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

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

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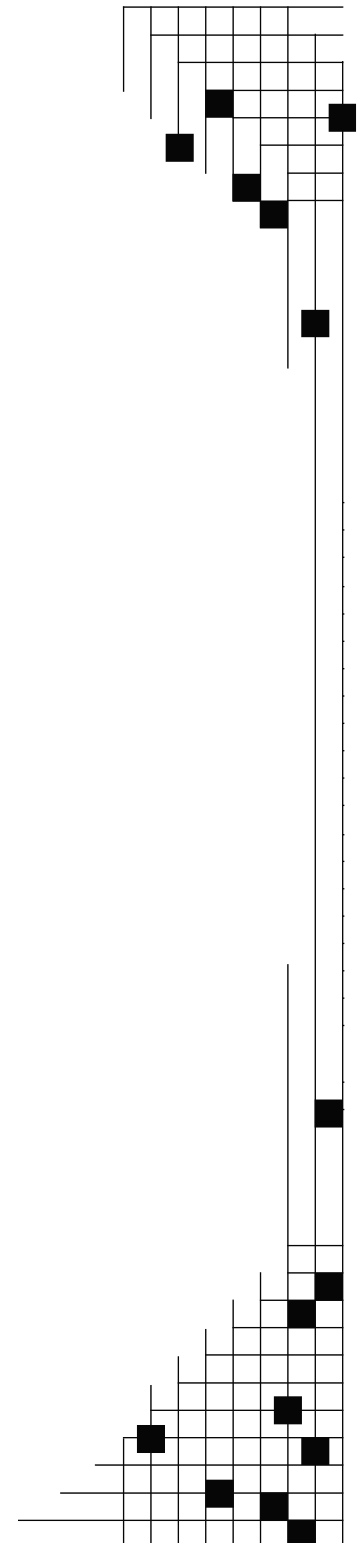
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Acronyms and Abbreviations

ADAMS$^®$ = Automatic Dynamic Analysis of Mechanical Systems
A2AD   = ADAMS-to-AeroDyn

BEM   = blade-element / momentum

CM   = center of mass

DLL   = dynamic link library
DOE   = U.S. Department of Energy
DOF   = degree of freedom
DOWEC   = Dutch Offshore Wind Energy Converter project
DU   = Delft University

ECN   = Energy Research Center of the Netherlands
equiripple = equalized-ripple

FAST   = Fatigue, Aerodynamics, Structures, and Turbulence

GE   = General Electric

IEA   = International Energy Agency

MSL   = mean sea level

NACA   = National Advisory Committee for Aeronautics
NREL   = National Renewable Energy Laboratory
NWTC   = National Wind Technology Center

OCS   = offshore continental shelf
OC3   = Offshore Code Comparison Collaborative

PI   = proportional-integral
PID   = proportional-integral-derivative

RECOFF = Recommendations for Design of Offshore Wind Turbines project

WindPACT = Wind Partnerships for Advanced Component Technology project
w.r.t. = with respect to

Nomenclature

A_d = discrete-time state matrix

B_d = discrete-time input matrix

C_d = discrete-time output state matrix

C_φ = effective damping in the equation of motion for the rotor-speed error

D_d = discrete-time input transmission matrix

f_c = corner frequency

GK = gain-correction factor

$I_{Drivetrain}$ = drivetrain inertia cast to the low-speed shaft

I_{Gen} = generator inertia relative to the high-speed shaft

I_{Rotor} = rotor inertia

K_D = blade-pitch controller derivative gain

K_I = blade-pitch controller integral gain

K_P = blade-pitch controller proportional gain

K_φ = effective stiffness in the equation of motion for the rotor-speed error

M_φ = effective inertia (mass) in the equation of motion for the rotor-speed error

n = discrete-time-step counter

N_{Gear} = high-speed to low-speed gearbox ratio

P = mechanical power

P_0 = rated mechanical power

$\partial P / \partial \theta$ = sensitivity of the aerodynamic power to the rotor-collective blade-pitch angle

t = simulation time

T_{Aero} = aerodynamic torque in the low-speed shaft

T_{Gen} = generator torque in the high-speed shaft

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

Executive Summary

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

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1 Introduction

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

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

- Feasible floater configurations for offshore wind turbines scoped out by Musial, Butterfield, and Boone [23] were based on the assumption of a 5-MW unit.

- Unpublished DOE offshore cost studies were based on a rotor diameter of 128 m, which is a size representative of a 5- to 6-MW wind turbine.

- The land-based Wind Partnerships for Advanced Component Technology (WindPACT) series of studies, considered wind turbine systems rated up to 5 MW [19,24,29].

- The Recommendations for Design of Offshore Wind Turbines project (known as RECOFF) based its conceptual design calculations on a wind turbine with a 5-MW rating [32].

- The Dutch Offshore Wind Energy Converter (DOWEC) project based its conceptual design calculations on a wind turbine with a 6-MW rating [8,14,17].

- At the time of this writing, the largest wind turbine prototypes in the world—the Multibrid M5000 [5,21,22] and the REpower 5M [18,26,27]—each had a 5-MW rating.

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

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

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

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

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

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

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 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)

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

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

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

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

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

We present other information about this model as follows:

- The blade structural properties in Section 2

- The blade aerodynamic properties in Section 3

- The hub and nacelle properties in Section 4

- The drivetrain properties in Section 5

- The tower properties in Section 6

- The baseline control system properties in Section 7

- The aero-servo-elastic FAST (Fatigue, Aerodynamics, Structures, and Turbulence) [11] with AeroDyn [16,20] and MSC.ADAMS® (Automatic Dynamic Analysis of Mechanical Systems) with A2AD (ADAMS-to-AeroDyn)[4] [6,15] and AeroDyn models of the wind turbine in Section 8

- The basic responses of the land-based version of the wind turbine, including its full-system natural frequencies and steady-state behavior in Section 9.

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

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

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

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

− 0.25) = −0.125].

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

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

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

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

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

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

Table 2-2. Undistributed Blade Structural Properties

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

3 Blade Aerodynamic Properties

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

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

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

Table 3-1. Distributed Blade Aerodynamic Properties

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

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

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[8] C. Lindenburg of the Energy Research Center of the Netherlands (ECN) provided numerical values for these coefficients.
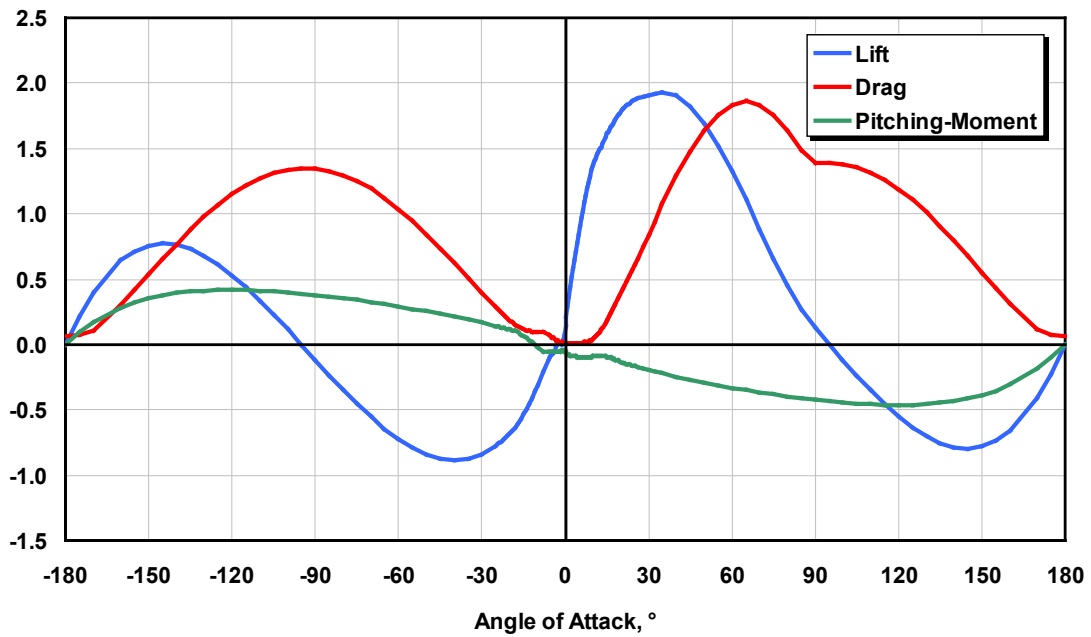
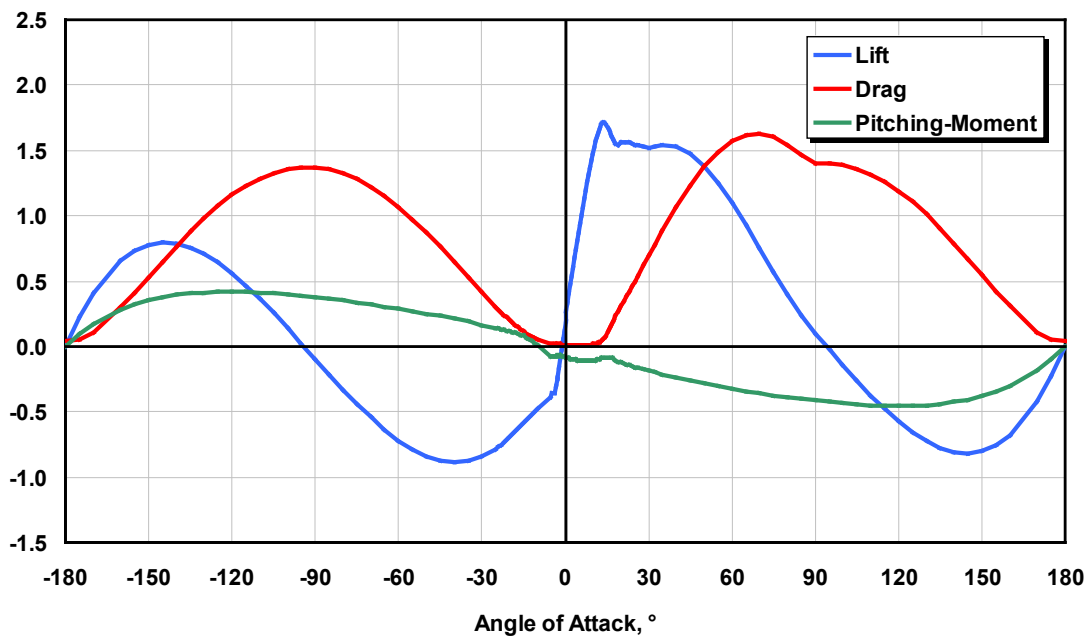**Figure 3-1. Corrected coefficients of the DU40 airfoil**

Figure 3-2. Corrected coefficients of the DU35 airfoil
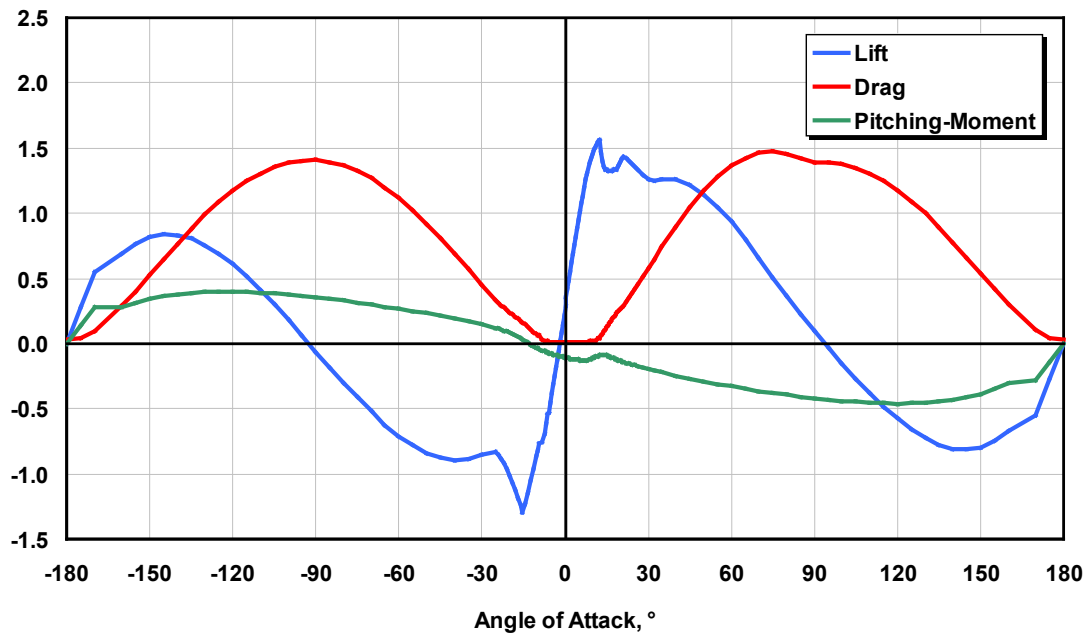
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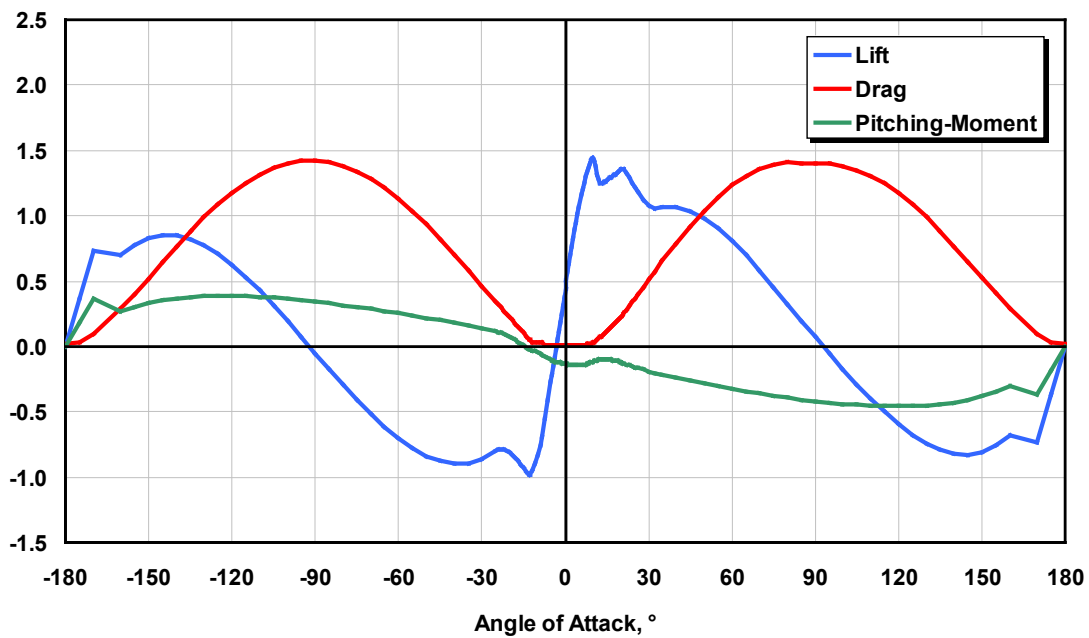**Figure 3-3. Corrected coefficients of the DU30 airfoil**

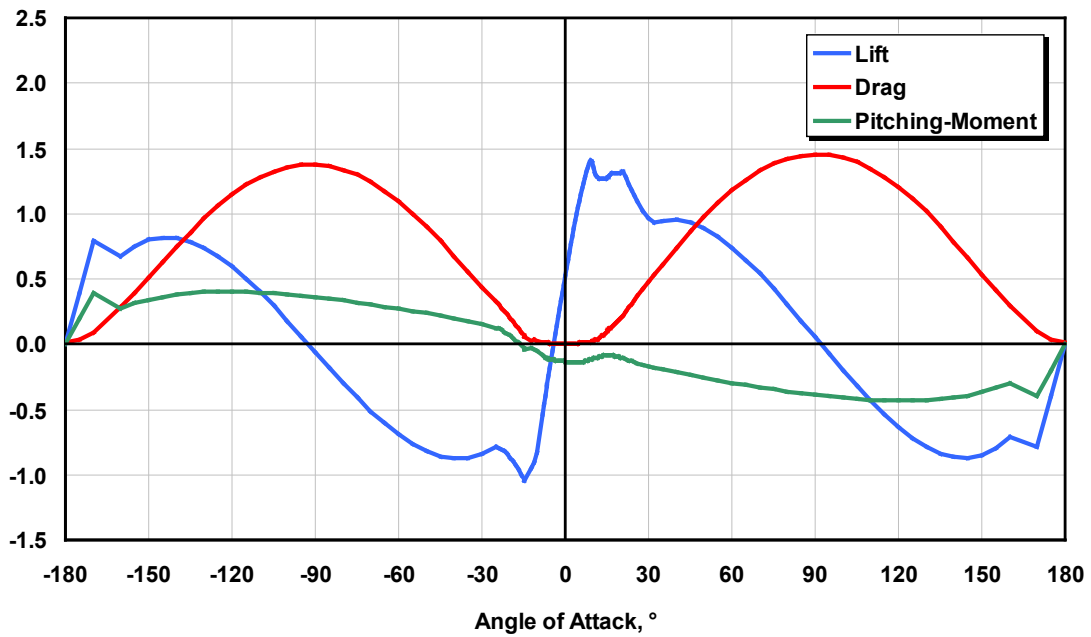**Figure 3-4. Corrected coefficients of the DU25 airfoil**

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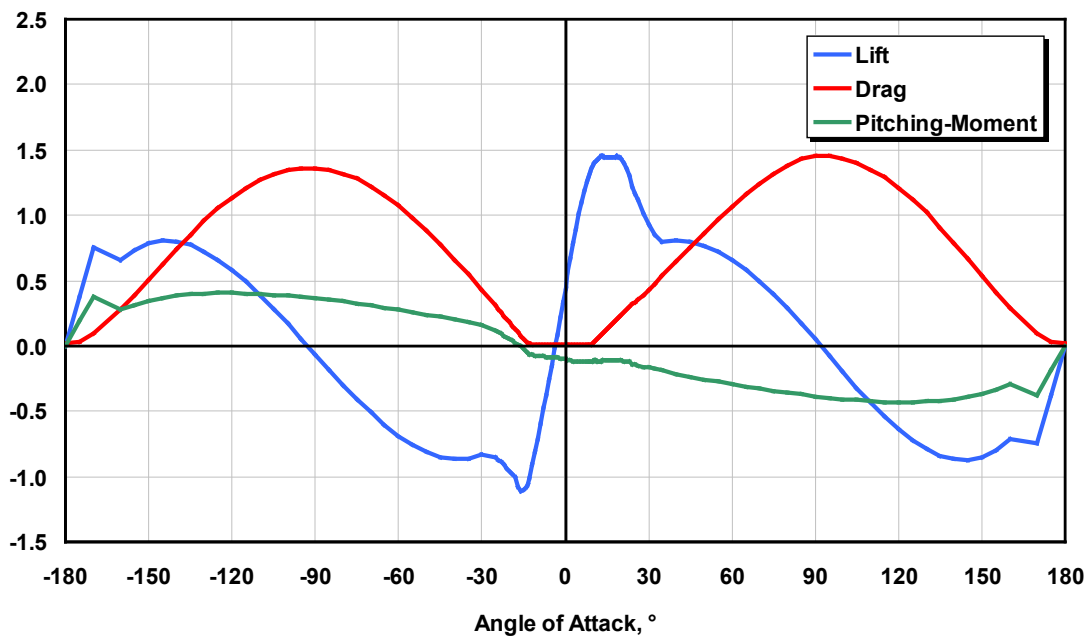**Figure 3-5. Corrected coefficients of the DU21 airfoil**

Figure 3-6. Corrected coefficients of the NACA64 airfoil

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4 Hub and Nacelle Properties

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

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

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

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

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

Table 4-1. Nacelle and Hub Properties

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

5 Drivetrain Properties

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

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

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

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

Table 5-1. Drivetrain Properties

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

6 Tower Properties

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

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

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

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

Table 6-1. Distributed Tower Properties

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