



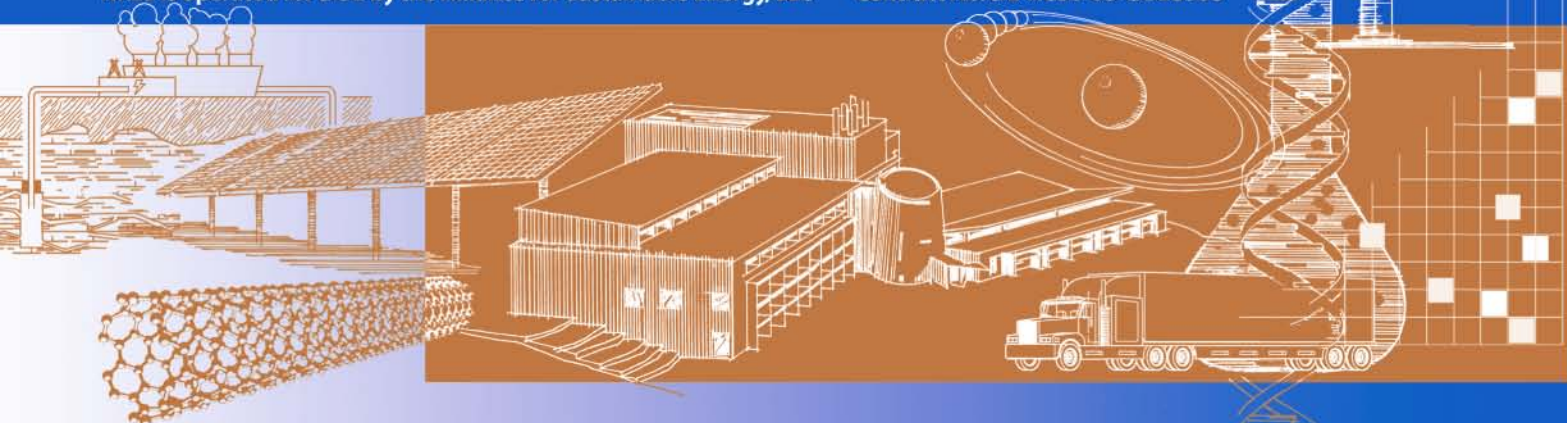
# Definition of a 5-MW Reference Wind Turbine for Offshore System Development

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

*Technical Report*  
NREL/TP-500-38060  
February 2009

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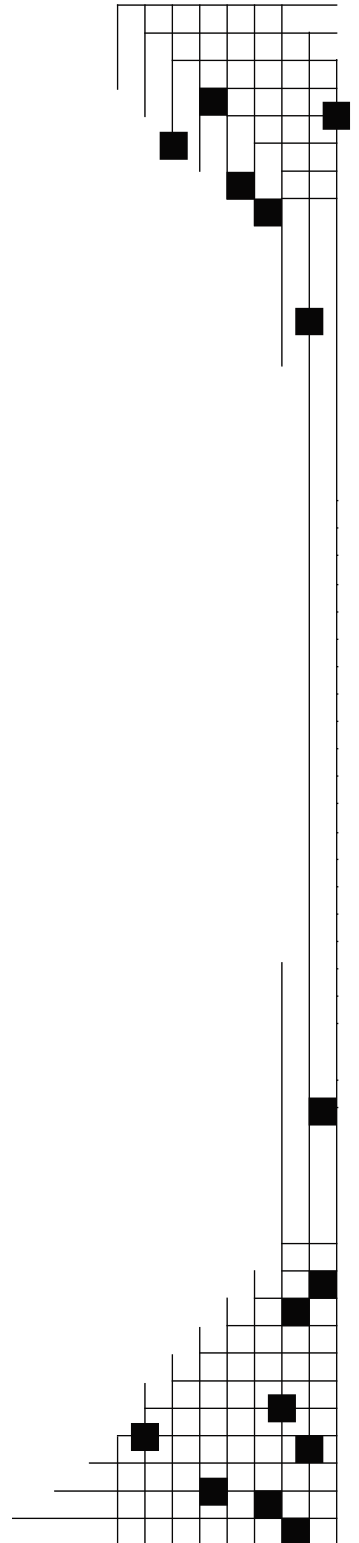


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Prepared under Task No. WER5.3301

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**National Renewable Energy Laboratory**  
1617 Cole Boulevard, Golden, Colorado 80401-3393  
303-275-3000 • [www.nrel.gov](http://www.nrel.gov)

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## Acronyms and Abbreviations

|                    |   |  |
|--------------------|---|--|
| ADAMS <sup>®</sup> | = | 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  |
| $C_\varphi$                    | = 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                                       |
| $K_\varphi$                    | = effective stiffness in the equation of motion for the rotor-speed error        |
| $M_\varphi$                    | = 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  |
| $\alpha$             | = 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   |
| $\zeta_\varphi$      | = damping ratio of the response associated with the equation of motion for the rotor-speed error                            |
| $\theta$             | = full-span rotor-collective blade-pitch angle  |
| $\theta_K$           | = rotor-collective blade-pitch angle at which the pitch sensitivity has doubled from its value at the rated operating point |
| $\pi$                | = the ratio of a circle's circumference to its diameter   |
| $\varphi$            | = 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   |
| $\Omega$             | = low-speed shaft rotational speed  |
| $\Omega_0$           | = 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].<sup>1</sup> 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.

---

<sup>1</sup> 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<sup>2</sup> 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.<sup>3</sup> 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, 5°, 2.5°                      |
| 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)            |

<sup>2</sup> 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.

<sup>3</sup> 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  $2.5^\circ$ -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  $(126 \text{ m}) \times \cos(2.5^\circ) = 125.88 \text{ m}$  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<sup>®</sup> (Automatic Dynamic Analysis of Mechanical Systems) with A2AD (ADAMS-to-AeroDyn)<sup>4</sup> [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<sup>5</sup> 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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<sup>4</sup> Note that we use the term "ADAMS" to mean "MSC.ADAMS with A2AD" in this work.

<sup>5</sup> 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<sup>6</sup> and the International Energy Agency (IEA) Wind Annex XXIII Subtask 2<sup>7</sup> 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.

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<sup>6</sup> Web site: <http://www.upwind.eu/default.aspx>

<sup>7</sup> 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). “BIFract” 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., BIFract = 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., BIFract = 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) | BIFract (0) | AeroCent (0) | StrcTwst (°) | BMassDen (kg/m) | FipStiff (Nm <sup>2</sup> ) | EdgStiff (Nm <sup>2</sup> ) | GJStiff (Nm <sup>2</sup> ) | EASStiff (N) | Alpha (°) | FipIner (kgm <sup>2</sup> ) | EdgIner (kgm <sup>2</sup> ) | PrecurRef (m) | PreswpRef (m) | FipcOf (m) | EdgecOf (m) | FipEAOI (m) | EdgeAOI (m) |
|------------|-------------|--------------|--------------|-----------------|-----------------------------|-----------------------------|----------------------------|--------------|-----------|-----------------------------|-----------------------------|---------------|---------------|------------|-------------|-------------|-------------|
| 1.50       | 0.00000     | 0.25000      | 13.308       | 678.635         | 18110.00E+6                 | 18113.60E+6                 | 5564.40E+6                 | 9729.48E+6   | 0.0       | 972.86                      | 973.04                      | 0.0           | 0.0           | 0.0        | 0.0         | 0.00017     | 0.0         |
| 1.70       | 0.00325     | 0.25000      | 13.308       | 678.635         | 18110.00E+6                 | 18113.60E+6                 | 5564.40E+6                 | 9729.48E+6   | 0.0       | 972.86                      | 973.04                      | 0.0           | 0.0           | 0.0        | 0.0         | 0.00017     | 0.0         |
| 2.70       | 0.01951     | 0.24951      | 13.308       | 773.363         | 19424.90E+6                 | 19558.80E+6                 | 5431.59E+6                 | 10789.50E+6  | 0.0       | 1091.52                     | 1066.38                     | 0.0           | 0.0           | 0.0        | 0.0         | -0.02309    | 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        | 0.0         | 0.00344     | 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        | 0.0         | 0.04345     | 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        | 0.0         | 0.05893     | 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        | 0.0         | 0.06494     | 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        | 0.0         | 0.07718     | 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        | 0.0         | 0.08394     | 0.0         |
| 9.70       | 0.13333     | 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        | 0.0         | 0.10174     | 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        | 0.0         | 0.10758     | 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        | 0.0         | 0.15829     | 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        | 0.0         | 0.22235     | 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        | 0.0         | 0.30756     | 0.0         |
| 14.70      | 0.21463     | 0.12500      | 12.192       | 381.420         | 2933.74E+6                  | 6244.53E+6                  | 448.84E+6                  | 3688.34E+6   | 0.0       | 187.11                      | 546.56                      | 0.0           | 0.0           | 0.0        | 0.0         | 0.30386     | 0.0         |
| 15.70      | 0.23089     | 0.12500      | 11.561       | 352.222         | 2568.96E+6                  | 5048.96E+6                  | 335.92E+6                  | 3147.76E+6   | 0.0       | 160.84                      | 468.71                      | 0.0           | 0.0           | 0.0        | 0.0         | 0.26519     | 0.0         |
| 16.70      | 0.24715     | 0.12500      | 11.072       | 349.477         | 2388.65E+6                  | 4948.48E+6                  | 311.35E+6                  | 3011.56E+6   | 0.0       | 148.56                      | 453.76                      | 0.0           | 0.0           | 0.0        | 0.0         | 0.25941     | 0.0         |
| 17.70      | 0.26341     | 0.12500      | 10.782       | 346.538         | 2271.99E+6                  | 4808.02E+6                  | 291.84E+6                  | 2882.62E+6   | 0.0       | 140.30                      | 436.22                      | 0.0           | 0.0           | 0.0        | 0.0         | 0.25607     | 0.0         |
| 19.70      | 0.29595     | 0.12500      | 10.232       | 339.333         | 2050.05E+6                  | 4501.40E+6                  | 261.00E+6                  | 2613.47E+6   | 0.0       | 124.61                      | 398.18                      | 0.0           | 0.0           | 0.0        | 0.0         | 0.23155     | 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        | 0.0         | 0.20382     | 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        | 0.0         | 0.19934     | 0.0         |
| 25.70      | 0.39350     | 0.12500      | 8.534        | 313.820         | 1361.93E+6                  | 3750.78E+6                  | 174.38E+6                  | 1944.09E+6   | 0.0       | 80.24                       | 308.57                      | 0.0           | 0.0           | 0.0        | 0.0         | 0.19323     | 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        | 0.0         | 0.14994     | 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        | 0.0         | 0.15421     | 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        | 0.0         | 0.13252     | 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        | 0.0         | 0.13313     | 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        | 0.0         | 0.14035     | 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        | 0.0         | 0.13950     | 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        | 0.0         | 0.15134     | 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        | 0.0         | 0.17478     | 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        | 0.0         | 0.24922     | 0.0         |
| 45.70      | 0.71870     | 0.12500      | 2.890        | 154.411         | 107.26E+6                   | 1020.16E+6                  | 18.54E+6                   | 480.01E+6    | 0.0       | 6.22                        | 85.78                       | 0.0           | 0.0           | 0.0        | 0.0         | 0.26022     | 0.0         |
| 47.70      | 0.75122     | 0.12500      | 2.503        | 139.335         | 90.88E+6                    | 797.81E+6                   | 16.28E+6                   | 375.75E+6    | 0.0       | 5.19                        | 69.96                       | 0.0           | 0.0           | 0.0        | 0.0         | 0.22554     | 0.0         |
| 49.70      | 0.78374     | 0.12500      | 2.116        | 129.555         | 76.31E+6                    | 709.61E+6                   | 14.53E+6                   | 326.89E+6    | 0.0       | 4.36                        | 61.41                       | 0.0           | 0.0           | 0.0        | 0.0         | 0.22759     | 0.0         |
| 51.70      | 0.81626     | 0.12500      | 1.730        | 107.284         | 61.05E+6                    | 518.19E+6                   | 9.07E+6                    | 244.04E+6    | 0.0       | 3.36                        | 45.44                       | 0.0           | 0.0           | 0.0        | 0.0         | 0.20600     | 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        | 0.0         | 0.21682     | 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        | 0.0         | 0.22784     | 0.0         |
| 57.70      | 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        | 0.0         | 0.23124     | 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        | 0.0         | 0.14826     | 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                        | 18.63                       | 0.0           | 0.0           | 0.0        | 0.0         | 0.15346     | 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        | 0.0         | 0.15382     | 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        | 0.0         | 0.09470     | 0.0         |
| 60.20      | 0.95447     | 0.12500      | 0.216        | 55.914          | 16.00E+6                    | 137.88E+6                   | 3.66E+6                    | 53.97E+6     | 0.0       | 0.89                        | 9.77                        | 0.0           | 0.0           | 0.0        | 0.0         | 0.09018     | 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        | 0.0         | 0.08561     | 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        | 0.0         | 0.08035     | 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        | 0.0         | 0.07096     | 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        | 0.0         | 0.05424     | 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        | 0.0         | 0.05387     | 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        | 0.0         | 0.05181     | 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—“EASStff” 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, “FlpEAOOf” and “EdgEAOOf,” 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<sup>2</sup>, 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 <sup>2</sup> |
| 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  $-0.09182^\circ$  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 ( $^\circ$ ) | 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]).<sup>8</sup> 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.

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<sup>8</sup> C. Lindenburg of the Energy Research Center of the Netherlands (ECN) provided numerical values for these coefficients.

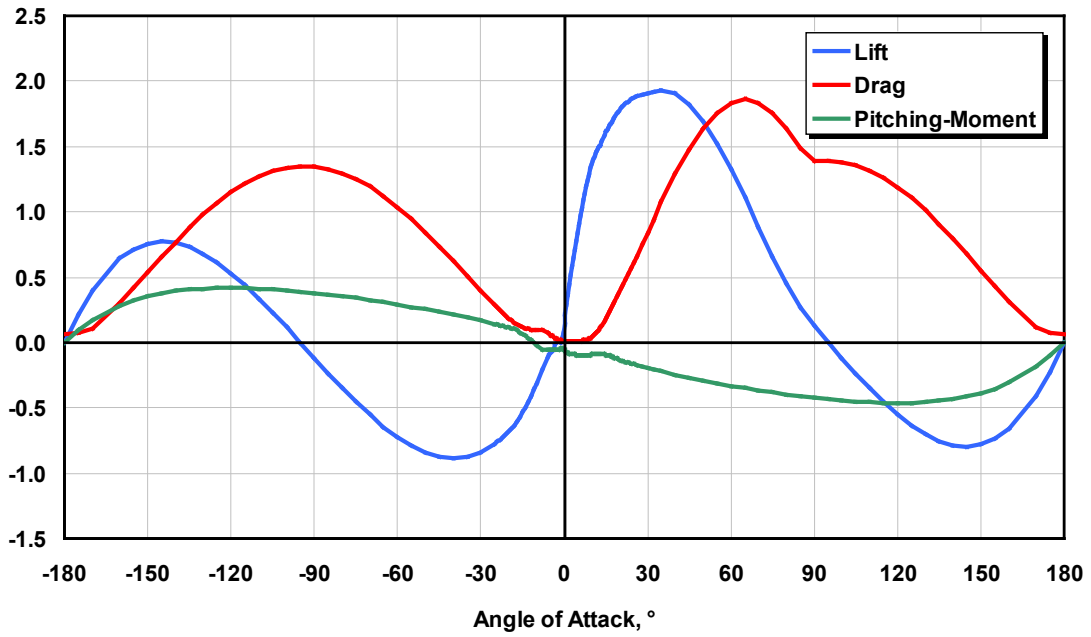


Figure 3-1. Corrected coefficients of the DU40 airfoil

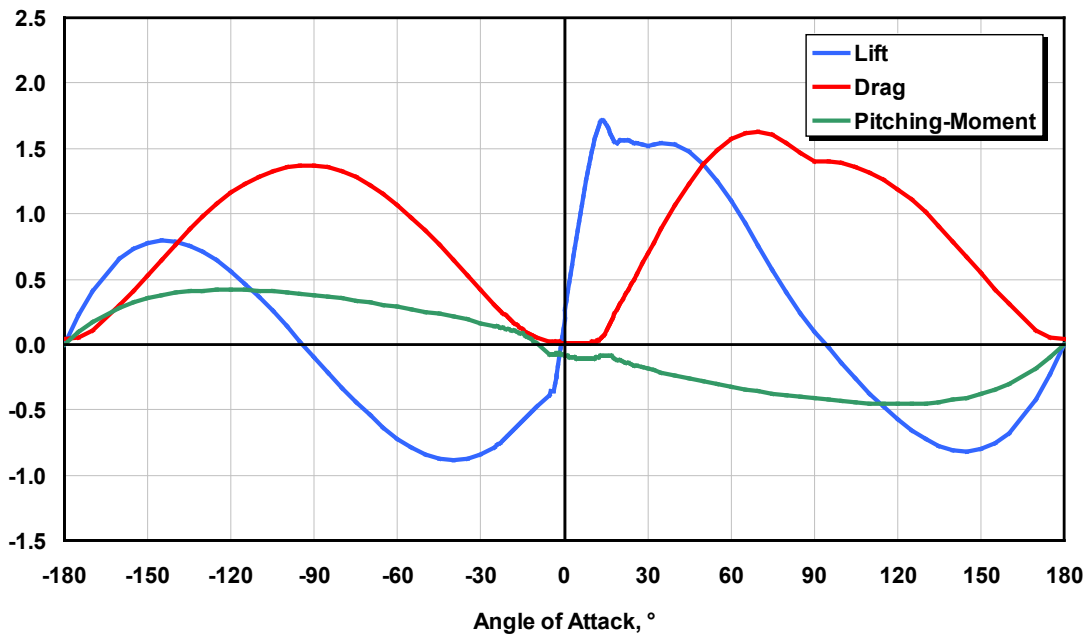


Figure 3-2. Corrected coefficients of the DU35 airfoil

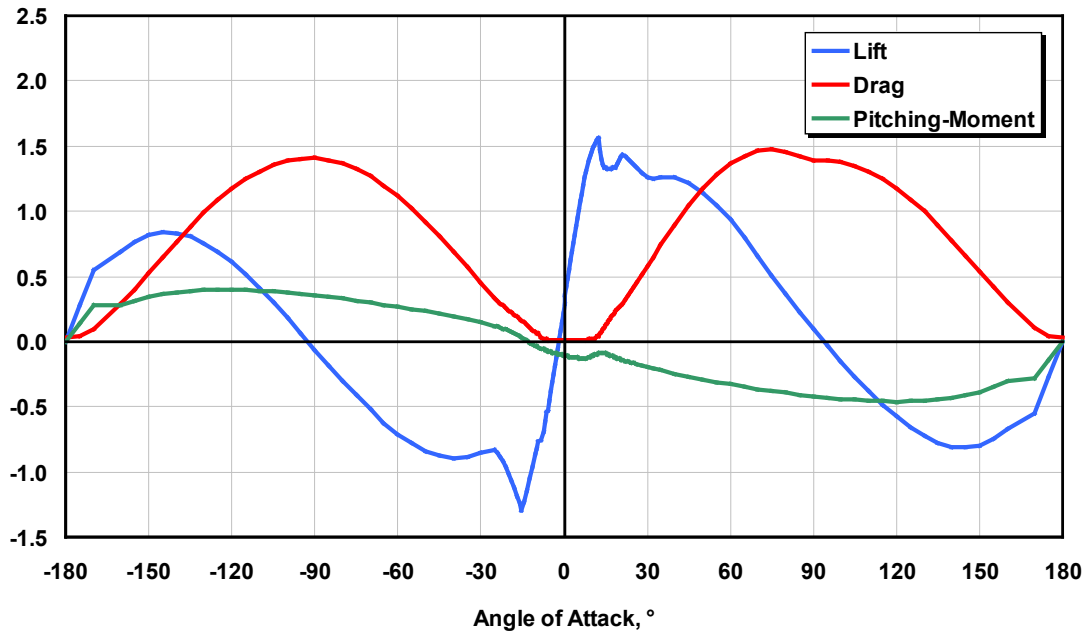


Figure 3-3. Corrected coefficients of the DU30 airfoil

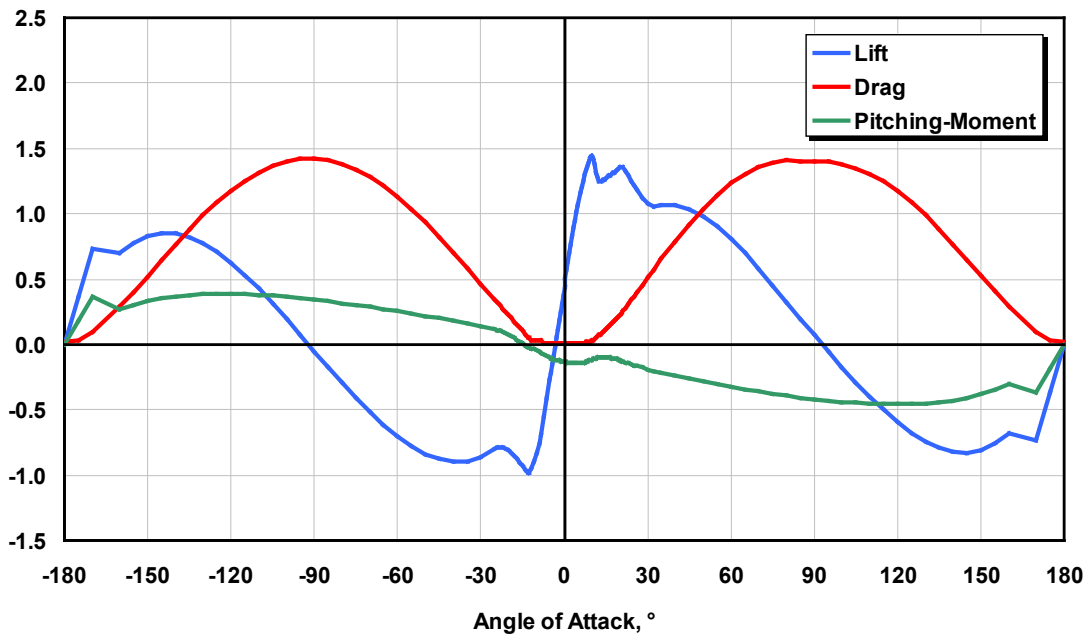


Figure 3-4. Corrected coefficients of the DU25 airfoil

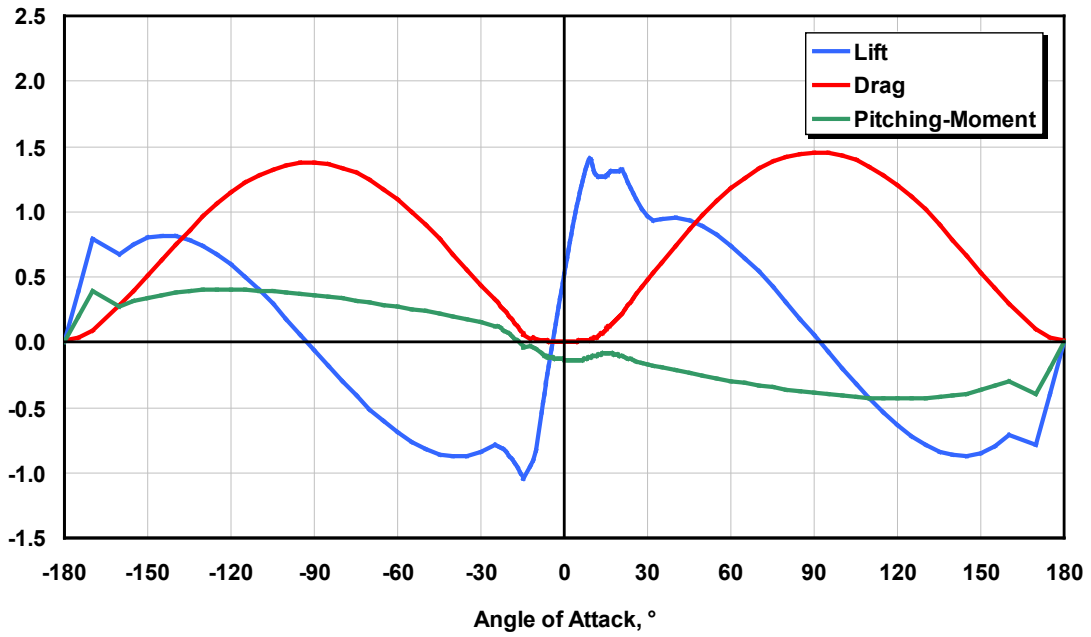


Figure 3-5. Corrected coefficients of the DU21 airfoil

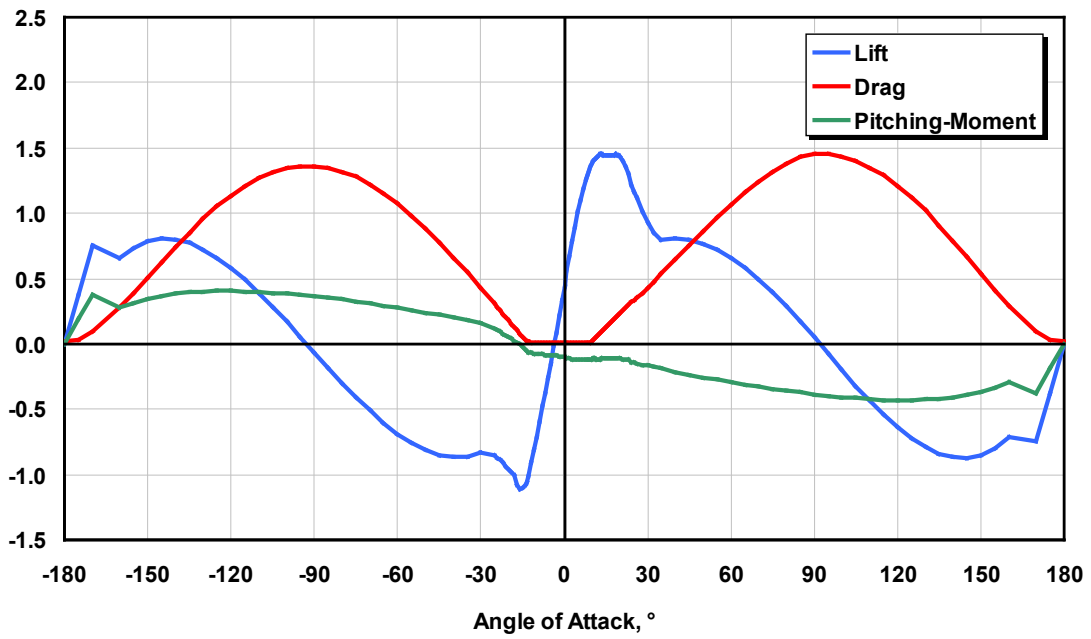


Figure 3-6. Corrected coefficients of the NACA64 airfoil

## 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  $5^\circ$ , 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  $115,926 \text{ kg}\cdot\text{m}^2$ , 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  $2,607,890 \text{ kg}\cdot\text{m}^2$ . 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  $9,028,320,000 \text{ N}\cdot\text{m}/\text{rad}$  and an equivalent nacelle-yaw-actuator linear-damping constant of  $19,160,000 \text{ N}\cdot\text{m}/(\text{rad}/\text{s})$ . The nominal nacelle-yaw rate was chosen to be the same as that for the DOWEC 6-MW turbine, or  $0.3^\circ/\text{s}$  (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 <sup>2</sup>   |
| Nacelle Mass   | 240,000 kg                  |
| Nacelle Inertia about Yaw Axis                             | 2,607,890 kg•m <sup>2</sup> |
| 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 °/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 to 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<sup>2</sup>, which is the same equivalent low-speed shaft generator inertia used in the DOWEC study (i.e., 5,025,500 kg·m<sup>2</sup> 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 <sup>2</sup> |
| 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<sup>3</sup>. The density of 8,500 kg/m<sup>3</sup> was meant to be an increase above steel’s typical value of 7,850 kg/m<sup>3</sup> 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<br>(m) | HtFract<br>(-) | TMassDen<br>(kg/m) | TwFASTif<br>(N•m <sup>2</sup> ) | TwSSStif<br>(N•m <sup>2</sup> ) | TwGJStif<br>(N•m <sup>2</sup> ) | TwEASTif<br>(N) | TwFAlner<br>(kg•m) | TwSSIner<br>(kg•m) | TwFACgOf<br>(m) | TwSScgOf<br>(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

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

with

$$\alpha = e^{-2\pi T_s f_c}, \quad (7-2)$$

where  $y$  is the filtered generator speed (output measurement),  $u$  is the unfiltered generator speed (input),  $\alpha$  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,

$$x[n] = y[n-1], \quad (7-3a)$$

or

$$x[n+1] = y[n], \quad (7-3b)$$

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

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

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

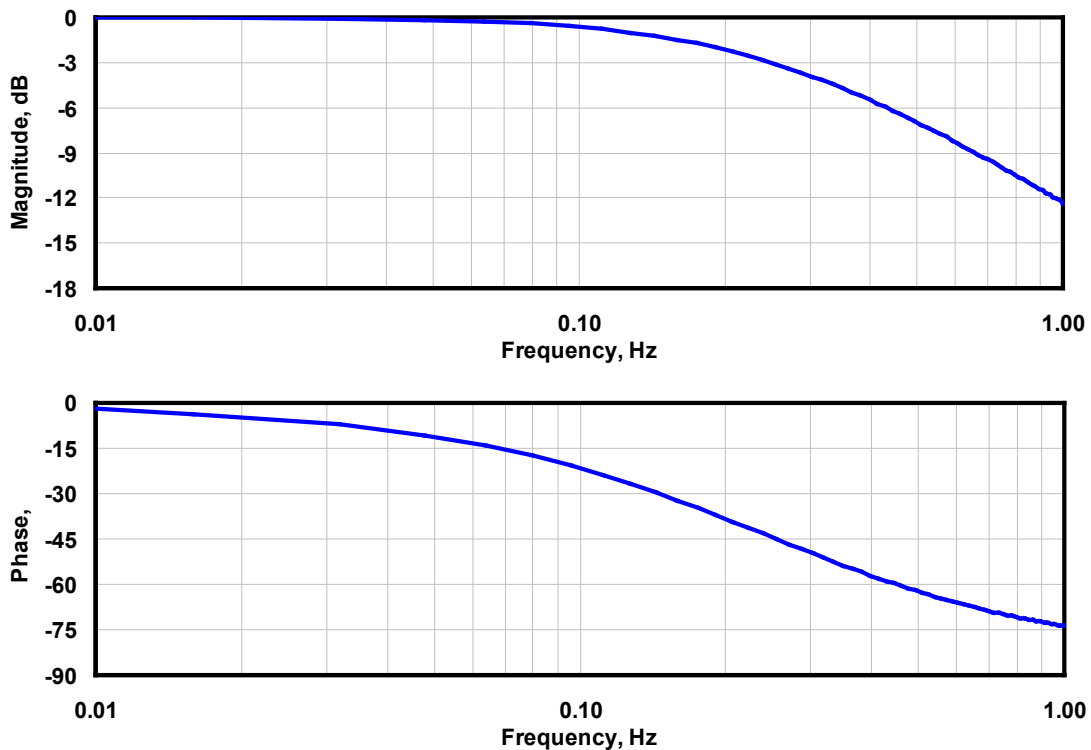


Figure 7-1. Bode plot of generator speed low-pass filter frequency response

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<sup>2</sup> 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.

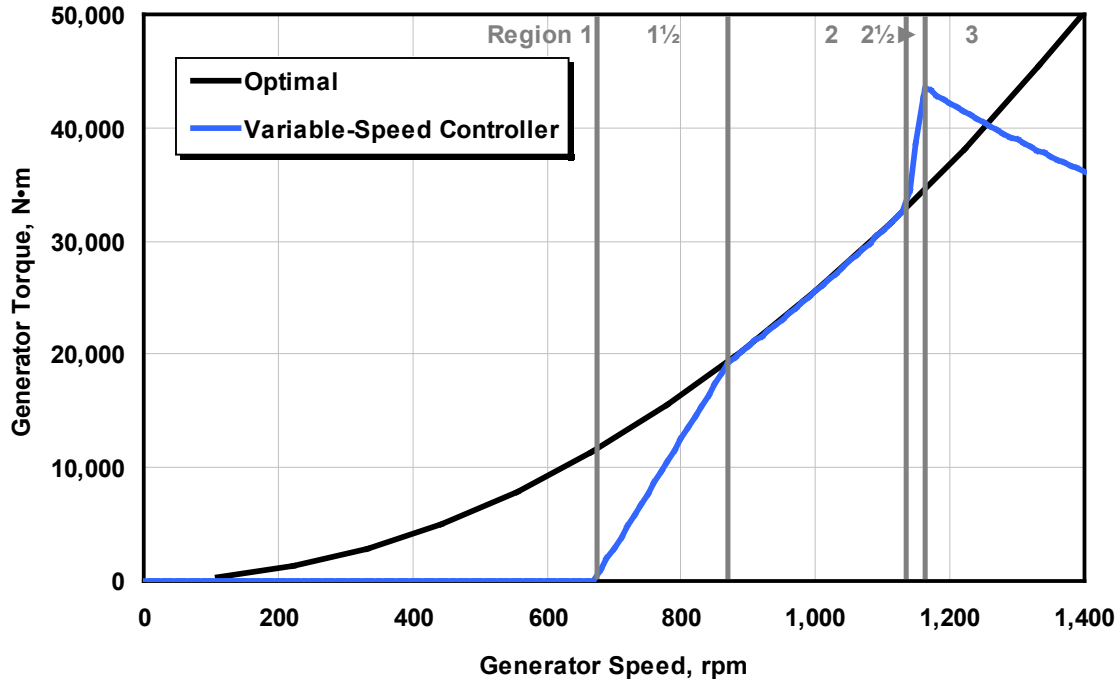


Figure 7-2. Torque-versus-speed response of the variable-speed controller

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  $1^\circ$  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

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

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,  $\Omega_0$  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

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

where  $P_0$  is the rated mechanical power and  $\Omega$  is the low-speed shaft rotational speed.

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

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

where  $P$  is the mechanical power and  $\theta$  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

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

and

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

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

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

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

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



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

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,  $\zeta_\varphi$ , equal to

$$\omega_{\varphi n} = \sqrt{\frac{K_\varphi}{M_\varphi}} \quad (7-12)$$

and

$$\zeta_\varphi = \frac{C_\varphi}{2\sqrt{K_\varphi M_\varphi}} = \frac{C_\varphi}{2M_\varphi \omega_{\varphi n}}. \quad (7-13)$$

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  $\zeta_\varphi = 0.6$  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:

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

and

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

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 ( $\Omega_0 = 12.1$  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 (°) | $\partial P/\partial\theta$ (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:

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

or

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

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

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

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.

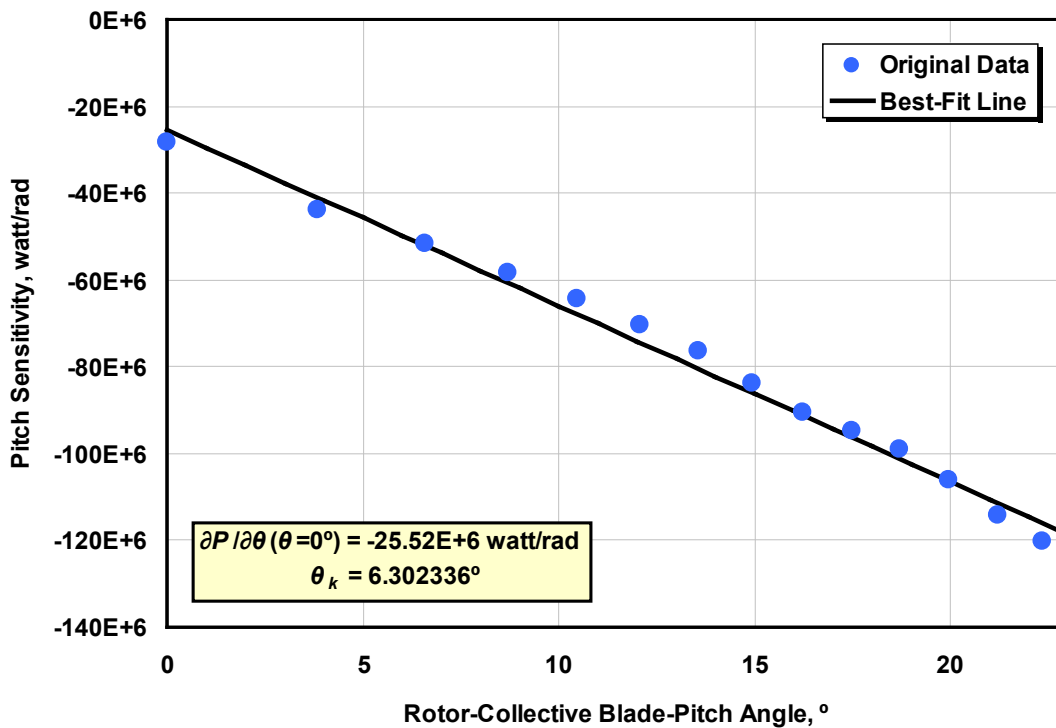


Figure 7-3. Best-fit line of pitch sensitivity in Region 3

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,

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

and

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

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

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

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  $K_D = 0.0$  s<sup>2</sup>. 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,  $\zeta_\phi = 0.7$ , 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  $\omega_{\phi n}$  and

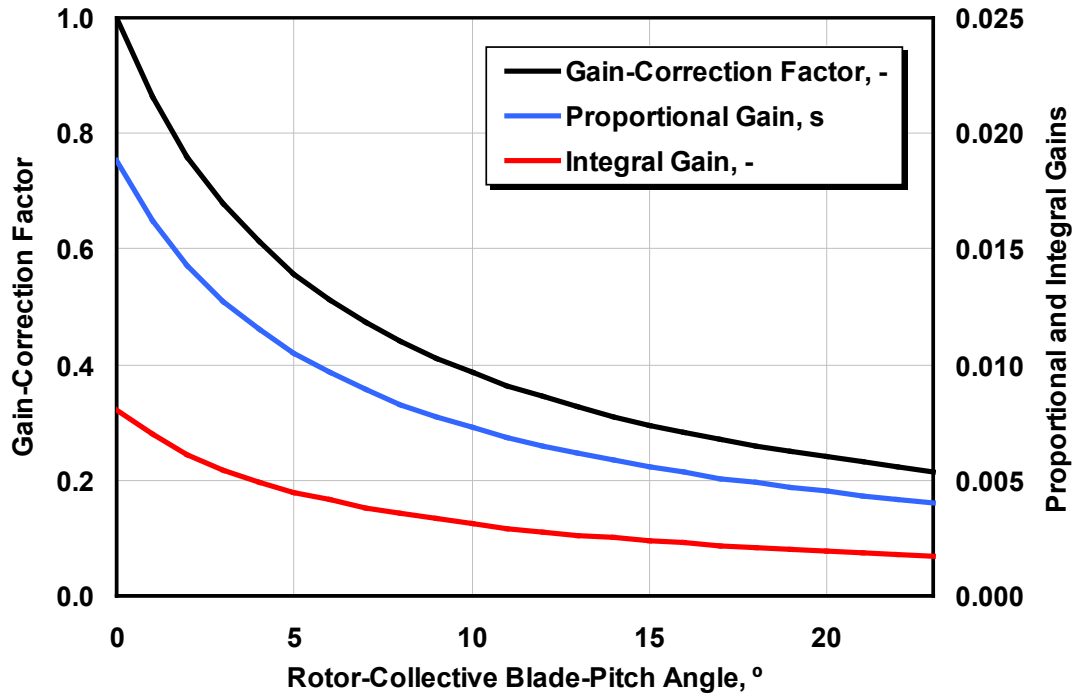


Figure 7-4. Baseline blade-pitch control system gain-scheduling law

$\zeta_\varphi$ ) 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  $8^\circ/\text{s}$  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  $0^\circ$  and  $90^\circ$ , 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.

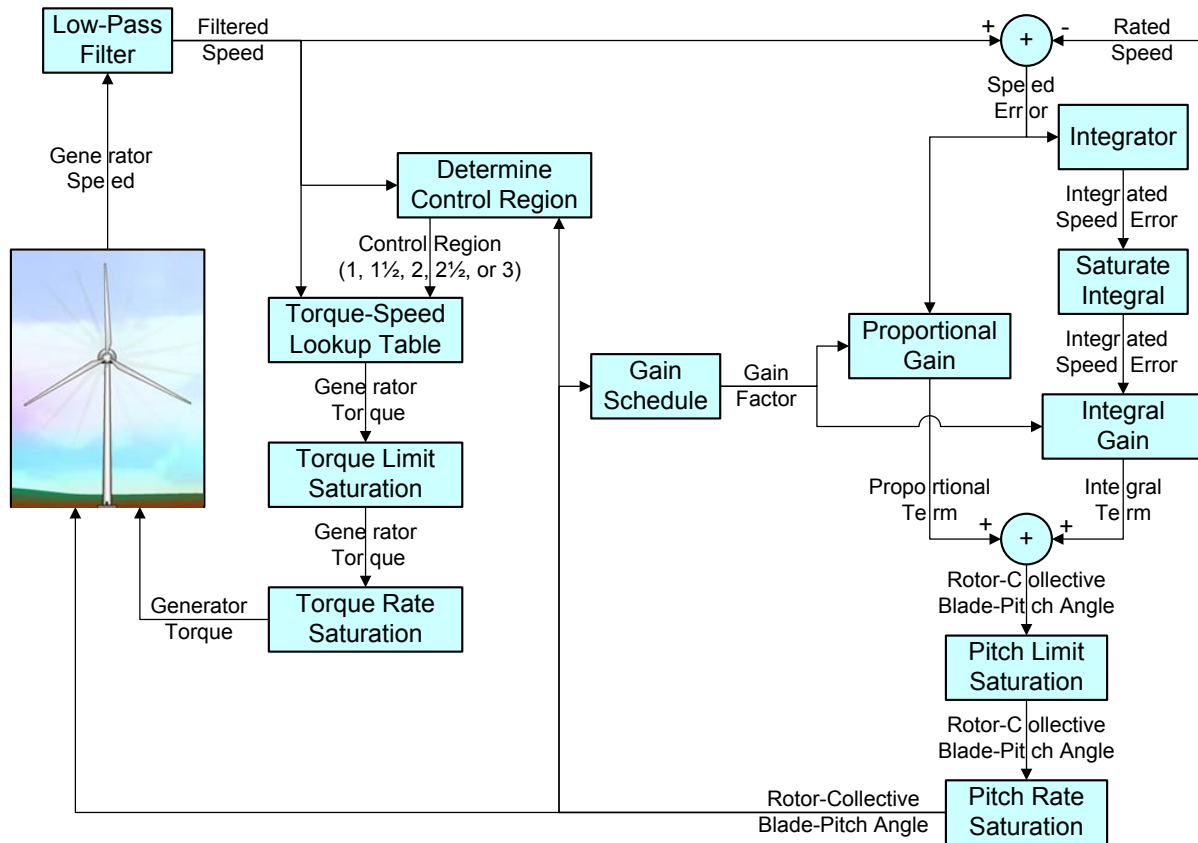


Figure 7-5. Flowchart of the baseline control system

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 °                          |
| Generator-Torque Constant in Region 2                        | 0.0255764 N•m/rpm <sup>2</sup> |
| 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 °                            |
| 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 °                     |
| Minimum Blade-Pitch Setting                                  | 0 °                            |
| Maximum Blade-Pitch Setting                                  | 90 °                           |
| Maximum Absolute Blade Pitch Rate                            | 8 °/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 ( $0^\circ$ ), 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.

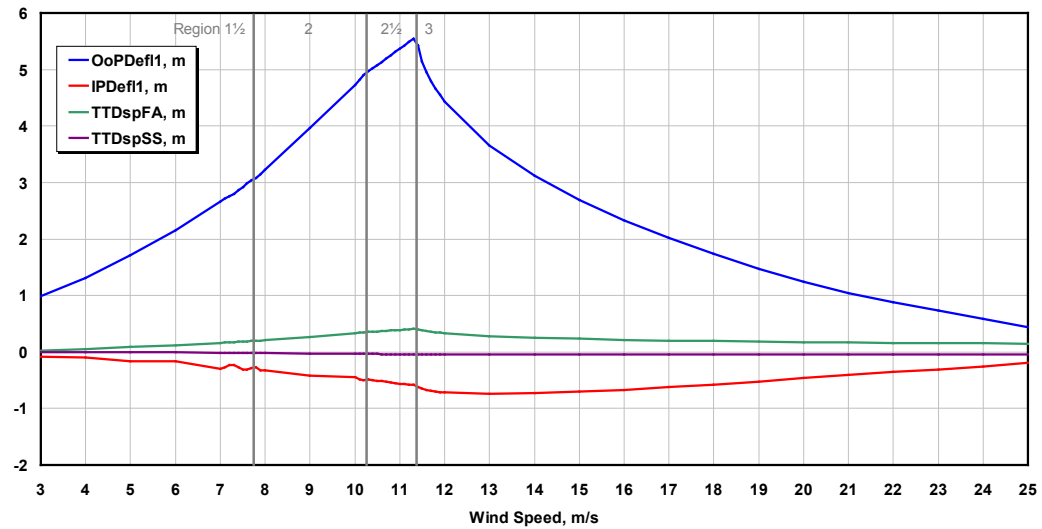
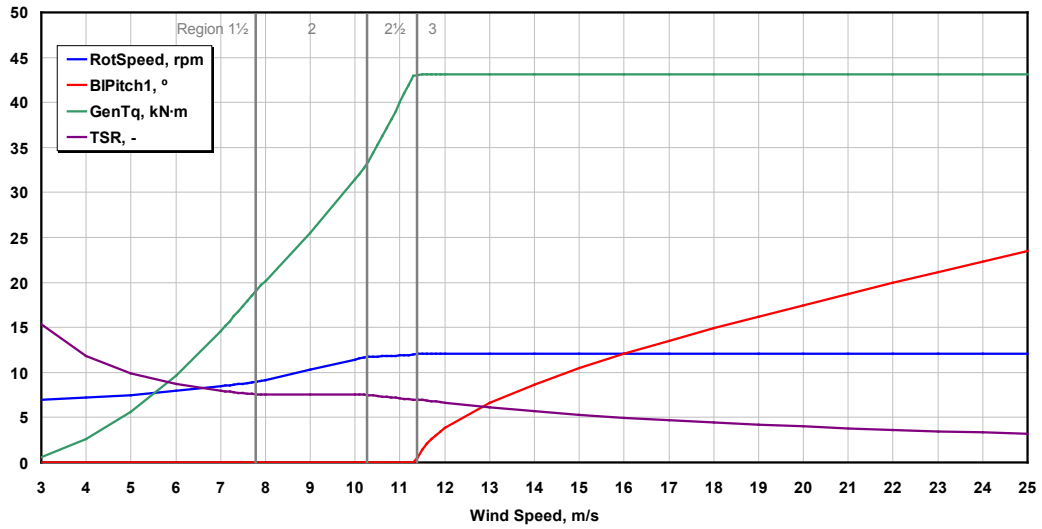
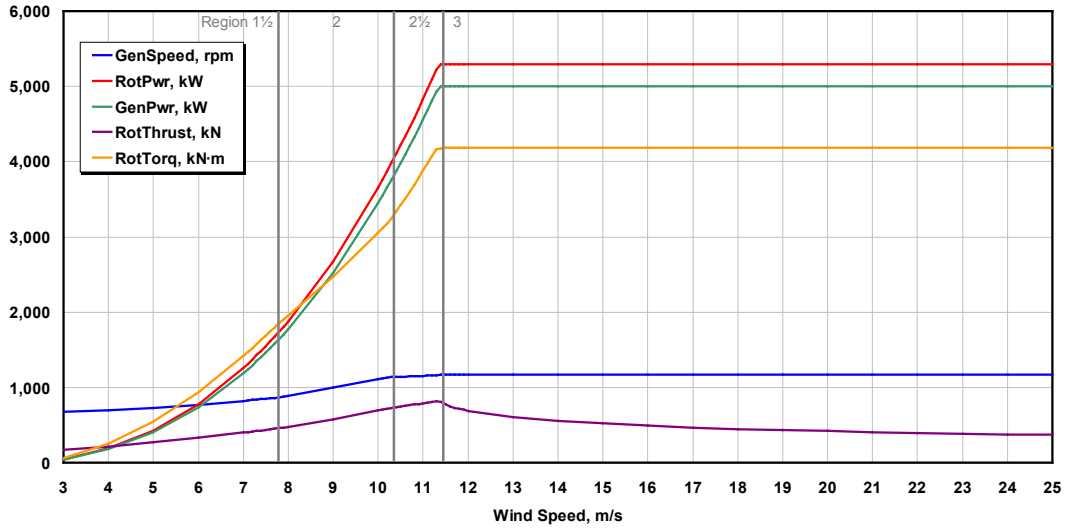


Figure 9-1. Steady-state responses as a function of wind speed

## 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     TdDynBrk  - 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)

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----- 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)
28.116E3 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_NP01 - 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=1]
0.0  TeetSStP - Rotor-teeter soft-stop position (degrees) [used only for 2 blades and when TeetMod=1]
0.0  TeetHStP - Rotor-teeter hard-stop position (degrees) [used only for 2 blades and when TeetMod=1]
0.0  TeetSSp - Rotor-teeter soft-stops 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 -----

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"NRELOffshrBslne5MW_AeroDyn.ipt"          ADFile      - Name of file containing AeroDyn input parameters (quoted strin
-----
NoiseFile      - Name of file containing aerodynamic noise input parameters (quoted string) [used only when CompNoise
-----
ADAMS
"NRELOffshrBslne5MW_ADAMSSpecific.dat"      ADAMSFile    - Name of file containing ADAMS-specific input parameters (quote
-----
LINEARIZATION CONTROL -----
"NRELOffshrBslne5MW_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
"NcIMUTAx , NcIMUTAy , NcIMUTAz"         - 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 coefficient
END of FAST input file (the word "END" must appear in the first 3 columns of this last line).
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## A.2 Blade Input File – NRELOffshrBslne5MW\_Blade.dat

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----- 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 -----

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| 1.0                                      | FlStTunnr(1) | - Blade flapwise modal stiffness tuner, 1st mode (-) |          |            |            |           |            |       |         |         |           |     |
|--|--------------|--|----------|------------|------------|-----------|------------|-------|---------|---------|-----------|-----|
| 1.0                                      | FlStTunnr(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 | FlpStfff   | EdgStfff   | GJStfff   | EASTfff    | 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 – NRELOffshrBslne5MW\_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 FASTtunnr(1) - Tower fore-aft modal stiffness tuner, 1st mode (-)
1.0 FASTtunnr(2) - Tower fore-aft modal stiffness tuner, 2nd mode (-)
1.0 SSSttunnr(1) - Tower side-to-side stiffness tuner, 1st mode (-)
1.0 SSSttunnr(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 – NRELOffshrBslne5MW\_ADAMSSpecific.dat

```

----- FAST 2 ADAMS PREPROCESSOR, ADAMS-SPECIFIC DATA FILE -----
NREL 5.0 MW offshore baseline ADAMS-specific input properties.
----- FEATURE FLAGS -----
True SaveGrphics - 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 – NRELOffshrBslne5MW\_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         Md1Order  - 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 DT Aero - 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) :: BIPitch (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 slightly greater than unity in si
REAL(4), PARAMETER :: PC_DT = 0.00125 ! Communication interval for pitch controle
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 controle
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/slope of region 1 1/2 cut-in t
REAL(4), SAVE :: VS_Slope25 ! Torque/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_S1Pc )
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_S1Pc    <= 0.0 ) THEN
    aviFAIL = -1
    cMessage = 'VS_S1Pc 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//'PitComI'
  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 occurred 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 controller 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 controller 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 )

```



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! 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 maximum
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  
!=====
```

# REPORT DOCUMENTATION PAGE

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