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Definition of a 5-MW Reference Wind Turbine for Offshore System Development

J. Jonkman, S. Butterfield, W. Musial, and G. Scott

Technical Report
NREL/TP-500-38060
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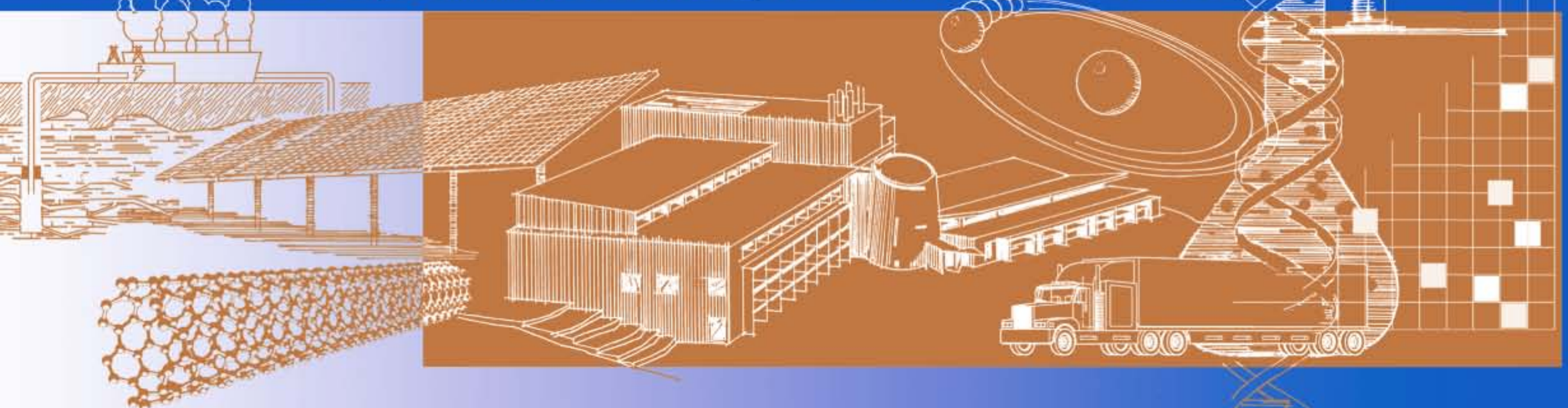

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Acronyms and Abbreviations

ADAMS®	=	Automatic Dynamic Analysis of Mechanical Systems
A2AD	=	ADAMS-to-AeroDyn
BEM	=	blade-element / momentum
CM	=	center of mass
DLL	=	dynamic link library
DOE	=	U.S. Department of Energy
DOF	=	degree of freedom
DOWEC	=	Dutch Offshore Wind Energy Converter project
DU	=	Delft University
ECN	=	Energy Research Center of the Netherlands
equiripple	=	equalized-ripple
FAST	=	Fatigue, Aerodynamics, Structures, and Turbulence
GE	=	General Electric
IEA	=	International Energy Agency
MSL	=	mean sea level
NACA	=	National Advisory Committee for Aeronautics
NREL	=	National Renewable Energy Laboratory
NWTC	=	National Wind Technology Center
OCS	=	offshore continental shelf
OC3	=	Offshore Code Comparison Collaborative
PI	=	proportional-integral
PID	=	proportional-integral-derivative
RECOFF	=	Recommendations for Design of Offshore Wind Turbines project
WindPACT	=	Wind Partnerships for Advanced Component Technology project
w.r.t.	=	with respect to

Nomenclature

A_d	=	discrete-time state matrix
B_d	=	discrete-time input matrix
C_d	=	discrete-time output state matrix
C_φ	=	effective damping in the equation of motion for the rotor-speed error
D_d	=	discrete-time input transmission matrix
f_c	=	corner frequency
GK	=	gain-correction factor
$I_{Drivetrain}$	=	drivetrain inertia cast to the low-speed shaft
I_{Gen}	=	generator inertia relative to the high-speed shaft
I_{Rotor}	=	rotor inertia
K_D	=	blade-pitch controller derivative gain
K_I	=	blade-pitch controller integral gain
K_P	=	blade-pitch controller proportional gain
K_φ	=	effective stiffness in the equation of motion for the rotor-speed error
M_φ	=	effective inertia (mass) in the equation of motion for the rotor-speed error
n	=	discrete-time-step counter
N_{Gear}	=	high-speed to low-speed gearbox ratio
P	=	mechanical power
P_0	=	rated mechanical power
$\partial P/\partial \theta$	=	sensitivity of the aerodynamic power to the rotor-collective blade-pitch angle
t	=	simulation time
T_{Aero}	=	aerodynamic torque in the low-speed shaft
T_{Gen}	=	generator torque in the high-speed shaft

T_s	=	discrete-time step
u	=	unfiltered generator speed
x	=	for the control-measurement filter, the filter state
x,y,z	=	set of orthogonal axes making up a reference-frame coordinate system
y	=	for the control-measurement filter, the filtered generator speed
α	=	low-pass filter coefficient
$\Delta\theta$	=	small perturbation of the blade-pitch angles about their operating point
$\Delta\Omega$	=	small perturbation of the low-speed shaft rotational speed about the rated speed
$\Delta\dot{\Omega}$	=	low-speed shaft rotational acceleration
ζ_φ	=	damping ratio of the response associated with the equation of motion for the rotor-speed error
θ	=	full-span rotor-collective blade-pitch angle
θ_K	=	rotor-collective blade-pitch angle at which the pitch sensitivity has doubled from its value at the rated operating point
π	=	the ratio of a circle's circumference to its diameter
φ	=	the integral of $\dot{\varphi}$ with respect to time
$\dot{\varphi}$	=	small perturbation of the low-speed shaft rotational speed about the rated speed
$\ddot{\varphi}$	=	low-speed shaft rotational acceleration
Ω	=	low-speed shaft rotational speed
Ω_0	=	rated low-speed shaft rotational speed
$\omega_{\varphi n}$	=	natural frequency of the response associated with the equation of motion for the rotor-speed error

Executive Summary

To support concept studies aimed at assessing offshore wind technology, we developed the specifications of a representative utility-scale multimegawatt turbine now known as the "NREL offshore 5-MW baseline wind turbine." This wind turbine is a conventional three-bladed upwind variable-speed variable blade-pitch-to-feather-controlled turbine. To create the model, we obtained some broad design information from the published documents of turbine manufacturers, with a heavy emphasis on the REpower 5M machine. Because detailed data was unavailable, however, we also used the publicly available properties from the conceptual models in the WindPACT, RECOFF, and DOWEC projects. We then created a composite from these data, extracting the best available and most representative specifications. This report documents the specifications of the NREL offshore 5-MW baseline wind turbine—including the aerodynamic, structural, and control-system properties—and the rationale behind its development. The model has been, and will likely continue to be, used as a reference by research teams throughout the world to standardize baseline offshore wind turbine specifications and to quantify the benefits of advanced land- and sea-based wind energy technologies.

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1 Introduction

The U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL), through the National Wind Technology Center (NWTC), has sponsored conceptual studies aimed at assessing offshore wind technology suitable in the shallow and deep waters off the U.S. offshore continental shelf (OCS) and other offshore sites worldwide. To obtain useful information from such studies, use of realistic and standardized input data is required. This report documents the turbine specifications of what is now called the "NREL offshore 5-MW baseline wind turbine" and the rationale behind its development. Our objective was to establish the detailed specifications of a large wind turbine that is representative of typical utility-scale land- and sea-based multimegawatt turbines, and suitable for deployment in deep waters.

Before establishing the detailed specifications, however, we had to choose the basic size and power rating of the machine. Because of the large portion of system costs in the support structure of an offshore wind system, we understood from the outset that if a deepwater wind system is to be cost-effective, each individual wind turbine must be rated at 5 MW or higher [23].[1] Ratings considered for the baseline ranged from 5 MW to 20 MW. We decided that the baseline should be 5 MW because it has precedence:

- Feasible floater configurations for offshore wind turbines scoped out by Musial, Butterfield, and Boone [23] were based on the assumption of a 5-MW unit.
- Unpublished DOE offshore cost studies were based on a rotor diameter of 128 m, which is a size representative of a 5- to 6-MW wind turbine.
- The land-based Wind Partnerships for Advanced Component Technology (WindPACT) series of studies, considered wind turbine systems rated up to 5 MW [19,24,29].
- The Recommendations for Design of Offshore Wind Turbines project (known as RECOFF) based its conceptual design calculations on a wind turbine with a 5-MW rating [32].
- The Dutch Offshore Wind Energy Converter (DOWEC) project based its conceptual design calculations on a wind turbine with a 6-MW rating [8,14,17].
- At the time of this writing, the largest wind turbine prototypes in the world—the Multibrid M5000 [5,21,22] and the REpower 5M [18,26,27]—each had a 5-MW rating.

We gathered the publicly available information on the Multibrid M5000 and REpower 5M prototype wind turbines. And because detailed information on these machines was unavailable, we also used the publicly available properties from the conceptual models used in the WindPACT, RECOFF, and DOWEC projects. These models contained much greater detail than was available about the prototypes. We then created a composite from these models, extracting the best available and most representative specifications.

[1] A single 5-MW wind turbine can supply enough energy annually to power 1,250 average American homes.

The Multibrid M5000 machine has a significantly higher tip speed than typical onshore wind turbines and a lower tower-top mass than would be expected from scaling laws previously developed in one of the WindPACT studies [29]. In contrast, the REpower 5M machine has properties that are more "expected" and "conventional." For this reason, we decided to use the specifications of the REpower 5M machine as the target specifications[2] for our baseline model.

The wind turbine used in the DOWEC project had a slightly higher rating than the rating of the REpower 5M machine, but many of the other basic properties of the DOWEC turbine matched the REpower 5M machine very well. In fact, the DOWEC turbine matched many of the properties of the REpower 5M machine better than the turbine properties derived for the WindPACT and RECOFF studies.[3] As a result of these similarities, we made the heaviest use of data from the DOWEC study in our development of the NREL offshore 5-MW baseline wind turbine.

The REpower 5M machine has a rotor radius of about 63 m. Wanting the same radius and the lowest reasonable hub height possible to minimize the overturning moment acting on an offshore substructure, we decided that the hub height for the baseline wind turbine should be 90 m. This would give a 15-m air gap between the blade tips at their lowest point when the wind turbine is undeflected and an estimated extreme 50-year individual wave height of 30 m (i.e., 15-m amplitude). The additional gross properties we chose for the NREL 5-MW baseline wind turbine, most of which are identical to those of the REpower 5M, are given in Table 1-1. The (x,y,z) coordinates of the overall center of mass (CM) location of the wind turbine are indicated in a tower-base coordinate system, which originates along the tower centerline at ground or mean

Table 1-1. Gross Properties Chosen for the NREL 5-MW Baseline Wind Turbine

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5º, 2.5º
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg
Coordinate Location of Overall CM	(-0.2 m, 0.0 m, 64.0 m)

[2] Note that we established the target specifications using information about the REpower 5M machine that was published in January 2005 [26,27]. Some of the information presented in Refs. [26] and [27] disagrees with more recently published information. For example, the published nacelle and rotor masses of the REpower 5M are higher in the more recent publications.

[3] This was probably because the REpower 5M prototype utilized blades provided by LM Glasfiber [18], a company that helped establish the structural properties of the blades used in the DOWEC study.

sea level (MSL). The *x*-axis of this coordinate system is directed nominally downwind, the *y*-axis is directed transverse to the nominal wind direction, and the *z*-axis is directed vertically from the tower base to the yaw bearing.

The actual REpower 5M wind turbine uses blades with built-in prebend as a means of increasing tower clearance without a large rotor overhang. Because many of the available simulation tools and design codes cannot support blades with built-in prebend, we chose a 2.5°-upwind precone in the baseline wind turbine to represent the smaller amount of precone and larger amount of prebend that are built into the actual REpower 5M machine.

The rotor diameter indicated in Table 1-1 ignores the effect of blade precone, which reduces the actual diameter and swept area. The exact rotor diameter in the turbine specifications (assuming that the blades are undeflected) is actually (126 m) × cos(2.5°) = 125.88 m and the actual swept area is $(\pi/4) \times (125.88\ \text{m})^2 = 12{,}445.3\ \text{m}^2$.

We present other information about this model as follows:

- The blade structural properties in Section 2
- The blade aerodynamic properties in Section 3
- The hub and nacelle properties in Section 4
- The drivetrain properties in Section 5
- The tower properties in Section 6
- The baseline control system properties in Section 7
- The aero-servo-elastic FAST (Fatigue, Aerodynamics, Structures, and Turbulence) [11] with AeroDyn [16,20] and MSC.ADAMS® (Automatic Dynamic Analysis of Mechanical Systems) with A2AD (ADAMS-to-AeroDyn)[4] [6,15] and AeroDyn models of the wind turbine in Section 8
- The basic responses of the land-based version of the wind turbine, including its full-system natural frequencies and steady-state behavior in Section 9.

Although we summarize much of this information[5] for conciseness and clarity, Section 7 contains a high level of detail about the development of the wind turbine's baseline control system. These details are provided because they are fundamental to the development of more advanced control systems.

The NREL offshore 5-MW baseline wind turbine has been used to establish the reference specifications for a number of research projects supported by the U.S. DOE's Wind & Hydropower Technologies Program [1,2,7,12,28,33,34]. In addition, the integrated European

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[4] Note that we use the term "ADAMS" to mean "MSC.ADAMS with A2AD" in this work.

[5] Note that some of the turbine properties are presented with a large number (>4) of significant figures. Most of these were carried over from the turbine properties documented in the DOWEC study [8,14,17]—We did not truncate their precision to maintain consistency with the original data source.

Union UpWind research program[6] and the International Energy Agency (IEA) Wind Annex XXIII Subtask 2[7] Offshore Code Comparison Collaboration (OC3) [13,25] have adopted the NREL offshore 5-MW baseline wind turbine as their reference model. The model has been, and will likely continue to be, used as a reference by research teams throughout the world to standardize baseline offshore wind turbine specifications and to quantify the benefits of advanced land- and sea-based wind energy technologies.

[6] Web site: http://www.upwind.eu/default.aspx

[7] Web site: http://www.ieawind.org/Annex%20XXIII/Subtask2.html

2 Blade Structural Properties

The NREL offshore 5-MW baseline wind turbine has three blades. We based the distributed blade structural properties of each blade on the structural properties of the 62.6-m-long LM Glasfiber blade used in the DOWEC study (using the data given in Appendix A of Ref. [17]). Because the blades in the DOWEC study were 1.1 m longer than the 61.5-m-long LM Glasfiber blades [18] used on the actual REpower 5M machine, we truncated the 62.6-m blades at 61.5-m span to obtain the structural properties of the NREL 5-MW baseline blades (we found the structural properties at the blade tip by interpolating between the 61.2-m and 61.7-m stations given in Appendix A of Ref. [17]). Table 2-1 lists the resulting properties.

The entries in the first column of Table 2-1, labeled "Radius," are the spanwise locations along the blade-pitch axis relative to the rotor center (apex). "BlFract" is the fractional distance along the blade-pitch axis from the root (0.0) to the tip (1.0). We located the blade root 1.5 m along the pitch axis from the rotor center, equivalent to half the hub diameter listed in Table 1-1.

"AeroCent" is the name of a FAST input parameter. The FAST code assumes that the blade-pitch axis passes through each airfoil section at 25% chord. By definition, then, the quantity (AeroCent − 0.25) is the fractional distance to the aerodynamic center from the blade-pitch axis along the chordline, positive toward the trailing edge. Thus, at the root (i.e., BlFract = 0.0), AeroCent = 0.25 means that the aerodynamic center lies on the blade-pitch axis [because (0.25 − 0.25) = 0.0], and at the tip (i.e., BlFract = 1.0), AeroCent = 0.125 means that the aerodynamic center lies 0.125 chordlengths toward the leading edge from the blade-pitch axis [because (0.125

Table 2-1. Distributed Blade Structural Properties

Radius (m)	BlFract (-)	AeroCent (-)	StrcTwst (°)	BMassDen (kg/m)	FlpStff (N•m²)	EdgStff (N•m²)	GJStff (N•m²)	EAStff (N)	Alpha (-)	FlpIner (kg•m)	EdgIner (kg•m)	PrecrvRef (m)	PreswpRef (m)	FlpcgOf (m)	EdgcgOf (m)	FlpEAOf (m)	EdgEAOf (m)
1.50	0.00000	0.25000	13.308	678.935	18110.00E+6	18113.60E+6	5564.40E+6	9729.48E+6	0.0	972.86	973.04	0.0	0.0	0.0	0.00017	0.0	0.0
1.70	0.00325	0.25000	13.308	678.935	18110.00E+6	18113.60E+6	5564.40E+6	9729.48E+6	0.0	972.86	973.04	0.0	0.0	0.0	0.00017	0.0	0.0
2.70	0.01951	0.24951	13.308	773.363	19424.90E+6	19558.60E+6	5431.59E+6	10789.50E+6	0.0	1091.52	1066.38	0.0	0.0	0.0	-0.02309	0.0	0.0
3.70	0.03577	0.24510	13.308	740.550	17455.90E+6	19497.80E+6	4993.98E+6	10067.23E+6	0.0	966.09	1047.36	0.0	0.0	0.0	0.00344	0.0	0.0
4.70	0.05203	0.23284	13.308	740.042	15287.40E+6	19788.80E+6	4666.59E+6	9867.78E+6	0.0	873.81	1099.75	0.0	0.0	0.0	0.04345	0.0	0.0
5.70	0.06829	0.22059	13.308	592.496	10782.40E+6	14858.50E+6	3474.71E+6	7607.86E+6	0.0	648.55	873.02	0.0	0.0	0.0	0.05893	0.0	0.0
6.70	0.08455	0.20833	13.308	450.275	7229.72E+6	10220.60E+6	2323.54E+6	5491.26E+6	0.0	456.76	641.49	0.0	0.0	0.0	0.06494	0.0	0.0
7.70	0.10081	0.19608	13.308	424.054	6309.54E+6	9144.70E+6	1907.87E+6	4971.30E+6	0.0	400.53	593.73	0.0	0.0	0.0	0.07718	0.0	0.0
8.70	0.11707	0.18382	13.308	400.638	5528.36E+6	8063.16E+6	1570.36E+6	4493.95E+6	0.0	351.61	547.18	0.0	0.0	0.0	0.08394	0.0	0.0
9.70	0.13335	0.17156	13.308	382.062	4980.06E+6	6884.44E+6	1158.26E+6	4034.80E+6	0.0	316.12	490.84	0.0	0.0	0.0	0.10174	0.0	0.0
10.70	0.14959	0.15931	13.308	399.655	4936.84E+6	7009.18E+6	1002.12E+6	4037.29E+6	0.0	303.60	503.86	0.0	0.0	0.0	0.10758	0.0	0.0
11.70	0.16585	0.14706	13.308	426.321	4691.66E+6	7167.68E+6	855.90E+6	4169.72E+6	0.0	289.24	544.70	0.0	0.0	0.0	0.15829	0.0	0.0
12.70	0.18211	0.13481	13.181	416.820	3949.46E+6	7271.66E+6	672.27E+6	4082.35E+6	0.0	246.57	569.90	0.0	0.0	0.0	0.22235	0.0	0.0
13.70	0.19837	0.12500	12.848	406.186	3386.52E+6	7081.70E+6	547.49E+6	4085.97E+6	0.0	215.91	601.28	0.0	0.0	0.0	0.30756	0.0	0.0
14.70	0.21465	0.12500	12.192	381.420	2933.74E+6	6244.53E+6	448.84E+6	3668.34E+6	0.0	187.11	546.56	0.0	0.0	0.0	0.30386	0.0	0.0
15.70	0.23089	0.12500	11.561	352.822	2568.96E+6	5048.96E+6	335.92E+6	3147.76E+6	0.0	160.84	468.71	0.0	0.0	0.0	0.26519	0.0	0.0
16.70	0.24715	0.12500	11.072	349.477	2388.65E+6	4948.49E+6	311.35E+6	3011.58E+6	0.0	148.56	453.76	0.0	0.0	0.0	0.25941	0.0	0.0
17.70	0.26341	0.12500	10.792	346.538	2271.99E+6	4808.02E+6	291.94E+6	2882.62E+6	0.0	140.30	436.22	0.0	0.0	0.0	0.25007	0.0	0.0
19.70	0.29595	0.12500	10.232	339.333	2050.05E+6	4501.40E+6	261.00E+6	2613.97E+6	0.0	124.61	398.18	0.0	0.0	0.0	0.23155	0.0	0.0
21.70	0.32846	0.12500	9.672	330.004	1828.25E+6	4244.07E+6	228.82E+6	2357.48E+6	0.0	109.42	362.08	0.0	0.0	0.0	0.20382	0.0	0.0
23.70	0.36098	0.12500	9.110	321.990	1588.71E+6	3995.28E+6	200.75E+6	2146.86E+6	0.0	94.36	335.01	0.0	0.0	0.0	0.19934	0.0	0.0
25.70	0.39350	0.12500	8.534	313.820	1361.93E+6	3750.76E+6	174.38E+6	1944.09E+6	0.0	80.24	308.57	0.0	0.0	0.0	0.19323	0.0	0.0
27.70	0.42602	0.12500	7.932	294.734	1102.38E+6	3447.14E+6	144.47E+6	1632.70E+6	0.0	62.67	263.87	0.0	0.0	0.0	0.14994	0.0	0.0
29.70	0.45855	0.12500	7.321	287.120	875.80E+6	3139.07E+6	119.98E+6	1432.40E+6	0.0	49.42	237.06	0.0	0.0	0.0	0.15421	0.0	0.0
31.70	0.49106	0.12500	6.711	263.343	681.30E+6	2734.24E+6	81.19E+6	1168.76E+6	0.0	37.34	196.41	0.0	0.0	0.0	0.13252	0.0	0.0
33.70	0.52358	0.12500	6.122	253.207	534.72E+6	2554.87E+6	69.09E+6	1047.43E+6	0.0	29.14	180.34	0.0	0.0	0.0	0.13313	0.0	0.0
35.70	0.55610	0.12500	5.546	241.666	408.90E+6	2334.03E+6	57.45E+6	922.95E+6	0.0	22.16	162.43	0.0	0.0	0.0	0.14035	0.0	0.0
37.70	0.58862	0.12500	4.971	220.638	314.54E+6	1828.73E+6	45.92E+6	760.82E+6	0.0	17.33	134.83	0.0	0.0	0.0	0.13950	0.0	0.0
39.70	0.62115	0.12500	4.401	200.293	238.63E+6	1584.10E+6	35.98E+6	648.03E+6	0.0	13.30	116.30	0.0	0.0	0.0	0.15134	0.0	0.0
41.70	0.65366	0.12500	3.834	179.404	175.88E+6	1323.36E+6	27.44E+6	539.70E+6	0.0	9.96	97.98	0.0	0.0	0.0	0.17418	0.0	0.0
43.70	0.68618	0.12500	3.332	165.094	126.01E+6	1183.68E+6	20.90E+6	531.15E+6	0.0	7.30	98.93	0.0	0.0	0.0	0.24922	0.0	0.0
45.70	0.71870	0.12500	2.890	154.411	107.26E+6	1020.16E+6	18.54E+6	460.01E+6	0.0	6.22	85.78	0.0	0.0	0.0	0.26022	0.0	0.0
47.70	0.75122	0.12500	2.503	138.935	90.88E+6	797.81E+6	16.28E+6	375.75E+6	0.0	5.19	69.96	0.0	0.0	0.0	0.22554	0.0	0.0
49.70	0.78376	0.12500	2.116	129.555	76.31E+6	709.61E+6	14.53E+6	328.89E+6	0.0	4.36	61.41	0.0	0.0	0.0	0.22795	0.0	0.0
51.70	0.81626	0.12500	1.730	107.264	61.05E+6	518.19E+6	9.07E+6	244.04E+6	0.0	3.36	45.44	0.0	0.0	0.0	0.20600	0.0	0.0
53.70	0.84878	0.12500	1.342	98.776	49.48E+6	454.87E+6	8.06E+6	211.60E+6	0.0	2.75	39.57	0.0	0.0	0.0	0.21662	0.0	0.0
55.70	0.88130	0.12500	0.954	90.248	39.36E+6	395.12E+6	7.08E+6	181.52E+6	0.0	2.21	34.09	0.0	0.0	0.0	0.22784	0.0	0.0
56.70	0.89756	0.12500	0.760	83.001	34.67E+6	353.72E+6	6.09E+6	160.25E+6	0.0	1.93	30.12	0.0	0.0	0.0	0.23124	0.0	0.0
57.70	0.91382	0.12500	0.574	72.906	30.41E+6	304.73E+6	5.75E+6	109.23E+6	0.0	1.69	20.15	0.0	0.0	0.0	0.14826	0.0	0.0
58.70	0.93008	0.12500	0.404	68.772	26.52E+6	281.42E+6	5.33E+6	100.08E+6	0.0	1.49	18.53	0.0	0.0	0.0	0.15346	0.0	0.0
59.20	0.93821	0.12500	0.319	66.264	23.84E+6	261.71E+6	4.94E+6	92.24E+6	0.0	1.34	17.11	0.0	0.0	0.0	0.15382	0.0	0.0
59.70	0.94636	0.12500	0.253	59.340	19.63E+6	158.81E+6	4.24E+6	63.23E+6	0.0	1.10	11.55	0.0	0.0	0.0	0.09470	0.0	0.0
60.20	0.95447	0.12500	0.216	55.914	16.00E+6	137.88E+6	3.66E+6	53.32E+6	0.0	0.89	9.77	0.0	0.0	0.0	0.09018	0.0	0.0
60.70	0.96260	0.12500	0.178	52.484	12.83E+6	118.79E+6	3.13E+6	44.53E+6	0.0	0.71	8.19	0.0	0.0	0.0	0.08561	0.0	0.0
61.20	0.97073	0.12500	0.140	49.114	10.08E+6	101.63E+6	2.64E+6	36.90E+6	0.0	0.56	6.82	0.0	0.0	0.0	0.08035	0.0	0.0
61.70	0.97886	0.12500	0.101	45.818	7.55E+6	85.07E+6	2.17E+6	29.92E+6	0.0	0.42	5.57	0.0	0.0	0.0	0.07096	0.0	0.0
62.20	0.98699	0.12500	0.062	41.669	4.60E+6	64.26E+6	1.58E+6	21.31E+6	0.0	0.25	4.01	0.0	0.0	0.0	0.05424	0.0	0.0
62.70	0.99512	0.12500	0.023	11.453	0.25E+6	6.61E+6	0.25E+6	4.85E+6	0.0	0.04	0.94	0.0	0.0	0.0	0.05387	0.0	0.0
63.00	1.00000	0.12500	0.000	10.319	0.17E+6	5.01E+6	0.19E+6	3.53E+6	0.0	0.02	0.68	0.0	0.0	0.0	0.05181	0.0	0.0

− 0.25) = −0.125].

The flapwise and edgewise section stiffness and inertia values, "FlpStff," "EdgStff," "FlpIner," and "EdgIner" in Table 2-1, are given about the principal structural axes of each cross section as oriented by the structural-twist angle, "StrcTwst." The values of the structural twist were assumed to be identical to the aerodynamic twist discussed in Section 3.

"GJStff" represents the values of the blade torsion stiffness. Because the DOWEC blade data did not contain extensional stiffness information, we estimated the blade extensional stiffness values—"EAStff" in Table 2-1—to be 10^7 times the average mass moment of inertia at each blade station. This came from a rule of thumb derived from the data available in the WindPACT rotor design study [19], but the exact values are not important because of the low rotational speed of the rotor.

The edgewise CM offset values, "EdgcgOf," are the distances in meters along the chordline from the blade-pitch axis to the CM of the blade section, positive toward the trailing edge. We neglected the insignificant values of the flapwise CM offsets, "FlpcgOf," and flapwise and edgewise elastic offsets, "FlpEAOf" and "EdgEAOf," given in Appendix A of Ref. [17]. Instead, we assumed that they were zero as shown in Table 2-1.

The distributed blade section mass per unit length values, "BMassDen," given in Table 2-1 are the values documented in Appendix A of Ref. [17]. We increased these by 4.536% in the model to scale the overall (integrated) blade mass to 17,740 kg, which was the nominal mass of the blades in the REpower 5M prototype. In our baseline specifications, the nominal second mass moment of inertia, nominal first mass moment of inertia, and the nominal radial CM location of each blade are 11,776,047 kg•m^2, 363,231 kg•m, and 20.475 m with respect to (w.r.t.) the blade root, respectively.

We specified a structural-damping ratio of 0.477465% critical in all modes of the isolated blade, which corresponds to the 3% logarithmic decrement used in the DOWEC study from page 20 of Ref. [14].

Table 2-2 summarizes the undistributed blade structural properties discussed in this section.

Table 2-2. Undistributed Blade Structural Properties

Length (w.r.t. Root Along Preconed Axis)	61.5 m
Mass Scaling Factor	4.536 %
Overall (Integrated) Mass	17,740 kg
Second Mass Moment of Inertia (w.r.t. Root)	11,776,047 kg•m^2
First Mass Moment of Inertia (w.r.t. Root)	363,231 kg•m
CM Location (w.r.t. Root along Preconed Axis)	20.475 m
Structural-Damping Ratio (All Modes)	0.477465 %

3 Blade Aerodynamic Properties

Similar to the blade structural properties, we based the blade aerodynamic properties of the NREL 5-MW baseline wind turbine on the DOWEC blades (using the data described in Table 1 on page 13 of Ref. [14] and in Appendix A of Ref. [17]). We set the FAST with AeroDyn and ADAMS with AeroDyn models to use 17 blade elements for integration of the aerodynamic and structural forces. To better capture the large structural gradients at the blade root and the large aerodynamic gradients at the blade tip, the 3 inboard and 3 outboard elements are two-thirds the size of the 11 equally spaced midspan elements. Table 3-1 gives the aerodynamic properties at the blade nodes, which are located at the center of the blade elements.

The blade node locations, labeled as “RNodes” in Table 3-1, are directed along the blade-pitch axis from the rotor center (apex) to the blade cross sections. The element lengths, “DRNodes,” sum to the total blade length of 61.5 m indicated in Table 2-2. The aerodynamic twist, “AeroTwst,” as given in Table 3-1, are offset by −0.09182° from the values provided in Appendix A of Ref. [17] to ensure that the zero-twist reference location is at the blade tip. Integrating the chord distribution along the blade span reveals that the rotor solidity is roughly 5.16%.

As indicated in Table 3-1, we incorporated eight unique airfoil-data tables for the NREL offshore 5-MW baseline wind turbine. The two innermost airfoil tables represent cylinders with drag coefficients of 0.50 (Cylinder1.dat) and 0.35 (Cylinder2.dat) and no lift. We created the remaining six airfoil tables by making corrections for three-dimensional behavior to the two-dimensional airfoil-data coefficients of the six airfoils used in the DOWEC study (as detailed in

Table 3-1. Distributed Blade Aerodynamic Properties

Node (-)	RNodes (m)	AeroTwst (º)	DRNodes (m)	Chord (m)	Airfoil Table (-)
1	2.8667	13.308	2.7333	3.542	Cylinder1.dat
2	5.6000	13.308	2.7333	3.854	Cylinder1.dat
3	8.3333	13.308	2.7333	4.167	Cylinder2.dat
4	11.7500	13.308	4.1000	4.557	DU40_A17.dat
5	15.8500	11.480	4.1000	4.652	DU35_A17.dat
6	19.9500	10.162	4.1000	4.458	DU35_A17.dat
7	24.0500	9.011	4.1000	4.249	DU30_A17.dat
8	28.1500	7.795	4.1000	4.007	DU25_A17.dat
9	32.2500	6.544	4.1000	3.748	DU25_A17.dat
10	36.3500	5.361	4.1000	3.502	DU21_A17.dat
11	40.4500	4.188	4.1000	3.256	DU21_A17.dat
12	44.5500	3.125	4.1000	3.010	NACA64_A17.dat
13	48.6500	2.319	4.1000	2.764	NACA64_A17.dat
14	52.7500	1.526	4.1000	2.518	NACA64_A17.dat
15	56.1667	0.863	2.7333	2.313	NACA64_A17.dat
16	58.9000	0.370	2.7333	2.086	NACA64_A17.dat
17	61.6333	0.106	2.7333	1.419	NACA64_A17.dat

Appendix A of Ref. [14]).[8] In these airfoil tables, "DU" refers to Delft University and "NACA" refers to the National Advisory Committee for Aeronautics. We used AirfoilPrep v2.0 [9] to "tailor" these airfoil data. We first corrected the lift and drag coefficients for rotational stall delay using the Selig and Eggars method for 0° to 90° angles of attack. We then corrected the drag coefficients using the Viterna method for 0° to 90° angles of attack assuming an aspect ratio of 17. Finally, we estimated the Beddoes-Leishman dynamic-stall hysteresis parameters. We made no corrections to the DOWEC-supplied pitching-moment coefficients. The resulting three-dimensionally corrected airfoil-data coefficients are illustrated graphically in Figure 3-1 through Figure 3-6. The numerical values are documented in the AeroDyn airfoil-data input files that make up Appendix B.

[8] C. Lindenburg of the Energy Research Center of the Netherlands (ECN) provided numerical values for these coefficients.

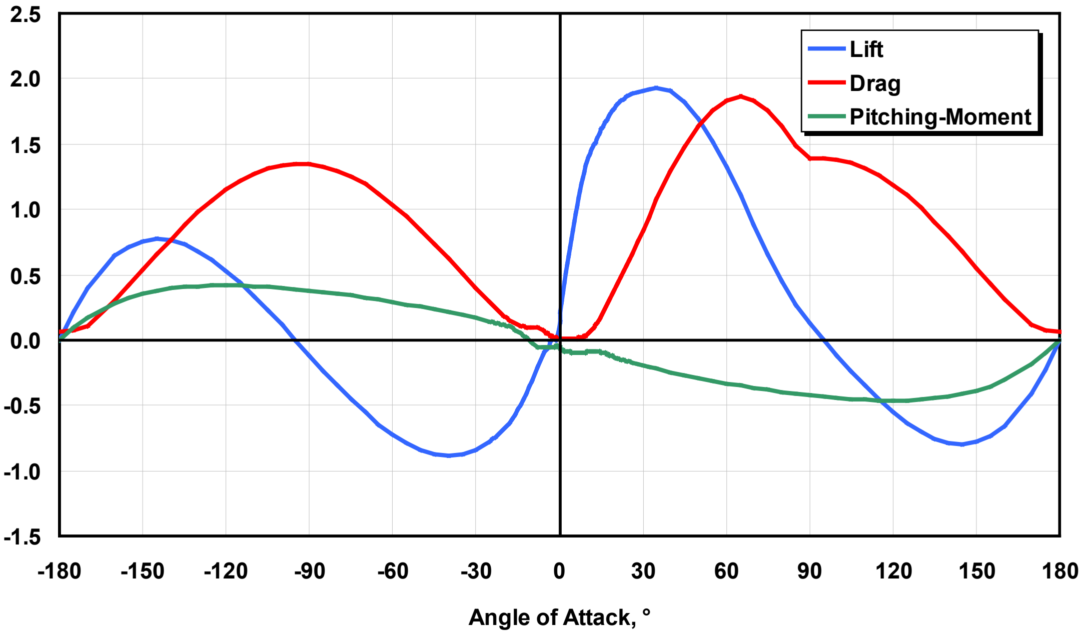

Figure 3-1. Corrected coefficients of the DU40 airfoil

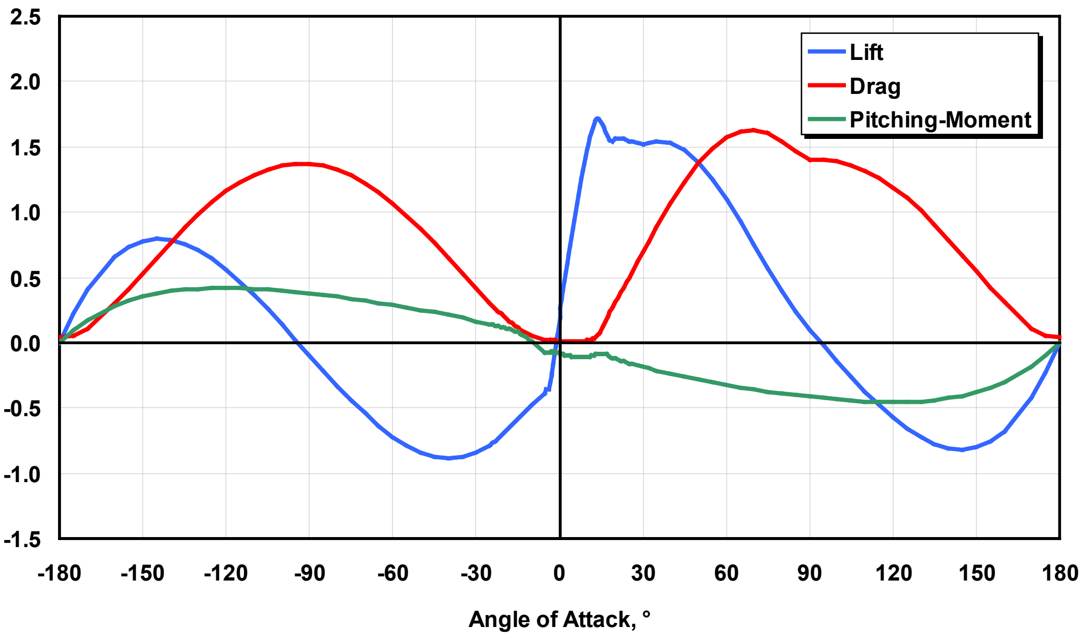

Figure 3-2. Corrected coefficients of the DU35 airfoil

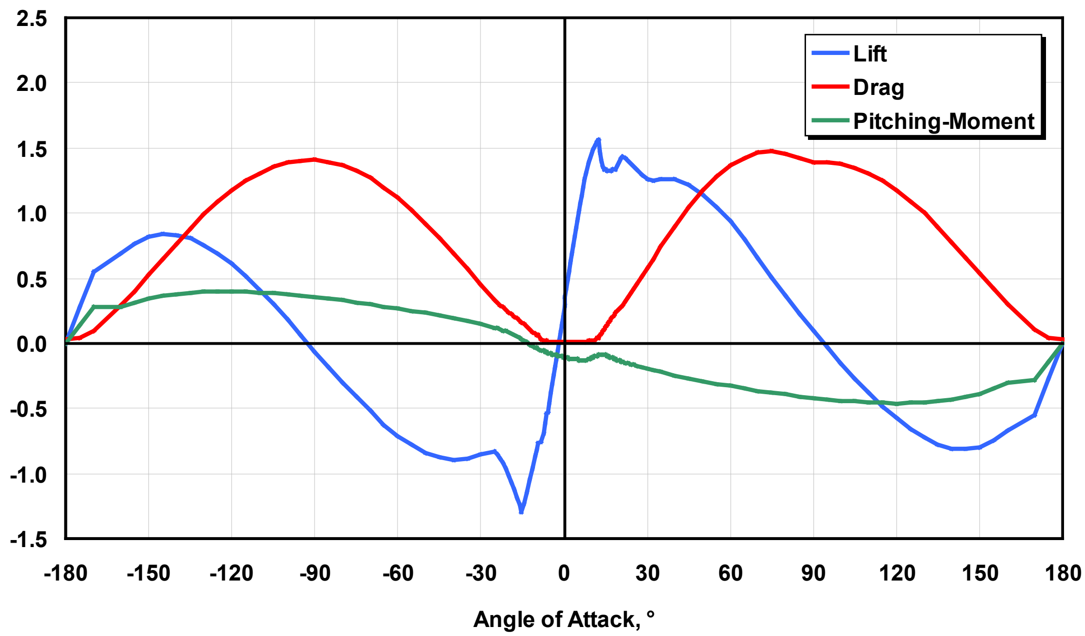

Figure 3-3. Corrected coefficients of the DU30 airfoil

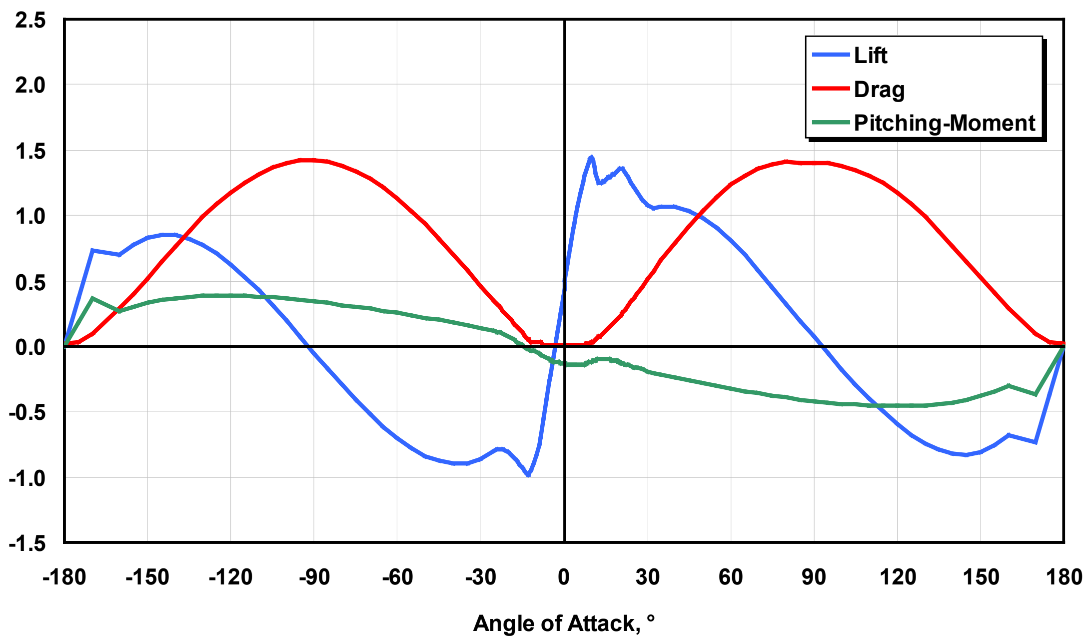

Figure 3-4. Corrected coefficients of the DU25 airfoil

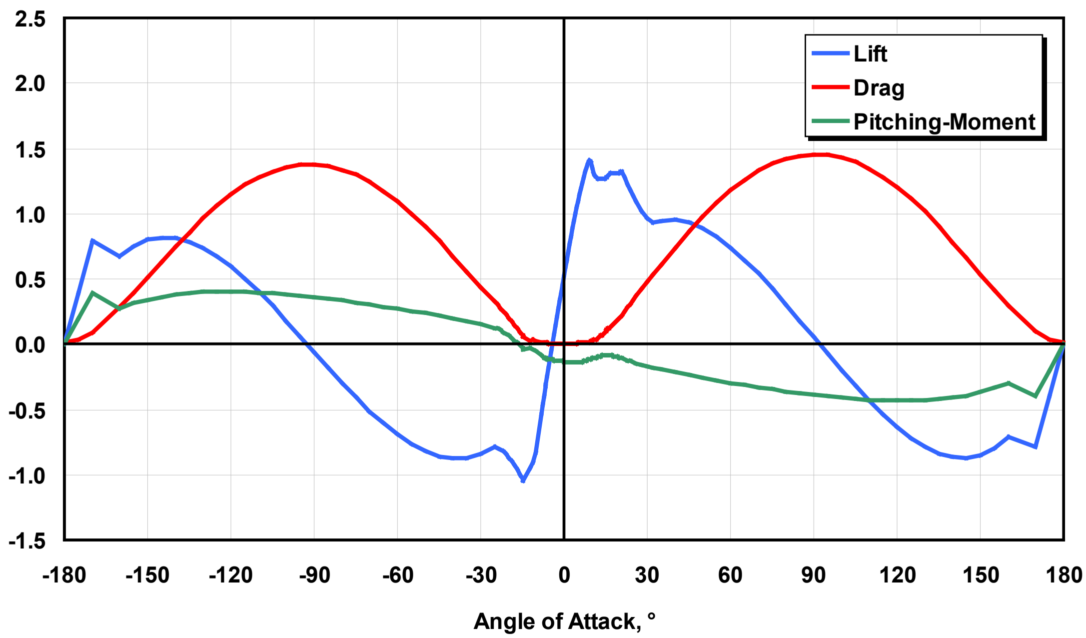

Figure 3-5. Corrected coefficients of the DU21 airfoil

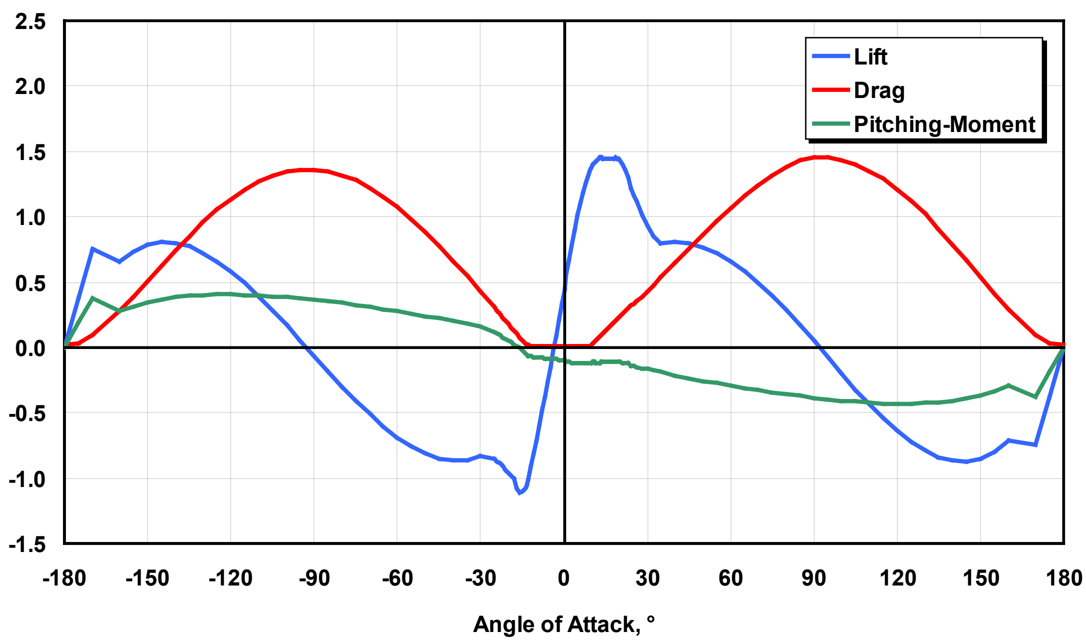

Figure 3-6. Corrected coefficients of the NACA64 airfoil

4 Hub and Nacelle Properties

As indicated in Table 1-1, we located the hub of the NREL 5-MW baseline wind turbine 5 m upwind of the tower centerline at an elevation of 90 m above the ground when the system is undeflected. We also specified the same vertical distance from the tower top to the hub height used by the DOWEC study—that is, 2.4 m (as specified in Table 6 on page 26 of Ref. [14]). Consequently, the elevation of the yaw bearing above ground or MSL is 87.6 m. With a shaft tilt of 5°, this made the distance directed along the shaft from the hub center to the yaw axis 5.01910 m and the vertical distance along the yaw axis from the tower top to the shaft 1.96256 m. The distance directed along the shaft from the hub center to the main bearing was taken to be 1.912 m (from Table 6 on page 26 of Ref. [14]).

We specified the hub mass to be 56,780 kg like in the REpower 5M, and we located its CM at the hub center. The hub inertia about the shaft, taken to be 115,926 kg•m^2, was found by assuming that the hub casting is a thin spherical shell with a radius of 1.75 m (this is 0.25 m longer than the actual hub radius because the nacelle height of the DOWEC turbine was 3.5 m, based on the data in Table 6 on page 26 of Ref. [14]).

We specified the nacelle mass to be 240,000 kg like in the REpower 5M and we located its CM 1.9 m downwind of the yaw axis like in the DOWEC turbine (from Table 7 on page 27 of Ref. [14]) and 1.75 m above the yaw bearing, which was half the height of the DOWEC turbine's nacelle (from Table 6 on page 26 of Ref. [14]). The nacelle inertia about the yaw axis was taken to be 2,607,890 kg•m^2. We chose this to be equivalent to the DOWEC turbine's nacelle inertia about its nacelle CM, but translated to the yaw axis using the parallel-axis theorem with the nacelle mass and downwind distance to the nacelle CM.

We took the nacelle-yaw actuator to have a natural frequency of 3 Hz, which is roughly equivalent to the highest full-system natural frequency in the FAST model (see Section 9), and a damping ratio of 2% critical. This resulted in an equivalent nacelle-yaw-actuator linear-spring constant of 9,028,320,000 N•m/rad and an equivalent nacelle-yaw-actuator linear-damping constant of 19,160,000 N•m/(rad/s). The nominal nacelle-yaw rate was chosen to be the same as that for the DOWEC 6-MW turbine, or 0.3°/s (from page 27 of Ref. [14]).

Table 4-1 summarizes the nacelle and hub properties discussed in this section.

Table 4-1. Nacelle and Hub Properties

Elevation of Yaw Bearing above Ground	87.6 m
Vertical Distance along Yaw Axis from Yaw Bearing to Shaft	1.96256 m
Distance along Shaft from Hub Center to Yaw Axis	5.01910 m
Distance along Shaft from Hub Center to Main Bearing	1.912 m
Hub Mass	56,780 kg
Hub Inertia about Low-Speed Shaft	115,926 kg•m^2
Nacelle Mass	240,000 kg
Nacelle Inertia about Yaw Axis	2,607,890 kg•m^2
Nacelle CM Location Downwind of Yaw Axis	1.9 m
Nacelle CM Location above Yaw Bearing	1.75 m
Equivalent Nacelle-Yaw-Actuator Linear-Spring Constant	9,028,320,000 N•m/rad
Equivalent Nacelle-Yaw-Actuator Linear-Damping Constant	19,160,000 N•m/(rad/s)
Nominal Nacelle-Yaw Rate	0.3 º/s

5 Drivetrain Properties

We specified the NREL 5-MW baseline wind turbine to have the same rated rotor speed (12.1 rpm), rated generator speed (1173.7 rpm), and gearbox ratio (97:1) as the REpower 5M machine. The gearbox was assumed be a typical multiple-stage gearbox but with no frictional losses—a requirement of the preprocessor functionality in FAST for creating ADAMS models [11]. The electrical efficiency of the generator was taken to be 94.4%. This was chosen to be roughly the same as the total mechanical-to-electrical conversion loss used by the DOWEC turbine at rated power—that is, the DOWEC turbine had about 0.35 MW of power loss at about 6.25 MW of aerodynamic power (from Figure 15, page 24 of Ref. [14]). The generator inertia about the high-speed shaft was taken to be 534.116 kg•m^2, which is the same equivalent low-speed shaft generator inertia used in the DOWEC study (i.e., 5,025,500 kg•m^2 from page 36 of Ref. [14]).

The driveshaft was taken to have the same natural frequency as the RECOFF turbine model and a structural-damping ratio—associated with the free-free mode of a drivetrain composed of a rigid generator and rigid rotor—of 5% critical. This resulted in an equivalent driveshaft linear-spring constant of 867,637,000 N•m/rad and a linear-damping constant of 6,215,000 N•m/(rad/s).

The high-speed shaft brake was assumed to have the same ratio of maximum brake torque to maximum generator torque and the same time lag as used in the DOWEC study (from page 29 of Ref. [14]). This resulted in a fully deployed high-speed shaft brake torque of 28,116.2 N•m and a time lag of 0.6 s. This time lag is the amount of time it takes for the brake to fully engage once deployed. The FAST and ADAMS models employ a simple linear ramp from nothing to full braking over the 0.6-s period.

Table 5-1 summarizes the drivetrain properties discussed in this section.

Table 5-1. Drivetrain Properties

Rated Rotor Speed	12.1 rpm
Rated Generator Speed	1173.7 rpm
Gearbox Ratio	97 :1
Electrical Generator Efficiency	94.4 %
Generator Inertia about High-Speed Shaft	534.116 kg•m^2
Equivalent Drive-Shaft Torsional-Spring Constant	867,637,000 N•m/rad
Equivalent Drive-Shaft Torsional-Damping Constant	6,215,000 N•m/(rad/s)
Fully-Deployed High-Speed Shaft Brake Torque	28,116.2 N•m
High-Speed Shaft Brake Time Constant	0.6 s

6 Tower Properties

The properties of the tower for the NREL offshore 5-MW baseline wind turbine will depend on the type support structure used to carry the rotor-nacelle assembly. The type of support structure will, in turn, depend on the installation site, whose properties vary significantly through differences in water depth, soil type, and wind and wave severity. Offshore support-structure types include fixed-bottom monopiles, gravity bases, and space-frames—such as tripods, quadpods, and lattice frames (e.g., "jackets")—and floating structures. This section documents the tower properties for the equivalent land-based version of the NREL 5-MW baseline wind turbine. These properties provide a basis with which to design towers for site-specific offshore support structures. For example, different types of offshore support structures for the NREL 5-MW baseline wind turbine have been designed for—and investigated in—separate phases of the OC3 project [13,25].

We based the distributed properties of the land-based tower for the NREL 5-MW baseline wind turbine on the base diameter (6 m) and thickness (0.027 m), top diameter (3.87 m) and thickness (0.019 m), and effective mechanical steel properties of the tower used in the DOWEC study (as given in Table 9 on page 31 of Ref. [14]). The Young's modulus was taken to be 210 GPa, the shear modulus was taken to be 80.8 GPa, and the effective density of the steel was taken to be 8,500 kg/m^3. The density of 8,500 kg/m^3 was meant to be an increase above steel's typical value of 7,850 kg/m^3 to account for paint, bolts, welds, and flanges that are not accounted for in the tower thickness data. The radius and thickness of the tower were assumed to be linearly tapered from the tower base to tower top. Because the REpower 5M machine had a larger tower-top mass than the DOWEC wind turbine, we scaled up the thickness of the tower relative to the values given earlier in this paragraph to strengthen the tower. We chose an increase of 30% to ensure that the first fore-aft and side-to-side tower frequencies were placed between the one- and three-per-rev frequencies throughout the operational range of the wind turbine in a Campbell diagram. Table 6-1 gives the resulting distributed tower properties.

The entries in the first column, "Elevation," are the vertical locations along the tower centerline relative to the tower base. "HtFract" is the fractional height along the tower centerline from the tower base (0.0) to the tower top (1.0). The rest of columns are similar to those described for the distributed blade properties presented in Table 2-1.

The resulting overall (integrated) tower mass is 347,460 kg and is centered at 38.234 m along the

Table 6-1. Distributed Tower Properties

Elevation (m)	HtFract (-)	TMassDen (kg/m)	TwFAStif (N•m^2)	TwSSStif (N•m^2)	TwGJStif (N•m^2)	TwEAStif (N)	TwFAIner (kg•m)	TwSSIner (kg•m)	TwFAcgOf (m)	TwSScgOf (m)
0.00	0.0	5590.87	614.34E+9	614.34E+9	472.75E+9	138.13E+9	24866.3	24866.3	0.0	0.0
8.76	0.1	5232.43	534.82E+9	534.82E+9	411.56E+9	129.27E+9	21647.5	21647.5	0.0	0.0
17.52	0.2	4885.76	463.27E+9	463.27E+9	356.50E+9	120.71E+9	18751.3	18751.3	0.0	0.0
26.28	0.3	4550.87	399.13E+9	399.13E+9	307.14E+9	112.43E+9	16155.3	16155.3	0.0	0.0
35.04	0.4	4227.75	341.88E+9	341.88E+9	263.09E+9	104.45E+9	13838.1	13838.1	0.0	0.0
43.80	0.5	3916.41	291.01E+9	291.01E+9	223.94E+9	96.76E+9	11779.0	11779.0	0.0	0.0
52.56	0.6	3616.83	246.03E+9	246.03E+9	189.32E+9	89.36E+9	9958.2	9958.2	0.0	0.0
61.32	0.7	3329.03	206.46E+9	206.46E+9	158.87E+9	82.25E+9	8356.6	8356.6	0.0	0.0
70.08	0.8	3053.01	171.85E+9	171.85E+9	132.24E+9	75.43E+9	6955.9	6955.9	0.0	0.0
78.84	0.9	2788.75	141.78E+9	141.78E+9	109.10E+9	68.90E+9	5738.6	5738.6	0.0	0.0
87.60	1.0	2536.27	115.82E+9	115.82E+9	89.13E+9	62.66E+9	4688.0	4688.0	0.0	0.0

tower centerline above the ground. This result follows directly from the overall tower height of 87.6 m.

We specified a structural-damping ratio of 1% critical in all modes of the isolated tower (without the rotor-nacelle assembly mass present), which corresponds to the values used in the DOWEC study (from page 21 of Ref. [14]).

Table 6-2 summarizes the undistributed tower properties discussed in this section.

Table 6-2. Undistributed Tower Properties

Height above Ground	87.6 m
Overall (Integrated) Mass	347,460 kg
CM Location (w.r.t. Ground along Tower Centerline)	38.234 m
Structural-Damping Ratio (All Modes)	1 %

7 Baseline Control System Properties

For the NREL 5-MW baseline wind turbine, we chose a conventional variable-speed, variable blade-pitch-to-feather configuration. In such wind turbines, the conventional approach for controlling power-production operation relies on the design of two basic control systems: a generator-torque controller and a full-span rotor-collective blade-pitch controller. The two control systems are designed to work independently, for the most part, in the below-rated and above-rated wind-speed range, respectively. The goal of the generator-torque controller is to maximize power capture below the rated operation point. The goal of the blade-pitch controller is to regulate generator speed above the rated operation point.

We based the baseline control system for the NREL 5-MW wind turbine on this conventional design approach. We did not establish additional control actions for nonpower-production operations, such as control actions for normal start-up sequences, normal shutdown sequences, and safety and protection functions. Nor did we develop control actions to regulate the nacelle-yaw angle. (The nacelle-yaw control system is generally neglected within aero-servo-elastic simulation because its response is slow enough that it does not generally contribute to large extreme loads or fatigue damage.)

We describe the development of our baseline control system next, including the control-measurement filter (Section 7.1), the generator-torque controller (Section 7.2), the blade-pitch controller (Section 7.3), and the blade-pitch actuator (Section 7.4). Section 7.5 shows how these systems are put together in the overall integrated control system.

7.1 Baseline Control-Measurement Filter

As is typical in utility-scale multimegawatt wind turbines, both the generator-torque and blade-pitch controllers use the generator speed measurement as the sole feedback input. To mitigate high-frequency excitation of the control systems, we filtered the generator speed measurement for both the torque and pitch controllers using a recursive, single-pole low-pass filter with exponential smoothing [30]. The discrete-time recursion (difference) equation for this filter is

$$y[n] = (1-\alpha)u[n] + \alpha y[n-1], \tag{7-1}$$

with

$$\alpha = e^{-2\pi T_s f_c}, \tag{7-2}$$

where y is the filtered generator speed (output measurement), u is the unfiltered generator speed (input), α is the low-pass filter coefficient, n is the discrete-time-step counter, T_s is the discrete time step, and f_c is the corner frequency.

By defining the filter state,

$$x[n] = y[n-1], \tag{7-3a}$$

or

$$x[n+1] = y[n], \tag{7-3b}$$

one can derive a discrete-time state-space representation of this filter:

$$\begin{aligned} x[n+1] &= A_d x[n] + B_d u[n] \\ y[n] &= C_d x[n] + D_d u[n] \end{aligned}, \tag{7-4}$$

where $A_d = \alpha$ is the discrete-time state matrix, $B_d = 1-\alpha$ is the discrete-time input matrix, $C_d = \alpha$ is the discrete-time output state matrix, and $D_d = 1-\alpha$ is the discrete-time input transmission matrix.

The state-space representation of Eq. (7-4) is useful for converting the filter into other forms, such as transfer-function form or frequency-response form [31].

We set the corner frequency (the -3 dB point in Figure 7-1) of the low-pass filter to be roughly one-quarter of the blade's first edgewise natural frequency (see Section 9) or 0.25 Hz. For a discrete time step of 0.0125 s, the frequency response of the resulting filter is shown in the Bode plot of Figure 7-1.

We chose the recursive, single-pole filter for its simplicity in implementation and effectiveness

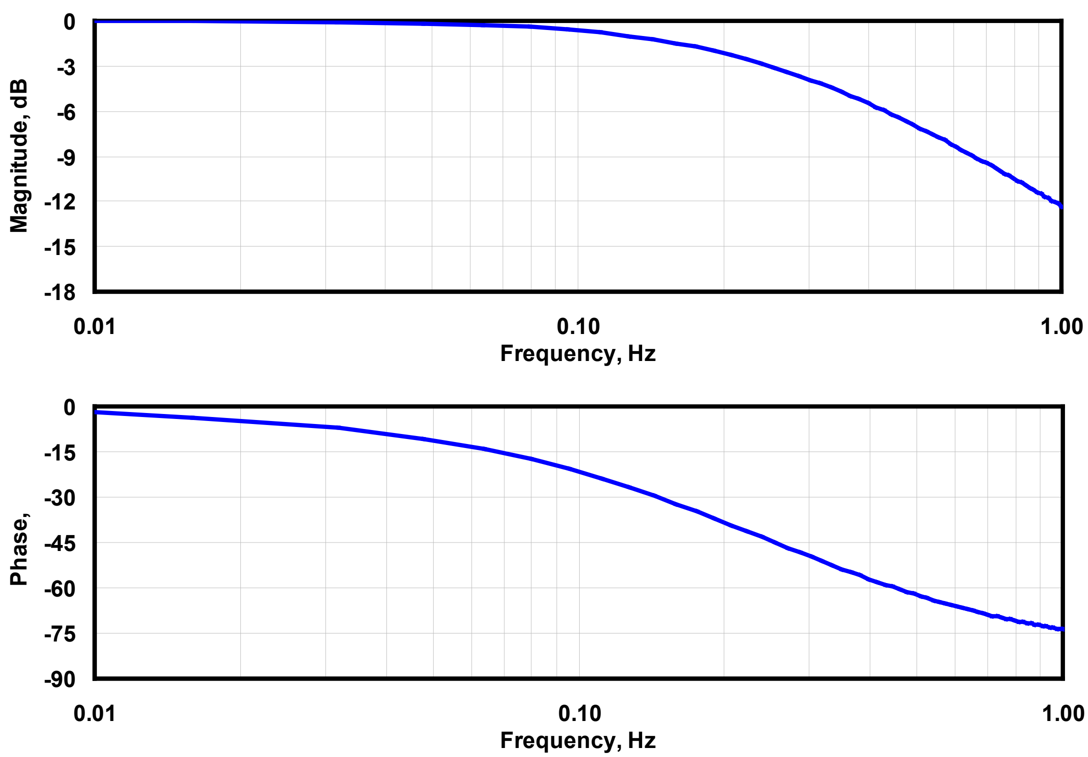

Figure 7-1. Bode plot of generator speed low-pass filter frequency response

in the time domain. The drawbacks to this filter are its gentle roll-off in the stop band (-6 dB/octave) and the magnitude and nonlinearity of its phase lag in the pass band [30]. We considered other linear low-pass filters, such as Butterworth, Chebyshev, Elliptic, and Bessel filters because of their inherent advantages relative to the chosen filter. Like the chosen filter, a Butterworth filter has a frequency response that is flat in the pass band, but the Butterworth filter offers steeper roll-off in the stop band. Chebyshev filters offer even steeper roll-off in the stop band at the expense of equalized-ripple (equiripple) in the pass band (Type 1) or stop band (Type 2), respectively. Elliptic filters offer the steepest roll-off of any linear filter, but have equiripple in both the pass and stop bands. Bessel filters offer the flattest group delay (linear phase lag) in the pass band. We designed and tested examples of each of these other low-pass filter types, considering state-space representations of up to fourth order (four states). None were found to give superior performance in the overall system response, however, so they did not warrant the added complexity of implementation.

7.2 Baseline Generator-Torque Controller

The generator torque is computed as a tabulated function of the filtered generator speed, incorporating five control regions: 1, 1½, 2, 2½, and 3. Region 1 is a control region before cut-in wind speed, where the generator torque is zero and no power is extracted from the wind; instead, the wind is used to accelerate the rotor for start-up. Region 2 is a control region for optimizing power capture. Here, the generator torque is proportional to the square of the filtered generator speed to maintain a constant (optimal) tip-speed ratio. In Region 3, the generator power is held constant so that the generator torque is inversely proportional to the filtered generator speed. Region 1½, a start-up region, is a linear transition between Regions 1 and 2. This region is used to place a lower limit on the generator speed to limit the wind turbine's operational speed range. Region 2½ is a linear transition between Regions 2 and 3 with a torque slope corresponding to the slope of an induction machine. Region 2½ is typically needed (as is the case for my 5-MW turbine) to limit tip speed (and hence noise emissions) at rated power.

We found the peak of the power coefficient as a function of the tip-speed ratio and blade-pitch surface by running FAST with AeroDyn simulations at a number of given rotor speeds and a number of given rotor-collective blade-pitch angles at a fixed wind speed of 8 m/s. From these simulations, we found that the peak power coefficient of 0.482 occurred at a tip-speed ratio of 7.55 and a rotor-collective blade-pitch angle of 0.0˚. With the 97:1 gearbox ratio, this resulted in an optimal constant of proportionality of 0.0255764 N•m/rpm^2 in the Region 2 control law. With the rated generator speed of 1173.7 rpm, rated electric power of 5 MW, and a generator efficiency of 94.4%, the rated mechanical power is 5.296610 MW and the rated generator torque is 43,093.55 N•m. We defined Region 1½ to span the range of generator speeds between 670 rpm and 30% above this value (or 871 rpm). The minimum generator speed of 670 rpm corresponds to the minimum rotor speed of 6.9 rpm used by the actual REpower 5M machine [26]. We took the transitional generator speed between Regions 2½ and 3 to be 99% of the rated generator speed, or 1,161.963 rpm. The generator-slip percentage in Region 2½ was taken to be 10%, in accordance with the value used in the DOWEC study (see page 24 of Ref. [14]). Figure 7-2 shows the resulting generator-torque versus generator speed response curve.

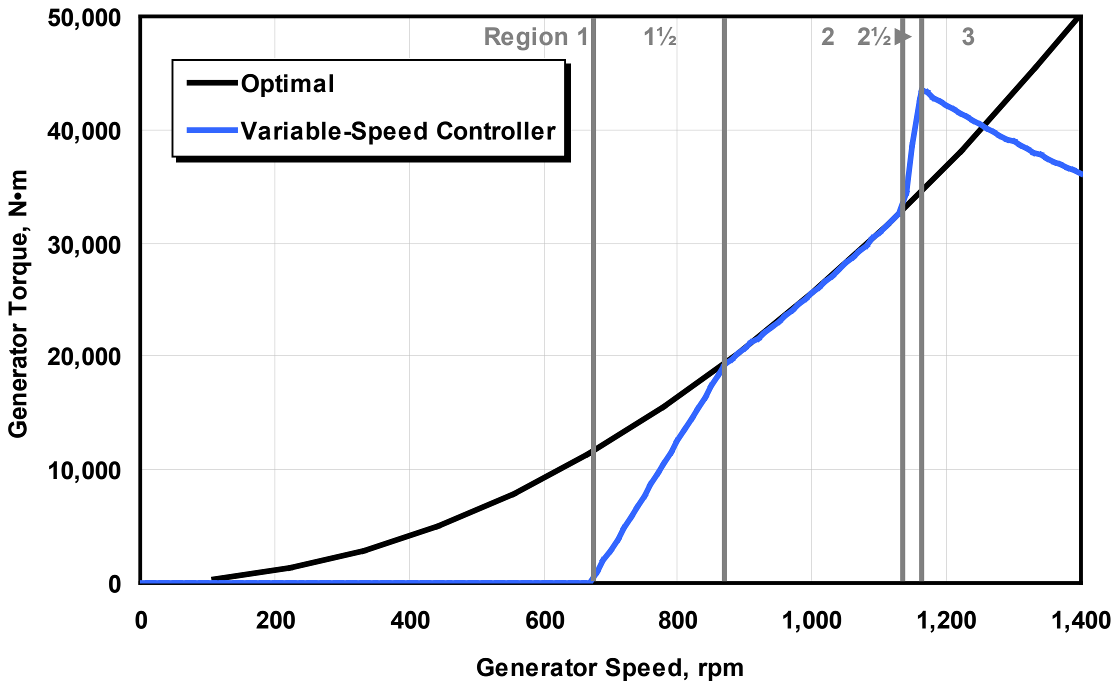

Figure 7-2. Torque-versus-speed response of the variable-speed controller

Because of the high intrinsic structural damping of the drivetrain, we did not need to incorporate a control loop for damping drivetrain torsional vibration in our baseline generator-torque controller.

We did, however, place a conditional statement on the generator-torque controller so that the torque would be computed as if it were in Region 3—regardless of the generator speed—whenever the previous blade-pitch-angle command was 1º or greater. This results in improved output power quality (fewer dips below rated) at the expense of short-term overloading of the generator and the gearbox. To avoid this excessive overloading, we saturated the torque to a maximum of 10% above rated, or 47,402.91 N•m. We also imposed a torque rate limit of 15,000 N•m/s. In Region 3, the blade-pitch control system takes over.

7.3 Baseline Blade-Pitch Controller

In Region 3, the full-span rotor-collective blade-pitch-angle commands are computed using gain-scheduled proportional-integral (PI) control on the speed error between the filtered generator speed and the rated generator speed (1173.7 rpm).

We designed the blade-pitch control system using a simple single-degree-of-freedom (single-DOF) model of the wind turbine. Because the goal of the blade-pitch control system is to regulate the generator speed, this DOF is the angular rotation of the shaft. To compute the required control gains, it is beneficial to examine the equation of motion of this single-DOF system. From a simple free-body diagram of the drivetrain, the equation of motion is

$$T_{Aero} - N_{Gear}T_{Gen} = \left(I_{Rotor} + N_{Gear}^2 I_{Gen}\right)\frac{d}{dt}\left(\Omega_0 + \Delta\Omega\right) = I_{Drivetrain}\Delta\dot{\Omega}\,, \tag{7-5}$$

where T_{Aero} is the low-speed shaft aerodynamic torque, T_{Gen} is the high-speed shaft generator torque, N_{Gear} is the high-speed to low-speed gearbox ratio, $I_{Drivetrain}$ is the drivetrain inertia cast to the low-speed shaft, I_{Rotor} is the rotor inertia, I_{Gen} is the generator inertia relative to the high-speed shaft, Ω_0 is the rated low-speed shaft rotational speed, $\Delta\Omega$ is the small perturbation of low-speed shaft rotational speed about the rated speed, $\Delta\dot{\Omega}$ is the low-speed shaft rotational acceleration, and t is the simulation time.

Because the generator-torque controller maintains constant generator power in Region 3, the generator torque in Region 3 is inversely proportional to the generator speed (see Figure 7-2), or

$$T_{Gen}\left(N_{Gear}\Omega\right)=\frac{P_0}{N_{Gear}\Omega}, \tag{7-6}$$

where P_0 is the rated mechanical power and Ω is the low-speed shaft rotational speed.

Similarly, assuming negligible variation of aerodynamic torque with rotor speed, the aerodynamic torque in Region 3 is

$$T_{Aero}\left(\theta\right)=\frac{P\left(\theta,\Omega_0\right)}{\Omega_0}, \tag{7-7}$$

where P is the mechanical power and θ is the full-span rotor-collective blade-pitch angle.

Using a first-order Taylor series expansion of Eqs. (7-6) and (7-7), one can see that

$$T_{Gen}\approx\frac{P_0}{N_{Gear}\Omega_0}-\frac{P_0}{N_{Gear}\Omega_0^2}\Delta\Omega \tag{7-8}$$

and

$$T_{Aero}\approx\frac{P_0}{\Omega_0}+\frac{1}{\Omega_0}\left(\frac{\partial P}{\partial\theta}\right)\Delta\theta, \tag{7-9}$$

where $\Delta\theta$ is a small perturbation of the blade-pitch angles about their operating point. With proportional-integral-derivative (PID) control, this is related to the rotor-speed perturbations by

$$\Delta\theta=K_P N_{Gear}\Delta\Omega+K_I\int_0^t N_{Gear}\Delta\Omega dt+K_D N_{Gear}\Delta\dot{\Omega}, \tag{7-10}$$

where K_P, K_I, and K_D are the blade-pitch controller proportional, integral, and derivative gains, respectively.

By setting $\dot{\varphi}=\Delta\Omega$, combining the above expressions, and simplifying, the equation of motion for the rotor-speed error becomes

$$\underbrace{\left[I_{Drivetrain}+\frac{1}{\Omega_0}\left(-\frac{\partial P}{\partial \theta}\right)N_{Gear}K_D\right]}_{M_\varphi}\ddot{\varphi}+\underbrace{\left[\frac{1}{\Omega_0}\left(-\frac{\partial P}{\partial \theta}\right)N_{Gear}K_P-\frac{P_0}{\Omega_0^2}\right]}_{C_\varphi}\dot{\varphi}+\underbrace{\left[\frac{1}{\Omega_0}\left(-\frac{\partial P}{\partial \theta}\right)N_{Gear}K_I\right]}_{K_\varphi}\varphi=0 \,. \tag{7-11}$$

One can see that the idealized PID-controlled rotor-speed error will respond as a second-order system with the natural frequency, $\omega_{\varphi n}$, and damping ratio, ζ_φ, equal to

$$\omega_{\varphi n}=\sqrt{\frac{K_\varphi}{M_\varphi}} \tag{7-12}$$

and

$$\zeta_\varphi=\frac{C_\varphi}{2\sqrt{K_\varphi M_\varphi}}=\frac{C_\varphi}{2M_\varphi\omega_{\varphi n}} \,. \tag{7-13}$$

In an active pitch-to-feather wind turbine, the sensitivity of aerodynamic power to the rotor-collective blade-pitch angle, $\partial P/\partial\theta$, is negative in Region 3. With positive control gains, then, the derivative term acts to increase the effective inertia of the drivetrain, the proportional term adds damping, and the integral term adds restoring. Also, because the generator torque drops with increasing speed error (to maintain constant power) in Region 3, one can see that the generator-torque controller introduces a negative damping in the speed error response [indicated by the $-P_0/\Omega_0^2$ term in Eq. (7-11)]. This negative damping must be compensated by the proportional term in the blade-pitch controller.

In the design of the blade-pitch controller, Ref. [10] recommends neglecting the derivative gain, ignoring the negative damping from the generator-torque controller, and aiming for the response characteristics given by $\omega_{\varphi n}$ = 0.6 rad/s and ζ_φ = 0.6 to 0.7. This specification leads to direct expressions for choosing appropriate PI gains once the sensitivity of aerodynamic power to rotor-collective blade pitch, $\partial P/\partial\theta$, is known:

$$K_P=\frac{2I_{Drivetrain}\Omega_0\zeta_\varphi\omega_{\varphi n}}{N_{Gear}\left(-\frac{\partial P}{\partial\theta}\right)} \tag{7-14}$$

and

$$K_I=\frac{I_{Drivetrain}\Omega_0\omega_{\varphi n}^2}{N_{Gear}\left(-\frac{\partial P}{\partial\theta}\right)} \,. \tag{7-15}$$

The blade-pitch sensitivity, $\partial P/\partial\theta$, is an aerodynamic property of the rotor that depends on the wind speed, rotor speed, and blade-pitch angle. We calculated it for the NREL offshore 5-MW baseline wind turbine by performing a linearization analysis in FAST with AeroDyn at a number of given, steady, and uniform wind speeds; at the rated rotor speed (Ω_0 = 12.1 rpm); and at the corresponding blade-pitch angles that produce the rated mechanical power (P_0 = 5.296610 MW). The linearization analysis involves perturbing the rotor-collective blade-pitch angle at each operating point and measuring the resulting variation in aerodynamic power. Within FAST, the partial derivative is computed using the central-difference-perturbation numerical technique. We created a slightly customized copy of FAST with AeroDyn so that the linearization procedure would invoke the frozen-wake assumption, in which the induced wake velocities are held constant while the blade-pitch angle is perturbed. This gives a more accurate linearization for heavily loaded rotors (i.e., for operating points in Region 3 closest to rated). Table 7-1 presents the results.

Table 7-1. Sensitivity of Aerodynamic Power to Blade Pitch in Region 3

Wind Speed (m/s)	Rotor Speed (rpm)	Pitch Angle (º)	$\partial P/\partial\theta$ (watt/rad)
11.4 - Rated	12.1	0.00	-28.24E+6
12.0	12.1	3.83	-43.73E+6
13.0	12.1	6.60	-51.66E+6
14.0	12.1	8.70	-58.44E+6
15.0	12.1	10.45	-64.44E+6
16.0	12.1	12.06	-70.46E+6
17.0	12.1	13.54	-76.53E+6
18.0	12.1	14.92	-83.94E+6
19.0	12.1	16.23	-90.67E+6
20.0	12.1	17.47	-94.71E+6
21.0	12.1	18.70	-99.04E+6
22.0	12.1	19.94	-105.90E+6
23.0	12.1	21.18	-114.30E+6
24.0	12.1	22.35	-120.20E+6
25.0	12.1	23.47	-125.30E+6

As Table 7-1 shows, the sensitivity of aerodynamic power to rotor-collective blade pitch varies considerably over Region 3, so constant PI gains are not adequate for effective speed control. The pitch sensitivity, though, varies nearly linearly with blade-pitch angle:

$$\frac{\partial P}{\partial \theta} = \left[\frac{\frac{\partial P}{\partial \theta}(\theta = 0)}{\theta_K} \right] \theta + \left[\frac{\partial P}{\partial \theta}(\theta = 0) \right] \tag{7-16a}$$

or

$$\frac{1}{\frac{\partial P}{\partial \theta}} = \frac{1}{\frac{\partial P}{\partial \theta}(\theta = 0)\left(1 + \frac{\theta}{\theta_K}\right)}, \tag{7-16b}$$

where $\frac{\partial P}{\partial \theta}(\theta = 0)$ is the pitch sensitivity at rated and θ_K is the blade-pitch angle at which the pitch sensitivity has doubled from its value at the rated operating point; that is,

$$\frac{\partial P}{\partial \theta}(\theta = \theta_K) = 2\frac{\partial P}{\partial \theta}(\theta = 0). \tag{7-17}$$

On the right-hand side of Eq. (7-16a), the first and second terms in square brackets represent the slope and intercept of the best-fit line, respectively. We computed this regression for the NREL 5-MW baseline wind turbine and present the results in Figure 7-3.

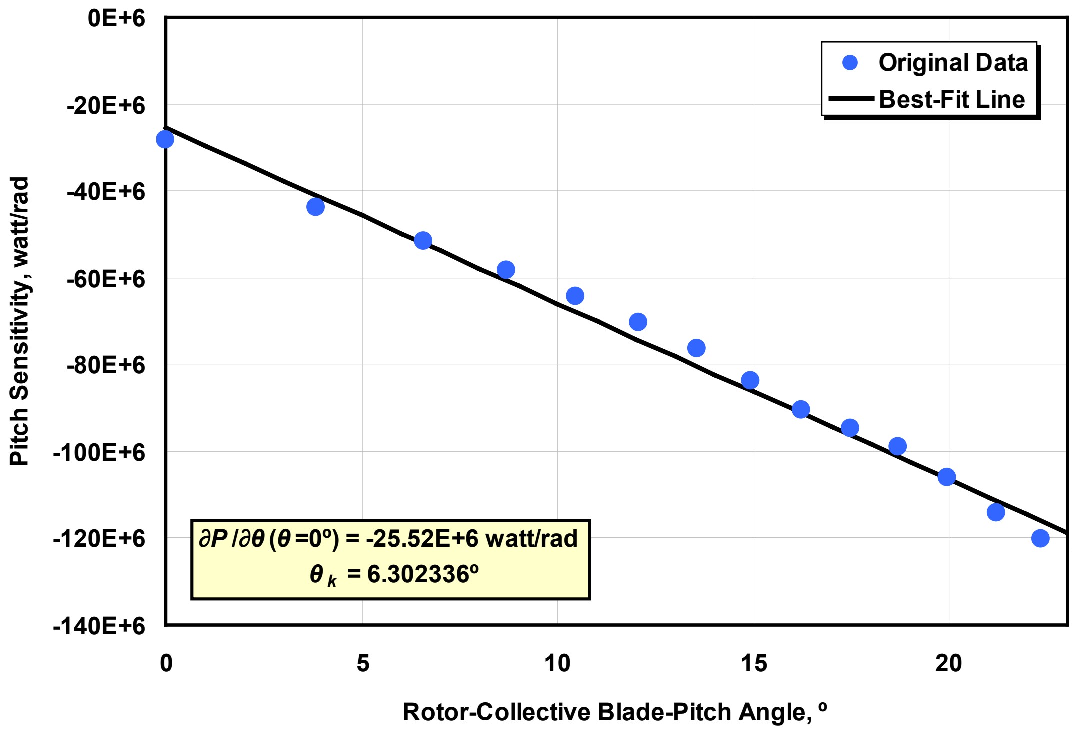

Figure 7-3. Best-fit line of pitch sensitivity in Region 3

The linear relation between pitch sensitivity and blade-pitch angle presents a simple technique for implementing gain scheduling based on blade-pitch angle; that is,

$$K_P(\theta) = \frac{2 I_{Drivetrain} \Omega_0 \zeta_\varphi \omega_{\varphi n}}{N_{Gear}\left[-\frac{\partial P}{\partial \theta}(\theta = 0)\right]} GK(\theta) \tag{7-18}$$

and

$$K_I(\theta) = \frac{I_{Drivetrain}\Omega_0\omega_{\varphi n}^2}{N_{Gear}\left[-\frac{\partial P}{\partial \theta}(\theta=0)\right]} GK(\theta), \tag{7-19}$$

where $GK(\theta)$ is the dimensionless gain-correction factor (from Ref. [10]), which is dependent on the blade-pitch angle:

$$GK(\theta) = \frac{1}{1+\frac{\theta}{\theta_K}}. \tag{7-20}$$

In our implementation of the gain-scheduled PI blade-pitch controller, we used the blade-pitch angle from the previous controller time step to calculate the gain-correction factor at the next time step.

Using the properties for the baseline wind turbine and the recommended response characteristics from Ref. [10], the resulting gains are $K_P(\theta = 0^\circ) = 0.01882681$ s, $K_I(\theta = 0^\circ) = 0.008068634$, and $K_D = 0.0\ \mathrm{s}^2$. Figure 7-4 presents the gains at other blade-pitch angles, along with the gain-correction factor. We used the upper limit of the recommended damping ratio range, $\zeta_\varphi = 0.7$, to compensate for neglecting negative damping from the generator-torque controller in the determination of K_P.

Unfortunately, the simple gain-scheduling law derived in this section for the proportional and integral gains cannot retain consistent response characteristics (i.e., constant values of $\omega_{\varphi n}$ and

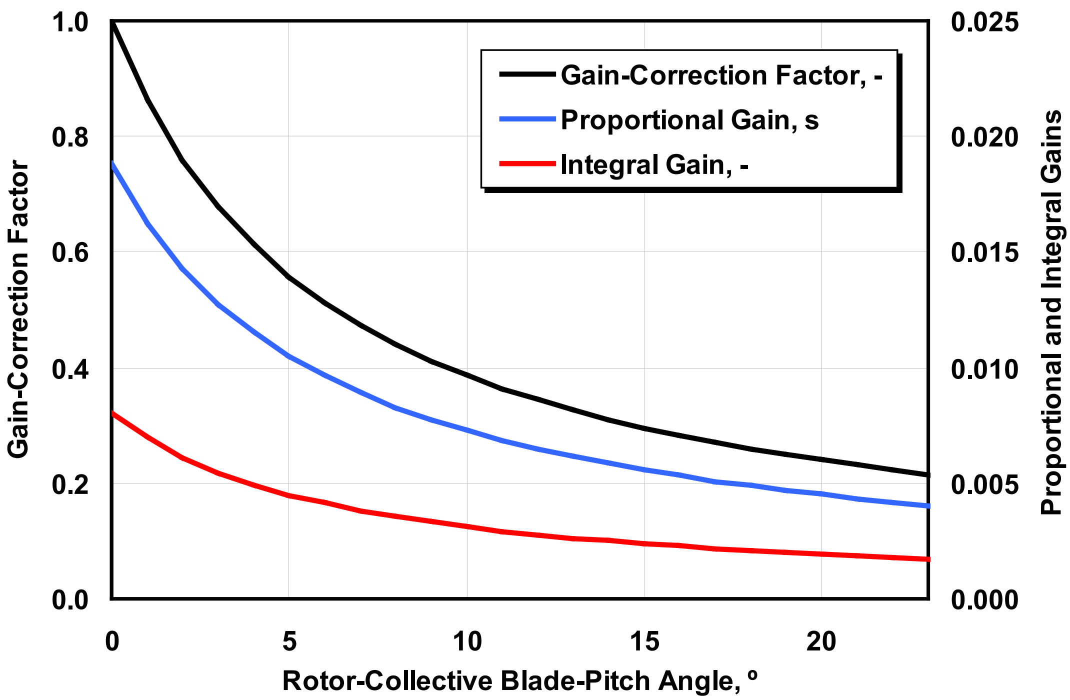

Figure 7-4. Baseline blade-pitch control system gain-scheduling law

ζ_φ) across all of Region 3 when applied to the derivative gain. We, nevertheless, considered adding a derivative term by selecting and testing a range of gains, but none were found to give better performance in the overall system response. Instead, the baseline control system uses the gains derived previously in this section (without the derivative term).

We set the blade-pitch rate limit to 8°/s in absolute value. This is speculated to be the blade-pitch rate limit of conventional 5-MW machines based on General Electric (GE) Wind's long-blade test program. We also set the minimum and maximum blade-pitch settings to 0° and 90°, respectively. The lower limit is the set blade pitch for maximizing power in Region 2, as described in Section 7.2. The upper limit is very close to the fully feathered blade pitch for neutral torque. We saturated the integral term in the PI controller between these limits to ensure a fast response in the transitions between Regions 2 and 3.

7.4 Baseline Blade-Pitch Actuator

Because of limitations in the FAST code, the FAST model does not include any blade-pitch actuator dynamic effects. Blade-pitch actuator dynamics are, however, needed in ADAMS. To enable successful comparisons between the FAST and ADAMS response predictions, then, we found it beneficial to reduce the effect of the blade-pitch actuator response in ADAMS. Consequently, we designed the blade-pitch actuator in the ADAMS model with a very high natural frequency of 30 Hz, which is higher than the highest full-system natural frequency in the FAST model (see Section 9), and a damping ratio of 2% critical. This resulted in an equivalent blade-pitch actuator linear-spring constant of 971,350,000 N•m/rad and an equivalent blade-pitch actuator linear-damping constant of 206,000 N•m/(rad/s).

7.5 Summary of Baseline Control System Properties

We implemented the NREL offshore 5-MW wind turbine's baseline control system as an external dynamic link library (DLL) in the style of Garrad Hassan's *BLADED* wind turbine software package [3]. Appendix C contains the source code for this DLL, and Figure 7-5 presents a flowchart of the overall integrated control system calculations. Table 7-2 summarizes the baseline generator-torque and blade-pitch control properties we discussed earlier in this section.

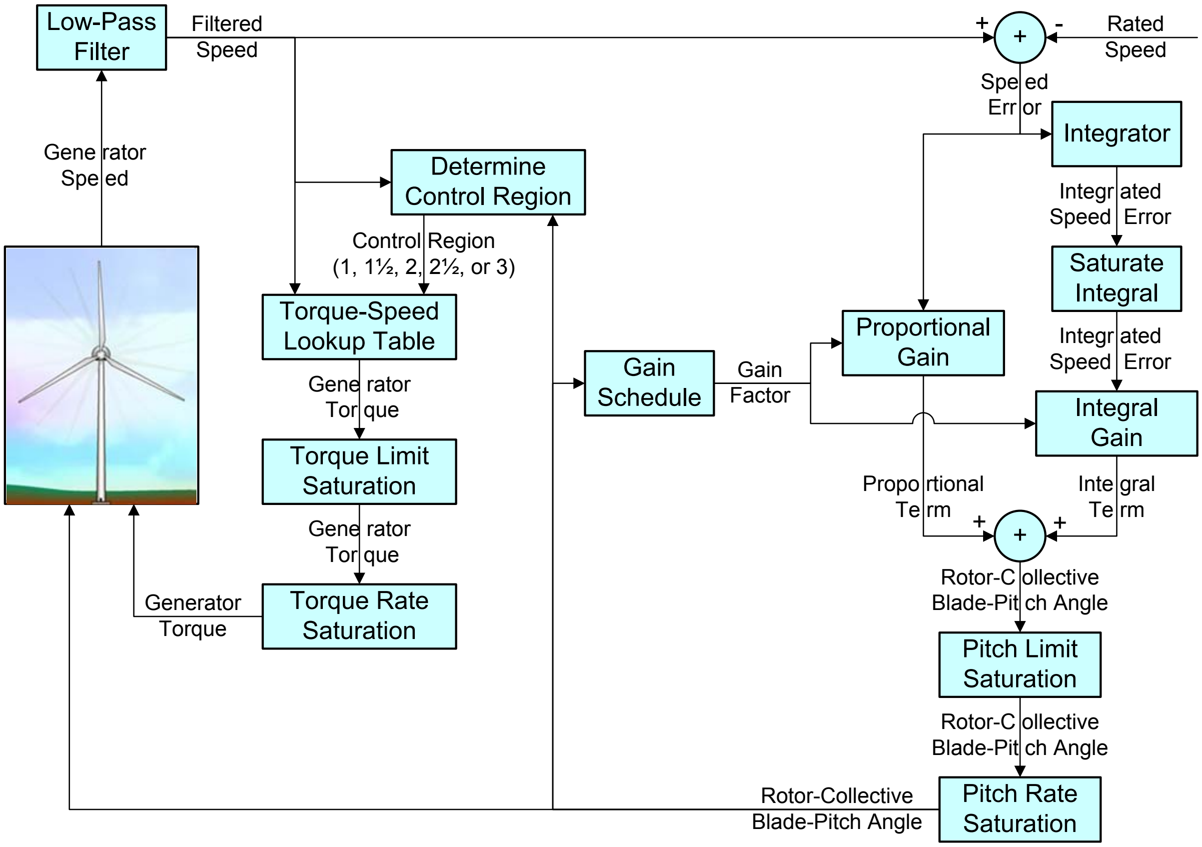

Figure 7-5. Flowchart of the baseline control system

Table 7-2. Baseline Control System Properties

Corner Frequency of Generator-Speed Low-Pass Filter	0.25 Hz
Peak Power Coefficient	0.482
Tip-Speed Ratio at Peak Power Coefficient	7.55
Rotor-Collective Blade-Pitch Angle at Peak Power Coefficient	0.0 º
Generator-Torque Constant in Region 2	0.0255764 N•m/rpm^2
Rated Mechanical Power	5.296610 MW
Rated Generator Torque	43,093.55 N•m
Transitional Generator Speed between Regions 1 and 1½	670 rpm
Transitional Generator Speed between Regions 1½ and 2	871 rpm
Transitional Generator Speed between Regions 2½ and 3	1,161.963 rpm
Generator Slip Percentage in Region 2½	10 %
Minimum Blade Pitch for Ensuring Region 3 Torque	1 º
Maximum Generator Torque	47,402.91 N•m
Maximum Generator Torque Rate	15,000 N•m/s
Proportional Gain at Minimum Blade-Pitch Setting	0.01882681 s
Integral Gain at Minimum Blade-Pitch Setting	0.008068634
Blade-Pitch Angle at which the Rotor Power Has Doubled	6.302336 º
Minimum Blade-Pitch Setting	0 º
Maximum Blade-Pitch Setting	90 º
Maximum Absolute Blade Pitch Rate	8 º/s
Equivalent Blade-Pitch-Actuator Linear-Spring Constant	971,350,000 N•m/rad
Equivalent Blade-Pitch-Actuator Linear-Damping Constant	206,000 N•m/rad/s

8 FAST with AeroDyn and ADAMS with AeroDyn Models

Using the turbine properties described previously in this report, we put together models of the NREL offshore 5-MW baseline wind turbine within FAST [11] with AeroDyn [16,20]. The input files for these models are given in Appendix A and Appendix B, for version (v) 6.10a-jmj of FAST and v12.58 of AeroDyn, respectively. We then generated the higher fidelity ADAMS with AeroDyn models through the preprocessor functionality built into the FAST code.

The input files in Appendix A are for the FAST model of the equivalent land-based version of the NREL 5-MW baseline wind turbine. The input files for other versions of the model, such as those for different support structures, require only a few minor changes. These include changes to input parameters “PtfmModel” and “PtfmFile,” which identify the type and properties of the support platform, and modifications to the prescribed mode shapes in the tower input file, “TwrFile.”

Although most of the input-parameter specifications in Appendix A and Appendix B are self-explanatory, the specifications of the prescribed mode shapes needed by FAST to characterize the flexibility of the blades and tower deserve a special explanation. The required mode shapes depend on the member’s boundary conditions. For the blade modes, we used v2.22 of the Modes program [4] to derive the equivalent polynomial representations of the blade mode shapes needed by FAST. The Modes program calculates the mode shapes of rotating blades, assuming that a blade mode shape is unaffected by its coupling with other system modes of motion. This is a common assumption in wind turbine analysis. For the tower modes, however, there is a great deal of coupling with the rotor motions, and in offshore floating systems, there is coupling with the platform motions as well. To take the former factor into account, we used the linearization functionality of the full-system ADAMS model to obtain the tower modes for the land-based version of the NREL 5-MW baseline wind turbine. In other words, we built an ADAMS model of the wind turbine, enabled all system DOFs, and linearized the model. Then we passed a best-fit polynomial through the resulting tower mode shapes to get the equivalent polynomial representations of the tower mode shapes needed by FAST.

Not including platform motions, the FAST model of the land-based version of the NREL 5-MW baseline wind turbine incorporates 16 DOFs as follows:

- Two flapwise and one edgewise bending-mode DOFs for each of the three blades
- One variable-generator speed DOF and one driveshaft torsional DOF
- One nacelle-yaw-actuator DOF
- Two fore-aft and two side-to-side bending-mode DOFs in the tower.

Not including platform motion, the higher fidelity ADAMS model of the land-based version of the wind turbine incorporates 438 DOFs as follows:

- One hundred and two DOFs in each of the three blades, including flapwise and edgewise shear and bending, torsion, and extension DOFs
- One blade-pitch actuator DOF in each of the three blades

- One variable-generator speed DOF and one driveshaft torsional DOF
- One nacelle-yaw actuator DOF
- One hundred and twenty-six DOFs in the tower, including fore-aft and side-to-side shear and bending, torsion, and extension DOFs.

The support platform motions in, for example, the floating-platform versions of the NREL 5-MW baseline wind turbine add six DOFs per model.

We use a constant time step of 0.0125 s in FAST's fixed-step-size time-integration scheme and a maximum step size of 0.0125 s in ADAMS' variable-step-size time integrator. We have AeroDyn perform aerodynamic calculations every other structural time step (i.e., 0.025 s) to ensure that there are at least 200-azimuth-step computations per revolution at 12 rpm. Data are output at 20 Hz or every fourth structural time step. We made these time steps as large as possible to ensure numerical stability and suitable output resolution across a range of operating conditions.

9 Full-System Natural Frequencies and Steady-State Behavior

To provide a cursory overview of the overall system behavior of the equivalent land-based version of the NREL 5-MW baseline wind turbine, we calculated the full-system natural frequencies and the steady-state response of the system as a function of wind speed.

We obtained the full-system natural frequencies with both the FAST model and the ADAMS model. In FAST, we calculated the natural frequencies by performing an eigenanalysis on the first-order state matrix created from a linearization analysis. In ADAMS, we obtained the frequencies by invoking a "LINEAR/EIGENSOL" command, which linearizes the complete ADAMS model and computes eigendata. To avoid the rigid-body drivetrain mode, the analyses considered the wind turbine in a stationary condition with the high-speed shaft brake engaged. The blades were pitched to their minimum set point (0º), but aerodynamic damping was ignored. Table 9-1 lists results for the first 13 full-system natural frequencies.

Table 9-1. Full-System Natural Frequencies in Hertz

Mode	Description	FAST	ADAMS
1	1st Tower Fore-Aft	0.3240	0.3195
2	1st Tower Side-to-Side	0.3120	0.3164
3	1st Drivetrain Torsion	0.6205	0.6094
4	1st Blade Asymmetric Flapwise Yaw	0.6664	0.6296
5	1st Blade Asymmetric Flapwise Pitch	0.6675	0.6686
6	1st Blade Collective Flap	0.6993	0.7019
7	1st Blade Asymmetric Edgewise Pitch	1.0793	1.0740
8	1st Blade Asymmetric Edgewise Yaw	1.0898	1.0877
9	2nd Blade Asymmetric Flapwise Yaw	1.9337	1.6507
10	2nd Blade Asymmetric Flapwise Pitch	1.9223	1.8558
11	2nd Blade Collective Flap	2.0205	1.9601
12	2nd Tower Fore-Aft	2.9003	2.8590
13	2nd Tower Side-to-Side	2.9361	2.9408

The agreement between FAST and ADAMS is quite good. The biggest differences exist in the predictions of the blades' second asymmetric flapwise yaw and pitch modes. By "yaw" and "pitch" we mean that these blade asymmetric modes couple with the nacelle-yaw and nacelle-pitching motions, respectively. Because of the offsets of the blade section CM from the pitch axis, higher-order modes, and tower-torsion DOFs—which are available in ADAMS, but not in FAST—ADAMS predicts lower natural frequencies in these modes than FAST does.

Bir and Jonkman have published [2] a much more exhaustive eigenanalysis for the NREL 5-MW baseline wind turbine. The referenced publication documents the natural frequencies and damping ratios of the land- and floating-platform versions of the 5-MW turbine across a range of operating conditions.

We obtained the steady-state response of the land-based 5-MW baseline wind turbine by running a series of FAST with AeroDyn simulations at a number of given, steady, and uniform wind speeds. The simulations lengths were long enough to ensure that all transient behavior had died out; we then recorded the steady-state output values. We ran the simulations using the blade-element / momentum (BEM) wake option of AeroDyn and with all available and relevant land-based DOFs enabled. Figure 9-1 shows the results for several output parameters, which are defined as follows:

- "GenSpeed" represents the rotational speed of the generator (high-speed shaft).
- "RotPwr" and "GenPwr" represent the mechanical power within the rotor and the electrical output of the generator, respectively.
- "RotThrust" represents the rotor thrust.
- "RotTorq" represents the mechanical torque in the low-speed shaft.
- "RotSpeed" represents the rotational speed of the rotor (low-speed shaft).
- "BlPitch1" represents the pitch angle of Blade 1.
- "GenTq" represents the electrical torque of the generator.
- "TSR" represents the tip-speed ratio.
- "OoPDefl1" and "IPDefl1" represent the out-of-plane and in-plane tip deflections of Blade 1 relative to the undeflected blade-pitch axis.
- "TTDspFA" and "TTDspSS" represent the fore-aft and side-to-side deflection of the tower top relative to the centerline of the undeflected tower.

As planned, the generator and rotor speeds increase linearly with wind speed in Region 2 to maintain constant tip-speed ratio and optimal wind-power conversion efficiency. Similarly, the generator and rotor powers and generator and rotor torques increase dramatically with wind speed in Region 2, increasing cubically and quadratically, respectively. Above rated, the generator and rotor powers are held constant by regulating to a fixed speed with active blade-pitch control. The out-of-plane tip deflection of the reference blade (Blade 1) reaches a maximum at the rated operating point before dropping again. This response characteristic is the result of the peak in rotor thrust at rated. This peak is typical of variable generator speed variable blade-pitch-to-feather wind turbines because of the transition that occurs in the control system at rated between the active generator-torque and the active blade-pitch control regions. This peak in response is also visible, though less pronounced, in the in-plane tip deflection of the reference blade and the tower-top fore-aft displacement.

Start-up transient behavior is an artifact of computational analysis. To mitigate this behavior, we suggest using the steady-state values of the rotor speed and blade-pitch angles found in Figure 9-1 as initial conditions in simulations.

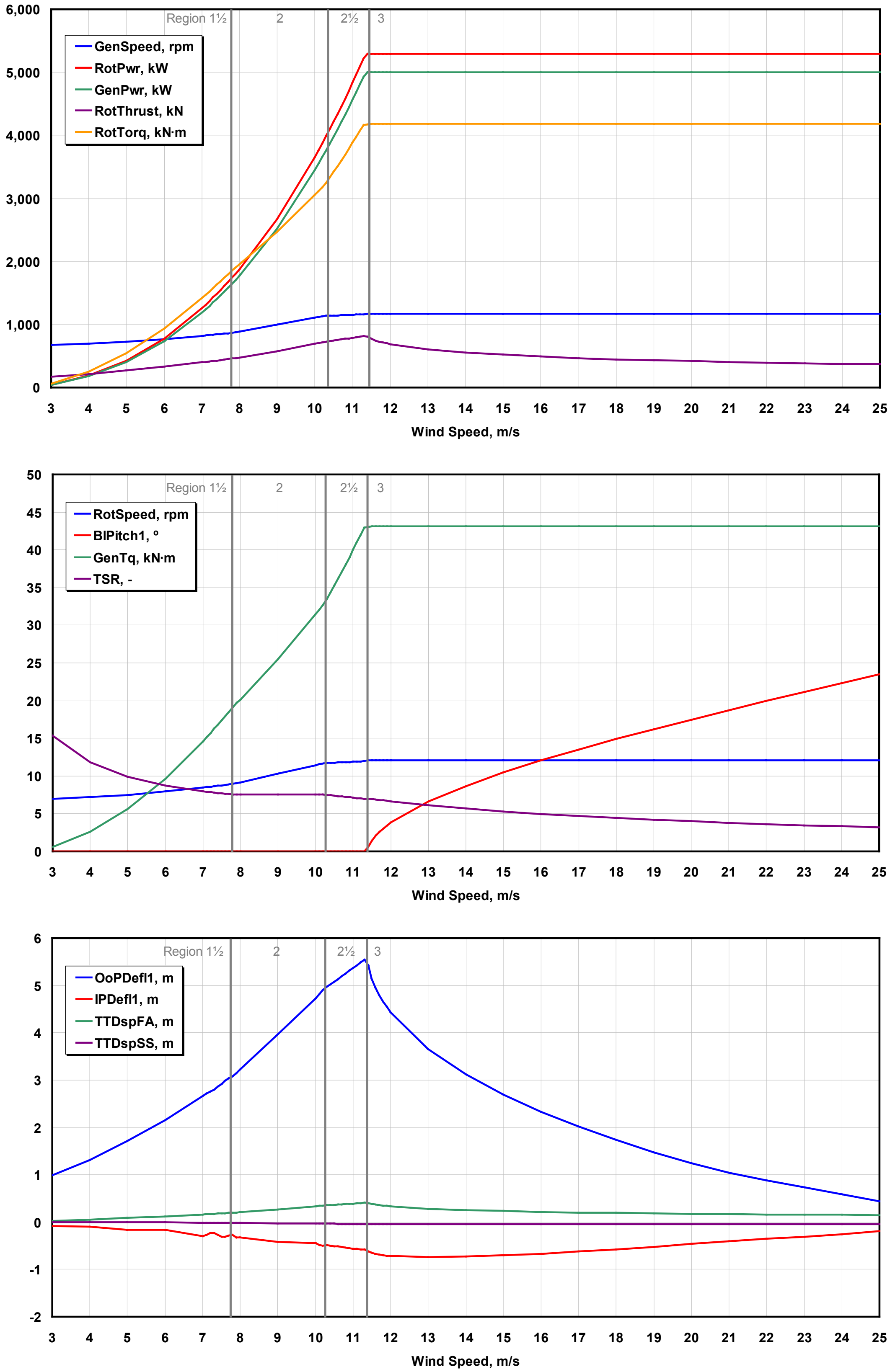

Figure 9-1. Steady-state responses as a function of wind speed

10 Conclusions

To support concept studies aimed at assessing offshore wind technology, we developed the specifications of a representative utility-scale multimegawatt turbine now known as the "NREL offshore 5-MW baseline wind turbine." This wind turbine is a conventional three-bladed upwind variable-speed variable blade-pitch-to-feather-controlled turbine. To create the model, we obtained some broad design information from the published documents of turbine manufacturers, with a heavy emphasis on the REpower 5M machine. Because detailed data was unavailable, however, we also used the publicly available properties from the conceptual models in the WindPACT, RECOFF, and DOWEC projects. We then created a composite from these data, extracting the best available and most representative specifications. This report documented the specifications of the NREL offshore 5-MW baseline wind turbine—including the aerodynamic, structural, and control-system properties—and the rationale behind its development. The model has been, and will likely continue to be, used as a reference by research teams throughout the world to standardize baseline offshore wind turbine specifications and to quantify the benefits of advanced land- and sea-based wind energy technologies.

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Appendix A FAST Input Files

A.1 Primary Input File

```
--------------------------------------------------------------------------------
------- FAST INPUT FILE --------------------------------------------------------
NREL 5.0 MW Baseline Wind Turbine for Use in Offshore Analysis.
Properties from Dutch Offshore Wind Energy Converter (DOWEC) 6MW Pre-Design (10046_009.pdf) and REpower 5M 5MW (5m_uk.pdf); C
---------------------- SIMULATION CONTROL --------------------------------------
False       Echo        - Echo input data to "echo.out" (flag)
   3        ADAMSPrep   - ADAMS preprocessor mode {1: Run FAST, 2: use FAST as a preprocessor to create an ADAMS model, 3: do
   1        AnalMode    - Analysis mode {1: Run a time-marching simulation, 2: create a periodic linearized model} (switch)
   3        NumBl       - Number of blades (-)
 630.0      TMax        - Total run time (s)
   0.0125   DT          - Integration time step (s)
---------------------- TURBINE CONTROL -----------------------------------------
   0        YCMode      - Yaw control mode {0: none, 1: user-defined from routine UserYawCont, 2: user-defined from Simulink}
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
   0.0      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: use
9999.9      VS_RtGnSp   - Rated generator speed for simple variable-speed generator control (HSS side) (rpm) [used only when
9999.9      VS_RtTq     - Rated generator torque/constant generator torque in Region 3 for simple variable-speed generator co
9999.9      VS_Rgn2K    - Generator torque constant in Region 2 for simple variable-speed generator control (HSS side) (N-m/r
9999.9      VS_SlPc     - Rated generator slip percentage in Region 2 1/2 for simple variable-speed generator control (%) [us
   2        GenModel    - Generator model {1: simple, 2: Thevenin, 3: user-defined from routine UserGen} (switch) [used only
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)
9999.9      SpdGenOn    - Generator speed to turn on the generator for a startup (HSS speed) (rpm) [used only when GenTiStr=F
   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      TTpBrDp(1)  - Time to initiate deployment of tip brake 1 (s)
9999.9      TTpBrDp(2)  - Time to initiate deployment of tip brake 2 (s)
9999.9      TTpBrDp(3)  - Time to initiate deployment of tip brake 3 (s) [unused for 2 blades]
9999.9      TBDepISp(1) - Deployment-initiation speed for the tip brake on blade 1 (rpm)
9999.9      TBDepISp(2) - Deployment-initiation speed for the tip brake on blade 2 (rpm)
9999.9      TBDepISp(3) - 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)
   0.3      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 override yaw maneuvers (degrees)
9999.9      TPitManS(1) - Time to start override pitch maneuver for blade 1 and end standard pitch control (s)
9999.9      TPitManS(2) - Time to start override pitch maneuver for blade 2 and end standard pitch control (s)
9999.9      TPitManS(3) - Time to start override pitch maneuver for blade 3 and end standard pitch control (s) [unused for 2
   8.0      PitManRat(1)- Pitch rate (in absolute value) at which override pitch maneuver for blade 1 heads toward final pitc
   8.0      PitManRat(2)- Pitch rate (in absolute value) at which override pitch maneuver for blade 2 heads toward final pitc
   8.0      PitManRat(3)- Pitch rate (in absolute value) at which override pitch maneuver for blade 3 heads toward final pitc
   0.0      BlPitch(1)  - Blade 1 initial pitch (degrees)
   0.0      BlPitch(2)  - Blade 2 initial pitch (degrees)
   0.0      BlPitch(3)  - Blade 3 initial pitch (degrees) [unused for 2 blades]
   0.0      BlPitchF(1) - Blade 1 final pitch for override pitch maneuvers (degrees)
   0.0      BlPitchF(2) - Blade 2 final pitch for override pitch maneuvers (degrees)
   0.0      BlPitchF(3) - Blade 3 final pitch for override 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)
True        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)
  12.1      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 -----------------------------------
  63.0      TipRad       - The distance from the rotor apex to the blade tip (meters)
   1.5      HubRad       - The distance from the rotor apex to the blade root (meters)
   1        PSpnElN      - Number of the innermost blade element which is still part of the pitchable portion of the blade for
   0.0      UndSling     - Undersling length [distance from teeter pin to the rotor apex] (meters) [unused for 3 blades]
   0.0      HubCM        - Distance from rotor apex to hub mass [positive downwind] (meters)
  -5.01910  OverHang     - Distance from yaw axis to rotor apex [3 blades] or teeter pin [2 blades] (meters)
   1.9      NacCMxn      - Downwind distance from the tower-top to the nacelle CM (meters)
   0.0      NacCMyn      - Lateral  distance from the tower-top to the nacelle CM (meters)
   1.75     NacCMzn      - Vertical distance from the tower-top to the nacelle CM (meters)
  87.6      TowerHt      - Height of tower above ground level [onshore] or MSL [offshore] (meters)
   1.96256  Twr2Shft     - Vertical distance from the tower-top to the rotor shaft (meters)
   0.0      TwrRBHt      - Tower rigid base height (meters)
  -5.0      ShftTilt     - Rotor shaft tilt angle (degrees)
   0.0      Delta3       - Delta-3 angle for teetering rotors (degrees) [unused for 3 blades]
  -2.5      PreCone(1)   - Blade 1 cone angle (degrees)
  -2.5      PreCone(2)   - Blade 2 cone angle (degrees)
  -2.5      PreCone(3)   - Blade 3 cone angle (degrees) [unused for 2 blades]
   0.0      AzimB1Up     - Azimuth value to use for I/O when blade 1 points up (degrees)
---------------------- MASS AND INERTIA ----------------------------------------
   0.0      YawBrMass    - Yaw bearing mass (kg)
 240.00E3   NacMass      - Nacelle mass (kg)
  56.78E3   HubMass      - Hub mass (kg)
   0.0      TipMass(1)   - Tip-brake mass, blade 1 (kg)
   0.0      TipMass(2)   - Tip-brake mass, blade 2 (kg)
   0.0      TipMass(3)   - Tip-brake mass, blade 3 (kg) [unused for 2 blades]
2607.89E3   NacYIner     - Nacelle inertia about yaw axis (kg m^2)
 534.116    GenIner      - Generator inertia about HSS (kg m^2)
 115.926E3  HubIner      - Hub inertia about rotor axis [3 blades] or teeter axis [2 blades] (kg m^2)
---------------------- DRIVETRAIN ----------------------------------------------
 100.0      GBoxEff      - Gearbox efficiency (%)
  94.4      GenEff       - Generator efficiency [ignored by the Thevenin and user-defined generator models] (%)
  97.0      GBRatio      - Gearbox ratio (-)
False       GBRevers     - Gearbox reversal {T: if rotor and generator rotate in opposite directions} (flag)
  28.1162E3 HSSBrTqF     - Fully deployed HSS-brake torque (N-m)
   0.6      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] (quote
 867.637E6  DTTorSpr     - Drivetrain torsional spring (N-m/rad)
   6.215E6  DTTorDmp     - Drivetrain torsional damper (N-m/(rad/s))
---------------------- SIMPLE INDUCTION GENERATOR ------------------------------
9999.9      SIG_SlPc     - Rated generator slip percentage (%) [used only when VSContrl=0 and GenModel=1]
9999.9      SIG_SySp     - Synchronous (zero-torque) generator speed (rpm) [used only when VSContrl=0 and GenModel=1]
9999.9      SIG_RtTq     - Rated torque (N-m) [used only when VSContrl=0 and GenModel=1]
9999.9      SIG_PORt     - Pull-out ratio (Tpullout/Trated) (-) [used only when VSContrl=0 and GenModel=1]
---------------------- THEVENIN-EQUIVALENT INDUCTION GENERATOR -----------------
9999.9      TEC_Freq     - Line frequency [50 or 60] (Hz) [used only when VSContrl=0 and GenModel=2]
9998        TEC_NPol     - Number of poles [even integer > 0] (-) [used only when VSContrl=0 and GenModel=2]
9999.9      TEC_SRes     - Stator resistance (ohms) [used only when VSContrl=0 and GenModel=2]
9999.9      TEC_RRes     - Rotor resistance (ohms) [used only when VSContrl=0 and GenModel=2]
9999.9      TEC_VLL      - Line-to-line RMS voltage (volts) [used only when VSContrl=0 and GenModel=2]
9999.9      TEC_SLR      - Stator leakage reactance (ohms) [used only when VSContrl=0 and GenModel=2]
9999.9      TEC_RLR      - Rotor leakage reactance (ohms) [used only when VSContrl=0 and GenModel=2]
9999.9      TEC_MR       - Magnetizing reactance (ohms) [used only when VSContrl=0 and GenModel=2]
---------------------- PLATFORM ------------------------------------------------
   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 ---------------------------------------------------
  20        TwrNodes     - Number of tower nodes used for analysis (-)
"NRELOffshrBsline5MW_Tower_Onshore.dat"          TwrFile      - Name of file containing tower properties (quoted string)
---------------------- NACELLE-YAW ---------------------------------------------
9028.32E6   YawSpr       - Nacelle-yaw spring constant (N-m/rad)
  19.16E6   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)
            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} (swi
   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
   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 ---------------------------------------------------
"NRELOffshrBsline5MW_Blade.dat"                  BldFile(1)  - Name of file containing properties for blade 1 (quoted string)
"NRELOffshrBsline5MW_Blade.dat"                  BldFile(2)  - Name of file containing properties for blade 2 (quoted string)
"NRELOffshrBsline5MW_Blade.dat"                  BldFile(3)  - Name of file containing properties for blade 3 (quoted string)
---------------------- AERODYN -------------------------------------------------
```

```
"NRELOffshrBsline5MW_AeroDyn.ipt"              ADFile      - Name of file containing AeroDyn input parameters (quoted strin
---------------------- NOISE --------------------------------------------------
           NoiseFile   - Name of file containing aerodynamic noise input parameters (quoted string) [used only when CompNois
---------------------- ADAMS --------------------------------------------------
"NRELOffshrBsline5MW_ADAMSSpecific.dat"         ADAMSFile   - Name of file containing ADAMS-specific input parameters (quote
---------------------- LINEARIZATION CONTROL ----------------------------------
"NRELOffshrBsline5MW_Linear.dat"                LinFile     - Name of file containing FAST linearization parameters (quoted
---------------------- 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 strin
  30.0      TStart      - Time to begin tabular output (s)
   4        DecFact     - Decimation factor for tabular output {1: output every time step} (-)
   1.0      SttsTime    - Amount of time between screen status messages (sec)
  -3.09528  NcIMUxn     - Downwind distance from the tower-top to the nacelle IMU (meters)
   0.0      NcIMUyn     - Lateral  distance from the tower-top to the nacelle IMU (meters)
   2.23336  NcIMUzn     - Vertical distance from the tower-top to the nacelle IMU (meters)
   1.912    ShftGagL    - Distance from rotor apex [3 blades] or teeter pin [2 blades] to shaft strain gages [positive for up
   1        NTwGages    - Number of tower nodes that have strain gages for output [0 to 9] (-)
  10        TwrGagNd    - List of tower nodes that have strain gages [1 to TwrNodes] (-) [unused if NTwGages=0]
   1        NBlGages    - Number of blade nodes that have strain gages for output [0 to 9] (-)
   9        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
"WindVxi  , WindVyi  , WindVzi"                             - Longitudinal, lateral, and vertical wind speeds
"WaveElev"                                                  - Wave elevation at the platform reference point
"Wave1Vxi , Wave1Vyi , Wave1Vzi"                            - Longitudinal, lateral, and vertical wave particle velocities a
"Wave1Axi , Wave1Ayi , Wave1Azi"                            - Longitudinal, lateral, and vertical wave particle acceleration
"GenPwr   , GenTq"                                          - Electrical generator power and torque
"HSSBrTq"                                                   - High-speed shaft brake torque
"BldPitch1, BldPitch2, BldPitch3"                           - Pitch angles for blades 1, 2, and 3
"Azimuth"                                                   - Blade 1 azimuth angle
"RotSpeed , GenSpeed"                                       - Low-speed shaft and high-speed shaft speeds
"NacYaw   , NacYawErr"                                      - Nacelle yaw angle and nacelle yaw error estimate
"OoPDefl1 , IPDefl1  , TwstDefl1"                           - Blade 1 out-of-plane and in-plane deflections and tip twist
"OoPDefl2 , IPDefl2  , TwstDefl2"                           - Blade 2 out-of-plane and in-plane deflections and tip twist
"OoPDefl3 , IPDefl3  , TwstDefl3"                           - Blade 3 out-of-plane and in-plane deflections and tip twist
"TwrClrnc1, TwrClrnc2, TwrClrnc3"                           - Tip-to-tower clearance estimate for blades 1, 2, and 3
"NcIMUTAxs, NcIMUTAys, NcIMUTAzs"                           - Nacelle IMU translational accelerations (absolute) in the nonr
"TTDspFA  , TTDspSS  , TTDspTwst"                           - Tower fore-aft and side-to-side displacements and top twist
"PtfmSurge, PtfmSway , PtfmHeave"                           - Platform translational surge, sway, and heave displacements
"PtfmRoll , PtfmPitch, PtfmYaw"                             - Platform rotational roll, pitch and yaw displacements
"PtfmTAxt , PtfmTAyt , PtfmTAzt"                            - Platform translation accelerations (absolute) in the tower-bas
"RootFxc1 , RootFyc1 , RootFzc1"                            - Out-of-plane shear, in-plane shear, and axial forces at the ro
"RootMxc1 , RootMyc1 , RootMzc1"                            - In-plane bending, out-of-plane bending, and pitching moments a
"RootFxc2 , RootFyc2 , RootFzc2"                            - Out-of-plane shear, in-plane shear, and axial forces at the ro
"RootMxc2 , RootMyc2 , RootMzc2"                            - In-plane bending, out-of-plane bending, and pitching moments a
"RootFxc3 , RootFyc3 , RootFzc3"                            - Out-of-plane shear, in-plane shear, and axial forces at the ro
"RootMxc3 , RootMyc3 , RootMzc3"                            - In-plane bending, out-of-plane bending, and pitching moments a
"Spn1MLxb1, Spn1MLyb1, Spn1MLzb1"                           - Blade 1 local edgewise bending, flapwise bending, and pitching
"Spn1MLxb2, Spn1MLyb2, Spn1MLzb2"                           - Blade 2 local edgewise bending, flapwise bending, and pitching
"Spn1MLxb3, Spn1MLyb3, Spn1MLzb3"                           - Blade 3 local edgewise bending, flapwise bending, and pitching
"RotThrust, LSSGagFya, LSSGagFza"                           - Rotor thrust and low-speed shaft 0- and 90-rotating shear forc
"RotTorq  , LSSGagMya, LSSGagMza"                           - Rotor torque and low-speed shaft 0- and 90-rotating bending mo
"YawBrFxp , YawBrFyp , YawBrFzp"                            - Fore-aft shear, side-to-side shear, and vertical forces at the
"YawBrMxp , YawBrMyp , YawBrMzp"                            - Side-to-side bending, fore-aft bending, and yaw moments at the
"TwrBsFxt , TwrBsFyt , TwrBsFzt"                            - Fore-aft shear, side-to-side shear, and vertical forces at the
"TwrBsMxt , TwrBsMyt , TwrBsMzt"                            - Side-to-side bending, fore-aft bending, and yaw moments at the
"TwHt1MLxt, TwHt1MLyt, TwHt1MLzt"                           - Local side-to-side bending, fore-aft bending, and yaw moments
"Fair1Ten , Fair1Ang , Anch1Ten , Anch1Ang"                 - Line 1 fairlead and anchor effective tensions and vertical ang
"Fair2Ten , Fair2Ang , Anch2Ten , Anch2Ang"                 - Line 2 fairlead and anchor effective tensions and vertical ang
"Fair3Ten , Fair3Ang , Anch3Ten , Anch3Ang"                 - Line 3 fairlead and anchor effective tensions and vertical ang
"Fair4Ten , Fair4Ang , Anch4Ten , Anch4Ang"                 - Line 4 fairlead and anchor effective tensions and vertical ang
"Fair5Ten , Fair5Ang , Anch5Ten , Anch5Ang"                 - Line 5 fairlead and anchor effective tensions and vertical ang
"Fair6Ten , Fair6Ang , Anch6Ten , Anch6Ang"                 - Line 6 fairlead and anchor effective tensions and vertical ang
"Fair7Ten , Fair7Ang , Anch7Ten , Anch7Ang"                 - Line 7 fairlead and anchor effective tensions and vertical ang
"Fair8Ten , Fair8Ang , Anch8Ten , Anch8Ang"                 - Line 8 fairlead and anchor effective tensions and vertical ang
"TipSpdRat, RotCp    , RotCt    , RotCq"                    - Rotor tip speed ratio and power, thrust, and torque coefficien
END of FAST input file (the word "END" must appear in the first 3 columns of this last line).
-------------------------------------------------------------------------------
```

A.2 Blade Input File – NRELOffshrBsline5MW_Blade.dat

```
-------------------------------------------------------------------------------
---------------------- FAST INDIVIDUAL BLADE FILE ------------------------------
NREL 5.0 MW offshore baseline blade input properties.
---------------------- BLADE PARAMETERS ---------------------------------------
  49        NBlInpSt    - Number of blade input stations (-)
False       CalcBMode   - Calculate blade mode shapes internally {T: ignore mode shapes from below, F: use mode shapes from b
   0.477465 BldFlDmp(1) - Blade flap mode #1 structural damping in percent of critical (%)
   0.477465 BldFlDmp(2) - Blade flap mode #2 structural damping in percent of critical (%)
   0.477465 BldEdDmp(1) - Blade edge mode #1 structural damping in percent of critical (%)
---------------------- BLADE ADJUSTMENT FACTORS -------------------------------
```

```
   1.0      FlStTunr(1) - Blade flapwise modal stiffness tuner, 1st mode (-)
   1.0      FlStTunr(2) - Blade flapwise modal stiffness tuner, 2nd mode (-)
   1.04536  AdjBlMs     - Factor to adjust blade mass density (-)
   1.0      AdjFlSt     - Factor to adjust blade flap stiffness (-)
   1.0      AdjEdSt     - Factor to adjust blade edge stiffness (-)
---------------------- DISTRIBUTED BLADE PROPERTIES ----------------------------
BlFract  AeroCent  StrcTwst  BMassDen  FlpStff     EdgStff     GJStff     EAStff      Alpha  FlpIner  EdgIner  PrecrvRef  Pre
(-)      (-)       (deg)     (kg/m)    (Nm^2)      (Nm^2)      (Nm^2)     (N)         (-)    (kg m)   (kg m)   (m)        (m)
0.00000  0.25000   13.308    678.935   18110.00E6  18113.60E6  5564.40E6   9729.48E6  0.0     972.86   973.04  0.0        0.0
0.00325  0.25000   13.308    678.935   18110.00E6  18113.60E6  5564.40E6   9729.48E6  0.0     972.86   973.04  0.0        0.0
0.01951  0.24951   13.308    773.363   19424.90E6  19558.60E6  5431.59E6  10789.50E6  0.0    1091.52  1066.38  0.0        0.0
0.03577  0.24510   13.308    740.550   17455.90E6  19497.80E6  4993.98E6  10067.23E6  0.0     966.09  1047.36  0.0        0.0
0.05203  0.23284   13.308    740.042   15287.40E6  19788.80E6  4666.59E6   9867.78E6  0.0     873.81  1099.75  0.0        0.0
0.06829  0.22059   13.308    592.496   10782.40E6  14858.50E6  3474.71E6   7607.86E6  0.0     648.55   873.02  0.0        0.0
0.08455  0.20833   13.308    450.275    7229.72E6  10220.60E6  2323.54E6   5491.26E6  0.0     456.76   641.49  0.0        0.0
0.10081  0.19608   13.308    424.054    6309.54E6   9144.70E6  1907.87E6   4971.30E6  0.0     400.53   593.73  0.0        0.0
0.11707  0.18382   13.308    400.638    5528.36E6   8063.16E6  1570.36E6   4493.95E6  0.0     351.61   547.18  0.0        0.0
0.13335  0.17156   13.308    382.062    4980.06E6   6884.44E6  1158.26E6   4034.80E6  0.0     316.12   490.84  0.0        0.0
0.14959  0.15931   13.308    399.655    4936.84E6   7009.18E6  1002.12E6   4037.29E6  0.0     303.60   503.86  0.0        0.0
0.16585  0.14706   13.308    426.321    4691.66E6   7167.68E6   855.90E6   4169.72E6  0.0     289.24   544.70  0.0        0.0
0.18211  0.13481   13.181    416.820    3949.46E6   7271.66E6   672.27E6   4082.35E6  0.0     246.57   569.90  0.0        0.0
0.19837  0.12500   12.848    406.186    3386.52E6   7081.70E6   547.49E6   4085.97E6  0.0     215.91   601.28  0.0        0.0
0.21465  0.12500   12.192    381.420    2933.74E6   6244.53E6   448.84E6   3668.34E6  0.0     187.11   546.56  0.0        0.0
0.23089  0.12500   11.561    352.822    2568.96E6   5048.96E6   335.92E6   3147.76E6  0.0     160.84   468.71  0.0        0.0
0.24715  0.12500   11.072    349.477    2388.65E6   4948.49E6   311.35E6   3011.58E6  0.0     148.56   453.76  0.0        0.0
0.26341  0.12500   10.792    346.538    2271.99E6   4808.02E6   291.94E6   2882.62E6  0.0     140.30   436.22  0.0        0.0
0.29595  0.12500   10.232    339.333    2050.05E6   4501.40E6   261.00E6   2613.97E6  0.0     124.61   398.18  0.0        0.0
0.32846  0.12500    9.672    330.004    1828.25E6   4244.07E6   228.82E6   2357.48E6  0.0     109.42   362.08  0.0        0.0
0.36098  0.12500    9.110    321.990    1588.71E6   3995.28E6   200.75E6   2146.86E6  0.0      94.36   335.01  0.0        0.0
0.39350  0.12500    8.534    313.820    1361.93E6   3750.76E6   174.38E6   1944.09E6  0.0      80.24   308.57  0.0        0.0
0.42602  0.12500    7.932    294.734    1102.38E6   3447.14E6   144.47E6   1632.70E6  0.0      62.67   263.87  0.0        0.0
0.45855  0.12500    7.321    287.120     875.80E6   3139.07E6   119.98E6   1432.40E6  0.0      49.42   237.06  0.0        0.0
0.49106  0.12500    6.711    263.343     681.30E6   2734.24E6    81.19E6   1168.76E6  0.0      37.34   196.41  0.0        0.0
0.52358  0.12500    6.122    253.207     534.72E6   2554.87E6    69.09E6   1047.43E6  0.0      29.14   180.34  0.0        0.0
0.55610  0.12500    5.546    241.666     408.90E6   2334.03E6    57.45E6    922.95E6  0.0      22.16   162.43  0.0        0.0
0.58862  0.12500    4.971    220.638     314.54E6   1828.73E6    45.92E6    760.82E6  0.0      17.33   134.83  0.0        0.0
0.62115  0.12500    4.401    200.293     238.63E6   1584.10E6    35.98E6    648.03E6  0.0      13.30   116.30  0.0        0.0
0.65366  0.12500    3.834    179.404     175.88E6   1323.36E6    27.44E6    539.70E6  0.0       9.96    97.98  0.0        0.0
0.68618  0.12500    3.332    165.094     126.01E6   1183.68E6    20.90E6    531.15E6  0.0       7.30    98.93  0.0        0.0
0.71870  0.12500    2.890    154.411     107.26E6   1020.16E6    18.54E6    460.01E6  0.0       6.22    85.78  0.0        0.0
0.75122  0.12500    2.503    138.935      90.88E6    797.81E6    16.28E6    375.75E6  0.0       5.19    69.96  0.0        0.0
0.78376  0.12500    2.116    129.555      76.31E6    709.61E6    14.53E6    328.89E6  0.0       4.36    61.41  0.0        0.0
0.81626  0.12500    1.730    107.264      61.05E6    518.19E6     9.07E6    244.04E6  0.0       3.36    45.44  0.0        0.0
0.84878  0.12500    1.342     98.776      49.48E6    454.87E6     8.06E6    211.60E6  0.0       2.75    39.57  0.0        0.0
0.88130  0.12500    0.954     90.248      39.36E6    395.12E6     7.08E6    181.52E6  0.0       2.21    34.09  0.0        0.0
0.89756  0.12500    0.760     83.001      34.67E6    353.72E6     6.09E6    160.25E6  0.0       1.93    30.12  0.0        0.0
0.91382  0.12500    0.574     72.906      30.41E6    304.73E6     5.75E6    109.23E6  0.0       1.69    20.15  0.0        0.0
0.93008  0.12500    0.404     68.772      26.52E6    281.42E6     5.33E6    100.08E6  0.0       1.49    18.53  0.0        0.0
0.93821  0.12500    0.319     66.264      23.84E6    261.71E6     4.94E6     92.24E6  0.0       1.34    17.11  0.0        0.0
0.94636  0.12500    0.253     59.340      19.63E6    158.81E6     4.24E6     63.23E6  0.0       1.10    11.55  0.0        0.0
0.95447  0.12500    0.216     55.914      16.00E6    137.88E6     3.66E6     53.32E6  0.0       0.89     9.77  0.0        0.0
0.96260  0.12500    0.178     52.484      12.83E6    118.79E6     3.13E6     44.53E6  0.0       0.71     8.19  0.0        0.0
0.97073  0.12500    0.140     49.114      10.08E6    101.63E6     2.64E6     36.90E6  0.0       0.56     6.82  0.0        0.0
0.97886  0.12500    0.101     45.818       7.55E6     85.07E6     2.17E6     29.92E6  0.0       0.42     5.57  0.0        0.0
0.98699  0.12500    0.062     41.669       4.60E6     64.26E6     1.58E6     21.31E6  0.0       0.25     4.01  0.0        0.0
0.99512  0.12500    0.023     11.453       0.25E6      6.61E6     0.25E6      4.85E6  0.0       0.04     0.94  0.0        0.0
1.00000  0.12500    0.000     10.319       0.17E6      5.01E6     0.19E6      3.53E6  0.0       0.02     0.68  0.0        0.0
---------------------- BLADE MODE SHAPES ---------------------------------------
   0.0622   BldFl1Sh(2) - Flap mode 1, coeff of x^2
   1.7254   BldFl1Sh(3) -            , coeff of x^3
  -3.2452   BldFl1Sh(4) -            , coeff of x^4
   4.7131   BldFl1Sh(5) -            , coeff of x^5
  -2.2555   BldFl1Sh(6) -            , coeff of x^6
  -0.5809   BldFl2Sh(2) - Flap mode 2, coeff of x^2
   1.2067   BldFl2Sh(3) -            , coeff of x^3
 -15.5349   BldFl2Sh(4) -            , coeff of x^4
  29.7347   BldFl2Sh(5) -            , coeff of x^5
 -13.8255   BldFl2Sh(6) -            , coeff of x^6
   0.3627   BldEdgSh(2) - Edge mode 1, coeff of x^2
   2.5337   BldEdgSh(3) -            , coeff of x^3
  -3.5772   BldEdgSh(4) -            , coeff of x^4
   2.3760   BldEdgSh(5) -            , coeff of x^5
  -0.6952   BldEdgSh(6) -            , coeff of x^6
```

A.3 Tower Input File – NRELOffshrBsline5MW_Tower_Onshore.dat

```
--------------------------------------------------------------------------------
---------------------- FAST TOWER FILE -----------------------------------------
NREL 5.0 MW offshore baseline tower input properties.
---------------------- TOWER PARAMETERS ----------------------------------------
  11        NTwInpSt    - Number of input stations to specify tower geometry
False       CalcTMode   - Calculate tower mode shapes internally {T: ignore mode shapes from below, F: use mode shapes from b
```

```
   1.0      TwrFADmp(1) - Tower 1st fore-aft mode structural damping ratio (%)
   1.0      TwrFADmp(2) - Tower 2nd fore-aft mode structural damping ratio (%)
   1.0      TwrSSDmp(1) - Tower 1st side-to-side mode structural damping ratio (%)
   1.0      TwrSSDmp(2) - Tower 2nd side-to-side mode structural damping ratio (%)
---------------------- TOWER ADJUSTMUNT FACTORS --------------------------------
   1.0      FAStTunr(1) - Tower fore-aft modal stiffness tuner, 1st mode (-)
   1.0      FAStTunr(2) - Tower fore-aft modal stiffness tuner, 2nd mode (-)
   1.0      SSStTunr(1) - Tower side-to-side stiffness tuner, 1st mode (-)
   1.0      SSStTunr(2) - Tower side-to-side stiffness tuner, 2nd mode (-)
   1.0      AdjTwMa     - Factor to adjust tower mass density (-)
   1.0      AdjFASt     - Factor to adjust tower fore-aft stiffness (-)
   1.0      AdjSSSt     - Factor to adjust tower side-to-side stiffness (-)
---------------------- DISTRIBUTED TOWER PROPERTIES ----------------------------
HtFract  TMassDen  TwFAStif   TwSSStif   TwGJStif   TwEAStif   TwFAIner  TwSSIner  TwFAcgOf  TwSScgOf
(-)      (kg/m)    (Nm^2)     (Nm^2)     (Nm^2)     (N)        (kg m)    (kg m)    (m)       (m)
0.0      5590.87   614.343E9  614.343E9  472.751E9  138.127E9  24866.3   24866.3   0.0       0.0
0.1      5232.43   534.821E9  534.821E9  411.558E9  129.272E9  21647.5   21647.5   0.0       0.0
0.2      4885.76   463.267E9  463.267E9  356.495E9  120.707E9  18751.3   18751.3   0.0       0.0
0.3      4550.87   399.131E9  399.131E9  307.141E9  112.433E9  16155.3   16155.3   0.0       0.0
0.4      4227.75   341.883E9  341.883E9  263.087E9  104.450E9  13838.1   13838.1   0.0       0.0
0.5      3916.41   291.011E9  291.011E9  223.940E9   96.758E9  11779.0   11779.0   0.0       0.0
0.6      3616.83   246.027E9  246.027E9  189.323E9   89.357E9   9958.2    9958.2   0.0       0.0
0.7      3329.03   206.457E9  206.457E9  158.874E9   82.247E9   8356.6    8356.6   0.0       0.0
0.8      3053.01   171.851E9  171.851E9  132.244E9   75.427E9   6955.9    6955.9   0.0       0.0
0.9      2788.75   141.776E9  141.776E9  109.100E9   68.899E9   5738.6    5738.6   0.0       0.0
1.0      2536.27   115.820E9  115.820E9   89.126E9   62.661E9   4688.0    4688.0   0.0       0.0
---------------------- TOWER FORE-AFT MODE SHAPES ------------------------------
   0.7004   TwFAM1Sh(2) - Mode 1, coefficient of x^2 term
   2.1963   TwFAM1Sh(3) -       , coefficient of x^3 term
  -5.6202   TwFAM1Sh(4) -       , coefficient of x^4 term
   6.2275   TwFAM1Sh(5) -       , coefficient of x^5 term
  -2.5040   TwFAM1Sh(6) -       , coefficient of x^6 term
 -70.5319   TwFAM2Sh(2) - Mode 2, coefficient of x^2 term
 -63.7623   TwFAM2Sh(3) -       , coefficient of x^3 term
 289.7369   TwFAM2Sh(4) -       , coefficient of x^4 term
-176.5134   TwFAM2Sh(5) -       , coefficient of x^5 term
  22.0706   TwFAM2Sh(6) -       , coefficient of x^6 term
---------------------- TOWER SIDE-TO-SIDE MODE SHAPES --------------------------
   1.3850   TwSSM1Sh(2) - Mode 1, coefficient of x^2 term
  -1.7684   TwSSM1Sh(3) -       , coefficient of x^3 term
   3.0871   TwSSM1Sh(4) -       , coefficient of x^4 term
  -2.2395   TwSSM1Sh(5) -       , coefficient of x^5 term
   0.5357   TwSSM1Sh(6) -       , coefficient of x^6 term
-121.2097   TwSSM2Sh(2) - Mode 2, coefficient of x^2 term
 184.4151   TwSSM2Sh(3) -       , coefficient of x^3 term
-224.9037   TwSSM2Sh(4) -       , coefficient of x^4 term
 298.5360   TwSSM2Sh(5) -       , coefficient of x^5 term
-135.8377   TwSSM2Sh(6) -       , coefficient of x^6 term
```

A.4 ADAMS Input File – NRELOffshrBsline5MW_ADAMSSpecific.dat

```
--------------------------------------------------------------------------------
---------------------- FAST 2 ADAMS PREPROCESSOR, ADAMS-SPECIFIC DATA FILE -----
NREL 5.0 MW offshore baseline ADAMS-specific input properties.
---------------------- FEATURE FLAGS -------------------------------------------
True        SaveGrphcs  - Save GRAPHICS output (flag)
False       MakeLINacf  - Make an ADAMS/LINEAR control / command file (flag)
---------------------- DAMPING PARAMETERS --------------------------------------
   0.01     CRatioTGJ   - Ratio of damping to stiffness for the tower torsion     deflection  (-)
   0.01     CRatioTEA   - Ratio of damping to stiffness for the tower extensional deflection  (-)
   0.01     CRatioBGJ   - Ratio of damping to stiffness for the blade torsion     deflections (-)
   0.01     CRatioBEA   - Ratio of damping to stiffness for the blade extensional deflections (-)
---------------------- BLADE PITCH ACTUATOR PARAMETERS -------------------------
 971.350E6  BPActrSpr   - Blade pitch actuator spring stiffness constant (N-m/rad)
   0.206E6  BPActrDmp   - Blade pitch actuator damping          constant (N-m/(rad/s))
---------------------- GRAPHICS PARAMETERS -------------------------------------
  20        NSides      - Number of sides used in GRAPHICS CYLINDER and FRUSTUM statements (-)
   3.000    TwrBaseRad  - Tower base radius used for linearly tapered tower GRAPHICS CYLINDERs (m)
   1.935    TwrTopRad   - Tower top  radius used for linearly tapered tower GRAPHICS CYLINDERs (m)
   7.0      NacLength   - Length of nacelle used for the nacelle GRAPHICS (m)
   1.75     NacRadBot   - Bottom (opposite rotor) radius of nacelle FRUSTUM used for the nacelle GRAPHICS (m)
   1.75     NacRadTop   - Top    (rotor end)      radius of nacelle FRUSTUM used for the nacelle GRAPHICS (m)
   1.0      GBoxLength  - Length, width, and height of the gearbox BOX for gearbox GRAPHICS (m)
   2.39     GenLength   - Length of the generator CYLINDER used for generator GRAPHICS (m)
   1.195    HSSLength   - Length of the high-speed shaft CYLINDER used for HSS GRAPHICS (m)
   4.78     LSSLength   - Length of the low-speed shaft CYLINDER used for LSS GRAPHICS (m)
   0.75     GenRad      - Radius of the generator CYLINDER used for generator GRAPHICS (m)
   0.2      HSSRad      - Radius of the high-speed shaft CYLINDER used for HSS GRAPHICS (m)
   0.4      LSSRad      - Radius of the low -speed shaft CYLINDER used for LSS GRAPHICS (m)
   0.875    HubCylRad   - Radius of hub CYLINDER used for hub GRAPHICS (m)
   0.18     ThkOvrChrd  - Ratio of blade thickness to blade chord used for blade element BOX GRAPHICS (-)
   0.0      BoomRad     - Radius of the tail boom CYLINDER used for tail boom GRAPHICS (m)
```

A.5 Linearization Input File – NRELOffshrBsline5MW_Linear.dat

```
--------------------------------------------------------------------------------
---------------------- FAST LINEARIZATION CONTROL FILE -------------------------
NREL 5.0 MW offshore baseline linearization input properties.
---------------------- PERIODIC STEADY STATE SOLUTION --------------------------
True        CalcStdy    - Calculate periodic steady state condition {False: linearize about initial conditions} (flag)
   3        TrimCase    - Trim case {1: find nacelle yaw, 2: find generator torque, 3: find collective blade pitch} (switch)
   0.0001   DispTol     - Convergence tolerance for the 2-norm of displacements in the periodic steady state calculation (rad
   0.0010   VelTol      - Convergence tolerance for the 2-norm of velocities    in the periodic steady state calculation (rad
---------------------- MODEL LINEARIZATION -------------------------------------
  36        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, Vel
---------------------- INPUTS AND DISTURBANCES ---------------------------------
   0        NInputs     - Number of control inputs [0 (none) or 1 to 4+NumBl] (-)
            CntrlInpt   - List   of control inputs [1 to NInputs] {1: nacelle yaw angle, 2: nacelle yaw rate, 3: generator to
   0        NDisturbs   - Number of wind disturbances [0 (none) or 1 to 7] (-)
            Disturbnc   - List   of input wind disturbances [1 to NDisturbs] {1: horizontal hub-height wind speed, 2: horizon
```

Appendix B AeroDyn Input Files

B.1 Primary Input File – NRELOffshrBsline5MW_AeroDyn.ipt

```
NREL 5.0 MW offshore baseline aerodynamic input properties; Compatible with AeroDyn v12.58.
SI          SysUnits    - System of units used for input and output [must be SI for FAST] (unquoted string)
BEDDOES     StallMod    - Dynamic stall included [BEDDOES or STEADY] (unquoted string)
USE_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)
   0.005    AToler      - Induction-factor tolerance (convergence criteria) (-)
PRANDtl     TLModel     - Tip-loss model (EQUIL only) [PRANDtl, GTECH, or NONE] (unquoted string)
PRANDtl     HLModel     - Hub-loss model (EQUIL only) [PRANdtl or NONE] (unquoted string)
"WindData\90m_12mps"                          WindFile    - Name of file containing wind data (quoted string)
  90.0      HH          - Wind reference (hub) height [TowerHt+Twr2Shft+OverHang*SIN(ShftTilt)] (m)
   0.0      TwrShad     - Tower-shadow velocity deficit (-)
9999.9      ShadHWid    - Tower-shadow half width (m)
9999.9      T_Shad_Refpt- Tower-shadow reference point (m)
   1.225    AirDens     - Air density (kg/m^3)
   1.464E-5 KinVisc     - Kinematic air viscosity [CURRENTLY IGNORED] (m^2/sec)
   0.02479  DTAero      - Time interval for aerodynamic calculations (sec)
   8        NumFoil     - Number of airfoil files (-)
"AeroData\Cylinder1.dat"                      FoilNm      - Names of the airfoil files [NumFoil lines] (quoted strings)
"AeroData\Cylinder2.dat"
"AeroData\DU40_A17.dat"
"AeroData\DU35_A17.dat"
"AeroData\DU30_A17.dat"
"AeroData\DU25_A17.dat"
"AeroData\DU21_A17.dat"
"AeroData\NACA64_A17.dat"
  17        BldNodes    - Number of blade nodes used for analysis (-)
RNodes   AeroTwst  DRNodes  Chord  NFoil  PrnElm
 2.8667  13.308    2.7333   3.542  1      NOPRINT
 5.6000  13.308    2.7333   3.854  1      NOPRINT
 8.3333  13.308    2.7333   4.167  2      NOPRINT
11.7500  13.308    4.1000   4.557  3      NOPRINT
15.8500  11.480    4.1000   4.652  4      NOPRINT
19.9500  10.162    4.1000   4.458  4      NOPRINT
24.0500   9.011    4.1000   4.249  5      NOPRINT
28.1500   7.795    4.1000   4.007  6      NOPRINT
32.2500   6.544    4.1000   3.748  6      NOPRINT
36.3500   5.361    4.1000   3.502  7      NOPRINT
40.4500   4.188    4.1000   3.256  7      NOPRINT
44.5500   3.125    4.1000   3.010  8      NOPRINT
48.6500   2.319    4.1000   2.764  8      NOPRINT
52.7500   1.526    4.1000   2.518  8      NOPRINT
56.1667   0.863    2.7333   2.313  8      NOPRINT
58.9000   0.370    2.7333   2.086  8      NOPRINT
61.6333   0.106    2.7333   1.419  8      NOPRINT
```

B.2 Airfoil-Data Input File – Cylinder1.dat

```
Round root section with a Cd of 0.50
Made by Jason Jonkman
   1        Number of airfoil tables in this file
   0.0      Table ID parameter
   0.0      Stall angle (deg)
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
   0.0      Zero Cn angle of attack (deg)
   0.0      Cn slope for zero lift (dimensionless)
   0.0      Cn extrapolated to value at positive stall angle of attack
   0.0      Cn at stall value for negative angle of attack
   0.0      Angle of attack for minimum CD (deg)
   0.50     Minimum CD value
-180.00    0.000   0.5000   0.000
   0.00    0.000   0.5000   0.000
 180.00    0.000   0.5000   0.000
```

B.3 Airfoil-Data Input File – Cylinder2.dat

```
Round root section with a Cd of 0.35
Made by Jason Jonkman
   1        Number of airfoil tables in this file
```

```
   0.0      Table ID parameter
   0.0      Stall angle (deg)
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
   0.0      Zero Cn angle of attack (deg)
   0.0      Cn slope for zero lift (dimensionless)
   0.0      Cn extrapolated to value at positive stall angle of attack
   0.0      Cn at stall value for negative angle of attack
   0.0      Angle of attack for minimum CD (deg)
   0.35     Minimum CD value
-180.00    0.000   0.3500   0.000
   0.00    0.000   0.3500   0.000
 180.00    0.000   0.3500   0.000
```

B.4 Airfoil-Data Input File – DU40_A17.dat

```
DU40 airfoil with an aspect ratio of 17.  Original -180 to 180deg Cl, Cd, and Cm versus AOA data taken from Appendix A of DOW
Cl and Cd values corrected for rotational stall delay and Cd values corrected using the Viterna method for 0 to 90deg AOA by
   1        Number of airfoil tables in this file
   0.0      Table ID parameter
   9.00     Stall angle (deg)
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
  -1.3430   Zero Cn angle of attack (deg)
   7.4888   Cn slope for zero lift (dimensionless)
   1.3519   Cn extrapolated to value at positive stall angle of attack
  -0.3226   Cn at stall value for negative angle of attack
   0.00     Angle of attack for minimum CD (deg)
   0.0113   Minimum CD value
-180.00    0.000   0.0602   0.0000
-175.00    0.218   0.0699   0.0934
-170.00    0.397   0.1107   0.1697
-160.00    0.642   0.3045   0.2813
-155.00    0.715   0.4179   0.3208
-150.00    0.757   0.5355   0.3516
-145.00    0.772   0.6535   0.3752
-140.00    0.762   0.7685   0.3926
-135.00    0.731   0.8777   0.4048
-130.00    0.680   0.9788   0.4126
-125.00    0.613   1.0700   0.4166
-120.00    0.532   1.1499   0.4176
-115.00    0.439   1.2174   0.4158
-110.00    0.337   1.2716   0.4117
-105.00    0.228   1.3118   0.4057
-100.00    0.114   1.3378   0.3979
 -95.00   -0.002   1.3492   0.3887
 -90.00   -0.120   1.3460   0.3781
 -85.00   -0.236   1.3283   0.3663
 -80.00   -0.349   1.2964   0.3534
 -75.00   -0.456   1.2507   0.3394
 -70.00   -0.557   1.1918   0.3244
 -65.00   -0.647   1.1204   0.3084
 -60.00   -0.727   1.0376   0.2914
 -55.00   -0.792   0.9446   0.2733
 -50.00   -0.842   0.8429   0.2543
 -45.00   -0.874   0.7345   0.2342
 -40.00   -0.886   0.6215   0.2129
 -35.00   -0.875   0.5067   0.1906
 -30.00   -0.839   0.3932   0.1670
 -25.00   -0.777   0.2849   0.1422
 -24.00   -0.761   0.2642   0.1371
 -23.00   -0.744   0.2440   0.1320
 -22.00   -0.725   0.2242   0.1268
 -21.00   -0.706   0.2049   0.1215
 -20.00   -0.685   0.1861   0.1162
 -19.00   -0.662   0.1687   0.1097
 -18.00   -0.635   0.1533   0.1012
 -17.00   -0.605   0.1398   0.0907
 -16.00   -0.571   0.1281   0.0784
 -15.00   -0.534   0.1183   0.0646
 -14.00   -0.494   0.1101   0.0494
 -13.00   -0.452   0.1036   0.0330
 -12.00   -0.407   0.0986   0.0156
 -11.00   -0.360   0.0951  -0.0026
 -10.00   -0.311   0.0931  -0.0213
  -8.00   -0.208   0.0930  -0.0600
  -6.00   -0.111   0.0689  -0.0500
  -5.50   -0.090   0.0614  -0.0516
  -5.00   -0.072   0.0547  -0.0532
  -4.50   -0.065   0.0480  -0.0538
```

-4.00	-0.054	0.0411	-0.0544
-3.50	-0.017	0.0349	-0.0554
-3.00	0.003	0.0299	-0.0558
-2.50	0.014	0.0255	-0.0555
-2.00	0.009	0.0198	-0.0534
-1.50	0.004	0.0164	-0.0442
-1.00	0.036	0.0147	-0.0469
-0.50	0.073	0.0137	-0.0522
0.00	0.137	0.0113	-0.0573
0.50	0.213	0.0114	-0.0644
1.00	0.292	0.0118	-0.0718
1.50	0.369	0.0122	-0.0783
2.00	0.444	0.0124	-0.0835
2.50	0.514	0.0124	-0.0866
3.00	0.580	0.0123	-0.0887
3.50	0.645	0.0120	-0.0900
4.00	0.710	0.0119	-0.0914
4.50	0.776	0.0122	-0.0933
5.00	0.841	0.0125	-0.0947
5.50	0.904	0.0129	-0.0957
6.00	0.967	0.0135	-0.0967
6.50	1.027	0.0144	-0.0973
7.00	1.084	0.0158	-0.0972
7.50	1.140	0.0174	-0.0972
8.00	1.193	0.0198	-0.0968
8.50	1.242	0.0231	-0.0958
9.00	1.287	0.0275	-0.0948
9.50	1.333	0.0323	-0.0942
10.00	1.368	0.0393	-0.0926
10.50	1.400	0.0475	-0.0908
11.00	1.425	0.0580	-0.0890
11.50	1.449	0.0691	-0.0877
12.00	1.473	0.0816	-0.0870
12.50	1.494	0.0973	-0.0870
13.00	1.513	0.1129	-0.0876
13.50	1.538	0.1288	-0.0886
14.50	1.587	0.1650	-0.0917
15.00	1.614	0.1845	-0.0939
15.50	1.631	0.2052	-0.0966
16.00	1.649	0.2250	-0.0996
16.50	1.666	0.2467	-0.1031
17.00	1.681	0.2684	-0.1069
17.50	1.699	0.2900	-0.1110
18.00	1.719	0.3121	-0.1157
19.00	1.751	0.3554	-0.1242
19.50	1.767	0.3783	-0.1291
20.50	1.798	0.4212	-0.1384
21.00	1.810	0.4415	-0.1416
22.00	1.830	0.4830	-0.1479
23.00	1.847	0.5257	-0.1542
24.00	1.861	0.5694	-0.1603
25.00	1.872	0.6141	-0.1664
26.00	1.881	0.6593	-0.1724
28.00	1.894	0.7513	-0.1841
30.00	1.904	0.8441	-0.1954
32.00	1.915	0.9364	-0.2063
35.00	1.929	1.0722	-0.2220
40.00	1.903	1.2873	-0.2468
45.00	1.820	1.4796	-0.2701
50.00	1.690	1.6401	-0.2921
55.00	1.522	1.7609	-0.3127
60.00	1.323	1.8360	-0.3321
65.00	1.106	1.8614	-0.3502
70.00	0.880	1.8347	-0.3672
75.00	0.658	1.7567	-0.3830
80.00	0.449	1.6334	-0.3977
85.00	0.267	1.4847	-0.4112
90.00	0.124	1.3879	-0.4234
95.00	0.002	1.3912	-0.4343
100.00	-0.118	1.3795	-0.4437
105.00	-0.235	1.3528	-0.4514
110.00	-0.348	1.3114	-0.4573
115.00	-0.453	1.2557	-0.4610
120.00	-0.549	1.1864	-0.4623
125.00	-0.633	1.1041	-0.4606
130.00	-0.702	1.0102	-0.4554
135.00	-0.754	0.9060	-0.4462
140.00	-0.787	0.7935	-0.4323
145.00	-0.797	0.6750	-0.4127
150.00	-0.782	0.5532	-0.3863
155.00	-0.739	0.4318	-0.3521
160.00	-0.664	0.3147	-0.3085
170.00	-0.410	0.1144	-0.1858
175.00	-0.226	0.0702	-0.1022

```
180.00    0.000   0.0602   0.0000
```

B.5 Airfoil-Data Input File – DU35_A17.dat

```
DU35 airfoil with an aspect ratio of 17.  Original -180 to 180deg Cl, Cd, and Cm versus AOA data taken from Appendix A of DOW
Cl and Cd values corrected for rotational stall delay and Cd values corrected using the Viterna method for 0 to 90deg AOA by
   1        Number of airfoil tables in this file
   0.0      Table ID parameter
  11.50     Stall angle (deg)
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
  -1.8330   Zero Cn angle of attack (deg)
   7.1838   Cn slope for zero lift (dimensionless)
   1.6717   Cn extrapolated to value at positive stall angle of attack
  -0.3075   Cn at stall value for negative angle of attack
   0.00     Angle of attack for minimum CD (deg)
   0.0094   Minimum CD value
-180.00    0.000   0.0407   0.0000
-175.00    0.223   0.0507   0.0937
-170.00    0.405   0.1055   0.1702
-160.00    0.658   0.2982   0.2819
-155.00    0.733   0.4121   0.3213
-150.00    0.778   0.5308   0.3520
-145.00    0.795   0.6503   0.3754
-140.00    0.787   0.7672   0.3926
-135.00    0.757   0.8785   0.4046
-130.00    0.708   0.9819   0.4121
-125.00    0.641   1.0756   0.4160
-120.00    0.560   1.1580   0.4167
-115.00    0.467   1.2280   0.4146
-110.00    0.365   1.2847   0.4104
-105.00    0.255   1.3274   0.4041
-100.00    0.139   1.3557   0.3961
 -95.00    0.021   1.3692   0.3867
 -90.00   -0.098   1.3680   0.3759
 -85.00   -0.216   1.3521   0.3639
 -80.00   -0.331   1.3218   0.3508
 -75.00   -0.441   1.2773   0.3367
 -70.00   -0.544   1.2193   0.3216
 -65.00   -0.638   1.1486   0.3054
 -60.00   -0.720   1.0660   0.2884
 -55.00   -0.788   0.9728   0.2703
 -50.00   -0.840   0.8705   0.2512
 -45.00   -0.875   0.7611   0.2311
 -40.00   -0.889   0.6466   0.2099
 -35.00   -0.880   0.5299   0.1876
 -30.00   -0.846   0.4141   0.1641
 -25.00   -0.784   0.3030   0.1396
 -24.00   -0.768   0.2817   0.1345
 -23.00   -0.751   0.2608   0.1294
 -22.00   -0.733   0.2404   0.1243
 -21.00   -0.714   0.2205   0.1191
 -20.00   -0.693   0.2011   0.1139
 -19.00   -0.671   0.1822   0.1086
 -18.00   -0.648   0.1640   0.1032
 -17.00   -0.624   0.1465   0.0975
 -16.00   -0.601   0.1300   0.0898
 -15.00   -0.579   0.1145   0.0799
 -14.00   -0.559   0.1000   0.0682
 -13.00   -0.539   0.0867   0.0547
 -12.00   -0.519   0.0744   0.0397
 -11.00   -0.499   0.0633   0.0234
 -10.00   -0.480   0.0534   0.0060
  -5.54   -0.385   0.0245  -0.0800
  -5.04   -0.359   0.0225  -0.0800
  -4.54   -0.360   0.0196  -0.0800
  -4.04   -0.355   0.0174  -0.0800
  -3.54   -0.307   0.0162  -0.0800
  -3.04   -0.246   0.0144  -0.0800
  -3.00   -0.240   0.0240  -0.0623
  -2.50   -0.163   0.0188  -0.0674
  -2.00   -0.091   0.0160  -0.0712
  -1.50   -0.019   0.0137  -0.0746
  -1.00    0.052   0.0118  -0.0778
  -0.50    0.121   0.0104  -0.0806
   0.00    0.196   0.0094  -0.0831
   0.50    0.265   0.0096  -0.0863
   1.00    0.335   0.0098  -0.0895
   1.50    0.404   0.0099  -0.0924
   2.00    0.472   0.0100  -0.0949
   2.50    0.540   0.0102  -0.0973
```

```
   3.00    0.608   0.0103  -0.0996
   3.50    0.674   0.0104  -0.1016
   4.00    0.742   0.0105  -0.1037
   4.50    0.809   0.0107  -0.1057
   5.00    0.875   0.0108  -0.1076
   5.50    0.941   0.0109  -0.1094
   6.00    1.007   0.0110  -0.1109
   6.50    1.071   0.0113  -0.1118
   7.00    1.134   0.0115  -0.1127
   7.50    1.198   0.0117  -0.1138
   8.00    1.260   0.0120  -0.1144
   8.50    1.318   0.0126  -0.1137
   9.00    1.368   0.0133  -0.1112
   9.50    1.422   0.0143  -0.1100
  10.00    1.475   0.0156  -0.1086
  10.50    1.523   0.0174  -0.1064
  11.00    1.570   0.0194  -0.1044
  11.50    1.609   0.0227  -0.1013
  12.00    1.642   0.0269  -0.0980
  12.50    1.675   0.0319  -0.0953
  13.00    1.700   0.0398  -0.0925
  13.50    1.717   0.0488  -0.0896
  14.00    1.712   0.0614  -0.0864
  14.50    1.703   0.0786  -0.0840
  15.50    1.671   0.1173  -0.0830
  16.00    1.649   0.1377  -0.0848
  16.50    1.621   0.1600  -0.0880
  17.00    1.598   0.1814  -0.0926
  17.50    1.571   0.2042  -0.0984
  18.00    1.549   0.2316  -0.1052
  19.00    1.544   0.2719  -0.1158
  19.50    1.549   0.2906  -0.1213
  20.00    1.565   0.3085  -0.1248
  21.00    1.565   0.3447  -0.1317
  22.00    1.563   0.3820  -0.1385
  23.00    1.558   0.4203  -0.1452
  24.00    1.552   0.4593  -0.1518
  25.00    1.546   0.4988  -0.1583
  26.00    1.539   0.5387  -0.1647
  28.00    1.527   0.6187  -0.1770
  30.00    1.522   0.6978  -0.1886
  32.00    1.529   0.7747  -0.1994
  35.00    1.544   0.8869  -0.2148
  40.00    1.529   1.0671  -0.2392
  45.00    1.471   1.2319  -0.2622
  50.00    1.376   1.3747  -0.2839
  55.00    1.249   1.4899  -0.3043
  60.00    1.097   1.5728  -0.3236
  65.00    0.928   1.6202  -0.3417
  70.00    0.750   1.6302  -0.3586
  75.00    0.570   1.6031  -0.3745
  80.00    0.396   1.5423  -0.3892
  85.00    0.237   1.4598  -0.4028
  90.00    0.101   1.4041  -0.4151
  95.00   -0.022   1.4053  -0.4261
 100.00   -0.143   1.3914  -0.4357
 105.00   -0.261   1.3625  -0.4437
 110.00   -0.374   1.3188  -0.4498
 115.00   -0.480   1.2608  -0.4538
 120.00   -0.575   1.1891  -0.4553
 125.00   -0.659   1.1046  -0.4540
 130.00   -0.727   1.0086  -0.4492
 135.00   -0.778   0.9025  -0.4405
 140.00   -0.809   0.7883  -0.4270
 145.00   -0.818   0.6684  -0.4078
 150.00   -0.800   0.5457  -0.3821
 155.00   -0.754   0.4236  -0.3484
 160.00   -0.677   0.3066  -0.3054
 170.00   -0.417   0.1085  -0.1842
 175.00   -0.229   0.0510  -0.1013
 180.00    0.000   0.0407   0.0000
```

B.6 Airfoil-Data Input File – DU30_A17.dat

```
DU30 airfoil with an aspect ratio of 17.  Original -180 to 180deg Cl, Cd, and Cm versus AOA data taken from Appendix A of DOW
Cl and Cd values corrected for rotational stall delay and Cd values corrected using the Viterna method for 0 to 90deg AOA by
   1        Number of airfoil tables in this file
   0.0      Table ID parameter
   9.00     Stall angle (deg)
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
```

```
  -2.3220   Zero Cn angle of attack (deg)
   7.3326   Cn slope for zero lift (dimensionless)
   1.4490   Cn extrapolated to value at positive stall angle of attack
  -0.6138   Cn at stall value for negative angle of attack
   0.00     Angle of attack for minimum CD (deg)
   0.0087   Minimum CD value
-180.00    0.000   0.0267   0.0000
-175.00    0.274   0.0370   0.1379
-170.00    0.547   0.0968   0.2778
-160.00    0.685   0.2876   0.2740
-155.00    0.766   0.4025   0.3118
-150.00    0.816   0.5232   0.3411
-145.00    0.836   0.6454   0.3631
-140.00    0.832   0.7656   0.3791
-135.00    0.804   0.8807   0.3899
-130.00    0.756   0.9882   0.3965
-125.00    0.690   1.0861   0.3994
-120.00    0.609   1.1730   0.3992
-115.00    0.515   1.2474   0.3964
-110.00    0.411   1.3084   0.3915
-105.00    0.300   1.3552   0.3846
-100.00    0.182   1.3875   0.3761
 -95.00    0.061   1.4048   0.3663
 -90.00   -0.061   1.4070   0.3551
 -85.00   -0.183   1.3941   0.3428
 -80.00   -0.302   1.3664   0.3295
 -75.00   -0.416   1.3240   0.3153
 -70.00   -0.523   1.2676   0.3001
 -65.00   -0.622   1.1978   0.2841
 -60.00   -0.708   1.1156   0.2672
 -55.00   -0.781   1.0220   0.2494
 -50.00   -0.838   0.9187   0.2308
 -45.00   -0.877   0.8074   0.2113
 -40.00   -0.895   0.6904   0.1909
 -35.00   -0.889   0.5703   0.1696
 -30.00   -0.858   0.4503   0.1475
 -25.00   -0.832   0.3357   0.1224
 -24.00   -0.852   0.3147   0.1156
 -23.00   -0.882   0.2946   0.1081
 -22.00   -0.919   0.2752   0.1000
 -21.00   -0.963   0.2566   0.0914
 -20.00   -1.013   0.2388   0.0823
 -19.00   -1.067   0.2218   0.0728
 -18.00   -1.125   0.2056   0.0631
 -17.00   -1.185   0.1901   0.0531
 -16.00   -1.245   0.1754   0.0430
 -15.25   -1.290   0.1649   0.0353
 -14.24   -1.229   0.1461   0.0240
 -13.24   -1.148   0.1263   0.0100
 -12.22   -1.052   0.1051  -0.0090
 -11.22   -0.965   0.0886  -0.0230
 -10.19   -0.867   0.0740  -0.0336
  -9.70   -0.822   0.0684  -0.0375
  -9.18   -0.769   0.0605  -0.0440
  -8.18   -0.756   0.0270  -0.0578
  -7.19   -0.690   0.0180  -0.0590
  -6.65   -0.616   0.0166  -0.0633
  -6.13   -0.542   0.0152  -0.0674
  -6.00   -0.525   0.0117  -0.0732
  -5.50   -0.451   0.0105  -0.0766
  -5.00   -0.382   0.0097  -0.0797
  -4.50   -0.314   0.0092  -0.0825
  -4.00   -0.251   0.0091  -0.0853
  -3.50   -0.189   0.0089  -0.0884
  -3.00   -0.120   0.0089  -0.0914
  -2.50   -0.051   0.0088  -0.0942
  -2.00    0.017   0.0088  -0.0969
  -1.50    0.085   0.0088  -0.0994
  -1.00    0.152   0.0088  -0.1018
  -0.50    0.219   0.0088  -0.1041
   0.00    0.288   0.0087  -0.1062
   0.50    0.354   0.0087  -0.1086
   1.00    0.421   0.0088  -0.1107
   1.50    0.487   0.0089  -0.1129
   2.00    0.554   0.0090  -0.1149
   2.50    0.619   0.0091  -0.1168
   3.00    0.685   0.0092  -0.1185
   3.50    0.749   0.0093  -0.1201
   4.00    0.815   0.0095  -0.1218
   4.50    0.879   0.0096  -0.1233
   5.00    0.944   0.0097  -0.1248
   5.50    1.008   0.0099  -0.1260
   6.00    1.072   0.0101  -0.1270
   6.50    1.135   0.0103  -0.1280
```

```
   7.00    1.197   0.0107  -0.1287
   7.50    1.256   0.0112  -0.1289
   8.00    1.305   0.0125  -0.1270
   9.00    1.390   0.0155  -0.1207
   9.50    1.424   0.0171  -0.1158
  10.00    1.458   0.0192  -0.1116
  10.50    1.488   0.0219  -0.1073
  11.00    1.512   0.0255  -0.1029
  11.50    1.533   0.0307  -0.0983
  12.00    1.549   0.0370  -0.0949
  12.50    1.558   0.0452  -0.0921
  13.00    1.470   0.0630  -0.0899
  13.50    1.398   0.0784  -0.0885
  14.00    1.354   0.0931  -0.0885
  14.50    1.336   0.1081  -0.0902
  15.00    1.333   0.1239  -0.0928
  15.50    1.326   0.1415  -0.0963
  16.00    1.329   0.1592  -0.1006
  16.50    1.326   0.1743  -0.1042
  17.00    1.321   0.1903  -0.1084
  17.50    1.331   0.2044  -0.1125
  18.00    1.333   0.2186  -0.1169
  18.50    1.340   0.2324  -0.1215
  19.00    1.362   0.2455  -0.1263
  19.50    1.382   0.2584  -0.1313
  20.00    1.398   0.2689  -0.1352
  20.50    1.426   0.2814  -0.1406
  21.00    1.437   0.2943  -0.1462
  22.00    1.418   0.3246  -0.1516
  23.00    1.397   0.3557  -0.1570
  24.00    1.376   0.3875  -0.1623
  25.00    1.354   0.4198  -0.1676
  26.00    1.332   0.4524  -0.1728
  28.00    1.293   0.5183  -0.1832
  30.00    1.265   0.5843  -0.1935
  32.00    1.253   0.6492  -0.2039
  35.00    1.264   0.7438  -0.2193
  40.00    1.258   0.8970  -0.2440
  45.00    1.217   1.0402  -0.2672
  50.00    1.146   1.1686  -0.2891
  55.00    1.049   1.2779  -0.3097
  60.00    0.932   1.3647  -0.3290
  65.00    0.799   1.4267  -0.3471
  70.00    0.657   1.4621  -0.3641
  75.00    0.509   1.4708  -0.3799
  80.00    0.362   1.4544  -0.3946
  85.00    0.221   1.4196  -0.4081
  90.00    0.092   1.3938  -0.4204
  95.00   -0.030   1.3943  -0.4313
 100.00   -0.150   1.3798  -0.4408
 105.00   -0.267   1.3504  -0.4486
 110.00   -0.379   1.3063  -0.4546
 115.00   -0.483   1.2481  -0.4584
 120.00   -0.578   1.1763  -0.4597
 125.00   -0.660   1.0919  -0.4582
 130.00   -0.727   0.9962  -0.4532
 135.00   -0.777   0.8906  -0.4441
 140.00   -0.807   0.7771  -0.4303
 145.00   -0.815   0.6581  -0.4109
 150.00   -0.797   0.5364  -0.3848
 155.00   -0.750   0.4157  -0.3508
 160.00   -0.673   0.3000  -0.3074
 170.00   -0.547   0.1051  -0.2786
 175.00   -0.274   0.0388  -0.1380
 180.00    0.000   0.0267   0.0000
```

B.7 Airfoil-Data Input File – DU25_A17.dat

```
DU25 airfoil with an aspect ratio of 17.  Original -180 to 180deg Cl, Cd, and Cm versus AOA data taken from Appendix A of DOW
Cl and Cd values corrected for rotational stall delay and Cd values corrected using the Viterna method for 0 to 90deg AOA by
   1        Number of airfoil tables in this file
   0.0      Table ID parameter
   8.50     Stall angle (deg)
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
  -4.2422   Zero Cn angle of attack (deg)
   6.4462   Cn slope for zero lift (dimensionless)
   1.4336   Cn extrapolated to value at positive stall angle of attack
  -0.6873   Cn at stall value for negative angle of attack
   0.00     Angle of attack for minimum CD (deg)
   0.0065   Minimum CD value
```

-180.00	0.000	0.0202	0.0000
-175.00	0.368	0.0324	0.1845
-170.00	0.735	0.0943	0.3701
-160.00	0.695	0.2848	0.2679
-155.00	0.777	0.4001	0.3046
-150.00	0.828	0.5215	0.3329
-145.00	0.850	0.6447	0.3540
-140.00	0.846	0.7660	0.3693
-135.00	0.818	0.8823	0.3794
-130.00	0.771	0.9911	0.3854
-125.00	0.705	1.0905	0.3878
-120.00	0.624	1.1787	0.3872
-115.00	0.530	1.2545	0.3841
-110.00	0.426	1.3168	0.3788
-105.00	0.314	1.3650	0.3716
-100.00	0.195	1.3984	0.3629
-95.00	0.073	1.4169	0.3529
-90.00	-0.050	1.4201	0.3416
-85.00	-0.173	1.4081	0.3292
-80.00	-0.294	1.3811	0.3159
-75.00	-0.409	1.3394	0.3017
-70.00	-0.518	1.2833	0.2866
-65.00	-0.617	1.2138	0.2707
-60.00	-0.706	1.1315	0.2539
-55.00	-0.780	1.0378	0.2364
-50.00	-0.839	0.9341	0.2181
-45.00	-0.879	0.8221	0.1991
-40.00	-0.898	0.7042	0.1792
-35.00	-0.893	0.5829	0.1587
-30.00	-0.862	0.4616	0.1374
-25.00	-0.803	0.3441	0.1154
-24.00	-0.792	0.3209	0.1101
-23.00	-0.789	0.2972	0.1031
-22.00	-0.792	0.2730	0.0947
-21.00	-0.801	0.2485	0.0849
-20.00	-0.815	0.2237	0.0739
-19.00	-0.833	0.1990	0.0618
-18.00	-0.854	0.1743	0.0488
-17.00	-0.879	0.1498	0.0351
-16.00	-0.905	0.1256	0.0208
-15.00	-0.932	0.1020	0.0060
-14.00	-0.959	0.0789	-0.0091
-13.00	-0.985	0.0567	-0.0243
-13.00	-0.985	0.0567	-0.0243
-12.01	-0.953	0.0271	-0.0349
-11.00	-0.900	0.0303	-0.0361
-9.98	-0.827	0.0287	-0.0464
-8.98	-0.753	0.0271	-0.0534
-8.47	-0.691	0.0264	-0.0650
-7.45	-0.555	0.0114	-0.0782
-6.42	-0.413	0.0094	-0.0904
-5.40	-0.271	0.0086	-0.1006
-5.00	-0.220	0.0073	-0.1107
-4.50	-0.152	0.0071	-0.1135
-4.00	-0.084	0.0070	-0.1162
-3.50	-0.018	0.0069	-0.1186
-3.00	0.049	0.0068	-0.1209
-2.50	0.115	0.0068	-0.1231
-2.00	0.181	0.0068	-0.1252
-1.50	0.247	0.0067	-0.1272
-1.00	0.312	0.0067	-0.1293
-0.50	0.377	0.0067	-0.1311
0.00	0.444	0.0065	-0.1330
0.50	0.508	0.0065	-0.1347
1.00	0.573	0.0066	-0.1364
1.50	0.636	0.0067	-0.1380
2.00	0.701	0.0068	-0.1396
2.50	0.765	0.0069	-0.1411
3.00	0.827	0.0070	-0.1424
3.50	0.890	0.0071	-0.1437
4.00	0.952	0.0073	-0.1448
4.50	1.013	0.0076	-0.1456
5.00	1.062	0.0079	-0.1445
6.00	1.161	0.0099	-0.1419
6.50	1.208	0.0117	-0.1403
7.00	1.254	0.0132	-0.1382
7.50	1.301	0.0143	-0.1362
8.00	1.336	0.0153	-0.1320
8.50	1.369	0.0165	-0.1276
9.00	1.400	0.0181	-0.1234
9.50	1.428	0.0211	-0.1193
10.00	1.442	0.0262	-0.1152
10.50	1.427	0.0336	-0.1115
11.00	1.374	0.0420	-0.1081

```
  11.50    1.316   0.0515  -0.1052
  12.00    1.277   0.0601  -0.1026
  12.50    1.250   0.0693  -0.1000
  13.00    1.246   0.0785  -0.0980
  13.50    1.247   0.0888  -0.0969
  14.00    1.256   0.1000  -0.0968
  14.50    1.260   0.1108  -0.0973
  15.00    1.271   0.1219  -0.0981
  15.50    1.281   0.1325  -0.0992
  16.00    1.289   0.1433  -0.1006
  16.50    1.294   0.1541  -0.1023
  17.00    1.304   0.1649  -0.1042
  17.50    1.309   0.1754  -0.1064
  18.00    1.315   0.1845  -0.1082
  18.50    1.320   0.1953  -0.1110
  19.00    1.330   0.2061  -0.1143
  19.50    1.343   0.2170  -0.1179
  20.00    1.354   0.2280  -0.1219
  20.50    1.359   0.2390  -0.1261
  21.00    1.360   0.2536  -0.1303
  22.00    1.325   0.2814  -0.1375
  23.00    1.288   0.3098  -0.1446
  24.00    1.251   0.3386  -0.1515
  25.00    1.215   0.3678  -0.1584
  26.00    1.181   0.3972  -0.1651
  28.00    1.120   0.4563  -0.1781
  30.00    1.076   0.5149  -0.1904
  32.00    1.056   0.5720  -0.2017
  35.00    1.066   0.6548  -0.2173
  40.00    1.064   0.7901  -0.2418
  45.00    1.035   0.9190  -0.2650
  50.00    0.980   1.0378  -0.2867
  55.00    0.904   1.1434  -0.3072
  60.00    0.810   1.2333  -0.3265
  65.00    0.702   1.3055  -0.3446
  70.00    0.582   1.3587  -0.3616
  75.00    0.456   1.3922  -0.3775
  80.00    0.326   1.4063  -0.3921
  85.00    0.197   1.4042  -0.4057
  90.00    0.072   1.3985  -0.4180
  95.00   -0.050   1.3973  -0.4289
 100.00   -0.170   1.3810  -0.4385
 105.00   -0.287   1.3498  -0.4464
 110.00   -0.399   1.3041  -0.4524
 115.00   -0.502   1.2442  -0.4563
 120.00   -0.596   1.1709  -0.4577
 125.00   -0.677   1.0852  -0.4563
 130.00   -0.743   0.9883  -0.4514
 135.00   -0.792   0.8818  -0.4425
 140.00   -0.821   0.7676  -0.4288
 145.00   -0.826   0.6481  -0.4095
 150.00   -0.806   0.5264  -0.3836
 155.00   -0.758   0.4060  -0.3497
 160.00   -0.679   0.2912  -0.3065
 170.00   -0.735   0.0995  -0.3706
 175.00   -0.368   0.0356  -0.1846
 180.00    0.000   0.0202   0.0000
```

B.8 Airfoil-Data Input File – DU21_A17.dat

```
DU21 airfoil with an aspect ratio of 17.  Original -180 to 180deg Cl, Cd, and Cm versus AOA data taken from Appendix A of DOW
Cl and Cd values corrected for rotational stall delay and Cd values corrected using the Viterna method for 0 to 90deg AOA by
   1        Number of airfoil tables in this file
   0.0      Table ID parameter
   8.00     Stall angle (deg)
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
  -5.0609   Zero Cn angle of attack (deg)
   6.2047   Cn slope for zero lift (dimensionless)
   1.4144   Cn extrapolated to value at positive stall angle of attack
  -0.5324   Cn at stall value for negative angle of attack
  -1.50     Angle of attack for minimum CD (deg)
   0.0057   Minimum CD value
-180.00    0.000   0.0185   0.0000
-175.00    0.394   0.0332   0.1978
-170.00    0.788   0.0945   0.3963
-160.00    0.670   0.2809   0.2738
-155.00    0.749   0.3932   0.3118
-150.00    0.797   0.5112   0.3413
-145.00    0.818   0.6309   0.3636
-140.00    0.813   0.7485   0.3799
```

-135.00	0.786	0.8612	0.3911
-130.00	0.739	0.9665	0.3980
-125.00	0.675	1.0625	0.4012
-120.00	0.596	1.1476	0.4014
-115.00	0.505	1.2206	0.3990
-110.00	0.403	1.2805	0.3943
-105.00	0.294	1.3265	0.3878
-100.00	0.179	1.3582	0.3796
-95.00	0.060	1.3752	0.3700
-90.00	-0.060	1.3774	0.3591
-85.00	-0.179	1.3648	0.3471
-80.00	-0.295	1.3376	0.3340
-75.00	-0.407	1.2962	0.3199
-70.00	-0.512	1.2409	0.3049
-65.00	-0.608	1.1725	0.2890
-60.00	-0.693	1.0919	0.2722
-55.00	-0.764	1.0002	0.2545
-50.00	-0.820	0.8990	0.2359
-45.00	-0.857	0.7900	0.2163
-40.00	-0.875	0.6754	0.1958
-35.00	-0.869	0.5579	0.1744
-30.00	-0.838	0.4405	0.1520
-25.00	-0.791	0.3256	0.1262
-24.00	-0.794	0.3013	0.1170
-23.00	-0.805	0.2762	0.1059
-22.00	-0.821	0.2506	0.0931
-21.00	-0.843	0.2246	0.0788
-20.00	-0.869	0.1983	0.0631
-19.00	-0.899	0.1720	0.0464
-18.00	-0.931	0.1457	0.0286
-17.00	-0.964	0.1197	0.0102
-16.00	-0.999	0.0940	-0.0088
-15.00	-1.033	0.0689	-0.0281
-14.50	-1.050	0.0567	-0.0378
-12.01	-0.953	0.0271	-0.0349
-11.00	-0.900	0.0303	-0.0361
-9.98	-0.827	0.0287	-0.0464
-8.12	-0.536	0.0124	-0.0821
-7.62	-0.467	0.0109	-0.0924
-7.11	-0.393	0.0092	-0.1015
-6.60	-0.323	0.0083	-0.1073
-6.50	-0.311	0.0089	-0.1083
-6.00	-0.245	0.0082	-0.1112
-5.50	-0.178	0.0074	-0.1146
-5.00	-0.113	0.0069	-0.1172
-4.50	-0.048	0.0065	-0.1194
-4.00	0.016	0.0063	-0.1213
-3.50	0.080	0.0061	-0.1232
-3.00	0.145	0.0058	-0.1252
-2.50	0.208	0.0057	-0.1268
-2.00	0.270	0.0057	-0.1282
-1.50	0.333	0.0057	-0.1297
-1.00	0.396	0.0057	-0.1310
-0.50	0.458	0.0057	-0.1324
0.00	0.521	0.0057	-0.1337
0.50	0.583	0.0057	-0.1350
1.00	0.645	0.0058	-0.1363
1.50	0.706	0.0058	-0.1374
2.00	0.768	0.0059	-0.1385
2.50	0.828	0.0061	-0.1395
3.00	0.888	0.0063	-0.1403
3.50	0.948	0.0066	-0.1406
4.00	0.996	0.0071	-0.1398
4.50	1.046	0.0079	-0.1390
5.00	1.095	0.0090	-0.1378
5.50	1.145	0.0103	-0.1369
6.00	1.192	0.0113	-0.1353
6.50	1.239	0.0122	-0.1338
7.00	1.283	0.0131	-0.1317
7.50	1.324	0.0139	-0.1291
8.00	1.358	0.0147	-0.1249
8.50	1.385	0.0158	-0.1213
9.00	1.403	0.0181	-0.1177
9.50	1.401	0.0211	-0.1142
10.00	1.358	0.0255	-0.1103
10.50	1.313	0.0301	-0.1066
11.00	1.287	0.0347	-0.1032
11.50	1.274	0.0401	-0.1002
12.00	1.272	0.0468	-0.0971
12.50	1.273	0.0545	-0.0940
13.00	1.273	0.0633	-0.0909
13.50	1.273	0.0722	-0.0883
14.00	1.272	0.0806	-0.0865
14.50	1.273	0.0900	-0.0854

```
  15.00    1.275   0.0987  -0.0849
  15.50    1.281   0.1075  -0.0847
  16.00    1.284   0.1170  -0.0850
  16.50    1.296   0.1270  -0.0858
  17.00    1.306   0.1368  -0.0869
  17.50    1.308   0.1464  -0.0883
  18.00    1.308   0.1562  -0.0901
  18.50    1.308   0.1664  -0.0922
  19.00    1.308   0.1770  -0.0949
  19.50    1.307   0.1878  -0.0980
  20.00    1.311   0.1987  -0.1017
  20.50    1.325   0.2100  -0.1059
  21.00    1.324   0.2214  -0.1105
  22.00    1.277   0.2499  -0.1172
  23.00    1.229   0.2786  -0.1239
  24.00    1.182   0.3077  -0.1305
  25.00    1.136   0.3371  -0.1370
  26.00    1.093   0.3664  -0.1433
  28.00    1.017   0.4246  -0.1556
  30.00    0.962   0.4813  -0.1671
  32.00    0.937   0.5356  -0.1778
  35.00    0.947   0.6127  -0.1923
  40.00    0.950   0.7396  -0.2154
  45.00    0.928   0.8623  -0.2374
  50.00    0.884   0.9781  -0.2583
  55.00    0.821   1.0846  -0.2782
  60.00    0.740   1.1796  -0.2971
  65.00    0.646   1.2617  -0.3149
  70.00    0.540   1.3297  -0.3318
  75.00    0.425   1.3827  -0.3476
  80.00    0.304   1.4202  -0.3625
  85.00    0.179   1.4423  -0.3763
  90.00    0.053   1.4512  -0.3890
  95.00   -0.073   1.4480  -0.4004
 100.00   -0.198   1.4294  -0.4105
 105.00   -0.319   1.3954  -0.4191
 110.00   -0.434   1.3464  -0.4260
 115.00   -0.541   1.2829  -0.4308
 120.00   -0.637   1.2057  -0.4333
 125.00   -0.720   1.1157  -0.4330
 130.00   -0.787   1.0144  -0.4294
 135.00   -0.836   0.9033  -0.4219
 140.00   -0.864   0.7845  -0.4098
 145.00   -0.869   0.6605  -0.3922
 150.00   -0.847   0.5346  -0.3682
 155.00   -0.795   0.4103  -0.3364
 160.00   -0.711   0.2922  -0.2954
 170.00   -0.788   0.0969  -0.3966
 175.00   -0.394   0.0334  -0.1978
 180.00    0.000   0.0185   0.0000
```

B.9 Airfoil-Data Input File – NACA64_A17.dat

```
NACA64 airfoil with an aspect ratio of 17.  Original -180 to 180deg Cl, Cd, and Cm versus AOA data taken from Appendix A of D
Cl and Cd values corrected for rotational stall delay and Cd values corrected using the Viterna method for 0 to 90deg AOA by
   1        Number of airfoil tables in this file
   0.0      Table ID parameter
   9.00     Stall angle (deg)
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
   0.0      No longer used, enter zero
  -4.4320   Zero Cn angle of attack (deg)
   6.0031   Cn slope for zero lift (dimensionless)
   1.4073   Cn extrapolated to value at positive stall angle of attack
  -0.7945   Cn at stall value for negative angle of attack
  -1.00     Angle of attack for minimum CD (deg)
   0.0052   Minimum CD value
-180.00    0.000   0.0198   0.0000
-175.00    0.374   0.0341   0.1880
-170.00    0.749   0.0955   0.3770
-160.00    0.659   0.2807   0.2747
-155.00    0.736   0.3919   0.3130
-150.00    0.783   0.5086   0.3428
-145.00    0.803   0.6267   0.3654
-140.00    0.798   0.7427   0.3820
-135.00    0.771   0.8537   0.3935
-130.00    0.724   0.9574   0.4007
-125.00    0.660   1.0519   0.4042
-120.00    0.581   1.1355   0.4047
-115.00    0.491   1.2070   0.4025
-110.00    0.390   1.2656   0.3981
-105.00    0.282   1.3104   0.3918
```

-100.00	0.169	1.3410	0.3838
-95.00	0.052	1.3572	0.3743
-90.00	-0.067	1.3587	0.3636
-85.00	-0.184	1.3456	0.3517
-80.00	-0.299	1.3181	0.3388
-75.00	-0.409	1.2765	0.3248
-70.00	-0.512	1.2212	0.3099
-65.00	-0.606	1.1532	0.2940
-60.00	-0.689	1.0731	0.2772
-55.00	-0.759	0.9822	0.2595
-50.00	-0.814	0.8820	0.2409
-45.00	-0.850	0.7742	0.2212
-40.00	-0.866	0.6610	0.2006
-35.00	-0.860	0.5451	0.1789
-30.00	-0.829	0.4295	0.1563
-25.00	-0.853	0.3071	0.1156
-24.00	-0.870	0.2814	0.1040
-23.00	-0.890	0.2556	0.0916
-22.00	-0.911	0.2297	0.0785
-21.00	-0.934	0.2040	0.0649
-20.00	-0.958	0.1785	0.0508
-19.00	-0.982	0.1534	0.0364
-18.00	-1.005	0.1288	0.0218
-17.00	-1.082	0.1037	0.0129
-16.00	-1.113	0.0786	-0.0028
-15.00	-1.105	0.0535	-0.0251
-14.00	-1.078	0.0283	-0.0419
-13.50	-1.053	0.0158	-0.0521
-13.00	-1.015	0.0151	-0.0610
-12.00	-0.904	0.0134	-0.0707
-11.00	-0.807	0.0121	-0.0722
-10.00	-0.711	0.0111	-0.0734
-9.00	-0.595	0.0099	-0.0772
-8.00	-0.478	0.0091	-0.0807
-7.00	-0.375	0.0086	-0.0825
-6.00	-0.264	0.0082	-0.0832
-5.00	-0.151	0.0079	-0.0841
-4.00	-0.017	0.0072	-0.0869
-3.00	0.088	0.0064	-0.0912
-2.00	0.213	0.0054	-0.0946
-1.00	0.328	0.0052	-0.0971
0.00	0.442	0.0052	-0.1014
1.00	0.556	0.0052	-0.1076
2.00	0.670	0.0053	-0.1126
3.00	0.784	0.0053	-0.1157
4.00	0.898	0.0054	-0.1199
5.00	1.011	0.0058	-0.1240
6.00	1.103	0.0091	-0.1234
7.00	1.181	0.0113	-0.1184
8.00	1.257	0.0124	-0.1163
8.50	1.293	0.0130	-0.1163
9.00	1.326	0.0136	-0.1160
9.50	1.356	0.0143	-0.1154
10.00	1.382	0.0150	-0.1149
10.50	1.400	0.0267	-0.1145
11.00	1.415	0.0383	-0.1143
11.50	1.425	0.0498	-0.1147
12.00	1.434	0.0613	-0.1158
12.50	1.443	0.0727	-0.1165
13.00	1.451	0.0841	-0.1153
13.50	1.453	0.0954	-0.1131
14.00	1.448	0.1065	-0.1112
14.50	1.444	0.1176	-0.1101
15.00	1.445	0.1287	-0.1103
15.50	1.447	0.1398	-0.1109
16.00	1.448	0.1509	-0.1114
16.50	1.444	0.1619	-0.1111
17.00	1.438	0.1728	-0.1097
17.50	1.439	0.1837	-0.1079
18.00	1.448	0.1947	-0.1080
18.50	1.452	0.2057	-0.1090
19.00	1.448	0.2165	-0.1086
19.50	1.438	0.2272	-0.1077
20.00	1.428	0.2379	-0.1099
21.00	1.401	0.2590	-0.1169
22.00	1.359	0.2799	-0.1190
23.00	1.300	0.3004	-0.1235
24.00	1.220	0.3204	-0.1393
25.00	1.168	0.3377	-0.1440
26.00	1.116	0.3554	-0.1486
28.00	1.015	0.3916	-0.1577
30.00	0.926	0.4294	-0.1668
32.00	0.855	0.4690	-0.1759
35.00	0.800	0.5324	-0.1897

40.00	0.804	0.6452	-0.2126
45.00	0.793	0.7573	-0.2344
50.00	0.763	0.8664	-0.2553
55.00	0.717	0.9708	-0.2751
60.00	0.656	1.0693	-0.2939
65.00	0.582	1.1606	-0.3117
70.00	0.495	1.2438	-0.3285
75.00	0.398	1.3178	-0.3444
80.00	0.291	1.3809	-0.3593
85.00	0.176	1.4304	-0.3731
90.00	0.053	1.4565	-0.3858
95.00	-0.074	1.4533	-0.3973
100.00	-0.199	1.4345	-0.4075
105.00	-0.321	1.4004	-0.4162
110.00	-0.436	1.3512	-0.4231
115.00	-0.543	1.2874	-0.4280
120.00	-0.640	1.2099	-0.4306
125.00	-0.723	1.1196	-0.4304
130.00	-0.790	1.0179	-0.4270
135.00	-0.840	0.9064	-0.4196
140.00	-0.868	0.7871	-0.4077
145.00	-0.872	0.6627	-0.3903
150.00	-0.850	0.5363	-0.3665
155.00	-0.798	0.4116	-0.3349
160.00	-0.714	0.2931	-0.2942
170.00	-0.749	0.0971	-0.3771
175.00	-0.374	0.0334	-0.1879
180.00	0.000	0.0198	0.0000

Appendix C Source Code for the Control System DLL

```
!=======================================================================
SUBROUTINE DISCON ( avrSWAP, aviFAIL, accINFILE, avcOUTNAME, avcMSG )
!DEC$ ATTRIBUTES DLLEXPORT, ALIAS:'DISCON' :: DISCON


   ! This Bladed-style DLL controller is used to implement a variable-speed
   ! generator-torque controller and PI collective blade pitch controller for
   ! the NREL Offshore 5MW baseline wind turbine.  This routine was written by
   ! J. Jonkman of NREL/NWTC for use in the IEA Annex XXIII OC3 studies.


IMPLICIT                        NONE


   ! Passed Variables:

REAL(4),    INTENT(INOUT)    :: avrSWAP   (*)                                   ! The swap array, used to pass data to, and r

INTEGER(4), INTENT(  OUT)    :: aviFAIL                                         ! A flag used to indicate the success of this

INTEGER(1), INTENT(IN   )    :: accINFILE (*)                                   ! The address of the first record of an array
INTEGER(1), INTENT(  OUT)    :: avcMSG    (*)                                   ! The address of the first record of an array
INTEGER(1), INTENT(IN   )    :: avcOUTNAME(*)                                   ! The address of the first record of an array


   ! Local Variables:

REAL(4)                      :: Alpha                                           ! Current coefficient in the recursive, singl
REAL(4)                      :: BlPitch   (3)                                   ! Current values of the blade pitch angles, r
REAL(4)                      :: ElapTime                                        ! Elapsed time since the last call to the con
REAL(4), PARAMETER           :: CornerFreq    =       1.570796                  ! Corner frequency (-3dB point) in the recurs
REAL(4)                      :: GenSpeed                                        ! Current  HSS (generator) speed, rad/s.
REAL(4), SAVE                :: GenSpeedF                                       ! Filtered HSS (generator) speed, rad/s.
REAL(4)                      :: GenTrq                                          ! Electrical generator torque, N-m.
REAL(4)                      :: GK                                              ! Current value of the gain correction factor
REAL(4)                      :: HorWindV                                        ! Horizontal hub-heigh wind speed, m/s.
REAL(4), SAVE                :: IntSpdErr                                       ! Current integral of speed error w.r.t. time
REAL(4), SAVE                :: LastGenTrq                                      ! Commanded electrical generator torque the l
REAL(4), SAVE                :: LastTime                                        ! Last time this DLL was called, sec.
REAL(4), SAVE                :: LastTimePC                                      ! Last time the pitch  controller was called,
REAL(4), SAVE                :: LastTimeVS                                      ! Last time the torque controller was called,
REAL(4), PARAMETER           :: OnePlusEps    = 1.0 + EPSILON(OnePlusEps)       ! The number slighty greater than unity in si
REAL(4), PARAMETER           :: PC_DT         =       0.00125                   ! Communication interval for pitch  controlle
REAL(4), PARAMETER           :: PC_KI         =       0.008068634               ! Integral gain for pitch controller at rated
REAL(4), PARAMETER           :: PC_KK         =       0.1099965                 ! Pitch angle were the the derivative of the
REAL(4), PARAMETER           :: PC_KP         =       0.01882681                ! Proportional gain for pitch controller at r
REAL(4), PARAMETER           :: PC_MaxPit     =       1.570796                  ! Maximum pitch setting in pitch controller,
REAL(4), PARAMETER           :: PC_MaxRat     =       0.1396263                 ! Maximum pitch  rate (in absolute value) in
REAL(4), PARAMETER           :: PC_MinPit     =       0.0                       ! Minimum pitch setting in pitch controller,
REAL(4), PARAMETER           :: PC_RefSpd     =     122.9096                    ! Desired (reference) HSS speed for pitch con
REAL(4), SAVE                :: PitCom    (3)                                   ! Commanded pitch of each blade the last time
REAL(4)                      :: PitComI                                         ! Integral term of command pitch, rad.
REAL(4)                      :: PitComP                                         ! Proportional term of command pitch, rad.
REAL(4)                      :: PitComT                                         ! Total command pitch based on the sum of the
REAL(4)                      :: PitRate   (3)                                   ! Pitch rates of each blade based on the curr
REAL(4), PARAMETER           :: R2D           =      57.295780                  ! Factor to convert radians to degrees.
REAL(4), PARAMETER           :: RPS2RPM       =       9.5492966                 ! Factor to convert radians per second to rev
REAL(4)                      :: SpdErr                                          ! Current speed error, rad/s.
REAL(4)                      :: Time                                            ! Current simulation time, sec.
REAL(4)                      :: TrqRate                                         ! Torque rate based on the current and last t
REAL(4), PARAMETER           :: VS_CtInSp     =      70.16224                   ! Transitional generator speed (HSS side) bet
REAL(4), PARAMETER           :: VS_DT         =       0.00125                   ! Communication interval for torque controlle
REAL(4), PARAMETER           :: VS_MaxRat     =   15000.0                       ! Maximum torque rate (in absolute value) in
REAL(4), PARAMETER           :: VS_MaxTq      =   47402.91                      ! Maximum generator torque in Region 3 (HSS s
REAL(4), PARAMETER           :: VS_Rgn2K      =       2.332287                  ! Generator torque constant in Region 2 (HSS
REAL(4), PARAMETER           :: VS_Rgn2Sp     =      91.21091                   ! Transitional generator speed (HSS side) bet
REAL(4), PARAMETER           :: VS_Rgn3MP     =       0.01745329                ! Minimum pitch angle at which the torque is
REAL(4), PARAMETER           :: VS_RtGnSp     =     121.6805                    ! Rated generator speed (HSS side), rad/s. --
REAL(4), PARAMETER           :: VS_RtPwr      = 5296610.0                       ! Rated generator generator power in Region 3
REAL(4), SAVE                :: VS_Slope15                                      ! Torque/speed slope of region 1 1/2 cut-in t
REAL(4), SAVE                :: VS_Slope25                                      ! Torque/speed slope of region 2 1/2 inductio
REAL(4), PARAMETER           :: VS_SlPc       =      10.0                       ! Rated generator slip percentage in Region 2
REAL(4), SAVE                :: VS_SySp                                         ! Synchronous speed of region 2 1/2 induction
REAL(4), SAVE                :: VS_TrGnSp                                       ! Transitional generator speed (HSS side) bet

INTEGER(4)                   :: I                                               ! Generic index.
INTEGER(4)                   :: iStatus                                         ! A status flag set by the simulation as foll
INTEGER(4)                   :: K                                               ! Loops through blades.
INTEGER(4)                   :: NumBl                                           ! Number of blades, (-).
```

```
INTEGER(4), PARAMETER        :: UnDb          = 85                             ! I/O unit for the debugging information

INTEGER(1)                   :: iInFile   ( 256)                               ! CHARACTER string cInFile  stored as a 1-byt
INTEGER(1)                   :: iMessage  ( 256)                               ! CHARACTER string cMessage stored as a 1-byt
INTEGER(1), SAVE             :: iOutName  (1024)                               ! CHARACTER string cOutName stored as a 1-byt

LOGICAL(1), PARAMETER        :: PC_DbgOut     = .FALSE.                        ! Flag to indicate whether to output debuggin

CHARACTER( 256)              :: cInFile                                        ! CHARACTER string giving the name of the par
CHARACTER( 256)              :: cMessage                                       ! CHARACTER string giving a message that will
CHARACTER(1024), SAVE        :: cOutName                                       ! CHARACTER string giving the simulation run
CHARACTER(   1), PARAMETER   :: Tab           = CHAR( 9 )                      ! The tab character.
CHARACTER(  25), PARAMETER   :: FmtDat    = "(F8.3,99('"//Tab//"',ES10.3E2,:))" ! The format of the debugging data


   ! Set EQUIVALENCE relationships between INTEGER(1) byte arrays and CHARACTER strings:

EQUIVALENCE (iInFile , cInFile )
EQUIVALENCE (iMessage, cMessage)
EQUIVALENCE (iOutName, cOutName)




   ! Load variables from calling program (See Appendix A of Bladed User's Guide):

iStatus      = NINT( avrSWAP( 1) )
NumBl        = NINT( avrSWAP(61) )

BlPitch  (1) =       avrSWAP( 4)
BlPitch  (2) =       avrSWAP(33)
BlPitch  (3) =       avrSWAP(34)
GenSpeed     =       avrSWAP(20)
HorWindV     =       avrSWAP(27)
Time         =       avrSWAP( 2)



   ! Initialize aviFAIL to 0:

aviFAIL      = 0



   ! Read any External Controller Parameters specified in the User Interface
   !   and initialize variables:

IF ( iStatus == 0 )  THEN  ! .TRUE. if were on the first call to the DLL


   ! Convert byte arrays to CHARACTER strings, for convenience:

   DO I = 1,MIN(  256, NINT( avrSWAP(50) ) )
      iInFile (I) = accINFILE (I)   ! Sets cInfile  by EQUIVALENCE
   ENDDO
   DO I = 1,MIN( 1024, NINT( avrSWAP(51) ) )
      iOutName(I) = avcOUTNAME(I)   ! Sets cOutName by EQUIVALENCE
   ENDDO


   ! Inform users that we are using this user-defined routine:

   aviFAIL  = 1
   cMessage = 'Running with torque and pitch control of the NREL offshore '// &
              '5MW baseline wind turbine from DISCON.dll as written by J. '// &
              'Jonkman of NREL/NWTC for use in the IEA Annex XXIII OC3 '   // &
              'studies.'


   ! Determine some torque control parameters not specified directly:

   VS_SySp    = VS_RtGnSp/( 1.0 +  0.01*VS_SlPc )
   VS_Slope15 = ( VS_Rgn2K*VS_Rgn2Sp*VS_Rgn2Sp )/( VS_Rgn2Sp - VS_CtInSp )
   VS_Slope25 = ( VS_RtPwr/VS_RtGnSp           )/( VS_RtGnSp - VS_SySp   )
   IF ( VS_Rgn2K == 0.0 )  THEN  ! .TRUE. if the Region 2 torque is flat, and thus, the denominator in the ELSE condition is
      VS_TrGnSp = VS_SySp
   ELSE                          ! .TRUE. if the Region 2 torque is quadratic with speed
      VS_TrGnSp = ( VS_Slope25 - SQRT( VS_Slope25*( VS_Slope25 - 4.0*VS_Rgn2K*VS_SySp ) ) )/( 2.0*VS_Rgn2K )
   ENDIF


   ! Check validity of input parameters:

   IF ( CornerFreq <= 0.0 )  THEN
      aviFAIL  = -1
```

```
   cMessage = 'CornerFreq must be greater than zero.'
ENDIF

IF ( VS_DT     <= 0.0 )  THEN
   aviFAIL  = -1
   cMessage = 'VS_DT must be greater than zero.'
ENDIF

IF ( VS_CtInSp <  0.0 )  THEN
   aviFAIL  = -1
   cMessage = 'VS_CtInSp must not be negative.'
ENDIF

IF ( VS_Rgn2Sp <= VS_CtInSp )  THEN
   aviFAIL  = -1
   cMessage = 'VS_Rgn2Sp must be greater than VS_CtInSp.'
ENDIF

IF ( VS_TrGnSp <  VS_Rgn2Sp )  THEN
   aviFAIL  = -1
   cMessage = 'VS_TrGnSp must not be less than VS_Rgn2Sp.'
ENDIF

IF ( VS_SlPc   <= 0.0 )  THEN
   aviFAIL  = -1
   cMessage = 'VS_SlPc must be greater than zero.'
ENDIF

IF ( VS_MaxRat <= 0.0 )  THEN
   aviFAIL  =  -1
   cMessage = 'VS_MaxRat must be greater than zero.'
ENDIF

IF ( VS_RtPwr  <  0.0 )  THEN
   aviFAIL  = -1
   cMessage = 'VS_RtPwr must not be negative.'
ENDIF

IF ( VS_Rgn2K  <  0.0 )  THEN
   aviFAIL  = -1
   cMessage = 'VS_Rgn2K must not be negative.'
ENDIF

IF ( VS_Rgn2K*VS_RtGnSp*VS_RtGnSp > VS_RtPwr/VS_RtGnSp )  THEN
   aviFAIL  = -1
   cMessage = 'VS_Rgn2K*VS_RtGnSp^2 must not be greater than VS_RtPwr/VS_RtGnSp.'
ENDIF

IF ( VS_MaxTq                     < VS_RtPwr/VS_RtGnSp )  THEN
   aviFAIL  = -1
   cMessage = 'VS_RtPwr/VS_RtGnSp must not be greater than VS_MaxTq.'
ENDIF

IF ( PC_DT     <= 0.0 )  THEN
   aviFAIL  = -1
   cMessage = 'PC_DT must be greater than zero.'
ENDIF

IF ( PC_KI     <= 0.0 )  THEN
   aviFAIL  = -1
   cMessage = 'PC_KI must be greater than zero.'
ENDIF

IF ( PC_KK     <= 0.0 )  THEN
   aviFAIL  = -1
   cMessage = 'PC_KK must be greater than zero.'
ENDIF

IF ( PC_RefSpd <= 0.0 )  THEN
   aviFAIL  = -1
   cMessage = 'PC_RefSpd must be greater than zero.'
ENDIF

IF ( PC_MaxRat <= 0.0 )  THEN
   aviFAIL  = -1
   cMessage = 'PC_MaxRat must be greater than zero.'
ENDIF

IF ( PC_MinPit >= PC_MaxPit )  THEN
   aviFAIL  = -1
   cMessage = 'PC_MinPit must be less than PC_MaxPit.'
ENDIF


! If we're debugging the pitch controller, open the debug file and write the
```

```
   !   header:

   IF ( PC_DbgOut )  THEN

      OPEN ( UnDb, FILE=TRIM( cOutName )//'.dbg', STATUS='REPLACE' )

      WRITE (UnDb,'(/////)')
      WRITE (UnDb,'(A)')  'Time '//Tab//'ElapTime'//Tab//'HorWindV'//Tab//'GenSpeed'//Tab//'GenSpeedF'//Tab//'RelSpdErr'//Tab
                          'SpdErr '//Tab//'IntSpdErr'//Tab//'GK '//Tab//'PitComP'//Tab//'PitComI'//Tab//'PitComT'//Tab//
                          'PitRate1'//Tab//'PitCom1'
      WRITE (UnDb,'(A)')  '(sec)'//Tab//'(sec)   '//Tab//'(m/sec) '//Tab//'(rpm)   '//Tab//'(rpm)    '//Tab//'(%)      '//Tab
                          '(rad/s)'//Tab//'(rad)    '//Tab//'(-)'//Tab//'(deg)  '//Tab//'(deg)  '//Tab//'(deg)  '//Tab//
                          '(deg/s) '//Tab//'(deg)  '

   ENDIF


   ! Initialize the SAVEd variables:
   ! NOTE: LastGenTrq, though SAVEd, is initialized in the torque controller
   !       below for simplicity, not here.

   GenSpeedF  = GenSpeed                        ! This will ensure that generator speed filter will use the initial value of
   PitCom     = BlPitch                         ! This will ensure that the variable speed controller picks the correct contr
   GK         = 1.0/( 1.0 + PitCom(1)/PC_KK )   ! This will ensure that the pitch angle is unchanged if the initial SpdErr is
   IntSpdErr  = PitCom(1)/( GK*PC_KI )          ! This will ensure that the pitch angle is unchanged if the initial SpdErr is

   LastTime   = Time                            ! This will ensure that generator speed filter will use the initial value of
   LastTimePC = Time - PC_DT                    ! This will ensure that the pitch  controller is called on the first pass
   LastTimeVS = Time - VS_DT                    ! This will ensure that the torque controller is called on the first pass


ENDIF



   ! Main control calculations:

IF ( ( iStatus >= 0 ) .AND. ( aviFAIL >= 0 ) )  THEN  ! Only compute control calculations if no error has occured and we are



   ! Abort if the user has not requested a pitch angle actuator (See Appendix A
   !   of Bladed User's Guide):

   IF ( NINT(avrSWAP(10)) /= 0 )  THEN ! .TRUE. if a pitch angle actuator hasn't been requested
      aviFAIL  = -1
      cMessage = 'Pitch angle actuator not requested.'
   ENDIF


   ! Set unused outputs to zero (See Appendix A of Bladed User's Guide):

   avrSWAP(36) = 0.0 ! Shaft brake status: 0=off
   avrSWAP(41) = 0.0 ! Demanded yaw actuator torque
   avrSWAP(46) = 0.0 ! Demanded pitch rate (Collective pitch)
   avrSWAP(48) = 0.0 ! Demanded nacelle yaw rate
   avrSWAP(65) = 0.0 ! Number of variables returned for logging
   avrSWAP(72) = 0.0 ! Generator startup resistance
   avrSWAP(79) = 0.0 ! Request for loads: 0=none
   avrSWAP(80) = 0.0 ! Variable slip current status
   avrSWAP(81) = 0.0 ! Variable slip current demand


!=======================================================================


   ! Filter the HSS (generator) speed measurement:
   ! NOTE: This is a very simple recursive, single-pole, low-pass filter with
   !       exponential smoothing.

   ! Update the coefficient in the recursive formula based on the elapsed time
   !   since the last call to the controller:

   Alpha     = EXP( ( LastTime - Time )*CornerFreq )


   ! Apply the filter:

   GenSpeedF = ( 1.0 - Alpha )*GenSpeed + Alpha*GenSpeedF


!=======================================================================


   ! Variable-speed torque control:
```

```
   ! Compute the elapsed time since the last call to the controller:

   ElapTime = Time - LastTimeVS


   ! Only perform the control calculations if the elapsed time is greater than
   !   or equal to the communication interval of the torque controller:
   ! NOTE: Time is scaled by OnePlusEps to ensure that the contoller is called
   !       at every time step when VS_DT = DT, even in the presence of
   !       numerical precision errors.

   IF ( ( Time*OnePlusEps - LastTimeVS ) >= VS_DT )  THEN


   ! Compute the generator torque, which depends on which region we are in:

      IF ( (   GenSpeedF >= VS_RtGnSp ) .OR. (  PitCom(1) >= VS_Rgn3MP ) )  THEN ! We are in region 3 - power is constant
         GenTrq = VS_RtPwr/GenSpeedF
      ELSEIF ( GenSpeedF <= VS_CtInSp )  THEN                                  ! We are in region 1 - torque is zero
         GenTrq = 0.0
      ELSEIF ( GenSpeedF <  VS_Rgn2Sp )  THEN                                  ! We are in region 1 1/2 - linear ramp in to
         GenTrq = VS_Slope15*( GenSpeedF - VS_CtInSp )
      ELSEIF ( GenSpeedF <  VS_TrGnSp )  THEN                                  ! We are in region 2 - optimal torque is pro
         GenTrq = VS_Rgn2K*GenSpeedF*GenSpeedF
      ELSE                                                                     ! We are in region 2 1/2 - simple induction
         GenTrq = VS_Slope25*( GenSpeedF - VS_SySp   )
      ENDIF


   ! Saturate the commanded torque using the maximum torque limit:

      GenTrq  = MIN( GenTrq                    , VS_MaxTq  )   ! Saturate the command using the maximum torque limit


   ! Saturate the commanded torque using the torque rate limit:

      IF ( iStatus == 0 )  LastGenTrq = GenTrq                 ! Initialize the value of LastGenTrq on the first pass only
      TrqRate = ( GenTrq - LastGenTrq )/ElapTime               ! Torque rate (unsaturated)
      TrqRate = MIN( MAX( TrqRate, -VS_MaxRat ), VS_MaxRat )   ! Saturate the torque rate using its maximum absolute value
      GenTrq  = LastGenTrq + TrqRate*ElapTime                  ! Saturate the command using the torque rate limit


   ! Reset the values of LastTimeVS and LastGenTrq to the current values:

      LastTimeVS = Time
      LastGenTrq = GenTrq


   ENDIF


   ! Set the generator contactor status, avrSWAP(35), to main (high speed)
   !   variable-speed generator, the torque override to yes, and command the
   !   generator torque (See Appendix A of Bladed User's Guide):

   avrSWAP(35) = 1.0          ! Generator contactor status: 1=main (high speed) variable-speed generator
   avrSWAP(56) = 0.0          ! Torque override: 0=yes
   avrSWAP(47) = LastGenTrq   ! Demanded generator torque


!=======================================================================


   ! Pitch control:

   ! Compute the elapsed time since the last call to the controller:

   ElapTime = Time - LastTimePC


   ! Only perform the control calculations if the elapsed time is greater than
   !   or equal to the communication interval of the pitch controller:
   ! NOTE: Time is scaled by OnePlusEps to ensure that the contoller is called
   !       at every time step when PC_DT = DT, even in the presence of
   !       numerical precision errors.

   IF ( ( Time*OnePlusEps - LastTimePC ) >= PC_DT )  THEN


   ! Compute the gain scheduling correction factor based on the previously
   !   commanded pitch angle for blade 1:

      GK = 1.0/( 1.0 + PitCom(1)/PC_KK )
```

```
   ! Compute the current speed error and its integral w.r.t. time; saturate the
   !   integral term using the pitch angle limits:

      SpdErr    = GenSpeedF - PC_RefSpd                                 ! Current speed error
      IntSpdErr = IntSpdErr + SpdErr*ElapTime                           ! Current integral of speed error w.r.t. time
      IntSpdErr = MIN( MAX( IntSpdErr, PC_MinPit/( GK*PC_KI ) ), &
                                       PC_MaxPit/( GK*PC_KI )      )    ! Saturate the integral term using the pitch angle li


   ! Compute the pitch commands associated with the proportional and integral
   !   gains:

      PitComP   = GK*PC_KP*   SpdErr                                    ! Proportional term
      PitComI   = GK*PC_KI*IntSpdErr                                    ! Integral term (saturated)


   ! Superimpose the individual commands to get the total pitch command;
   !   saturate the overall command using the pitch angle limits:

      PitComT   = PitComP + PitComI                                     ! Overall command (unsaturated)
      PitComT   = MIN( MAX( PitComT, PC_MinPit ), PC_MaxPit )           ! Saturate the overall command using the pitch angle


   ! Saturate the overall commanded pitch using the pitch rate limit:
   ! NOTE: Since the current pitch angle may be different for each blade
   !       (depending on the type of actuator implemented in the structural
   !       dynamics model), this pitch rate limit calculation and the
   !       resulting overall pitch angle command may be different for each
   !       blade.

      DO K = 1,NumBl ! Loop through all blades

         PitRate(K) = ( PitComT - BlPitch(K) )/ElapTime                 ! Pitch rate of blade K (unsaturated)
         PitRate(K) = MIN( MAX( PitRate(K), -PC_MaxRat ), PC_MaxRat )   ! Saturate the pitch rate of blade K using its maximu
         PitCom (K) = BlPitch(K) + PitRate(K)*ElapTime                  ! Saturate the overall command of blade K using the p

      ENDDO          ! K - all blades


   ! Reset the value of LastTimePC to the current value:

      LastTimePC = Time


   ! Output debugging information if requested:

      IF ( PC_DbgOut )  WRITE (UnDb,FmtDat)  Time, ElapTime, HorWindV, GenSpeed*RPS2RPM, GenSpeedF*RPS2RPM,           &
                                             100.0*SpdErr/PC_RefSpd, SpdErr, IntSpdErr, GK, PitComP*R2D, PitComI*R2D, &
                                             PitComT*R2D, PitRate(1)*R2D, PitCom(1)*R2D


   ENDIF


   ! Set the pitch override to yes and command the pitch demanded from the last
   !   call to the controller (See Appendix A of Bladed User's Guide):

   avrSWAP(55) = 0.0       ! Pitch override: 0=yes

   avrSWAP(42) = PitCom(1) ! Use the command angles of all blades if using individual pitch
   avrSWAP(43) = PitCom(2) ! "
   avrSWAP(44) = PitCom(3) ! "

   avrSWAP(45) = PitCom(1) ! Use the command angle of blade 1 if using collective pitch


!=======================================================================


   ! Reset the value of LastTime to the current value:

   LastTime = Time


ENDIF


   ! Convert CHARACTER string to byte array for the return message:

DO I = 1,MIN(  256, NINT( avrSWAP(49) ) )
   avcMSG(I) = iMessage(I) ! Same as cMessage by EQUIVALENCE
ENDDO
```

```
RETURN
END SUBROUTINE DISCON
!======================================================================
```

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