 1.037E+03 -2.600E+01 4.116E+02 -1.295E+02 5.543E+02 1.078E+03 4.124E+02 5.692E+02 2.638E+02 1.250E+01 RootMxb2 Minimum DLC1.3_0066_25.0V0_S06.out 1.723E+02 6.835E+02 -4.166E+02 9.322E+01 -1.455E+01 6.070E+02 7.049E+02 4.269E+02 6.071E+02 6.071E+02 4.071E+02 3.078E+01 RootMxb2 Maximum DLC1.3_0055_23.0V0_S01.out 1.256E+02 -2.101E+02 4.252E+02 -2.126E+02 8.855E+01 -3.792E+02 2.447E+02 4.754E+02 1.331E+02 5.885E+02 1.77E+02 3.078E+01 RootMyb2 Minimum DLC1.3_0062_25.0V0_S01.out 1.256E+01 4.103E+02 3.337E+02 1.072E+03 -9.351E+01 5.909E+02 4.155E+02 1.123E+03 5.982E+02 4.227E+02 1.331E+02 5.885E+02 2.944E+01 RootMyb2 Maximum DLC1.3_0019_11.0V0_S01.out -6.576E+01 4.103E+02 3.337E+02 4.698E+02 -4.140E+02 6.653E+01 4.013E+02 4.917E+02 4.194E+02 5.882E+02 2.723E+01 RootMxb3 Minimum DLC1.3_0055_23.0V0_S01.out 9.437E+01 -3.664E+02 5.107E+01 -2.330E+02 4.159E+02 -2.456E+02 3.783E+02 2.385E+02 4.830E+02 1.171E+02 3.053E+01 RootMxb3 Maximum DLC1.3_0055_23.0V0_S01.out 9.437E+01 -3.664E+02 5.107E+01 -2.330E+02 4.159E+02 -2.456E+02 3.783E+02 2.385E+02 4.830E+02 1.171E+02 3.053E+01 RootMyb3 Minimum DLC1.3_0035_15.0V0_S02.out 1.408E+02 6.500E+01 2.601E+02 -9.960E+01 2.580E+02 -7.443E+02 1.003E+02 2.786E+02 7.877E+02 5.886E+02 3.073E+01 RootMyb3 Minimum DLC1.3_0032_15.0V0_S02.out -1.408E+02 6.500E+02 -9.661E+01 7.714E+02 3.366E+02 1.003E+02 1.03E+02 1.36E+02 1.312E+02 1.23E+03 3.820E+02 1.456E+01 RootB1Mag Maximum DLC1.3_0032_15.0V0_S02.out -1.408E+02 6.500E+02 -9.661E+01 7.714E+02 3.366E+02 1.069E+03 6.651E+02 7.774E+0

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC1.3_0003_05.0V0_S03.out -3.897E+03 -1.779E+03 4.284E+03 1.076E+02 8.643E+00 TwHt1Mlxt Maximum DLC1.3_0003_05.0V0_S03.out 3.946E+03 9.562E+02 4.060E+03 1.082E+02 9.101E+00 TwHt1Mlyt Minimum DLC1.3_0004_05.0V0_S04.out -1.415E+03 -2.642E+03 2.997E+03 1.459E+02 4.699E+00 TwHt1Mlyt Maximum DLC1.3_0042_17.0V0_S06.out 4.437E+02 3.595E+03 3.622E+03 2.656E+02 1.851E+01 Tower Mag Maximum DLC1.3_0044_05.0V0_S04.out -3.806E+03 -2.071E+03 4.333E+03 1.712E+02 3.382E+00

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC1.3_0004_05.0V0_S04.out -3.629E+01 1.780E+02 -9.510E-01 LSShftTq Maximum DLC1.3_0055_23.0V0_S01.out 3.065E+02 1.169E+02 3.154E+01

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMxb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*

RootMxb1 Minimum DLC1.4_0019_ECD-R-20.out -1.931E+02 2.731E+01 2.286E+02 8.699E+02 7.412E+01 2.732E+02 1.950E+02 8.995E+02 2.831E+02 5.058E+01 1.219E+01 RootMxb1 Maximum DLC1.4_0019_ECD-R-20.out 3.673E+02 8.780E+02 -7.560E+01 2.867E+02 -1.262E+02 2.097E+02 9.518E+02 2.940E+02 2.648E+02 4.810E+01 1.219E+01 RootMyb1 Minimum DLC1.4_0013_ECD+R+20.out -8.105E+01 -2.673E+02 -3.167E+00 2.940E+02 2.034E+02 1.694E+02 2.793E+02 2.940E+02 2.648E+02 4.810E+01 2.155E+01 RootMyb1 Maximum DLC1.4_0013_ECD+R+20.out 3.256E+02 9.540E+02 -4.409E+00 3.252E+02 -1.636E+02 1.271E+02 1.008E+03 3.252E+02 2.072E+02 5.556E+01 1.219E+01 RootMxb2 Minimum DLC1.4_0013_ECD+R+20.out 1.132E+02 8.177E+01 -1.924E+02 1.570E+02 1.221E+02 3.757E+02 1.396E+02 2.488E+02 3.951E+02 5.956E+01 1.219E+01 RootMxb2 Minimum DLC1.4_0013_ECD+R+20.out 1.184E+02 2.375E+02 3.680E+02 8.724E+02 8.231E+01 2.876E+02 2.654E+02 9.468E+02 2.991E+02 5.954E+01 1.219E+01 RootMxb2 Minimum DLC1.4_0013_ECD+R+20.out 2.025E+02 1.688E+02 -8.011E+01 -2.577E+02 8.012E+00 3.025E+02 3.032E+02 3.026E+02 4.762E+01 2.175E+01 RootMyb2 Maximum DLC1.4_0013_ECD+R+20.out 1.239E+02 3.740E+02 1.151E+02 7.181E+01 -1.922E+02 1.395E+02 3.940E+02 1.357E+02 5.360E+01 1.219E+01 RootMxb3 Minimum DLC1.4_0013_ECD+R+20.out 1.239E+02 3.740E+02 1.151E+02 7.181E+01 -1.922E+02 1.395E+02 3.940E+02 1.357E+02 2.375E+02 5.596E+01 2.101E+01 RootMxb3 Maximum DLC1.4_0013_ECD+R+20.out 1.239E+02 3.740E+02 1.151E+02 7.181E+01 -1.922E+02 1.395E+02 3.940E+02 1.357E+02 2.375E+02 5.596E+01 2.101E+01 RootMxb3 Maximum DLC1.4_0013_ECD+R+20.out 1.239E+02 3.740E+02 1.121E+02 2.118E+02 3.655E+02 8.551E+02 2.958E+02 2.442E+02 9.303E+02 5.566E+01 1.219E+01 RootMyb3 Minimum DLC1.4_0013_ECD+R+20.out 4.578E+00 3.054E+02 -1.021E+02 3.665E+02 8.551E+02 2.958E+02 2.442E+02 9.303E+02 5.468E+01 1.219E+01 RootMyb3 Maximum DLC1.4_0019_ECD-R-20.out -1.578E+00 3.054E+02 -1.692E+02 1.411E+02 3.218E+02 9.486E+02 3.054E+02 2.070E+02 2.791E+02 4.858E+01 2.135E+01 RootMyb3 Maximum DLC1.4_0019_ECD-R-20.out -1.578E+00 3.054E+02 -1.692E+02 1.411E+02

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC1.4_0031_ECD-R+20.out -2.804E+02 1.828E+01 2.810E+02 4.994E+01 2.101E+01 TwHt1Mlxt Maximum DLC1.4_0013_ECD+R+20.out 8.251E+02 6.041E+02 1.023E+03 4.824E+01 2.149E+01 TwHt1Mlyt Minimum DLC1.4_0031_ECD-R+20.out -1.543E+02 -1.746E+02 2.330E+02 4.798E+01 2.161E+01 TwHt1Mlyt Maximum DLC1.4_0019_ECD-R-20.out 2.277E+02 3.038E+03 3.046E+03 4.394E+01 1.544E+01 Tower Mag Maximum DLC1.4_0019_ECD-R-20.out 2.936E+02 3.032E+03 3.046E+03 4.386E+01 1.535E+01

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC1.4_0001_ECD+R-20.out 1.397E+02 5.078E+01 1.219E+01 LSShftTq Maximum DLC1.4_0001_ECD+R-20.out 2.666E+02 4.412E+01 1.563E+01

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMxb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*

RootMxb1 Minimum DLC1.5_0031_EWSH-07.0.out -1.912E+02 6.037E+01 1.236E+02 2.218E+02 1.102E+02 1.966E+02 2.005E+02 2.539E+02 2.253E+02 4.498E+01 7.000E+00 RootMxb1 Maximum DLC1.5_0103_EWSH-13.0.out 3.087E+02 7.221E+02 -6.599E+01 3.206E+02 -7.925E+01 3.663E+02 7.853E+02 3.273E+02 3.747E+02 4.566E+01 1.300E+01 RootMyb1 Minimum DLC1.5_0103_EWSH-13.0.out -7.016E+00 -3.413E+02 -8.404E+01 3.235E+02 1.862E+02 2.873E+02 3.414E+02 3.342E+02 3.423E+02 4.650E+01 2.500E+01 RootMyb1 Maximum DLC1.5_0103_EWSH-07.0.out 1.204E+02 7.225E+02 -4.820E+01 3.368E+02 -9.594E+01 3.474E+02 7.852E+02 3.403E+02 3.603E+02 4.564E+01 1.300E+01 RootMxb2 Minimum DLC1.5_0103_EWSH-07.0.out 1.204E+02 2.055E+02 -1.914E+02 5.882E+01 1.150E+02 2.226E+02 2.381E+02 2.003E+02 2.506E+02 4.670E+01 7.000E+00 RootMxb2 Maximum DLC1.5_0103_EWSH-13.0.out -8.622E+01 3.629E+02 3.075E+02 7.222E+02 -5.886E+01 3.270E+02 3.730E+02 7.850E+02 3.322E+02 4.662E+01 1.300E+01 RootMyb2 Minimum DLC1.5_0253_EWSV+25.0.out 1.870E+02 2.921E+02 -8.595E+00 -3.475E+02 -8.266E+01 3.245E+02 3.469E+02 3.342E+02 4.662E+01 1.300E+01 RootMyb2 Maximum DLC1.5_0103_EWSH-13.0.out -8.622E+01 3.629E+02 3.075E+02 7.222E+02 -5.886E+01 3.270E+02 3.730E+02 7.850E+02 3.322E+02 4.662E+01 1.300E+01 RootMyb3 Minimum DLC1.5_0031_EWSH-07.0.out 1.193E+02 2.241E+02 1.160E+02 2.037E+02 -1.918E+02 5.598E+01 2.539E+02 3.322E+02 4.662E+01 1.300E+01 RootMxb3 Minimum DLC1.5_0103_EWSH-13.0.out -6.377E+01 3.218E+02 -8.189E+01 3.619E+02 3.090E+02 7.251E+02 3.281E+02 3.711E+02 7.882E+02 4.614E+01 1.300E+01 RootMyb3 Minimum DLC1.5_0103_EWSH+13.0.out -6.377E+01 3.218E+02 -9.93E+01 3.206E+02 7.951E+02 3.395E+02 3.478E+02 3.396E+02 4.554E+01 2.500E+01 RootMyb3 Minimum DLC1.5_0103_EWSH+13.0.out -6.377E+01 3.218E+02 -9.32E+02 3.075E+02 7.251E+02 3.415E+02 3.478E+02 3.396E+02 4.554E+01 2.500E+01 RootMyb3 Maximum DLC1.5_0103_EWSH+13.0.out -4.625E+01 3.308E+02 7.925E+01 3.663E+02 7.925E+01 3.265E+02 7.850E+02 3.747E+02 4.564E+01 1.300E+01 RootB1Mag Maximum DLC1.5_0103_EWSH+13.0.out -6.377E+01 3.218E+02 -6.599E+01 3.206E+02

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC1.5_0259_EWSV-25.0.out -1.821E+02 -1.841E+01 1.830E+02 4.646E+01 2.500E+01 TwHt1Mlxt Maximum DLC1.5_0253_EWSV+25.0.out 9.308E+02 6.796E+02 1.153E+03 4.592E+01 2.500E+01 TwHt1Mlyt Minimum DLC1.5_0013_EWSV+05.0.out 1.667E+02 -8.290E+02 8.456E+02 4.810E+01 5.000E+00 TwHt1Mlyt Maximum DLC1.5_0109_EWSV+13.0.out 2.877E+02 2.684E+03 2.699E+03 4.528E+01 1.300E+01 Tower Mag Maximum DLC1.5_0109_EWSV+13.0.out 5.370E+02 2.664E+03 2.717E+03 4.580E+01 1.300E+01

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC1.5_0001_EWSH+05.0.out 2.801E+01 3.056E+01 5.000E+00 LSShftTq Maximum DLC1.5_0241_EWSH+25.0.out 2.196E+02 4.680E+01 2.500E+01

DLC 2.1

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMxb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*

RootMxb1 Minimum DLC2.1_0012_25.0V0_S06.out -3.275E+02 1.559E+02 2.268E+02 3.779E+02 9.458E+01 2.418E+01 3.627E+02 4.407E+02 9.762E+01 5.258E+01 2.754E+01 RootMxb1 Maximum DLC2.1_0012_25.0V0_S06.out 6.419E+02 5.457E+02 1.098E+01 -4.089E+02 1.111E+01 -3.829E+02 8.425E+02 4.091E+02 3.830E+02 6.206E+01 2.726E+01 RootMyb1 Minimum DLC2.1_0007_25.0V0_S01.out -6.622E+01 -5.414E+02 2.084E+02 6.055E+01 1.648E+02 1.002E+02 5.454E+02 2.171E+02 1.929E+02 4.392E+01 3.128E+01 RootMyb1 Maximum DLC2.1_0008_25.0V0_S02.out 5.376E+02 1.156E+03 1.650E+02 -3.552E+02 9.854E+01 -6.477E+02 1.275E+03 3.916E+02 6.552E+02 6.162E+01 3.064E+01 RootMxb2 Minimum DLC2.1_0008_25.0V0_S02.out 1.539E+02 3.946E+02 -3.055E+02 8.757E+01 5.450E+01 3.054E+02 4.236E+02 3.178E+02 3.102E+02 3.754E+01 2.943E+01 RootMxb2 Maximum DLC2.1_0012_25.0V0_S06.out 1.625E+02 6.581E+02 1.523E+02 -5.096E+02 2.742E+02 -3.343E+02 6.779E+02 6.248E+02 6.110E+01 2.598E+01 RootMyb2 Minimum DLC2.1_0007_25.0V0_S01.out 2.034E+02 8.325E+02 1.523E+02 -6.348E+02 3.686E+02 -2.884E+02 8.570E+02 6.528E+02 4.680E+02 6.110E+01 2.598E+01 RootMyb2 Maximum DLC2.1_0004_13.5V0_S04.out -9.858E+01 4.791E+02 2.870E+01 7.898E+02 2.269E+02 5.756E+02 4.892E+02 7.903E+02 6.188E+02 5.700E+01 1.371E+01 RootMxb3 Minimum DLC2.1_0012_25.0V0_S06.out 1.933E+02 6.383E+02 2.049E+02 -5.272E+02 -7.062E+02 6.669E+02 5.656E+02 8.245E+02 6.098E+01 2.244E+01 RootMyb3 Minimum DLC2.1_0012_25.0V0_S06.out 1.933E+02 6.383E+02 2.049E+02 -5.272E+02 -7.062E+02 6.669E+02 5.656E+02 8.245E+02 6.098E+01 2.244E+01 RootMyb3 Minimum DLC2.1_0012_25.0V0_S06.out 1.933E+02 6.383E+02 2.049E+02 -5.272E+02 -7.062E+02 6.669E+02 5.656E+02 8.245E+02 6.098E+01 2.244E+01 RootMyb3 Minimum DLC2.1_0012_25.0V0_S06.out 1.933E+02 6.383E+02 2.049E+02 -5.272E+02 -7.062E+02 6.669E+02 5.656E+02 8.245E+02 6.098E+01 2.244E+01 RootMyb3 Minimum DLC2.1_0004_13.5V0_S04.out 1.939E+02 4.1009E+02 5.358E+02 6.014E+01 8.509E+02 4.607E+02 5.452E+02 8.530E+02 6.662E+01 3.064E+01 RootB1Mag Maximum DLC2.1_0004_13.5V0_S04.out 1.939E+02 4.1009E+02 5.358E+02 6.014E

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC2.1_0008_25.0V0_S02.out -5.253E+03 -8.763E+03 1.022E+04 6.242E+01 2.933E+01 TwHt1Mlxt Maximum DLC2.1_0010_25.0V0_S04.out 4.659E+03 6.380E+03 7.900E+03 6.184E+01 2.463E+01 TwHt1Mlyt Minimum DLC2.1_0010_25.0V0_S04.out -4.848E+03 -9.316E+03 1.050E+04 6.236E+01 2.615E+01 TwHt1Mlyt Maximum DLC2.1_0010_25.0V0_S02.out 3.652E+03 7.480E+03 8.324E+03 6.298E+01 2.635E+01 TwHt1Mlyt Maximum DLC2.1_0010_25.0V0_S02.out 3.652E+03 7.480E+03 1.060E+04 6.238E+01 2.623E+01 Tower Mag Maximum DLC2.1_0010_25.0V0_S04.out -5.085E+03 -9.300E+03 1.060E+04 6.238E+01 2.623E+01

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC2.1_0012_25.0V0_S06.out -6.654E+01 6.330E+01 2.916E+01 LSShftTq Maximum DLC2.1_0007_25.0V0_S01.out 2.990E+02 6.032E+01 2.359E+01

DLC 2.3

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMxb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*

RootMxb1 Minimum DLC2.3_0004_EOGR-20_S04.out -2.129E+02 2.686E+02 3.345E+01 3.071E+02 -4.411E+00 2.516E+02 3.427E+02 3.089E+02 2.516E+02 4.648E+01 1.316E+01 RootMxb1 Maximum DLC2.3_0012_EOGR+20_S06.out 3.411E+02 -2.213E+02 1.883E+02 -3.571E+02 1.092E+02 -4.281E+02 4.066E+02 4.037E+02 4.418E+02 5.202E+01 1.550E+01 RootMyb1 Minimum DLC2.3_0009_EOGR+20_S03.out 7.588E+01 -5.004E+02 3.090E+02 -3.070E+02 2.281E+02 -3.138E+02 5.061E+02 4.356E+02 3.880E+02 4.564E+01 2.022E+01 RootMyb1 Maximum DLC2.3_0004_EOGR-20_S04.out -1.419E+00 5.039E+02 1.806E+02 4.975E+02 -8.226E+01 4.627E+02 5.039E+02 5.293E+02 4.699E+02 4.528E+01 1.570E+01 RootMxb2 Minimum DLC2.3_0010_EOGR+20_S04.out 1.943E+01 8.858E+01 -2.142E+02 1.087E+02 3.633E+01 1.560E+02 9.069E+01 2.402E+02 1.602E+02 4.898E+01 1.070E+01 RootMxb2 Maximum DLC2.3_0010_EOGR+20_S04.out 1.943E+01 8.858E+01 -2.142E+02 1.087E+02 4.33E+02 -3.326E+02 4.136E+02 5.402E+02 3.822E+02 4.706E+01 1.532E+01 RootMxb2 Minimum DLC2.3_0004_EOGR-20_S04.out 2.630E+02 -4.337E+02 4.055E+01 -4.706E+02 1.883E+02 -3.326E+02 4.136E+02 5.402E+02 4.724E+01 1.053E+01 RootMyb2 Maximum DLC2.3_0004_EOGR-20_S04.out -7.434E+01 4.906E+02 1.851E+02 5.077E+02 -7.508E+00 4.569E+02 4.962E+02 5.404E+02 4.570E+02 4.570E+02 4.534E+01 1.550E+01 RootMxb3 Minimum DLC2.3_0007_EOGR+20_S01.out -3.858E+01 2.093E+02 4.191E+01 1.512E+02 -2.170E+02 1.214E+02 2.129E+02 1.569E+02 2.487E+02 4.020E+01 1.550E+01 RootMxb3 Maximum DLC2.3_0009_EOGR+20_S03.out 1.317E+02 -4.322E+02 1.805E+02 -3.959E+02 3.697E+02 -4.065E+02 4.518E+02 4.351E+02 5.122E+02 4.736E+01 1.46E+01 RootMyb3 Minimum DLC2.3_0004_EOGR-20_S04.out 2.372E+02 -3.816E+02 3.134E+02 -2.396E+00 5.266E+01 -5.095E+02 4.493E+02 5.122E+02 4.736E+01 1.550E+01 RootMyb3 Maximum DLC2.3_0004_EOGR-20_S04.out 2.072E+02 -3.816E+02 -2.396E+02 5.266E+01 -5.095E+02 4.493E+02 5.122E+02 4.736E+01 1.446E+01 RootMyb3 Maximum DLC2.3_0004_EOGR-20_S04.out 1.706E+02 4.870E+02 1.861E+01 4.256E+02 -9.658E+01 4.683E+02 4.518E+02 4.574E+01 1.538E+01 RootB1Mag Maximum DLC2.3_0004_EOGR+20_S04.out 1.792E+

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC2.3_0006_EOGR-20_S06.out -5.216E+02 -2.379E+03 2.436E+03 5.334E+01 1.150E+01 TwHt1Mlxt Maximum DLC2.3_0013_EOGO_S01.out 4.909E+02 3.699E+02 6.147E+02 4.016E+01 2.500E+01 TwHt1Mlyt Minimum DLC2.3_0010_EOGR+20_S04.out 1.056E+02 -5.782E+03 5.783E+03 4.724E+01 1.477E+01 TwHt1Mlyt Maximum DLC2.3_0004_EOGR-20_S04.out 3.990E+01 2.627E+03 2.627E+03 4.536E+01 1.568E+01 Tower Mag Maximum DLC2.3_0010_EOGR+20_S04.out 1.056E+02 -5.782E+03 5.783E+03 4.724E+01 1.477E+01

Extreme events for Shaft Torque:

LSShftTq Time WindVxi Parameter Type File (kN*m) (sec) (m/sec)

LSShftTq Minimum DLC2.3_0016_EOGO_S04.out -2.181E+02 4.688E+01 2.563E+01 LSShftTq Maximum DLC2.3_0004_EOGR-20_S04.out 2.234E+02 4.576E+01 1.519E+01

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMyb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) kN*m kN*m kN*m (sec) (m/sec)

RootMxb1 Minimum DLC6.1a_0010_40.4V0_352ny_S04.out -7.792E+01 -3.143E+02 -9.901E+00 1.465E+02 4.217E+01 1.963E+02 3.238E+02 1.468E+02 2.008E+02 4.317E+01 RootMxb1 Maximum DLC6.1a_0007_40.4V0_352ny_S03.out 1.034E+02 4.243E+02 -4.678E+00 -3.333E+02 -2.849E+01 -7.808E+01 4.367E+02 3.333E+02 8.312E+01 3.874E+01 5.007E+01 RootMyb1 Minimum DLC6.1a_0007_40.4V0_008ny_S06.out 8.239E+01 -4.975E+02 5.765E+01 3.251E+02 -1.457E+01 1.465E+02 4.975E+02 3.302E+02 1.472E+02 4.163E+02 4.807E+01 RootMyb1 Maximum DLC6.1a_0007_40.4V0_352ny_S03.out 8.720E+01 5.522E+02 -7.131E+00 -2.237E+02 -2.913E+00 -3.213E+02 5.590E+02 2.238E+02 3.213E+02 2.860E+02 5.285E+01 RootMxb2 Minimum DLC6.1a_0005_40.4V0_008ny_S01.out -2.169E+01 -3.974E+01 -6.889E+01 2.094E+01 -3.278E+01 1.590E+01 4.528E+01 7.200E+01 3.643E+01 3.584E+01 5.068E+01 RootMxb2 Maximum DLC6.1a_0013_40.4V0_008ny_S01.out -1.848E+01 -3.371E+02 -7.236E+00 -5.215E+02 3.452E+00 3.965E+02 1.547E+02 5.216E+02 3.965E+02 1.400E+02 4.781E+01 RootMyb2 Maximum DLC6.1a_0012_40.4V0_008ny_S04.out -2.668E+01 -2.338E+02 6.728E+01 5.404E+02 4.837E+00 -3.025E+02 2.353E+02 5.446E+02 3.026E+02 7.294E+01 4.772E+01 RootMxb3 Minimum DLC6.1a_0007_40.4V0_352ny_S03.out -2.408E+01 2.242E+02 1.386E+01 1.952E+02 -7.893E+01 -4.358E+02 2.255E+02 1.957E+02 4.429E+02 5.946E+02 5.922E+01 RootMxb3 Minimum DLC6.1a_0003_40.4V0_008ny_S01.out -1.027E+01 -1.340E+02 -1.844E+01 -3.528E+02 1.140E+02 4.990E+02 1.344E+02 3.532E+02 5.118E+02 6.285E+02 4.845E+01 RootMyb3 Minimum DLC6.1a_0004_40.4V0_352ny_S03.out -2.008E+02 2.857E+01 3.096E+02 6.980E+00 2.535E+02 2.55E+02 1.957E+02 4.429E+02 5.992E+01 4.772E+01 RootMyb3 Minimum DLC6.1a_0003_40.4V0_008ny_S01.out -1.027E+01 -1.340E+02 -1.844E+01 -3.528E+02 1.140E+02 4.990E+02 3.532E+02 5.118E+02 6.285E+02 4.845E+01 RootMyb3 Minimum DLC6.1a_0004_40.4V0_352ny_S03.out 8.720E+01 -5.822E+02 -7.831E+00 -5.335E+02 2.524E+02 3.109E+02 5.835E+02 5.299E+02 5.241E+01 RootMyb3 Maximum DLC6.1a_0003_40.4V0_008ny_S01.out 1.524E+01 -1.849E+02 -1.849E+02 -2.937E+00 -3.213E+02 2.524E+02 3.118E+02 5

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC6.1a_0007_40.4V0_352ny_S03.out -4.049E+03 -4.143E+02 4.070E+03 2.849E+02 5.251E+01 TwHt1Mlxt Maximum DLC6.1a_0009_40.4V0_008ny_S03.out 3.282E+03 -5.636E+02 3.330E+03 8.844E+01 5.075E+01 TwHt1Mlyt Minimum DLC6.1a_0006_40.4V0_008ny_S02.out 4.062E+02 -2.207E+03 2.244E+03 3.754E+01 3.820E+01 TwHt1Mlyt Maximum DLC6.1a_0006_40.4V0_008ny_S02.out 1.521E+03 1.238E+03 1.961E+03 3.586E+01 5.155E+01 Tower Mag Maximum DLC6.1a_0007_40.4V0_352ny_S03.out -4.049E+03 -4.143E+02 4.070E+03 2.849E+02 5.251E+01

Extreme events for Shaft Torque:

LSShftTq Minimum DLC6.1a_0007_40.4V0_352ny_S03.out -9.692E+01 3.609E+02 4.979E+01 LSShftTq Maximum DLC6.1a_0007_40.4V0_352ny_S03.out 9.707E+01 3.607E+02 4.785E+01

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMyb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) kN*m kN*m kN*m (sec) (m/sec)

RootMxb1 Minimum DLC6.2a_0011_40.4V0_040ny_S01.out -1.752E+02 -7.992E+02 7.742E+01 2.577E+02 6.750E+01 5.347E+02 8.182E+02 2.691E+02 5.390E+02 4.820E+02 4.604E+01 RootMxb1 Maximum DLC6.2a_0046_40.4V0_020ny_S03.out 2.290E+02 8.821E+02 -1.844E+01 -1.812E+02 -3.440E+00 -6.751E+02 9.113E+02 1.821E+02 6.751E+02 5.943E+02 5.501E+01 RootMyb1 Minimum DLC6.2a_0041_40.4V0_280ny_S03.out -1.289E+02 -9.412E+02 -1.105E+01 2.642E+02 5.412E+01 6.552E+02 9.500E+02 2.644E+02 6.574E+02 5.970E+02 5.126E+01 RootMyb1 Maximum DLC6.2a_0085_40.4V0_080ny_S05.out 6.547E+01 9.014E+02 -1.085E+02 -6.982E+02 -1.704E+01 -2.018E+02 9.038E+02 7.066E+02 2.025E+02 1.417E+02 5.613E+01 RootMxb2 Minimum DLC6.2a_0047_40.4V0_060ny_S01.out 3.344E+01 6.608E+02 -1.805E+02 -7.017E+02 -6.684E+00 1.928E+01 6.617E+02 7.246E+02 2.040E+01 1.140E+02 5.090E+01 RootMxb2 Maximum DLC6.2a_0047_40.4V0_040ny_S03.out -4.394E+01 -5.405E+02 1.890E+02 7.663E+02 -1.586E+01 -1.931E+02 5.432E+02 7.892E+02 4.040E+01 1.140E+02 5.090E+01 RootMyb2 Minimum DLC6.2a_0047_40.4V0_040ny_S03.out -7.482E+00 3.945E+02 -1.721E+02 -7.817E+02 1.039E+02 3.974E+02 3.945E+02 8.004E+02 4.108E+02 3.235E+02 5.425E+01 RootMyb2 Maximum DLC6.2a_0047_40.4V0_040ny_S03.out -5.490E+01 -5.115E+02 1.393E+02 8.031E+02 -4.952E+01 -2.611E+02 5.145E+02 8.151E+02 2.657E+02 2.860E+02 5.315E+01 RootMxb3 Minimum DLC6.2a_0047_40.4V0_040ny_S03.out -5.490E+01 -5.115E+02 2.935E+01 4.396E+02 -1.661E+02 -6.993E+02 2.446E+02 4.396E+02 7.187E+02 3.810E+02 5.087E+01 RootMxb3 Maximum DLC6.2a_0029_40.4V0_040ny_S03.out -5.490E+01 -5.318E+02 2.935E+01 -5.088E+02 2.119E+02 6.723E+02 2.006E+02 5.097E+02 7.482E+01 4.988E+01 RootMxb3 Maximum DLC6.2a_0029_40.4V0_040ny_S03.out -7.772E+01 -3.949E+02 -2.939E+01 -5.088E+02 2.119E+02 6.723E+02 4.952E+02 7.049E+02 7.428E+01 4.988E+01 RootMyb3 Maximum DLC6.2a_0044_40.4V0_040ny_S03.out -7.772E+01 -3.494E+02 -2.937E+02 4.371E+02 1.655E+02 8.243E+02 3.579E+02 4.372E+02 8.414E+02 1.396E+02 4.977E+01 RootMyb3 Maximum DLC6.2a_0044_40.4V0_040ny_S03.out -7.772E+01 -3.494E+02 -5.975E+00 -4.371E+0

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC6.2a_0008_40.4V0_340ny_S01.out -4.522E+03 7.086E+02 4.578E+03 1.137E+02 5.110E+01 TwHt1Mlxt Maximum DLC6.2a_0065_40.4V0_040ny_S04.out 6.001E+03 1.084E+02 6.002E+03 1.571E+02 5.677E+01 TwHt1Mlyt Minimum DLC6.2a_0011_40.4V0_040ny_S01.out 1.660E+03 -2.693E+03 3.164E+03 3.054E+01 3.876E+01 TwHt1Mlyt Maximum DLC6.2a_0013_40.4V0_080ny_S01.out 7.482E+02 5.805E+03 5.853E+03 1.139E+02 4.945E+01 Tower Mag Maximum DLC6.2a_0065_40.4V0_040ny_S04.out 6.001E+03 1.084E+02 6.002E+03 1.571E+02 5.677E+01

Extreme events for Shaft Torque:

LSShftTq Minimum DLC6.2a_0053_40.4V0_160ny_S03.out -9.990E+01_3.302E+01_4.738E+01 LSShftTq Maximum DLC6.2a_0028_40.4V0_020ny_S02.out 1.042E+02_5.539E+02_5.370E+01

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMyb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) kN*m kN*m kN*m (sec) (m/sec)

RootMxb1 Minimum DLC6.3a_0002_32.3V0_000ny_S01.out -5.202E+01 2.612E+01 -2.248E+01 3.745E+01 -2.261E+01 -4.321E+01 5.821E+01 4.368E+01 4.877E+01 6.253E+02 3.991E+01 RootMxb1 Maximum DLC6.3a_0009_32.3V0_020ny_S03.out 1.274E+02 5.077E+02 -2.398E+01 -4.803E+01 -5.983E+00 -4.594E+02 5.235E+02 5.368E+01 4.594E+02 5.941E+02 4.478E+01 RootMyb1 Minimum DLC6.3a_0009_32.3V0_020ny_S03.out 1.274E+02 5.077E+02 -2.398E+01 -4.803E+01 -5.983E+00 -4.594E+02 5.235E+02 5.368E+01 4.594E+02 5.941E+02 4.478E+01 RootMxb2 Minimum DLC6.3a_0009_32.3V0_020ny_S03.out 1.274E+02 5.077E+02 -2.398E+01 -4.803E+01 -5.983E+00 -4.594E+02 5.235E+02 5.368E+01 4.594E+02 5.941E+02 4.478E+01 RootMxb2 Minimum DLC6.3a_0012_32.3V0_020ny_S03.out 1.274E+02 5.077E+02 -2.398E+01 -4.803E+01 -5.983E+00 6.781E+01 2.209E+02 2.806E+02 6.826E+01 3.566E+01 3.955E+01 RootMxb2 Maximum DLC6.3a_0015_32.3V0_020ny_S05.out -2.796E+00 -3.606E+02 1.111E+02 4.086E+02 -1.409E+01 -3.559E+01 3.606E+02 4.235E+02 3.826E+01 3.556E+01 RootMyb2 Minimum DLC6.3a_0012_32.3V0_020ny_S05.out -2.246E+01 -2.693E+01 -9.778E+00 -4.309E+02 1.141E+02 4.320E+02 3.507E+01 4.310E+02 4.468E+02 7.534E+01 4.166E+01 RootMyb2 Maximum DLC6.3a_0013_32.3V0_340ny_S03.out -4.034E+01 -1.754E+02 7.880E+01 5.185E+02 -1.928E+01 -3.414E+02 1.799E+02 5.245E+02 3.420E+02 5.956E+02 3.960E+01 RootMxb3 Minimum DLC6.3a_0013_32.3V0_020ny_S03.out -2.061E+01 -3.985E+01 4.482E+01 2.913E+02 4.478E+01 -2.743E+02 4.487E+01 2.948E+02 2.785E+02 5.178E+02 3.638E+01 RootMxb3 Maximum DLC6.3a_0012_32.3V0_020ny_S03.out -1.426E+01 -2.624E+01 -6.002E+00 -3.398E+02 1.407E+00 3.841E+02 2.987E+01 3.398E+02 4.090E+02 7.444E+01 4.057E+01 RootMyb3 Minimum DLC6.3a_0012_32.3V0_020ny_S03.out 1.272E+02 5.058E+02 -2.141E+01 -4.929E+01 -8.047E+00 4.616E+02 5.216E+02 5.374E+01 4.616E+02 5.941E+02 4.460E+01 RootMyb3 Maximum DLC6.3a_0009_32.3V0_020ny_S03.out 1.272E+02 5.058E+02 -2.141E+01 -4.929E+01 -3.414E+02 1.799E+02 5.25E+02 3.40E+02 5.95E+02 3.40E+01 4.270E+01 RootB1Mag Maximum DLC6.3a_0009_32.3V0_020ny_S03.out 1.272E+02 5.058E+02 -2.141E+01 -

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC6.3a_0007_32.3V0_340ny_S03.out -3.055E+03 -6.309E+02 3.120E+03 6.510E+01 4.009E+01 TwHt1Mlxt Maximum DLC6.3a_0015_32.3V0_020ny_S05.out 3.266E+03 -2.724E+02 3.277E+03 4.983E+02 3.680E+01 TwHt1Mlyt Minimum DLC6.3a_0006_32.3V0_020ny_S02.out 9.974E+02 -2.352E+03 2.554E+03 3.056E+01 3.062E+01 TwHt1Mlyt Maximum DLC6.3a_0006_32.3V0_020ny_S02.out 1.692E+03 1.267E+03 2.113E+03 3.344E+01 3.813E+01 Tower Mag Maximum DLC6.3a_0009_32.3V0_020ny_S03.out 3.127E+03 -1.160E+03 3.335E+03 8.220E+01 3.698E+01

Extreme events for Shaft Torque:

LSShftTq Minimum DLC6.3a_0017_32.3V0_000ny_S06.out -5.863E+01_5.482E+02_3.675E+01 LSShftTq Maximum DLC6.3a_0017_32.3V0_000ny_S06.out 5.607E+01_5.476E+02_3.216E+01

DLC 7.1

Extreme events for Blade Moments:

RootMxb1 RootMyb1 RootMyb2 RootMyb2 RootMxb3 RootMyb3 RootB1Mag RootB2Mag RootB3Mag Time WindVxi Parameter Type File (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) (kN*m) kN*m kN*m kN*m (sec) (m/sec)

RootMxb1 Minimum DLC7.1a_0009_32.3V0_008ny_S03.out -1.762E+02 3.172E+02 3.548E+01 2.466E+02 -2.288E+00 -6.145E+01 3.629E+02 2.492E+02 6.149E+01 2.987E+02 3.521E+01 RootMxb1 Maximum DLC7.1a_0014_32.3V0_0352ny_S02.out 2.343E+02 4.651E+02 3.828E+00 6.287E+00 1.951E+00 -2.529E+02 5.208E+02 7.360E+00 2.529E+02 5.542E+02 4.364E+01 RootMyb1 Minimum DLC7.1a_0014_32.3V0_000ny_S05.out 3.775E+01 1.327E+02 -1.470E+01 -1.103E+02 -1.499E+01 7.765E+01 1.379E+02 1.113E+02 7.908E+01 4.035E+02 2.678E+01 RootMyb1 Maximum DLC7.1a_0007_32.3V0_352ny_S03.out 1.827E+02 6.812E+02 1.642E+00 6.619E+01 -1.005E+01 -2.456E+02 7.053E+02 6.621E+01 2.458E+02 2.855E+02 4.252E+01 RootMxb2 Minimum DLC7.1a_0003_32.3V0_008ny_S01.out -1.108E+02 3.582E+02 -4.111E+01 7.765E+01 -1.672E+01 3.187E+01 3.749E+02 8.786E+01 3.599E+01 3.118E+01 2.876E+01 RootMxb2 Minimum DLC7.1a_0003_32.3V0_008ny_S01.out -1.456E+02 3.781E+02 3.983E+01 2.011E+02 -2.289E+00 -2.725E+01 4.052E+02 2.050E+02 2.734E+01 5.440E+02 3.600E+01 RootMyb2 Minimum DLC7.1a_0013_32.3V0_008ny_S01.out -1.252E+02 4.946E+02 3.455E+01 1.768E+02 -9.912E+00 9.515E+01 3.36E+02 1.775E+02 9.566E+01 6.372E+01 3.223E+01 RootMxb3 Minimum DLC7.1a_0004_32.3V0_038ny_S01.out -1.252E+02 4.946E+02 3.455E+01 2.934E+02 -6.942E-01 -1.449E+02 5.102E+02 2.954E+02 1.449E+02 4.818E+02 3.624E+01 RootMxb3 Minimum DLC7.1a_0004_32.3V0_352ny_S02.out 1.782E+02 4.681E+02 -8.691E+00 4.104E+01 -5.374E+01 -2.160E+02 5.008E+02 4.195E+01 2.226E+02 5.318E+02 4.244E+01 RootMxb3 Maximum DLC7.1a_0004_32.3V0_352ny_S02.out 1.912E+02 4.638E+02 2.531E+01 4.102E+01 3.433E+01 -2.154E+02 5.016E+02 4.820E+01 2.181E+02 3.827E+01 RootMyb3 Minimum DLC7.1a_0004_32.3V0_352ny_S05.out 1.902E+02 5.318E+02 4.693E+00 -3.405E+01 -7.037E+00 1.464E+02 3.602E+02 3.437E+01 2.181E+02 3.827E+01 RootMyb3 Minimum DLC7.1a_0004_32.3V0_000ny_S05.out 1.902E+02 5.378E+02 4.292E+01 -7.037E+00 1.464E+02 5.016E+02 4.820E+01 2.181E+02 3.827E+01 RootMyb3 Maximum DLC7.1a_0004_32.3V0_000ny_S05.out 1.250E+02 3.378E+02 4.693E+00 -3.405E+01 -7.037E+00 1.464E+02 3.602E+02 3.43

Extreme events for Tower Moments:

TwHt1Mlxt TwHt1Mlyt Tower Mag Time WindVxi Parameter Type File (kN*m) (kN*m) kN*m (sec) (m/sec)

TwHt1Mlxt Minimum DLC7.1a_0007_32.3V0_352ny_S03.out -1.964E+03 -1.602E+02 1.970E+03 2.824E+02 3.561E+01 TwHt1Mlxt Maximum DLC7.1a_0018_32.3V0_008ny_S06.out 1.622E+03 -6.564E+01 1.624E+03 4.678E+02 3.792E+01 TwHt1Mlyt Minimum DLC7.1a_0003_32.3V0_008ny_S01.out 6.735E+02 -1.339E+03 1.499E+03 5.948E+02 3.104E+01 TwHt1Mlyt Maximum DLC7.1a_0004_32.3V0_352ny_S02.out -7.411E+02 1.983E+03 2.117E+03 5.295E+02 4.228E+01 Tower Mag Maximum DLC7.1a_0004_32.3V0_352ny_S02.out -7.611E+02 1.983E+03 2.124E+03 5.295E+02 4.214E+01

Extreme events for Shaft Torque:

LSShftTq Minimum DLC7.1a_0003_32.3V0_008ny_S01.out -4.477E+01 1.112E+02 4.306E+01 LSShftTq Maximum DLC7.1a_0006_32.3V0_008ny_S02.out 5.195E+01 6.007E+02 3.620E+01

D.2 Time Series Plots

DLC 1.1











Time Series Plots of Shaft Torque













Time Series Plots of Shaft Torque









Time Series Plots of Wind Speeds















Time Series Plots of Shaft Torque









Time Series Plots of Wind Speeds





Time Series Plots of Blade 1 Moments









Time Series Plots of Shaft Torque






DLC 2.1







Time Series Plots of Blade 2 Moments



Time Series Plots of Blade 3 Moments









DLC 2.3



Time Series Plots of Wind Speeds





Time Series Plots of Blade 2 Moments













DLC 6.1









D-30









DLC 6.2



Time Series Plots of Wind Speeds





Time Series Plots of Blade 3 Moments









DLC 6.3



Time Series Plots of Wind Speeds



Time Series Plots of Blade 1 Moments













DLC 7.1















REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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14. ABSTRACT (Maximum 200 Words) Wind turbines installed in regions that sometimes have extreme conditions can experience both fatigue and extreme loading. These loads affect individual components of a wind turbine differently. Wind turbines currently have a design life of 20 years, which is achieved by building a turbine with robust components that can withstand the fatigue and extreme loads for the duration. This report first discusses and identifies which wind turbine components can benefit from advanced control algorithms and also presents results from a preliminary loads case analysis using a baseline controller. Next, it describes the design, implementation, and simulation-based testing of an advanced controller to reduce loads on those components. The case-by-case loads analysis and advanced controller design will help guide future control research.					
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