September 2004 • NREL/SR-500-32087

Subcontractor Report

Geometry and Structural Properties for the Controls Advanced Research Turbine (CART) from Model Tuning

August 25, 2003–November 30, 2003

K.A. Stol
University of Auckland
Auckland, New Zealand

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

September 2004 • NREL/SR-500-32087

Geometry and Structural Properties for the Controls Advanced Research Turbine (CART) from Model Tuning

August 25, 2003–November 30, 2003

K.A. Stol
University of Auckland
Auckland, New Zealand

NREL Technical Monitor: A. Wright

Prepared under Subcontract No. AAM-3-33231-01

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

This publication received minimal editorial review at NREL

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Summary

A complete set of structural properties for the Controls Advanced Research Turbine (CART) is presented to enable accurate computational models of the turbine to be constructed. Properties include distributed mass and stiffness data for the tower and blades, uniform beam properties for the low-speed shaft, and lumped mass properties for the nacelle and hub components. Aerodynamic data, such as airfoil tables, are not included.

The CART properties are tuned to the results from a full system modal survey and from additional test data. ADAMS models are constructed by an automatic procedure from the property set and then linearized to compare modal frequencies. The systematic tuning process is described in detail. It involves tuning modes with weak coupling in their modeshapes, first, followed by tuning modes with stronger coupling. Only modes that involved first-order bending in their modeshapes were targeted for tuning. Target modal frequencies derived from the tuned properties are within 1% of those from the modal survey.

CONTENTS

List of Tables

List of Figures

1. Introduction

The Controls Advanced Research Turbine (CART) is a modified Westinghouse WWG-0600 machine rated at 600 kW. It is located at the National Wind Technology Center (NWTC) in Boulder, Colorado (Figure 1) and was installed to test new control schemes for power and load regulation. In its original configuration, the WWG-0600 uses a synchronous generator, fluid coupling, and hydraulic collective pitch actuation. However, the CART is fitted with an induction generator, rigid coupling, and individual electromechanical pitch actuators. The rotor runs upwind of the tower and consists of two blades and a teetering hub. Further details of the CART's configuration and purpose can be found in Fingersh and Johnson [1,2].

Figure 1. The CART at the NWTC

In order to design advanced control schemes for the CART, representative computational models are essential. These models must be generated from realistic structural properties of the turbine. Because many different design codes are available, with varying degrees of complexity, the properties presented in this report are free of most modeling assumptions and thus may be interpreted universally. In particular, the flexible tower and blades are described by distributed properties, which can then be interpolated and simplified, etc., by one's chosen design code. The properties have been extracted from an existing ADAMS model and then tuned using known mass properties and a modal survey. Blade airfoil properties are not provided, because these require tuning from operational test data. Aerodynamic performance is beyond the scope of this report.

A listing of the tuned structural properties is presented in Section 2. The model tuning procedure is described in Section 3, and supporting information is in the appendices.

2. Tuned Properties

2.1 Tower

The tower is idealized as an elastic beam cantilevered to the ground. Table 1 lists the distributed properties at 13 stations, referenced from the ground-attached coordinate system, as shown in Figure 2. The first station is at x = 0.0 m (ground) and the last station is at x = 34.862 m (tower top). The mass and the mass moments of inertia, I_y and I_z, are all per unit length. Attached to the tower top on the x-axis is a concentrated mass of 1610 kg, which represents components attached to the tower that contribute insignificantly to its bending stiffness, e.g., the yaw drive bull gear.

Table 1. Tower Distributed Properties

Height, x (m)	m/L (kg/m)	I_y/L (kg.m)	I_z/L (kg.m)	GJ (N.m^2)	EA (N)	EI_y (N.m^2)	EI_z (N.m^2)
0.000	1548	3444	3444	3.06E+10	3.81E+10	8.31E+10	8.31E+10
2.294	1361	2311	2311	2.05E+10	3.33E+10	5.58E+10	5.58E+10
6.867	1428	1277	1277	1.13E+10	3.50E+10	3.09E+10	3.09E+10
9.145	1311	742	742	6.57E+09	3.20E+10	1.80E+10	1.80E+10
11.481	1311	742	742	6.57E+09	3.20E+10	1.80E+10	1.80E+10
14.986	1311	742	742	6.57E+09	3.20E+10	1.80E+10	1.80E+10
17.909	878	482	482	4.28E+09	2.11E+10	1.17E+10	1.17E+10
21.417	878	482	482	4.28E+09	2.11E+10	1.17E+10	1.17E+10
24.339	878	482	482	4.28E+09	2.11E+10	1.17E+10	1.17E+10
27.248	599	317	317	2.81E+09	1.39E+10	7.65E+09	7.65E+09
30.727	599	317	317	2.81E+09	1.39E+10	7.65E+09	7.65E+09
33.664	1311	742	742	6.57E+09	3.20E+10	1.80E+10	1.80E+10
34.862	1311	742	742	6.57E+09	3.20E+10	1.80E+10	1.80E+10

2.2 Nacelle

The nacelle is assumed to be a rigid body attached to the tower top with a fixed tilt angle of 3.77°. It is capable of yawing about the tower x-axis, with a clockwise positive yaw when viewed from above. The mass and moments of inertia for all nonrotating parts are lumped with those of the nacelle, including the bedplate, shaft bearings, gearbox housing, and generator stator. In addition, the mass and lateral moments of inertia (I_y and I_z) of the high-speed shaft and generator rotor are included. The center-of-mass is located at a distance of 0.402 m along the shaft axis upwind of the tower axis. Using the coordinate system attached to the nacelle in Figure 2, the mass properties are as follows:

Mass: 23,228 kg

Moments of inertia: $I_x = 1.01\times10^3$ kg.m^2,
$I_y = 3.659\times10^4$ kg.m^2,
$I_z = 3.659\times10^4$ kg.m^2.

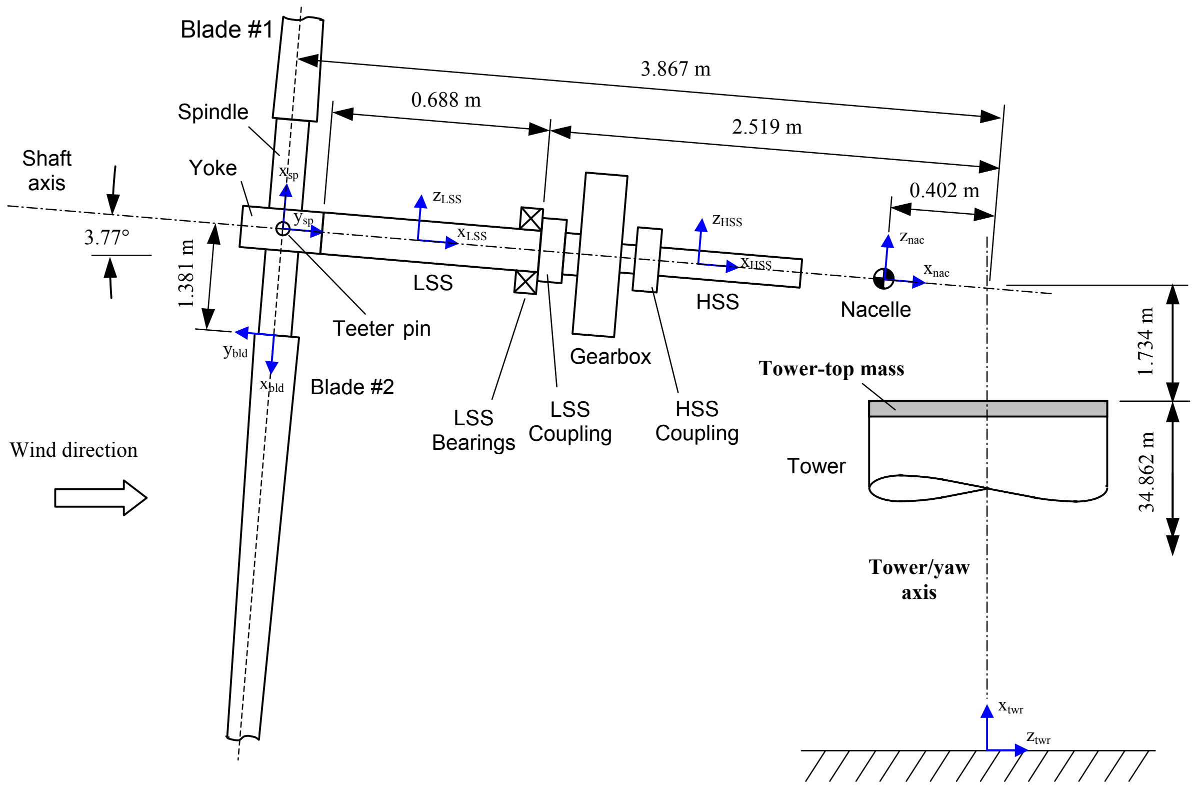

Figure 2. Turbine components and dimensions. Coordinate triads are right-handed

2.3 High-Speed Shaft

The high-speed shaft (HSS) is assumed to be a rigid body aligned with the shaft axis. Positive rotation is clockwise when viewed from upwind. The mass and lateral moments of inertia are lumped with the nacelle. The polar moment of inertia of the HSS, including rotating components in the gearbox between the shaft couplings, is given by

$$J = I_x = 34.4 \text{ kg.m}^2.$$

2.4 Gearbox

The two-stage gearbox rotates the high-speed shaft in the same direction as the low-speed shaft. The gear ratio is 43.165. The gearbox housing, shaft couplings, and low-speed shaft bearings can be treated as all coincident for modeling purposes. The gearbox housing is rigidly attached to the nacelle.

2.5 Low-Speed Shaft

The low-speed shaft (LSS) is modeled as a massless cylindrical beam of length 0.688 m, cantilevered at the shaft bearings and rigidly attached to the hub yoke. There are actually two sets of LSS bearings on the CART, but they can be modeled by one set that provides cantilever support to the LSS. The stiffness properties of the LSS are as follows:

$$EA = 1.519\times10^{10} \text{ N}$$
$$EI = 4.776\times10^{7} \text{ N.m}^2$$
$$GJ = 1.851\times10^{7} \text{ N.m}^2$$
$$GA = 5.889\times10^{9} \text{ N.}$$

2.6 Hub Yoke

The yoke comprises the nonteetering components attached to the end of the low-speed shaft. It is idealized as a mass, with no associated moments of inertia, concentrated at the teeter pin:

Yoke mass: 5885 kg.

2.7 Hub Spindle

The spindle behaves as a rigid body that teeters about a pin attached to the yoke. There is no δ_3 angle or precone. The spindle center of mass is assumed to lie on the teeter pin with a coordinate system, as shown in Figure 2. The mass properties of the spindle are as follows:

Mass:	5852 kg
Moments of inertia:	$I_x = 0$ kg.m^2,
	$I_y = 1.5\times10^4$ kg.m^2,
	$I_z = 1.5\times10^4$ kg.m^2.

2.8 Blades

Table 2 lists properties for each blade at 18 stations, referenced from the spindle end. The first station is at x = 0.0 m (blade root), and the last station is at x = 19.995 m (blade tip). The reference x-axis is the pitch axis, while the local y- and z-axes are aligned as shown in Figure 3 for each station. The z-axis always points toward the leading edge of the airfoil along the chord line, and the y-axis generally points upwind.

The cross-section center of mass is defined by the coordinates (y_{cg}, z_{cg}) and the elastic center is defined by (y_{elast}, z_{elast}), measured in the reference frame. The aerodynamic center is located along the chord line at a distance of z_{ac} from the reference x-axis. The structural twist, θ_{elast}, representing the orientation of the principal elastic axes and principal moments of inertia, is defined as positive when the leading edge is rotated into the wind. The aerodynamic twist, θ_{aero}, representing the orientation of the blade chord with respect to the plane of rotation, is defined the same way. For the CART blades, θ_{elast} is always assumed to be equal to θ_{aero}.

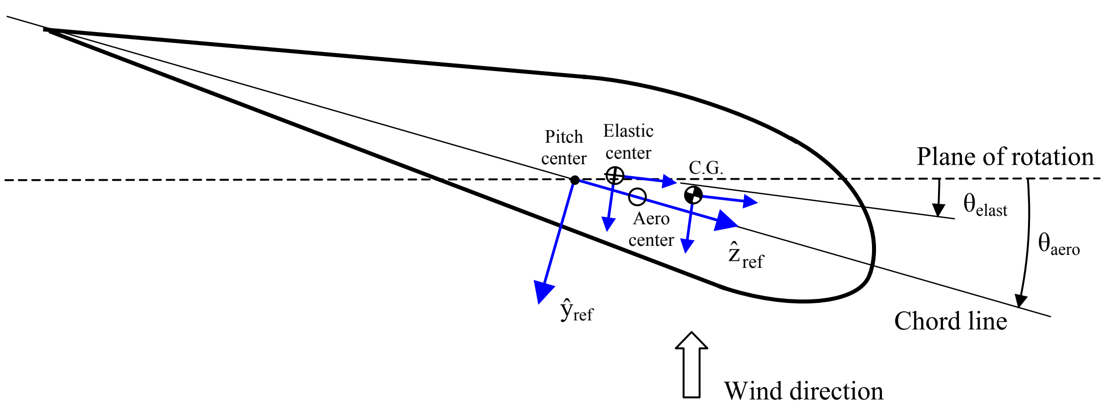

Figure 3. Blade section coordinates

Table 2. Blade Distributed Properties

Dist., x (m)	m/L (kg/m)	I_y/L (kg.m)	I_z/L (kg.m)	y_{cg} (m)	z_{cg} (m)	y_{elast} (m)	z_{elast} (m)	θ_{elast} (deg)	GJ (N.m^2)	EA (N)	EI_y (N.m^2)	EI_z (N.m^2)	chord (m)	z_{ac} (m)	θ_{aero} (deg)
0.000	282.92	29.47	12.33	0.00	-0.090	0.00	0.008	3.44	4.13E+07	4.94E+09	2.83E+08	1.65E+08	1.143	-0.020	3.44
0.448	290.24	33.11	11.97	0.00	-0.116	0.00	-0.019	3.37	4.11E+07	5.09E+09	3.18E+08	1.61E+08	1.196	-0.017	3.37
1.057	261.88	34.19	10.57	0.00	-0.156	0.00	-0.056	3.27	3.84E+07	4.57E+09	3.28E+08	1.42E+08	1.268	-0.014	3.27
2.276	201.28	31.97	7.35	0.00	-0.238	0.00	-0.131	3.08	2.86E+07	3.45E+09	3.07E+08	9.87E+07	1.411	-0.011	3.08
3.496	186.52	35.48	5.82	0.00	-0.314	0.00	-0.205	2.88	2.27E+07	3.21E+09	3.40E+08	7.84E+07	1.555	-0.008	2.88
4.715	169.1	35.67	4.41	0.00	-0.379	0.00	-0.279	2.69	1.67E+07	2.93E+09	3.42E+08	5.92E+07	1.699	-0.006	2.69
5.985	149.28	29.02	3.38	0.00	-0.370	0.00	-0.272	2.45	1.29E+07	2.59E+09	2.78E+08	4.54E+07	1.637	-0.003	2.45
7.255	133.19	24.71	2.54	0.00	-0.378	0.00	-0.265	2.21	9.74E+06	2.33E+09	2.37E+08	3.41E+07	1.575	0.000	2.21
8.525	111.74	17.58	1.86	0.00	-0.341	0.00	-0.249	1.91	7.24E+06	1.96E+09	1.69E+08	2.50E+07	1.494	0.000	1.91
9.795	96.86	14.34	1.33	0.00	-0.338	0.00	-0.234	1.61	5.29E+06	1.73E+09	1.38E+08	1.79E+07	1.412	0.000	1.61
11.065	78.57	9.81	0.92	0.00	-0.303	0.00	-0.219	1.24	3.71E+06	1.42E+09	9.40E+07	1.23E+07	1.331	0.000	1.24
12.335	65.03	7.54	0.61	0.00	-0.296	0.00	-0.204	0.86	2.53E+06	1.21E+09	7.25E+07	8.19E+06	1.250	0.000	0.86
13.605	49.68	4.87	0.38	0.00	-0.265	0.00	-0.189	0.38	1.63E+06	9.59E+08	4.67E+07	5.14E+06	1.168	0.000	0.38
14.875	37.59	3.40	0.23	0.00	-0.257	0.00	-0.174	-0.11	1.01E+06	7.74E+08	3.26E+07	3.02E+06	1.087	0.000	-0.11
16.145	25.01	1.98	0.12	0.00	-0.229	0.00	-0.159	-0.77	5.70E+05	5.79E+08	1.90E+07	1.62E+06	1.006	0.000	-0.77
17.415	16.01	1.35	0.06	0.00	-0.216	0.00	-0.144	-1.43	3.17E+05	4.53E+08	1.30E+07	8.68E+05	0.925	0.000	-1.43
18.685	10.73	0.92	0.03	0.00	-0.185	0.00	-0.129	-2.37	1.69E+05	3.98E+08	8.85E+06	4.68E+05	0.843	0.000	-2.37
19.955	6.02	0.71	0.02	0.00	-0.172	0.00	-0.114	-3.31	7.58E+04	3.53E+08	6.80E+06	2.09E+05	0.762	0.000	-3.31

3. Model Tuning

3.1 Properties before Tuning

In 1998, Global Energy Concepts, LLC (GEC), was contracted by NREL to perform a number of engineering studies on the WWG-0600 Advanced Research Turbines (ARTs). One of the key tasks assigned to GEC was to prepare an ADAMS model from drawings and component data. GEC intended to then tune the model to a modal survey, but this survey was not conducted until 2001 [3], leaving the model largely unchanged.

A draft report prepared by GEC [4] describes the data from which the ADAMS model was built. A listing of the ADAMS data set that was sent to NREL in October 2001 is provided in Appendix C. These documents were used to generate the full set of CART properties before tuning. Each major component is described next.

3.1.1 Tower

The tower is a steel tube; its section dimensions are shown in the first three columns of Table 3. These dimensions were taken directly from the GEC report. The distributed nonstructural mass data in column 4 are included as estimates for components such as the internal ladder, elevator guides, and electrical cables. Columns 5 through 10 are derived from the first four columns using standard section properties of a steel tube ($E = 2.0\times10^{11}$ N/m^2, $\nu = 0.29$, $\rho = 7870$ kg/m^3). A concentrated mass of 1610 kg with no associated inertia is located at the tower top to represent additional nonstructural mass such as the yaw drive bull gear and cables.

Table 3. Original Tower Distributed Properties

Height, x (m)	Tube inner diam. (m)	Tube wall thick. (m)	Non-struct. m/L (kg/m)	Total m/L (kg/m)	I_y/L, I_z/L (kg.m)	y_{cg}, z_{cg} offset (m)	GJ (N.m^2)	EA (N)	EI_y, EI_z (N.m^2)
0.000	4.267	0.0142	50	1548	3444	0.0	6.79E+10	3.81E+10	8.75E+10
2.294	3.734	0.0142	50	1361	2311	0.0	4.55E+10	3.33E+10	5.87E+10
6.867	2.692	0.0207	50	1428	1277	0.0	2.52E+10	3.50E+10	3.25E+10
9.145	2.134	0.0239	50	1311	742	0.0	1.46E+10	3.20E+10	1.89E+10
11.481	2.134	0.0239	50	1311	742	0.0	1.46E+10	3.20E+10	1.89E+10
14.986	2.134	0.0239	50	1311	742	0.0	1.46E+10	3.20E+10	1.89E+10
17.909	2.134	0.0157	50	878	482	0.0	9.50E+09	2.11E+10	1.23E+10
21.417	2.134	0.0157	50	878	482	0.0	9.50E+09	2.11E+10	1.23E+10
24.339	2.134	0.0157	50	878	482	0.0	9.50E+09	2.11E+10	1.23E+10
27.248	2.134	0.0104	50	599	317	0.0	6.24E+09	1.39E+10	8.05E+09
30.727	2.134	0.0104	50	599	317	0.0	6.24E+09	1.39E+10	8.05E+09
33.664	2.134	0.0239	50	1311	742	0.0	1.46E+10	3.20E+10	1.89E+10
34.862	2.134	0.0239	50	1311	742	0.0	1.46E+10	3.20E+10	1.89E+10

3.1.2 Nacelle

From the GEC ADAMS model, original PARTs (concentrated masses; see also Appendix B) for the nacelle (#2000), LSS bearings (#2500), and LSS (#3000) are combined to form a lumped nacelle body (Table 4). Note that the longitudinal moment of inertia for the LSS (I_x) is not included; it is treated separately. Center of gravity (c.g.) distances are measured horizontally from the tower axis, positive upwind. The combined c.g. of 0.401 m horizontally is equivalent to 0.402

m along the shaft axis, which is tilted by 4°. The tilt of the moments of inertia reference axes is assumed to have a negligible effect. The nacelle tilt axis of the CART has been accurately measured to be 3.77°. No tuning of the nacelle properties has been performed for this report; hence, the results of Table 4 match those described in Section 2.

Table 4. Nacelle Properties Formed from ADAMS PARTs

GEC ADAMS PART	Mass (kg)	c.g. (m)	I_x @ c.g. (kg.m^2)	I_y, I_z @ c.g. (kg.m^2)
Nacelle (#2000)	19,878	0.045	1000	1.9062×10^4
LSS bearing (#2500)	3073	2.513	10	66
LSS (#3000)	277	2.513	0	10
Combined:	23,228	0.401	1010	3.660×10^4

3.1.3 High-Speed Shaft

From the GEC ADAMS model, the polar moment of inertia of the HSS (PART #3100) is 500 kg.m^2. The HSS is assumed to be rigid.

3.1.4 Gearbox

The original gear ratio from the GEC ADAMS model is 42.857 but has been measured on the CART to be exactly 43 + 129/782 = 43.165.

3.1.5 Low-Speed Shaft

The CART uses two bearings to support the LSS housed in the pedestal, which is bolted to the nacelle bedplate. Essentially, the bearings act as simple supports for shaft bending. To simplify the model, the bearings are replaced by a single cantilever joint located midway between the original two bearings. The LSS is modeled as a cylindrical beam cantilevered at the idealized bearing location and rigidly attached to the hub yoke. This results in a LSS length of 0.688 m. In the GEC ADAMS model, the LSS beam extends to the teeter pin. Here, the yoke dimensions are accounted for. The stiffness properties listed below are calculated by assuming a diameter of 12.25 inches and solid steel construction ($E = 2.0\times10^{11}$ N/m^2, ν = 0.29). Mass properties are ignored because they can be lumped with those of other components (the nacelle, hub yoke, and spindle):

$$EA = 1.519\times10^{10}\ \text{N}$$
$$EI = 9.184\times10^{7}\ \text{N.m}^2$$
$$GJ = 7.120\times10^{7}\ \text{N.m}^2$$
$$GA = 5.889\times10^{9}\ \text{N}\ .$$

3.1.6 Hub

The hub comprises a nonteetering part attached to the shaft (the yoke) and a teetering part attached to the blades (the spindle). The yoke is assumed to be rigid, with a concentrated mass of 5885 kg located at the teeter pin on the shaft axis. This mass value is taken from the GEC ADAMS model PART #3500. Mass moments of inertia are ignored. The hub spindle is assumed to be rigid, with mass properties taken from the GEC ADAMS model by combining PARTs #4000, #4100, and #4200. This summation results in

Mass: 5852 kg
Moments of inertia: $I_x = 0$ kg.m^2,
$I_y = 2.74\times10^3$ kg.m^2,
$I_z = 2.74\times10^3$ kg.m^2 .

The x, y, and z axes for the spindle are shown in Figure 2, Section 2.

3.1.7 Blades

Blade distributed properties have been taken directly from the GEC report. The properties are listed in Table 5 and follow the coordinate convention in Figure 3, Section 2.

3.2 Tuning to Known Mass Properties

Limited field data were available from which to verify or tune the component mass properties. The blade mass and center of gravity were known, as well as the drive train and rotor inertias. All other mass properties were assumed to be correct.

3.2.1 Blade Mass and Center of Gravity

A typical blade for the CART has been weighed, and the following properties found:

$m_{desired}$ = 4650 lbs = 2113 kg
$c.g._{desired}$ = 232″ = 5.893 m from blade root.

Using an ADAMS model representation (Appendix B), we find that the original blade distributed mass data produce the following properties:

m_{orig} = 1984 kg
$c.g._{orig}$ = 6.259 m from blade root.

Because there is a difference in both total mass and center of gravity, a nonuniform scaling of mass distribution is required. A linear distribution of mass per unit length was added to the original data to match the desired properties; this distribution is given by

$$\left(\tfrac{m}{L}\right)_{add} = c_1 + c_2 x \ .$$

The constants c_1 and c_2 are found by simultaneously solving the equations for total mass and first moment of mass:

$$\begin{cases} m_{desired} = m_{orig} + \int_0^L \left(\tfrac{m}{L}\right)_{add} dx \\ m_{desired} . c_{desired} = m_{orig} . c_{orig} + \int_0^L \left(\tfrac{m}{L}\right)_{add} . x \, dx \end{cases} ,$$

resulting in c_1 = 25.47 kg/m and c_2 = -1.899 kg/m^2. The tuned mass distribution is shown in Table 6, indicating a change in mass per unit length of between +9% and -206%.

An ADAMS model (from Appendix B) of the tuned blade has the following moments of inertia:

I_x = 558 kg.m^2
$I_y = I_z = 1.55\times10^5$ kg.m^2 ,

where the reference x-axis is aligned with the pitch axis, and the y-axis is aligned with the shaft axis, pointing upwind.

Table 5. Original Blade Distributed Properties

Dist., x (m)	m/L (kg/m)	I_y/L (kg.m)	I_z/L (kg.m)	y_{cg} (m)	z_{cg} (m)	y_{elast} (m)	z_{elast} (m)	θ_{elast} (deg)	GJ ($N.m^2$)	EA (N)	EI_y ($N.m^2$)	EI_z ($N.m^2$)	chord (m)	z_{ac} (m)	θ_{aero} (deg)
0.000	257.45	29.47	12.33	0.00	-0.090	0.00	0.008	3.44	4.13E+07	4.94E+09	5.65E+08	2.36E+08	1.143	-0.020	3.44
0.448	265.62	33.11	11.97	0.00	-0.116	0.00	-0.019	3.37	4.11E+07	5.09E+09	6.35E+08	2.30E+08	1.196	-0.017	3.37
1.057	238.42	34.19	10.57	0.00	-0.156	0.00	-0.056	3.27	3.84E+07	4.57E+09	6.55E+08	2.03E+08	1.268	-0.014	3.27
2.276	180.14	31.97	7.35	0.00	-0.238	0.00	-0.131	3.08	2.86E+07	3.45E+09	6.13E+08	1.41E+08	1.411	-0.011	3.08
3.496	167.69	35.48	5.82	0.00	-0.314	0.00	-0.205	2.88	2.27E+07	3.21E+09	6.80E+08	1.12E+08	1.555	-0.008	2.88
4.715	152.59	35.67	4.41	0.00	-0.379	0.00	-0.279	2.69	1.67E+07	2.93E+09	6.84E+08	8.46E+07	1.699	-0.006	2.69
5.985	135.18	29.02	3.38	0.00	-0.370	0.00	-0.272	2.45	1.29E+07	2.59E+09	5.56E+08	6.49E+07	1.637	-0.003	2.45
7.255	121.50	24.71	2.54	0.00	-0.378	0.00	-0.265	2.21	9.74E+06	2.33E+09	4.74E+08	4.87E+07	1.575	0.000	2.21
8.525	102.46	17.58	1.86	0.00	-0.341	0.00	-0.249	1.91	7.24E+06	1.96E+09	3.37E+08	3.57E+07	1.494	0.000	1.91
9.795	89.99	14.34	1.33	0.00	-0.338	0.00	-0.234	1.61	5.29E+06	1.73E+09	2.75E+08	2.55E+07	1.412	0.000	1.61
11.065	74.11	9.81	0.92	0.00	-0.303	0.00	-0.219	1.24	3.71E+06	1.42E+09	1.88E+08	1.76E+07	1.331	0.000	1.24
12.335	62.98	7.54	0.61	0.00	-0.296	0.00	-0.204	0.86	2.53E+06	1.21E+09	1.45E+08	1.17E+07	1.250	0.000	0.86
13.605	50.04	4.87	0.38	0.00	-0.265	0.00	-0.189	0.38	1.63E+06	9.59E+08	9.34E+07	7.34E+06	1.168	0.000	0.38
14.875	40.37	3.40	0.23	0.00	-0.257	0.00	-0.174	-0.11	1.01E+06	7.74E+08	6.51E+07	4.32E+06	1.087	0.000	-0.11
16.145	30.20	1.98	0.12	0.00	-0.229	0.00	-0.159	-0.77	5.70E+05	5.79E+08	3.79E+07	2.32E+06	1.006	0.000	-0.77
17.415	23.61	1.35	0.06	0.00	-0.216	0.00	-0.144	-1.43	3.17E+05	4.53E+08	2.60E+07	1.24E+06	0.925	0.000	-1.43
18.685	20.74	0.92	0.03	0.00	-0.185	0.00	-0.129	-2.37	1.69E+05	3.98E+08	1.77E+07	6.69E+05	0.843	0.000	-2.37
19.955	18.44	0.71	0.02	0.00	-0.172	0.00	-0.114	-3.31	7.58E+04	3.53E+08	1.36E+07	2.98E+05	0.762	0.000	-3.31

Table 6. Blade Mass Distribution before and after Tuning

Dist., x (m)	Original m/L (kg/m)	Tuned m/L (kg/m)
0.000	257.45	282.92
0.448	265.62	290.24
1.057	238.42	261.88
2.276	180.14	201.28
3.496	167.69	186.52
4.715	152.59	169.1
5.985	135.18	149.28
7.255	121.50	133.19
8.525	102.46	111.74
9.795	89.99	96.86
11.065	74.11	78.57
12.335	62.98	65.03
13.605	50.04	49.68
14.875	40.37	37.59
16.145	30.20	25.01
17.415	23.61	16.01
18.685	20.74	10.73
19.955	18.44	6.02

3.2.2 Drive Train and Rotor Inertias

Based on experimental data from the CART that were taken during an emergency stop and motoring exercise, the drive train and rotor polar moments of inertia have been calculated. Details of these calculations can be found in Appendix A. The results are as follows:

Moment of inertia of generator, HSS, and gearbox shafts = 34.4 $kg.m^2$ (in HSS frame)
Moment of inertia of rotor and LSS = 3.25×10^5 $kg.m^2$ (in LSS frame).

For the CART properties listed in Section 3.1, the HSS component includes the polar inertia of the generator and gearbox. Tuning from an original value of 500 $kg.m^2$ to 34.4 $kg.m^2$ is a -93% change. The polar moment of inertia of the rotor includes the inertia of the two blades (3.10×10^5 $kg.m^2$ about the shaft axis, from Section 3.2.1), the hub yoke, and the hub spindle. Assuming the LSS and hub yoke have zero moments of inertia, then the hub spindle moment of inertia about the shaft axis is 1.5×10^4 $kg.m^2$ (3.25×10^5 - 3.10×10^5). This is a +447% change from the original value of 2.74×10^3 $kg.m^2$.

3.3 Tuning to Modal Survey

In August 2001, a full system modal survey of the CART was conducted at the National Wind Technology Center [3]. Two tests were performed. One test was conducted with the rotor blades in a horizontal azimuth position and in the second test, the blades were in a vertical position. In both cases, the drive train was parked via a brake on the HSS and the teeter and yaw brakes were engaged. Modal frequencies were collected over a bandwidth of 0 to 6.25 Hz with an uncertainty of ±0.004 Hz. The results of the survey are reproduced in Tables 7 and 8. The modal survey report [3] mentions that an anticipated drive train torsion mode was not found due to high measurement noise. Additional test data (in Appendix A) reveals that the first drive train torsion frequency is at 1.38 Hz.

Table 7. Results from the Modal Survey, Blades Vertical

Mode Number	Freq. (Hz)	Modeshape Description
1	0.858	1st tower fore-aft bending
2	0.877	1st tower lateral bending
3	1.58	1st flap asymmetric bending + shaft bending
4	2.06	1st flap symmetric
5	3.94	1st lag sym. + 2nd flap asym. + tower torsion
6	4.09	2nd flap asym. + 1st lag sym. + shaft bending
7	5.05	1st lag sym. + 2nd flap asym. + twr lateral bending + twr torsion + shaft bending
8	5.35	2nd flap sym. + 1st lag asym.
9	5.77	2nd tower lateral + 1st lag sym.
10	6.17	2nd flap asym. + 2nd tower fore-aft

Table 8. Results from the Modal Survey, Blades Horizontal

Mode Number	Freq. (Hz)	Modeshape Description
1	0.867	1st tower lateral bending
2	0.870	1st tower fore-aft bending
3	1.45	1st flap asym. + 1st lag sym.+ tower lateral + tower torsion
4	2.06	1st flap sym. + 1st lag asym.
5	3.90	2nd flap asym. + 1st lag sym.+ shaft bending
6	4.02	1st lag sym. + 2nd flap asym.+ shaft bending + tower torsion
7	5.39	2nd flap sym. + 1st lag asym.
8	5.67	1st lag sym. + 2nd flap asym. + shaft bending + 3rd tower fore-aft
9	6.01	2nd flap asym. + 1st lag asym. + shaft bending + 2nd tower lateral + tower torsion

In order to tune the original CART properties to match results of the modal survey, ADAMS models are constructed. The ADAMS code was chosen because it is capable of representing distributed parameter systems, such as nonuniform beams. ADAMS can also linearize nonrotating models to find their modal properties. The effect of aerodynamic damping is not included.

The procedure used to build the CART tower and blade components in ADAMS is detailed in Appendix B. Basically, the tower and blades are each discretized by 10 lumped masses (PARTs) connected by stiffness elements (FIELDs). The only other component that is assumed flexible on the CART is the low-speed shaft. This is modeled in ADAMS by a single stiffness element. To automatically generate the ADAMS input files (datasets), MATLAB script code was written. An example data set produced by this code is listed in Appendix D.

Model tuning is performed by uniformly scaling the stiffness properties of the tower, low-speed shaft, and blades to influence first mode bending or torsion of these components. A nonuniform scaling of stiffness would be required to affect second or higher mode bending. Therefore, the goal is to match only mode numbers 1, 2, 3, 4, 5, and 7 in Table 7 for the vertical blades case. Modal properties for the horizontal blades case will be verified at the end of the tuning procedure, when we will want to match mode numbers 1, 2, 3, and 4 in Table 8.

Matching modal data is generally a difficult task because components in the system may be strongly coupled, so that tuning the properties of one component alone may affect all the structural modes. Fortunately, the CART has a relatively stiff tower in comparison to the stiffness of the blades, which results in weak tower-blade coupling at low frequencies. This allows us to tune to the modal survey in a systematic way, beginning with modes that have weak component coupling and progressing to more strongly coupled modes.

We begin with an analysis of the original CART properties (Model #1) and build a new ADAMS model as each property is tuned. A total of eight models are analyzed. The natural frequencies of each model are listed in Table 9. Deviations of frequency from the modal survey are given as a percentage error. Note that the first drive train torsion mode is included (mode #3) even though it is not part of the original modal survey. The mode numbers are adjusted and no longer match those of Table 7.

The frequencies obtained from Model #1 are clearly very different from those of the modal survey. Only the first tower bending modes (#1 and #2) are within 10% of the target values.

3.3.1 Model #2: Tuned Blade Flap Stiffness

The first symmetric flap mode (#5) involves out-of-plane blade bending with a negligible amount of tower fore-aft motion. Since blade flap motion is isolated in this mode, we can use it to tune blade flap stiffness (EI_z). The frequency error in mode #5 is +19%. For simple harmonic motion, frequency scales with the inverse square-root of stiffness. Therefore, an initial guess for a uniform EI_z scaling factor is $1/(1+0.19)^2 = 0.7$. As shown in Table 9 for Model #2, the resulting mode #5 frequency error is 0%.

3.3.2 Model #3: Tuned Shaft Bending Stiffness

Mode #4 couples first asymmetric flap motion with low-speed shaft bending. Since blade flap stiffness has already been tuned, we can use mode #4 to tune the shaft bending stiffness (EI). Beginning with a frequency error of +12%, an initial guess for an EI scaling factor is $1/(1+0.12)^2 = 0.8$. The resulting mode #4 frequency error is +8% (not shown in Table 9). Our initial guess is not very accurate because we are dealing with a mode that has coupled motion, which is not well represented by a simple harmonic motion model. Trial and error produces a suitable EI scaling factor of 0.45. As shown in Table 9 for Model #3, the resulting mode #4 frequency error is 0%.

3.3.3 Model #4: Tuned Blade Lag Stiffness

The modeshape for mode #6 is predominantly first symmetric blade lag motion, so we can use this mode to tune blade lag stiffness (EI_z). Using an initial frequency error of +40% and some trial and error, we find that a suitable EI_z scale factor is 0.45. This results in a 0% frequency error in mode #6 for Model #4.

3.3.4 Model #5: Tuned Tower Bending Stiffness

Tower bending motion is a component of many modeshapes in the modal survey, but it is most dominant in modes #1 and #2. While it is possible to tune the tower fore-aft and lateral stiffnesses independently, doing so would disagree with the known axisymmetric structure of the tower. Instead, it is best to scale the common bending stiffness ($EI = EI_y = EI_z$) in order to best match the frequencies of modes #1 and #2. With an initial frequency error of 3% for mode #1, a suitable EI scale factor is $1/(1+0.03)^2 = 0.94$. This results in a +1% error in mode #1 and a -1% error in mode #2, as shown in Table 9. Generally, a difference in the fore-aft and lateral tower natural frequencies is caused by the unequal moments of inertia of the head mass (all components atop the tower) in the fore-aft and lateral directions. Because we cannot match both tower frequencies by changing tower stiffness, it is likely that one or more CART model mass properties are incorrect. However, a ±1% discrepancy in frequency is acceptable.

Table 9. Comparison of Modal Data from the ADAMS Models with the Modal Survey, Blades Vertical

	Modeshape Description	Modal Survey	ADAMS Model															
			#1 (Orig.)		#2		#3		#4		#5		#6		#7		#8 (Final)	
		Hz	Hz	%	Hz	%	Hz	%	Hz	%	Hz	%	Hz	%	Hz	%	Hz	%
1	1st tower fore-aft bending	0.858	0.891	*+4*	0.889	*+4*	0.888	*+3*	0.888	*+3*	0.866	*+1*	0.866	*+1*	0.866	*+1*	0.866	*+1*
2	1st tower lateral bending	0.877	0.894	*+2*	0.894	*+2*	0.893	*+2*	0.893	*+2*	0.870	*-1*	0.866	*-1*	0.862	*-2*	0.862	*-2*
3	1st shaft torsion + 1st lag asym. + 1st twr lat.	1.38*	2.56	*+86*	2.55	*+85*	2.55	*+85*	2.32	*+68*	2.32	*+68*	1.38	*0*	1.38	*0*	1.38	*0*
4	1st flap asym.+shaft bending	1.58	1.99	*+26*	1.76	*+12*	1.58	*0*	1.58	*0*	1.58	*0*	1.58	*0*	1.58	*0*	1.58	*0*
5	1st flap symmetric	2.06	2.45	*+19*	2.06	*0*	2.06	*0*	2.06	*0*	2.06	*0*	2.06	*0*	2.06	*0*	2.06	*0*
6	1st lag sym. + 2nd flap asym. + twr torsion + twr lat. (#1)	3.94	5.63	*+43*	5.61	*+42*	5.50	*+40*	3.95	*0*	3.94	*0*	3.94	*0*	3.80	*-4*	3.94	*0*
7	2nd flap asym. + 1st lag sym. + shaft bending	4.09	5.25	*+28*	4.69	*+15*	4.28	*+5*	4.30	*+5*	4.29	*+5*	4.29	*+5*	4.29	*+5*	4.30	*+5*
8	1st lag sym. + 2nd flap asym. + twr torsion + twr lat. (#2)	5.05	7.19	*+42*	7.19	*+42*	6.99	*+38*	6.54	*+29*	6.52	*+29*	6.52	*+29*	4.97	*-2*	5.05	*0*
9	2nd flap sym. + 1st lag asym.	5.35	6.96	*+30*	5.83	*+9*	5.83	*+9*	5.83	*+9*	5.83	*+9*	5.83	*+9*	5.83	*+9*	5.83	*+9*
10	2nd tower lateral + 1st lag sym	5.77	9.28	*+61*	9.28	*+61*	9.22	*+60*	8.97	*+55*	8.81	*+53*	8.79	*+52*	8.68	*+50*	8.72	*+51*
11	2nd flap asym. + 2nd twr fore-aft	6.17	7.97	*+29*	7.59	*+23*	7.54	*+22*	7.52	*+22*	7.41	*+20*	7.41	*+20*	7.41	*+20*	7.41	*+20*

*The shaft torsion frequency is calculated from additional test data (Appendix A), not from the modal survey.

3.3.5 Model #6: Tuned Shaft Torsional Stiffness

The modeshape for mode #3 is predominantly shaft twist motion. Therefore, we can use this mode to tune the low-speed shaft torsional stiffness (GJ). With an initial frequency error of +68% and some trial and error, a suitable GJ scale factor is 0.26. This 74% decrease in the original shaft flexibility is a large change because, in the original data, the flexibility of the high-speed shaft and gearbox was ignored. Now we have a low-speed shaft that represents the entire drive-train in torsion. The new frequency error in mode #3 is 0% (Model #6).

3.3.6 Model #7: Tuned Tower Torsional Stiffness

Tower twist is not a dominant motion in any of the modeshapes examined. However, tower twist does contribute noticeably to mode #8 and, to a lesser degree, to mode #6. It was found that the frequency of mode #8 could be improved by tuning the tower torsional stiffness (GJ). A stiffness scale factor of 0.45 results in a reduction in frequency error from +29% to –2%, as shown in the results of Model #7. The frequency of mode #6 is also affected (from 0% to –4%), requiring some retuning of blade lag stiffness. This is a consequence of dealing with more strongly coupled modes.

3.3.7 Model #8: Retuned Blade Lag Stiffness—Final Model

Modifying the scale factor of blade lag stiffness from 0.45 to 0.5 (as used in Model #4) improves the frequencies of modes #6 and #8. The other modal frequencies are not adversely affected by the retuning. The resulting frequency errors for modes #6 and #8 are both 0%. Model #8 is generated using the final set of tuned CART properties. The ADAMS dataset for this case is listed in Appendix D.

It is assumed in the ADAMS models that the tower and blades are each discretized into 10 equal length sections. To ensure that enough sections were used to represent the nonlinear variation of distributed properties, an additional ADAMS model was generated using 20 sections. The resulting modal frequencies are no more than 1% different from those listed for Model #8.

3.4 Tuning Summary

Table 10 lists the properties that have been modified as a result of the tuning process described in Sections 3.2 and 3.3.

Table 10. CART Properties Tuned and the Percentage They Changed

Property	Symbol	% change
Blade distributed mass	m/L	+9% to -206%
Spindle moments of inertia	I_y, I_z	+447%
HSS polar moment of inertia	I_x	-93%
Blade flap stiffness	EI_z	-30%
Blade lag stiffness	EI_y	-50%
LSS bending stiffness	EI	-48%
LSS torsional stiffness	GJ	-74%
Tower bending stiffness	EI_y, EI_z	-6%
Tower torsional stiffness	GJ	-55%

Modal results from the tuned ADAMS model are compared to the modal survey in Tables 11 and 12. In Table 11, the rotor is in a vertical azimuth position, consistent with the configuration used during the tuning process. Recall that only those modes that included fundamental bending or torsion shapes were targeted for tuning (modes #1–#6 and #8). These modes are matched in frequency to within 2%. The higher order modes do not match nearly as closely. In particular, the frequency of mode #10, involving the second tower lateral bending shape, is 51% greater in the ADAMS model than in the modal survey. A likely reason for this discrepancy is that the moments of inertia of the head mass (all components on top of the tower) are not correct in the model. This is plausible because combined moments of inertia are difficult to estimate and I have not been able to verify the assumed values. In comparison to mass, moments of inertia have a greater effect on higher order modes because rotation, rather than translation, of components is a principal component of the modeshapes. In any case, higher order modeshapes are generally not important when predicting loads from a dynamic model.

In Table 12, the rotor is in a horizontal azimuth position. Although the model has not been tuned for this particular configuration, all the listed frequencies are within 20% of the modal survey values. Modes that involve first order modeshapes (#1–#5) have frequency errors within 1%; modes that involve higher order modeshapes (#6–#10) predictably have the highest frequency errors.

Table 11: Comparison of Results from the Modal Survey and Tuned ADAMS Model, Blades Vertical

Mode Number	Modeshape Description	Modal Survey Freq. (Hz)	Tuned ADAMS Model Freq. (Hz)	Tuned ADAMS Model Diff. (%)
1	1st tower fore-aft bending	0.858	0.866	*+1*
2	1st tower lateral bending	0.877	0.862	*-2*
3	1st shaft torsion + 1st lag asym. + 1st twr lat.	1.38*	1.38	*0*
4	1st flap asym.+shaft bending	1.58	1.58	*0*
5	1st flap symmetric	2.06	2.06	*0*
6	1st lag sym. + 2nd flap asym. + twr torsion + twr lat. (#1)	3.94	3.94	*0*
7	2nd flap asym. + 1st lag sym. + shaft bending	4.09	4.30	*+5*
8	1st lag sym. + 2nd flap asym. + twr torsion + twr lat. (#2)	5.05	5.05	*0*
9	2nd flap sym. + 1st lag asym.	5.35	5.83	*+9*
10	2nd tower lateral + 1st lag sym	5.77	8.72	*+51*
11	2nd flap asym. + 2nd twr fore-aft	6.17	7.41	*+20*

* Mode #3 is not from the original modal survey.

Table 12. Comparison of Results from the Modal Survey and Tuned ADAMS Model, Blades Horizontal

Mode Number	Modeshape Description	Modal Survey Freq. (Hz)	Tuned ADAMS Model Freq. (Hz)	Tuned ADAMS Model Diff. (%)
1	1st tower lateral	0.867	0.861	*-1*
2	1st tower fore-aft + 1st flap symmetric	0.870	0.877	*+1*
3	1st shaft torsion + 1st flap asym.	1.38*	1.37	*0*
4	1st flap asym. + shaft bending + 1st twr lat.	1.45	1.45	*0*
5	1st flap sym. + 1st lag sym.	2.06	2.06	*0*
6	2nd flap asym. + 1st lag sym.+ shaft bending	3.90	3.87	*-1*
7	1st lag sym. + 2nd flap asym.+ shaft bending + 2nd twr fore-aft.	4.02	4.10	*+2*
8	2nd flap sym. + 1st lag asym.	5.39	5.83	*+8*
9	1st lag sym. + 2nd asym. flap + twr torsion + 2nd twr fore-aft	5.67	6.38	*+12*
10	2nd flap asym. + 2nd twr lat. + 1st lag asym.	6.01	6.99	*+16*

* Mode #3 is not from the original modal survey.

4. Acknowledgements

The data in this report were obtained with help from many people at the National Wind Technology Center. Alan Wright provided the original CART model and helped with ADAMS modeling details. Lee Fingersh provided descriptions of the CART and furnished the test data included in Appendix A. Gunjit Bir helped to scope the problem and provided a great deal of feedback. This report was supported under subcontract AAM-3-33231-01 with the U.S. Department of Energy's National Renewable Energy Laboratory.

5. References

[1] Fingersh, L.J.; Johnson, K.E. *Controls Advanced Research Turbine (CART) Commissioning and Baseline Data Collection.* NREL/TP-500-32879. Golden, CO: National Renewable Energy Laboratory, October 2002.

[2] Fingersh, L.J.; Johnson, K.E. 2004. "Baseline Results and Future Plans for the NREL Controls Advanced Research Turbine," *Proc. 23rd ASME Wind Energy Symposium*, Reno, Nevada.

[3] Osgood, R.M.; McFarland, H.G.; Johnson, G.L. *Full System Modal Survey of the Controls Advanced Research Turbine (CART).* Internal Letter Report, National Renewable Energy Laboratory, Golden, CO, 2002.

[4] Poore, R.Z. *Conceptual and Preliminary Design and Modeling of Large Scale Advanced Research Turbine (ART).* Draft Report. NREL Subcontract No. YAM-8-18208-01. Golden, CO: National Renewable Energy Laboratory, 2000.

[5] MDI Professional Services, 1998, "ADAMS/WT 2.0 User's Guide and Reference Manual," available online at http://wind.nrel.gov/designcodes/adamswt/docs_v2.0, National Renewable Energy Laboratory, Golden, CO.

Appendix A. Additional Experimental Results

The arrangement of drive train components in the CART is illustrated in Figure A.1, pictured from above. Position encoders measure the rotation angle of both the low-speed shaft (LSS) and the high-speed shaft (HSS). Torque transducers measure torsion within the LSS and HSS. The nomenclature below will be used in the calculations that follow.

T_{LSS}	Torque measured by the LSS torque transducer
T_{HSS}	Torque measured by the HSS torque transducer
Ω_{LSS}	Rotational speed deduced from the LSS position encoder
Ω_{HSS}	Rotational speed deduced from the HSS position encoder
I_{gen}	Polar moment of inertia of rotating parts within the generator up to the HSS coupling
I_{gear}	Polar moment of inertia of rotating parts within the gearbox between the LSS and HSS couplings
I_{rotor}	Polar moment of inertia of the rotor and LSS up to the LSS coupling

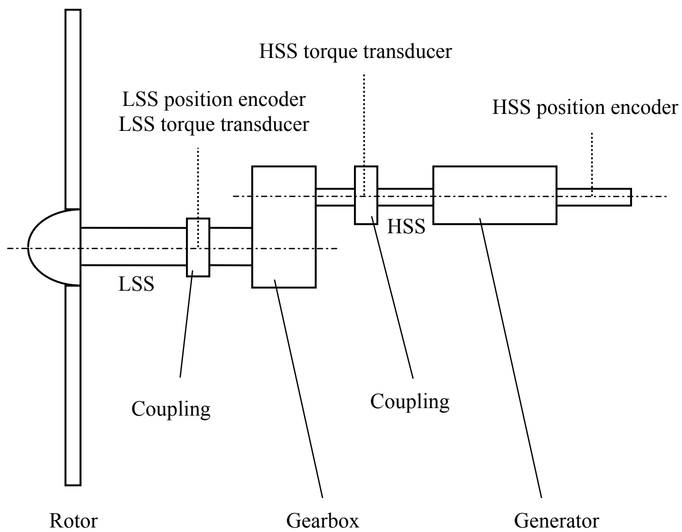

Figure A-1. CART drive train and measurement locations

A.1 Generator Moment of Inertia

On 1/9/2002, an emergency stop procedure was recorded. During this procedure, the blades were feathered to 90°, the rotor brake was engaged on the HSS, and the generator was disconnected. Because the generator is not applying torque to the HSS, the HSS torque transducer measures only inertial torques that accelerate the generator shaft, i.e., $T_{HSS} = I_{gen} \times$ (rate of change of Ω_{HSS}). During a test period of approximately constant HSS deceleration, we can then calculate I_{gen} from

$$I_{gen} = \frac{mean(T_{HSS})}{slope(\Omega_{HSS})}.$$

The emergency stop is recorded in data set *01091453.dat*. The stop occurred at approximately 321.5 seconds into the data. Over the interval 324.0–326.0 seconds, I_{gen} was calculated to be 12.87 kg.m^2. Over a smaller interval, 324.0–325.0 seconds, where Ω_{HSS} is more closely linear but contains less data, I_{gen} was calculated to be 12.02 kg.m^2. An average of these values results in I_{gen} = 12.4 kg.m^2.

A.2 Rotor and Gearbox Moments of Inertia

On 3/13/2002, a motoring test was performed. During this test, the blade pitch angles were set to zero and the generator torque setpoint was cycled between positive and negative values in order to cycle the drive train through positive and negative speeds. When passing through a rotor speed of zero, the aerodynamic drag on the rotor is negligible; therefore, the LSS torque transducer measures only inertial torques that accelerate the rotor. We can then calculate the rotor moment of inertia from

$$I_{rotor} = \frac{mean(T_{LSS})}{slope(\Omega_{LSS})} .$$

At the same time, the HSS torque transducer measures only inertial torques that the gearbox shafts plus rotor experience. The moments of inertia for the gearbox shafts (in the HSS frame of reference) can then be calculated from

$$I_{gear} = \frac{mean(T_{HSS})}{slope(\Omega_{HSS})} - \frac{I_{rotor}}{(\text{gear ratio})^2} ,$$

where the gear ratio is 43.165.

The motoring test was recorded in data set *03131804.dat*. I_{rotor} and I_{gear} are calculated when Ω_{LSS} is within ±1.0 rpm and Ω_{HSS} is within ±50.0 rpm. An equal number of accelerations and decelerations are included to average out hysteresis effects—six intervals in total. The resultant moments of inertia are

$I_{rotor} = 3.25\times10^5$ kg.m^2 (in the LSS reference frame), and

$I_{gear} = 22.0$ kg.m^2 (in the HSS reference frame).

A.3 Drive Train Torsional Stiffness and Modal Frequencies

During the motoring test in Section A.2, data set *03131804.dat*, ringing of the drive train was evident in both the LSS and HSS torque signals. Power spectral density analysis of these signals revealed a dominant mode at 3.4 Hz. Assuming the induction generator provides no stiffening effect on shaft rotation during operation, the drive train can be represented by two inertial bodies separated by a spring element, with free boundary conditions. This model is depicted in Figure A-2(a). The fundamental frequency of this system is given by

$$f_{free} = \frac{1}{2\pi}\sqrt{k\left(\frac{1}{I_{rotor}} + \frac{1}{I_{gen}+I_{gear}}\right)} = 3.4\ \text{Hz} ,$$

where k is the torsional stiffness of the drive train and rotor, which includes the gearbox shafts, LSS, hub, and rotor blades (in-plane bending). The HSS is assumed rigid. Given the moments of inertia calculated in Sections A.1 and A.2,

$k = 2.44\times10^7$ Nm/rad .

When the rotor brake is engaged, the HSS is locked, which changes the boundary conditions for vibration, Figure A.2(b). The fundamental frequency of the drive train is now

$$f_{parked} = \frac{1}{2\pi}\sqrt{\frac{k}{I_{rotor}}} = 1.38\ \text{Hz} .$$

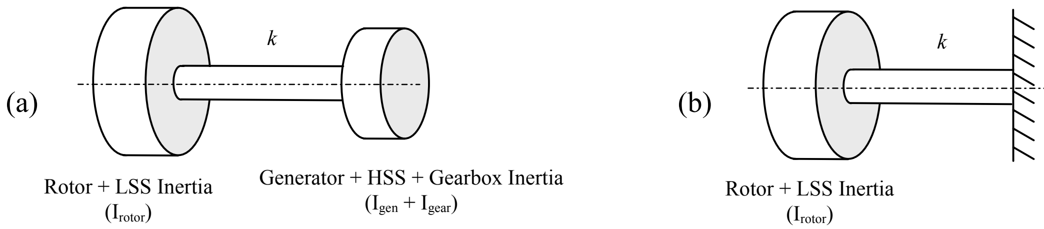

Figure A-2. Drive train inertia models; (a) rotor free, (b) rotor parked (HSS locked)

Appendix B. ADAMS Modeling of Beams

The following method is used to construct Euler-Bernoulli beam models in ADAMS. Its purpose is to systematically generate tower and blade components for the CART to facilitate model tuning. The method is almost identical to that used in ADAMS/WT v2.0, as described in the User's Guide [5]. The deviations from ADAMS/WT convention will be noted.

We begin with a set of distributed properties, such as in Table 5of Section 3.2. The reference x-axis is assumed to run the length of the component. We also assume that the properties vary linearly between stations.

x	Station distance from some datum
m	Mass per unit length
I_y, I_z	Mass moment of inertia per unit length ($I_x = I_y + I_z$ is assumed)
$y_{c.g.}$, $z_{c.g.}$	Center of gravity offsets
EA	Axial stiffness
EI_y, EI_z	Bending stiffnesses
GJ	Torsional stiffness

1. The component is divided into N sections of equal length as shown in Figure B-1(a). For the CART components, N = 10. The distances to the section boundaries are denoted by x_i, for i = 1 to N. The distance between section boundaries is denoted by L.
2. Linear interpolation is used to find the station properties at the section boundaries, e.g., m_i. In ADAMS/WT an unknown nonlinear scheme is used instead.
3. Each section represents an ADAMS 'PART,' which is a concentrated mass having the following properties.

   PART mass:

   $$M_i = \tfrac{L}{2}(m_i + m_{i-1}) \ .$$

   PART center of gravity:

   $$x_{c.g.(i)} = \frac{L(2m_i + m_{i-1})}{3(m_i + m_{i-1})} \text{ measured relative to } x_{i\text{-}1}$$

   $$y_{c.g.(i)} = y_{c.g.(i-1)} + \tfrac{x_{c.g.(i)}}{L}(y_{c.g.(i-1)} - y_{c.g.(i-1)}) \qquad .$$

   $$z_{c.g.(i)} = z_{c.g.(i-1)} + \tfrac{x_{c.g.(i)}}{L}(z_{c.g.(i-1)} - z_{c.g.(i-1)})$$

   PART mass moment of inertia:

   $$I_{x(i)} = \tfrac{L}{2}(I_{x(i)} + I_{x(i-1)}) + \tfrac{1}{L^2}((z_{c.g.(i)} - z_{c.g.(i-1)})^2 + (y_{c.g.(i)} - y_{c.g.(i-1)})^2).I_0$$

   $$I_{y(i)} = \tfrac{L}{2}(I_{y(i)} + I_{y(i-1)}) + I_0$$

   $$I_{z(i)} = \tfrac{L}{2}(I_{z(i)} + I_{z(i-1)}) + I_0 \qquad .$$

   $$\text{where } I_0 = \tfrac{L^3}{12}(3m_i + m_{i-1}) - \tfrac{x_{c.g.(i)}L^2}{3}(2m_i + m_{i-1}) + \tfrac{x_{c.g.(i)}{}^2 L}{2}(m_i + m_{i-1})$$

The ADAMS/WT User's Guide has an incorrect formula for I_0 (page E2) and does not include $y_{c.g.}$ in the formula for $I_{x(i)}$.

4. A 6×6 stiffness matrix (an ADAMS ‘FIELD’) is generated between PART center of gravity locations, as shown in Figure B-1(b). Linear interpolation is used to find the station stiffness properties at these locations, i.e., EA_i, $EI_{y(i)}$, $EI_{y(i)}$, GJ_i. Formulae for the FIELD entries can be found in the ADAMS/WT User’s Guide (pages D4-D5). In ADAMS/WT, a FIELD is not generated to connect the last PART to the end of the component, which implicitly assumes the end is rigid. This assumption is not valid in general.

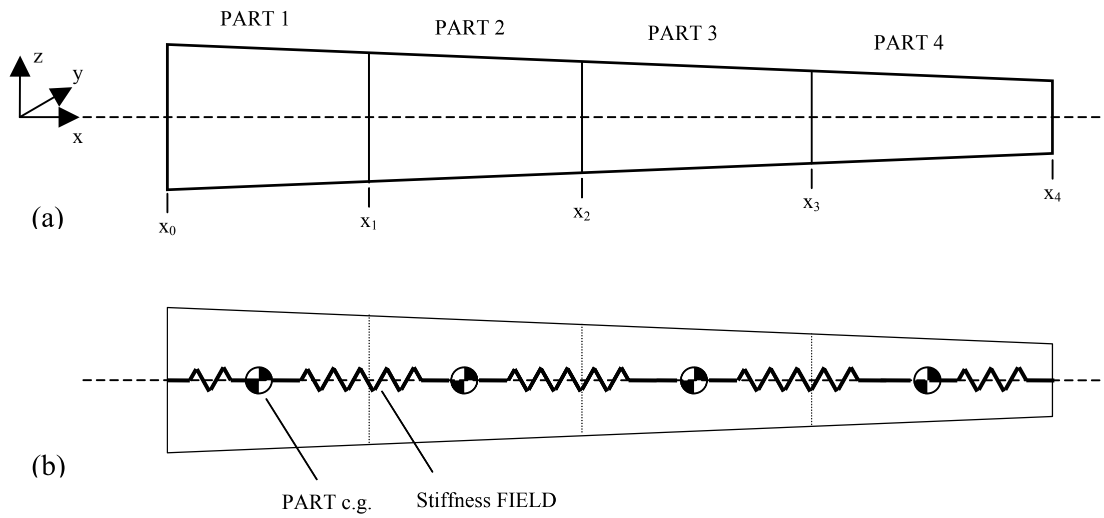

Figure B-1. ADAMS representation of a beam; (a) division into N = 4 parts, (b) FIELDs joining PART centers of gravity

Appendix C. Listing of Original ADAMS Model Dataset

```
MODEL-002 OF ART-1 (advanced research turbine, NWTC), with pitch controls
!  units: m, kg, s, Newtons
!
MARKER/1   , PART = 1             IGRND
MARKER/1010, PART = 1900          ITOWER
, QP  = 0.0, 0.0, 0.0
, REU = 90.0D, 180.0D, 90.0D
!
!    IHUB markers added 29 sept 98 for use with ver vfoa115
!     they are on non-teetering part of hub for identifying plane of rotation
!
MARKER/3510,PART=3500,REU=90D,90D,90D
MARKER/3520,PART=3500,REU=90D,90D,-90D
!
!==============================  Aero Requests  ============================
!
SENSOR/1000, FUNCTION = USER(1,2,3,4)\ VALUE=1
!
!                  ****** PSI Marker on Nacelle , x up, z out******* (RE-M)
    MARKER/2050, PART = 2000
,    QP  = 0.00, 0.0, 0.0
,    REU = 90.0D, 94.0D, 90.0D
!                  ****** PSI Marker on LSS (Blade-1), x axial (up), z dnwind (RE-M)
    MARKER/3051, PART = 3000
,    QP  = 0.0, 0.0, 0.0
,    REU = 90.0D,  90.0D,  90.0D
!                  ****** PSI Marker on LSS (Blade-2), x axial, z dnwind(RE-M)
    MARKER/3052, PART = 3000
,    QP  = 0.0, 0.0, 0.0
,    REU =  90.0D,  90.0D,-90D
!
!     blade #1 aero markers on ground
!
MARKER/  101, PART=1, FLOATING
MARKER/  102, PART=1, FLOATING
MARKER/  103, PART=1, FLOATING
MARKER/  104, PART=1, FLOATING
MARKER/  105, PART=1, FLOATING
MARKER/  106, PART=1, FLOATING
MARKER/  107, PART=1, FLOATING
MARKER/  108, PART=1, FLOATING
MARKER/  109, PART=1, FLOATING
MARKER/  110, PART=1, FLOATING
!
!     blade #1 aero markers on blade
!
MARKER/10101, PART=10100
, QP= 0.0, -.012, 0.0
MARKER/10201, PART=10200
, QP= 0.0, -.007, 0.0
MARKER/10301, PART=10300
, QP= 0.0, -.003, 0.0
MARKER/10401, PART=10400
, QP= 0.0,  .000, 0.0
MARKER/10501, PART=10500
, QP= 0.0,  .000, 0.0
MARKER/10601, PART=10600
, QP= 0.0,  .000, 0.0
MARKER/10701, PART=10700
, QP= 0.0,  .000, 0.0
MARKER/10801, PART=10800
, QP= 0.0,  .000, 0.0
MARKER/10901, PART=10900
, QP= 0.0,  .000, 0.0
MARKER/11001, PART=11000
, QP= 0.0,  .000, 0.0
!
!  blade #1    calls to VFORCESUB
```

```
!
GFORCE/10101, I=10101, JFLOAT=  101, RM=10101
,  FUNCTION = USER(1, 1, 0,10101)
GFORCE/10201, I=10201, JFLOAT=  102, RM=10201
,  FUNCTION = USER(1, 2, 0,10201)
GFORCE/10301, I=10301, JFLOAT=  103, RM=10301
,  FUNCTION = USER(1, 3, 0,10301)
GFORCE/10401, I=10401, JFLOAT=  104, RM=10401
,  FUNCTION = USER(1, 4, 0,10401)
GFORCE/10501, I=10501, JFLOAT=  105, RM=10501
,  FUNCTION = USER(1, 5, 0,10501)
GFORCE/10601, I=10601, JFLOAT=  106, RM=10601
,  FUNCTION = USER(1, 6, 0,10601)
GFORCE/10701, I=10701, JFLOAT=  107, RM=10701
,  FUNCTION = USER(1, 7, 0,10701)
GFORCE/10801, I=10801, JFLOAT=  108, RM=10801
,  FUNCTION = USER(1, 8, 0,10801)
GFORCE/10901, I=10901, JFLOAT=  109, RM=10901
,  FUNCTION = USER(1, 9, 0,10901)
GFORCE/11001, I=11001, JFLOAT=  110, RM=11001
,  FUNCTION = USER(1,10, 0,11001)
!
!     blade #2 aero markers on ground
!
MARKER/  201, PART=1, FLOATING
MARKER/  202, PART=1, FLOATING
MARKER/  203, PART=1, FLOATING
MARKER/  204, PART=1, FLOATING
MARKER/  205, PART=1, FLOATING
MARKER/  206, PART=1, FLOATING
MARKER/  207, PART=1, FLOATING
MARKER/  208, PART=1, FLOATING
MARKER/  209, PART=1, FLOATING
MARKER/  210, PART=1, FLOATING
!
!     blade #2 aero markers on blade
!
MARKER/20101, PART=20100
, QP= 0.0, -.012, 0.0
MARKER/20201, PART=20200
, QP= 0.0, -.007, 0.0
MARKER/20301, PART=20300
, QP= 0.0, -.003, 0.0
MARKER/20401, PART=20400
, QP= 0.0,  .000, 0.0
MARKER/20501, PART=20500
, QP= 0.0,  .000, 0.0
MARKER/20601, PART=20600
, QP= 0.0,  .000, 0.0
MARKER/20701, PART=20700
, QP= 0.0,  .000, 0.0
MARKER/20801, PART=20800
, QP= 0.0,  .000, 0.0
MARKER/20901, PART=20900
, QP= 0.0,  .000, 0.0
MARKER/21001, PART=21000
, QP= 0.0,  .000, 0.0
!
!  blade #2    calls to VFORCESUB
!
GFORCE/20101, I=20101, JFLOAT=  201, RM=20101
,  FUNCTION = USER(2, 1, 0,20101)
GFORCE/20201, I=20201, JFLOAT=  202, RM=20201
,  FUNCTION = USER(2, 2, 0,20201)
GFORCE/20301, I=20301, JFLOAT=  203, RM=20301
,  FUNCTION = USER(2, 3, 0,20301)
GFORCE/20401, I=20401, JFLOAT=  204, RM=20401
,  FUNCTION = USER(2, 4, 0,20401)
GFORCE/20501, I=20501, JFLOAT=  205, RM=20501
,  FUNCTION = USER(2, 5, 0,20501)
GFORCE/20601, I=20601, JFLOAT=  206, RM=20601
```

```
,  FUNCTION = USER(2, 6, 0,20601)
GFORCE/20701, I=20701, JFLOAT=  207, RM=20701
,  FUNCTION = USER(2, 7, 0,20701)
GFORCE/20801, I=20801, JFLOAT=  208, RM=20801
,  FUNCTION = USER(2, 8, 0,20801)
GFORCE/20901, I=20901, JFLOAT=  209, RM=20901
,  FUNCTION = USER(2, 9, 0,20901)
GFORCE/21001, I=21001, JFLOAT=  210, RM=21001
,  FUNCTION = USER(2,10, 0,21001)
!
! gravity and inertial constants
!
UNITS/SYSTEM=MKS
ACCGRAV/KGRAV=-9.81
!
!             ground definition.  global z axis vertical
!
PART/1,GROUND
MARKER/10,PART=1,QP=0,0,-00.000
!             marker oriented with x axis vertical
MARKER/11,PART=1,QP=0,0,0.0,REU=90D,90D,90D
!
!             first part of tower, #1100
!
PART/1100,MASS=6332.,CM=1100,IM=1100
,   IP=10796.,10796.,11471.,0,0,0
,   QG=0,0, 4.588,REU=0,0,0
MARKER/1100,PART=1100
!            marker for beams, x vertical
MARKER/1101,PART=1100,QP=0,0,0,REU=90D,90D,90D
GRAPHIC/100,OUTLINE=10,1100
!            beam connecting ground and 1100
BEAM/1100,I=1101,J=11
,   LENGTH=4.588,IXX=0.5872,IYY=0.2936,IZZ=0.2936
,   A=0.1665,ASY=1.00,ASZ=1.00,E=188.E9,G=76.E9,CRATIO=.00050
!
!           tower part #1200
!
PART/1200,MASS=6408,CM=1200,IM=1200
,   IP=10883,10883,7295,0,0,0
,   QG=0,0, 9.145,REU=0,0,0
MARKER/1200,PART=1200
GRAPHIC/1201,OUTLINE=1100,1200
!            marker for beams, x vertical
MARKER/1201,PART=1200,QP=0,0,0,REU=90D,90D,90D
!            beam connecting 1100 and 1200
BEAM/1200,I=1201,J=1101
,   LENGTH=4.557,IXX=0.3245,IYY=0.1622,IZZ=0.1622
,   A=0.1750,ASY=1.00,ASZ=1.00,E=188.E9,G=76.E9,CRATIO=.00050
!
!           tower part #1300
!
PART/1300,MASS=4563,CM=1300,IM=1300
,   IP= 6084,6084,5195,0,0,0
,   QG=0,0,13.817,REU=0,0,0
MARKER/1300,PART=1300
GRAPHIC/1301,OUTLINE=1200,1300
!            marker for beams, x vertical
MARKER/1301,PART=1300,QP=0,0,0,REU=90D,90D,90D
!            beam connecting 1200 and 1300
BEAM/1300,I=1301,J=1201
,   LENGTH=4.672,IXX=0.1886,IYY=0.0943,IZZ=0.0943
,   A=0.1602,ASY=1.00,ASZ=1.00,E=188.E9,G=76.E9,CRATIO=.00050
!
!           tower part #1400
!
PART/1400,MASS=3048,CM=1400,IM=1400
,   IP=2190,2190,3470,0,0,0
,   QG=0,0,16.155,REU=0,0,0
MARKER/1400,PART=1400
GRAPHIC/1401,OUTLINE=1300,1400
```

```
!            marker for beams, x vertical
MARKER/1401,PART=1400,QP=0,0,0,REU=90D,90D,90D
!            beam connecting 1300 and 1400
BEAM/1400,I=1401,J=1301
,   LENGTH=2.338,IXX=0.1886,IYY=0.0943,IZZ=0.0943
,   A=0.1602,ASY=1.00,ASZ=1.00,E=188.E9,G=76.E9,CRATIO=.00050
!
!           tower part #1500
!
PART/1500,MASS=3052,CM=1500,IM=1500
,   IP=3024,3024,3470,0,0,0
,   QG=0,0,19.663,REU=0,0,0
MARKER/1500,PART=1500
GRAPHIC/1501,OUTLINE=1400,1500
!            marker for beams, x vertical
MARKER/1501,PART=1500,QP=0,0,0,REU=90D,90D,90D
!            beam connecting 1400 and 1500
BEAM/1500,I=1501,J=1401
,   LENGTH=3.508,IXX=0.1225,IYY=0.0612,IZZ=0.0612
,   A=0.1052,ASY=1.00,ASZ=1.00,E=188.E9,G=76.E9,CRATIO=.00050
!
!           tower part #1600
!
PART/1600,MASS=2543,CM=1600,IM=1600
,   IP=2543,2543,2896,0,0,0
,   QG=0,0,23.170,REU=0,0,0
MARKER/1600,PART=1600
GRAPHIC/1601,OUTLINE=1500,1600
!            marker for beams, x vertical
MARKER/1601,PART=1600,QP=0,0,0,REU=90D,90D,90D
!            beam connecting 1500 and 1600
BEAM/1600,I=1601,J=1501
,   LENGTH=3.507,IXX=0.1225,IYY=0.0612,IZZ=0.0612
,   A=0.1052,ASY=1.00,ASZ=1.00,E=188.E9,G=76.E9,CRATIO=.00050
!
!           tower part #1700
!
PART/1700,MASS=2046,CM=1700,IM=1700
,   IP=1433,1433,2329.,0,0,0
,   QG=0,0,25.508,REU=0,0,0
MARKER/1700,PART=1700
GRAPHIC/1701,OUTLINE=1600,1700
!            marker for beams, x vertical
MARKER/1701,PART=1700,QP=0,0,0,REU=90D,90D,90D
!            beam connecting 1600 and 1700
BEAM/1700,I=1701,J=1601
,   LENGTH=2.338,IXX=0.1225,IYY=0.0612,IZZ=0.0612
,   A=0.1052,ASY=1.00,ASZ=1.00,E=188.E9,G=76.E9,CRATIO=.00050
!
!           PART 1800 of tower
!
PART/1800,MASS=2299,CM=1800,IM=1800
,   IP=1972,1972,2617.,0,0,0
,   QG=0,0,28.987,REU=0,0,0
MARKER/1800,PART=1800
GRAPHIC/1801,OUTLINE=1700,1800
!            marker for beams, x vertical
MARKER/1801,PART=1800,QP=0,0,0.0,REU=90D,90D,90D
!            beam connecting 1700 and 1800
BEAM/1800,I=1801,J=1701
,   LENGTH=3.479,IXX=0.0805,IYY=0.0403,IZZ=0.0403
,   A=0.0697,ASY=1.00,ASZ=1.00,E=188.E9,G=76.E9,CRATIO=.00050
!
!           PART 1900 of tower
!
PART/1900,MASS=3003,CM=1900,IM=1900
,   IP=1715,1715,3418,0,0,0
,   QG=0,0,32.466,REU=0,0,0
MARKER/1900,PART=1900
GRAPHIC/1901,OUTLINE=1800,1900
!            marker for beams, x vertical
```

```
MARKER/1901,PART=1900,QP=0,0,0.0,REU=90D,90D,90D
!             beam connecting 1800 and 1900
BEAM/1900,I=1901,J=1801
,   LENGTH=3.479,IXX=0.0805,IYY=0.0403,IZZ=0.0403
,   A=0.0697,ASY=1.00,ASZ=1.00,E=188.E9,G=76.E9,CRATIO=.00050
!
!            PART 1950 of tower
!
PART/1950,MASS=2512,CM=1950,IM=1950
,   IP=729,729,1400,0,0,0
,   QG=0,0,34.862,REU=0,0,0
MARKER/1950,PART=1950
GRAPHIC/1951,OUTLINE=1900,1950
!             marker for beams, x vertical
MARKER/1951,PART=1950,QP=0,0,0.0,REU=90D,90D,90D
MARKER/1953, PART=1950, QP=0,0,0.437, REU=0,0,0   ! connnection to yaw bearing
!             beam connecting 1800 and 1900
BEAM/1950,I=1951,J=1901
,   LENGTH=2.396,IXX=0.1886,IYY=0.0943,IZZ=0.0943
,   A=0.1602,ASY=1.00,ASZ=1.00,E=188.E9,G=76.E9,CRATIO=.00050
!
!                 nacelle and drive train (up to low speed bearings)
!
PART/2000,MASS=19878.,CM=2000,IM=2000
,   IP=1000 , 19062, 19062,0,0,0
,   QG=0,0,36.599,REU=0,0,0
MARKER/2000,PART=2000, QP=-0.045,0,0            !local cg coords
MARKER/2001,PART=2000, REU=90D,4D,-90D          ! marker for connection to 2500
MARKER/2004,PART=2000                           ! marker for Y action force
,   QP=0,0,0,REU=0,90D,0
MARKER/2003,PART=2000                           ! top of yaw bearing
,   QP=0,0,-1.300,REU=0,0,0
MARKER/2005,PART=2000                           ! marker for connection to yaw bearing
MARKER/2006, PART=2000, REU=90D,94D,90D          ! marker for connection to motor inertia
,   QP=-1.537,0,-0.1075
!
!                        generator rotor
!
PART/3100, MASS=10, CM=3100, IM=3100
,  IP=500.00,1.,1.,0,0,0
,  QG=-1.537,0,36.4915, REU=90D,4D,-90D
MARKER/3100, PART=3100
MARKER/3106, PART=3100, REU=90D,90D,90D
!
!          joint and coupling for generator
!
JOINT/3106, REVOLUTE, I=3106, J=2006
!
COUPLER/3106, JOINTS=3106,3, TYPE=R:R, SCALES=1,-42.857
!
!                  shaft bearings
!
PART/2500
,   MASS=3073,CM=2500, IM=2500
,   IP=10.,66.,66.,0,0,0
,   QG=-2.513,0.0,36.7749, REU=0,0,0
MARKER/2500
,   PART=2500, QP=0,0,0, REU=0,0,0
MARKER/2505                                     ! joint connection to yaw cl
,   PART=2500, QP=0,0,0, REU=90D,4D,-90D
MARKER/2501                                     ! marker for connection to shaft
,   PART=2500, QP=0.000,0,0, REU=90D,94D,90D
GRAPHIC/2501,OUTLINE=2505,2000                  ! graphic for beam to yaw bearings
GRAPHIC/2502,OUTLINE=2501,2505                  ! graphic for part 2500
BEAM/2500
,   I=2001, J=2505
,   LENGTH=2.519,IXX=4.170E-3,IYY=4.17E-3,IZZ=20.E-3
,   AREA=0.0700,ASY=1.0,ASZ=1.0,E=200.E9,G=80.E9,CRATIO=.00050
!
!                 low speed shaft (first part)
!
```

```
PART/3000,MASS=277,CM=3000,IM=3000
,   IP=200.0,10,10,0,0,0
,   QG=-2.513 ,0 ,36.7749,REU=90D,4D,-90D
MARKER/3000,PART=3000                            !local coords for lss
MARKER/3001                                    !marker for graphics and joint to bearings
,   QP=0.0,0.0,0.0,REU=90D,90D,90D
MARKER/3003, PART=3000                        !marker for connection to 2nd part
,   QP=0.0,0.0,0.0, REU= 0,0,0
!
!GRAPHIC/3000,OUTLINE=3001,2501                   ! graphic for lss
!
!                low speed shaft (2nd part)
!
PART/3500,MASS=5885,CM=3500,IM=3500
,   IP=10,10,10,0,0,0
,   QG=-3.858,0,36.869,REU=90D,4D,-90D
MARKER/3500,PART=3500                          !local coords for lss 2nd part
MARKER/3501,PART=3500
,   QP=0,0,0, REU= 90D, 90D, 90D               !marker for graphics
MARKER/3503                                    !marker for connection to 1st part lss
,   QP=0.000,0.0,0.0,REU=0,0,0
MARKER/3504                                    !marker for damper connection
,   QP=0.336,0,0, REU=90D, 90D, 90D
MARKER/3505                                    !marker for impulse displacements
,   QP=0.0,0,0, REU=90D, 90D, 90D
GRAPHIC/3500,OUTLINE=3501,3003                   ! graphic for lss
BEAM/3000                                        ! beam connecting 1st, 2nd lss
,   I=3003, J=3503
,   LENGTH=1.348,IXX=540.E-6,IYY=360.E-6,IZZ=360.E-6
,   A=.029,ASY=1.0,ASZ=1.0,E=200.E9,G=76.E9,CRATIO=.00050
!
!
!    hub parts
!
PART/4000, QG= -3.858,   .000, 36.869, REU=90D, 4.0D,-90D
,  MASS= 3116.0,CM=4000, IM=4000
,  IP=10,10,10,0,0,0
!
MARKER/4000, PART=4000
!
PART/ 4100,QG= -3.762,   .000, 38.247
,  REU=90D, 94.0D, 90.0D, MASS=1368.0,CM= 4100
,  IM= 4100,IP=10,10,10,0,0,0,
!
MARKER/4080, PART=4000          ! marker for aero force reference
!
MARKER/ 4100,PART= 4100
!
PART/ 4200,QG= -3.954,   .000, 35.491
,  REU=90D, 94.0D,-90.0D, MASS=1368.0,CM= 4200
,  IM= 4200,IP=10,10,10,0,0,0,
!
MARKER/ 4200,PART= 4200
!
!  hub beam connections
!
MARKER/ 4061, PART=4000, REU=90D,90D,  90D
!
MARKER/ 4150, PART= 4100
,  QP=0,0,0,REU=0,0,0
!
BEAM/ 4061, I= 4150, J= 4061
,  LENGTH=  1.381,IXX=  .347E-02,IYY=  .174E-02,IZZ=  .174E-02
,  AREA=   .2000,ASY=1.0, ASZ=1.0, E=200.E9, G=70.0E9, CRATIO=.00050
!
GRAPHIC/ 4061, OUTLINE= 4061, 4150
!
MARKER/ 4062, PART=4000, REU=90D,90D, 270D
!
MARKER/ 4250, PART= 4200
,  QP=0,0,0,REU=0,0,0
```

```
!
BEAM/ 4062, I= 4250, J= 4062
,  LENGTH=  1.381,IXX=  .347E-02,IYY=  .174E-02,IZZ=  .174E-02
,  AREA=   .2000,ASY=1.0, ASZ=1.0, E=200.E9, G=70.0E9, CRATIO=.00050
!
GRAPHIC/ 4062, OUTLINE= 4062, 4250
!
!        parts for blade #1
!
PART/ 5100
,  QG= -3.7617,   .0000, 38.2466
, ZG= -2.7641,   .0000, 38.1769
, XG= -3.6919,   .0000, 39.2442
, MASS=257.45,CM= 5100,IM= 5100
, IP=500.8000,115.2867, 98.1467, 0 , 0 , 0
!
MARKER/ 5100,PART= 5100
,QP=0.00, -.0900,  .0000
!
PART/10100
,  QG= -3.6222,   .0000, 40.2418
, ZG= -2.6246,   .0000, 40.1720
, XG= -3.5524,   .0000, 41.2393
, MASS=386.70,CM=10100,IM=10100
, IP= 81.1066,193.8482,145.0616, 0 , 0 , 0
!
MARKER/10100,PART=10100
,QP=0.00, -.2194,  .0000
!
PART/10200
,  QG= -3.4826,   .0000, 42.2369
, ZG= -2.4851,   .0000, 42.1671
, XG= -3.4129,   .0000, 43.2345
, MASS=322.89,CM=10200,IM=10200
, IP= 81.5905,178.7458,118.1019, 0 , 0 , 0
!
MARKER/10200,PART=10200
,QP=0.00, -.3409,  .0000
!
PART/10300
,  QG= -3.3431,   .0000, 44.2320
, ZG= -2.3456,   .0000, 44.1623
, XG= -3.2734,   .0000, 45.2296
, MASS=270.03,CM=10300,IM=10300
, IP= 64.6767,147.9477, 96.7507, 0 , 0 , 0
!
MARKER/10300,PART=10300
,QP=0.00, -.3701,  .0000
!
PART/10400
,  QG= -3.2036,   .0000, 46.2271
, ZG= -2.2061,   .0000, 46.1574
, XG= -3.1339,   .0000, 47.2247
, MASS=220.66,CM=10400,IM=10400
, IP= 45.3346,114.6045, 77.8339, 0 , 0 , 0
!
MARKER/10400,PART=10400
,QP=0.00, -.3563,  .0000
!
PART/10500
,  QG= -3.0641,   .0000, 48.2223
, ZG= -2.0665,   .0000, 48.1525
, XG= -2.9943,   .0000, 49.2198
, MASS=174.85,CM=10500,IM=10500
, IP= 29.7436, 85.4989, 60.8103, 0 , 0 , 0
!
MARKER/10500,PART=10500
,QP=0.00, -.3323,  .0000
!
PART/10600
,  QG= -2.9246,   .0000, 50.2174
```

```
, ZG= -1.9270,   .0000, 50.1476
, XG= -2.8548,   .0000, 51.2150
, MASS=131.83,CM=10600,IM=10600
, IP= 17.6603, 60.2196, 45.3262, 0 , 0 , 0
!
MARKER/10600,PART=10600
,QP=0.00, -.2978,  .0000
!
PART/10700
,  QG= -2.7851,   .0000, 52.2125
, ZG= -1.7875,   .0000, 52.1428
, XG= -2.7153,   .0000, 53.2101
, MASS= 94.06,CM=10700,IM=10700
, IP=  9.4918, 40.1790, 32.0206, 0 , 0 , 0
!
MARKER/10700,PART=10700
,QP=0.00, -.2625,  .0000
!
PART/10800
,  QG= -2.6456,   .0000, 54.2077
, ZG= -1.6480,   .0000, 54.1379
, XG= -2.5758,   .0000, 55.2052
, MASS= 62.72,CM=10800,IM=10800
, IP=  4.5489, 25.1902, 21.1714, 0 , 0 , 0
!
MARKER/10800,PART=10800
,QP=0.00, -.2322,  .0000
!
PART/10900
,  QG= -2.5060,   .0000, 56.2028
, ZG= -1.5085,   .0000, 56.1330
, XG= -2.4363,   .0000, 57.2004
, MASS= 44.07,CM=10900,IM=10900
, IP=  2.3691, 16.6403, 14.4538, 0 , 0 , 0
!
MARKER/10900,PART=10900
,QP=0.00, -.2017,  .0000
!
PART/11000
,  QG= -2.3697,   .0000, 58.1530
, ZG= -1.3721,   .0000, 58.0833
, XG= -2.2999,   .0000, 59.1506
, MASS= 18.03,CM=11000,IM=11000
, IP=   .7136,  6.4351,  5.7606, 0 , 0 , 0
!
MARKER/11000,PART=11000
,QP=0.00, -.1720,  .0000
!
!      connections for blade #1
!
FIELD/ 5100,I=10150,J= 5160,KMATRIX=   .216E+10
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .962E+08,   .000E+00,   .000E+00,   .000E+00,  -.966E+08
,   .000E+00,   .000E+00,   .788E+08,   .000E+00,   .774E+08,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .180E+08,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .774E+08,   .000E+00,   .164E+09,   .000E+00
,   .000E+00,  -.966E+08,   .000E+00,   .000E+00,   .000E+00,   .400E+09
,LENGTH=  2.0037,0,0,0,0,0, CRATIO=.0005000
!
MARKER/ 5160,PART= 5100
,QP=0.0,   .0080,   .0000
,REULER= -3.49D, -3.28D,0.0D
!
MARKER/10150,PART=10100
,QP=0.0,  -.1140,   .0000
,REULER= -3.49D, -3.28D,0.0D
!
GRAPHIC/ 5100,OUTLINE= 5100,10100
!
GRAPHIC/ 5101,OUTLINE=10100,10102
!
```

```
MARKER/10102, PART=10100, QP=0.0, -1.3786,   .0545
!
FIELD/10100,I=10250,J=10160,KMATRIX=   .170E+10
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .781E+08,   .000E+00,   .000E+00,   .000E+00,  -.784E+08
,   .000E+00,   .000E+00,   .588E+08,   .000E+00,   .575E+08,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .127E+08,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .575E+08,   .000E+00,   .114E+09,   .000E+00
,   .000E+00,  -.784E+08,   .000E+00,   .000E+00,   .000E+00,   .411E+09
,LENGTH=  2.0037,0,0,0,0,0, CRATIO=.0005000
!
MARKER/10160,PART=10100
,QP=0.0,  -.1140,   .0000
,REULER= -3.48D, -2.96D,0.0D
!
MARKER/10250,PART=10200
,QP=0.0,  -.2356,   .0000
,REULER= -3.48D, -2.96D,0.0D
!
GRAPHIC/10100,OUTLINE=10100,10200
!
GRAPHIC/10101,OUTLINE=10200,10202
!
MARKER/10202, PART=10200, QP=0.0, -1.6146,   .0489
!
FIELD/10200,I=10350,J=10260,KMATRIX=   .142E+10
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .661E+08,   .000E+00,   .000E+00,   .000E+00,  -.659E+08
,   .000E+00,   .000E+00,   .452E+08,   .000E+00,   .440E+08,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .827E+07,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .440E+08,   .000E+00,   .801E+08,   .000E+00
,   .000E+00,  -.659E+08,   .000E+00,   .000E+00,   .000E+00,   .359E+09
,LENGTH=  2.0003,0,0,0,0,0, CRATIO=.0005000
!
MARKER/10260,PART=10200
,QP=0.0,  -.2356,   .0000
,REULER= -1.04D, -2.62D,0.0D
!
MARKER/10350,PART=10300
,QP=0.0,  -.2719,   .0000
,REULER= -1.04D, -2.62D,0.0D
!
GRAPHIC/10200,OUTLINE=10200,10300
!
GRAPHIC/10201,OUTLINE=10300,10302
!
MARKER/10302, PART=10300, QP=0.0, -1.6363,   .0427
!
FIELD/10300,I=10450,J=10360,KMATRIX=   .117E+10
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .543E+08,   .000E+00,   .000E+00,   .000E+00,  -.541E+08
,   .000E+00,   .000E+00,   .338E+08,   .000E+00,   .327E+08,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .528E+07,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .327E+08,   .000E+00,   .556E+08,   .000E+00
,   .000E+00,  -.541E+08,   .000E+00,   .000E+00,   .000E+00,   .271E+09
,LENGTH=  2.0001,0,0,0,0,0, CRATIO=.0005000
!
MARKER/10360,PART=10300
,QP=0.0,  -.2719,   .0000
,REULER=   .47D, -2.24D,0.0D
!
MARKER/10450,PART=10400
,QP=0.0,  -.2556,   .0000
,REULER=   .47D, -2.24D,0.0D
!
GRAPHIC/10300,OUTLINE=10300,10400
!
GRAPHIC/10301,OUTLINE=10400,10402
!
MARKER/10402, PART=10400, QP=0.0, -1.5275,   .0355
!
```

```
FIELD/10400,I=10550,J=10460,KMATRIX=   .948E+09
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .432E+08,   .000E+00,   .000E+00,   .000E+00,  -.429E+08
,   .000E+00,   .000E+00,   .241E+08,   .000E+00,   .230E+08,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .333E+07,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .230E+08,   .000E+00,   .367E+08,   .000E+00
,   .000E+00,  -.429E+08,   .000E+00,   .000E+00,   .000E+00,   .190E+09
,LENGTH=  2.0001,0,0,0,0,0, CRATIO=.0005000
!
MARKER/10460,PART=10400
,QP=0.0,  -.2556,   .0000
,REULER=   .69D, -1.79D,0.0D
!
MARKER/10550,PART=10500
,QP=0.0,  -.2316,   .0000
,REULER=   .69D, -1.79D,0.0D
!
GRAPHIC/10400,OUTLINE=10400,10500
!
GRAPHIC/10401,OUTLINE=10500,10502
!
MARKER/10502, PART=10500, QP=0.0, -1.3989,   .0271
!
FIELD/10500,I=10650,J=10560,KMATRIX=   .736E+09
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .329E+08,   .000E+00,   .000E+00,   .000E+00,  -.326E+08
,   .000E+00,   .000E+00,   .159E+08,   .000E+00,   .150E+08,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .197E+07,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .150E+08,   .000E+00,   .225E+08,   .000E+00
,   .000E+00,  -.326E+08,   .000E+00,   .000E+00,   .000E+00,   .124E+09
,LENGTH=  2.0001,0,0,0,0,0, CRATIO=.0005000
!
MARKER/10560,PART=10500
,QP=0.0,  -.2316,   .0000
,REULER=   .68D, -1.26D,0.0D
!
MARKER/10650,PART=10600
,QP=0.0,  -.2080,   .0000
,REULER=   .68D, -1.26D,0.0D
!
GRAPHIC/10500,OUTLINE=10500,10600
!
GRAPHIC/10501,OUTLINE=10600,10602
!
MARKER/10602, PART=10600, QP=0.0, -1.2714,   .0168
!
FIELD/10600,I=10750,J=10660,KMATRIX=   .542E+09
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .235E+08,   .000E+00,   .000E+00,   .000E+00,  -.232E+08
,   .000E+00,   .000E+00,   .954E+07,   .000E+00,   .879E+07,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .107E+07,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .879E+07,   .000E+00,   .125E+08,   .000E+00
,   .000E+00,  -.232E+08,   .000E+00,   .000E+00,   .000E+00,   .743E+08
,LENGTH=  2.0001,0,0,0,0,0, CRATIO=.0005000
!
MARKER/10660,PART=10600
,QP=0.0,  -.2080,   .0000
,REULER=   .68D,  -.59D,0.0D
!
MARKER/10750,PART=10700
,QP=0.0,  -.1843,   .0000
,REULER=   .68D,  -.59D,0.0D
!
GRAPHIC/10600,OUTLINE=10600,10700
!
GRAPHIC/10601,OUTLINE=10700,10702
!
MARKER/10702, PART=10700, QP=0.0, -1.1428,   .0040
!
FIELD/10700,I=10850,J=10760,KMATRIX=   .376E+09
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
```

```
,   .000E+00,   .157E+08,   .000E+00,   .000E+00,   .000E+00,  -.153E+08
,   .000E+00,   .000E+00,   .495E+07,   .000E+00,   .440E+07,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .514E+06,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .440E+07,   .000E+00,   .587E+07,   .000E+00
,   .000E+00,  -.153E+08,   .000E+00,   .000E+00,   .000E+00,   .411E+08
,LENGTH=  2.0001,0,0,0,0,0, CRATIO=.0005000
!
MARKER/10760,PART=10700
,QP=0.0,  -.1843,   .0000
,REULER=   .68D,   .23D,0.0D
!
MARKER/10850,PART=10800
,QP=0.0,  -.1607,   .0000
,REULER=   .68D,   .23D,0.0D
!
GRAPHIC/10700,OUTLINE=10700,10800
!
GRAPHIC/10701,OUTLINE=10800,10802
!
MARKER/10802, PART=10800, QP=0.0, -1.0152,  -.0121
!
FIELD/10800,I=10950,J=10860,KMATRIX=   .257E+09
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .101E+08,   .000E+00,   .000E+00,   .000E+00,  -.989E+07
,   .000E+00,   .000E+00,   .219E+07,   .000E+00,   .192E+07,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .217E+06,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .192E+07,   .000E+00,   .246E+07,   .000E+00
,   .000E+00,  -.989E+07,   .000E+00,   .000E+00,   .000E+00,   .232E+08
,LENGTH=  2.0001,0,0,0,0,0, CRATIO=.0005000
!
MARKER/10860,PART=10800
,QP=0.0,  -.1607,   .0000
,REULER=   .68D,  1.28D,0.0D
!
MARKER/10950,PART=10900
,QP=0.0,  -.1371,   .0000
,REULER=   .68D,  1.28D,0.0D
!
GRAPHIC/10800,OUTLINE=10800,10900
!
GRAPHIC/10801,OUTLINE=10900,10902
!
MARKER/10902, PART=10900, QP=0.0,  -.8872,  -.0325
!
FIELD/10900,I=11050,J=10960,KMATRIX=   .200E+09
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .741E+07,   .000E+00,   .000E+00,   .000E+00,  -.709E+07
,   .000E+00,   .000E+00,   .928E+06,   .000E+00,   .759E+06,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .830E+05,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .759E+06,   .000E+00,   .907E+06,   .000E+00
,   .000E+00,  -.709E+07,   .000E+00,   .000E+00,   .000E+00,   .149E+08
,LENGTH=  1.9551,0,0,0,0,0, CRATIO=.0005000
!
MARKER/10960,PART=10900
,QP=0.0,  -.1371,   .0000
,REULER=   .68D,  2.59D,0.0D
!
MARKER/11050,PART=11000
,QP=0.0,  -.1140,   .0000
,REULER=   .68D,  2.59D,0.0D
!
GRAPHIC/10900,OUTLINE=10900,11000
!
GRAPHIC/10901,OUTLINE=11000,11002
!
MARKER/11002, PART=11000, QP=0.0,  -.7620,  -.0577
!
!        parts for blade #2
!
PART/ 5200
,  QG= -3.9543,   .0000, 35.4914
```

```
, ZG= -2.9568,   .0000, 35.4216
, XG= -4.0241,   .0000, 34.4938
, MASS=257.45,CM= 5200,IM= 5200
, IP=500.8000,115.2867, 98.1467, 0 , 0 , 0
!
MARKER/ 5200,PART= 5200
,QP=0.00, -.0900,  .0000
!
PART/20100
,  QG= -4.0938,   .0000, 33.4962
, ZG= -3.0963,   .0000, 33.4265
, XG= -4.1636,   .0000, 32.4987
, MASS=386.70,CM=20100,IM=20100
, IP= 81.1066,193.8482,145.0616, 0 , 0 , 0
!
MARKER/20100,PART=20100
,QP=0.00, -.2194,  .0000
!
PART/20200
,  QG= -4.2334,   .0000, 31.5011
, ZG= -3.2358,   .0000, 31.4314
, XG= -4.3031,   .0000, 30.5035
, MASS=322.89,CM=20200,IM=20200
, IP= 81.5905,178.7458,118.1019, 0 , 0 , 0
!
MARKER/20200,PART=20200
,QP=0.00, -.3409,  .0000
!
PART/20300
,  QG= -4.3729,   .0000, 29.5060
, ZG= -3.3753,   .0000, 29.4362
, XG= -4.4426,   .0000, 28.5084
, MASS=270.03,CM=20300,IM=20300
, IP= 64.6767,147.9477, 96.7507, 0 , 0 , 0
!
MARKER/20300,PART=20300
,QP=0.00, -.3701,  .0000
!
PART/20400
,  QG= -4.5124,   .0000, 27.5109
, ZG= -3.5148,   .0000, 27.4411
, XG= -4.5821,   .0000, 26.5133
, MASS=220.66,CM=20400,IM=20400
, IP= 45.3346,114.6045, 77.8339, 0 , 0 , 0
!
MARKER/20400,PART=20400
,QP=0.00, -.3563,  .0000
!
PART/20500
,  QG= -4.6519,   .0000, 25.5157
, ZG= -3.6543,   .0000, 25.4460
, XG= -4.7217,   .0000, 24.5182
, MASS=174.85,CM=20500,IM=20500
, IP= 29.7436, 85.4989, 60.8103, 0 , 0 , 0
!
MARKER/20500,PART=20500
,QP=0.00, -.3323,  .0000
!
PART/20600
,  QG= -4.7914,   .0000, 23.5206
, ZG= -3.7938,   .0000, 23.4508
, XG= -4.8612,   .0000, 22.5230
, MASS=131.83,CM=20600,IM=20600
, IP= 17.6603, 60.2196, 45.3262, 0 , 0 , 0
!
MARKER/20600,PART=20600
,QP=0.00, -.2978,  .0000
!
PART/20700
,  QG= -4.9309,   .0000, 21.5255
, ZG= -3.9334,   .0000, 21.4557
```

```
, XG= -5.0007,   .0000, 20.5279
, MASS= 94.06,CM=20700,IM=20700
, IP=  9.4918, 40.1790, 32.0206, 0 , 0 , 0
!
MARKER/20700,PART=20700
,QP=0.00, -.2625,  .0000
!
PART/20800
,  QG= -5.0704,   .0000, 19.5303
, ZG= -4.0729,   .0000, 19.4606
, XG= -5.1402,   .0000, 18.5328
, MASS= 62.72,CM=20800,IM=20800
, IP=  4.5489, 25.1902, 21.1714, 0 , 0 , 0
!
MARKER/20800,PART=20800
,QP=0.00, -.2322,  .0000
!
PART/20900
,  QG= -5.2100,   .0000, 17.5352
, ZG= -4.2124,   .0000, 17.4655
, XG= -5.2797,   .0000, 16.5376
, MASS= 44.07,CM=20900,IM=20900
, IP=  2.3691, 16.6403, 14.4538, 0 , 0 , 0
!
MARKER/20900,PART=20900
,QP=0.00, -.2017,  .0000
!
PART/21000
,  QG= -5.3463,   .0000, 15.5850
, ZG= -4.3488,   .0000, 15.5152
, XG= -5.4161,   .0000, 14.5874
, MASS= 18.03,CM=21000,IM=21000
, IP=   .7136,  6.4351,  5.7606, 0 , 0 , 0
!
MARKER/21000,PART=21000
,QP=0.00, -.1720,  .0000
!
!      connections for blade #2
!
FIELD/ 5200,I=20150,J= 5260,KMATRIX=   .216E+10
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .962E+08,   .000E+00,   .000E+00,   .000E+00,  -.966E+08
,   .000E+00,   .000E+00,   .788E+08,   .000E+00,   .774E+08,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .180E+08,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .774E+08,   .000E+00,   .164E+09,   .000E+00
,   .000E+00,  -.966E+08,   .000E+00,   .000E+00,   .000E+00,   .400E+09
,LENGTH=  2.0037,0,0,0,0,0, CRATIO=.0005000
!
MARKER/ 5260,PART= 5200
,QP=0.0,   .0080,   .0000
,REULER= -3.49D, -3.28D,0.0D
!
MARKER/20150,PART=20100
,QP=0.0,  -.1140,   .0000
,REULER= -3.49D, -3.28D,0.0D
!
GRAPHIC/ 5200,OUTLINE= 5200,20100
!
GRAPHIC/ 5201,OUTLINE=20100,20102
!
MARKER/20102, PART=20100, QP=0.0, -1.3786,   .0545
!
FIELD/20100,I=20250,J=20160,KMATRIX=   .170E+10
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .781E+08,   .000E+00,   .000E+00,   .000E+00,  -.784E+08
,   .000E+00,   .000E+00,   .588E+08,   .000E+00,   .575E+08,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .127E+08,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .575E+08,   .000E+00,   .114E+09,   .000E+00
,   .000E+00,  -.784E+08,   .000E+00,   .000E+00,   .000E+00,   .411E+09
,LENGTH=  2.0037,0,0,0,0,0, CRATIO=.0005000
!
```

```
MARKER/20160,PART=20100
,QP=0.0,  -.1140,   .0000
,REULER= -3.48D, -2.96D,0.0D
!
MARKER/20250,PART=20200
,QP=0.0,  -.2356,   .0000
,REULER= -3.48D, -2.96D,0.0D
!
GRAPHIC/20100,OUTLINE=20100,20200
!
GRAPHIC/20101,OUTLINE=20200,20202
!
MARKER/20202, PART=20200, QP=0.0, -1.6146,   .0489
!
FIELD/20200,I=20350,J=20260,KMATRIX=   .142E+10
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .661E+08,   .000E+00,   .000E+00,   .000E+00,  -.659E+08
,   .000E+00,   .000E+00,   .452E+08,   .000E+00,   .440E+08,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .827E+07,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .440E+08,   .000E+00,   .801E+08,   .000E+00
,   .000E+00,  -.659E+08,   .000E+00,   .000E+00,   .000E+00,   .359E+09
,LENGTH=  2.0003,0,0,0,0,0, CRATIO=.0005000
!
MARKER/20260,PART=20200
,QP=0.0,  -.2356,   .0000
,REULER= -1.04D, -2.62D,0.0D
!
MARKER/20350,PART=20300
,QP=0.0,  -.2719,   .0000
,REULER= -1.04D, -2.62D,0.0D
!
GRAPHIC/20200,OUTLINE=20200,20300
!
GRAPHIC/20201,OUTLINE=20300,20302
!
MARKER/20302, PART=20300, QP=0.0, -1.6363,   .0427
!
FIELD/20300,I=20450,J=20360,KMATRIX=   .117E+10
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .543E+08,   .000E+00,   .000E+00,   .000E+00,  -.541E+08
,   .000E+00,   .000E+00,   .338E+08,   .000E+00,   .327E+08,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .528E+07,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .327E+08,   .000E+00,   .556E+08,   .000E+00
,   .000E+00,  -.541E+08,   .000E+00,   .000E+00,   .000E+00,   .271E+09
,LENGTH=  2.0001,0,0,0,0,0, CRATIO=.0005000
!
MARKER/20360,PART=20300
,QP=0.0,  -.2719,   .0000
,REULER=   .47D, -2.24D,0.0D
!
MARKER/20450,PART=20400
,QP=0.0,  -.2556,   .0000
,REULER=   .47D, -2.24D,0.0D
!
GRAPHIC/20300,OUTLINE=20300,20400
!
GRAPHIC/20301,OUTLINE=20400,20402
!
MARKER/20402, PART=20400, QP=0.0, -1.5275,   .0355
!
FIELD/20400,I=20550,J=20460,KMATRIX=   .948E+09
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .432E+08,   .000E+00,   .000E+00,   .000E+00,  -.429E+08
,   .000E+00,   .000E+00,   .241E+08,   .000E+00,   .230E+08,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .333E+07,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .230E+08,   .000E+00,   .367E+08,   .000E+00
,   .000E+00,  -.429E+08,   .000E+00,   .000E+00,   .000E+00,   .190E+09
,LENGTH=  2.0001,0,0,0,0,0, CRATIO=.0005000
!
MARKER/20460,PART=20400
,QP=0.0,  -.2556,   .0000
```

```
,REULER=   .69D, -1.79D,0.0D
!
MARKER/20550,PART=20500
,QP=0.0,  -.2316,   .0000
,REULER=   .69D, -1.79D,0.0D
!
GRAPHIC/20400,OUTLINE=20400,20500
!
GRAPHIC/20401,OUTLINE=20500,20502
!
MARKER/20502, PART=20500, QP=0.0, -1.3989,   .0271
!
FIELD/20500,I=20650,J=20560,KMATRIX=   .736E+09
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .329E+08,   .000E+00,   .000E+00,   .000E+00,  -.326E+08
,   .000E+00,   .000E+00,   .159E+08,   .000E+00,   .150E+08,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .197E+07,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .150E+08,   .000E+00,   .225E+08,   .000E+00
,   .000E+00,  -.326E+08,   .000E+00,   .000E+00,   .000E+00,   .124E+09
,LENGTH=  2.0001,0,0,0,0,0, CRATIO=.0005000
!
MARKER/20560,PART=20500
,QP=0.0,  -.2316,   .0000
,REULER=   .68D, -1.26D,0.0D
!
MARKER/20650,PART=20600
,QP=0.0,  -.2080,   .0000
,REULER=   .68D, -1.26D,0.0D
!
GRAPHIC/20500,OUTLINE=20500,20600
!
GRAPHIC/20501,OUTLINE=20600,20602
!
MARKER/20602, PART=20600, QP=0.0, -1.2714,   .0168
!
FIELD/20600,I=20750,J=20660,KMATRIX=   .542E+09
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .235E+08,   .000E+00,   .000E+00,   .000E+00,  -.232E+08
,   .000E+00,   .000E+00,   .954E+07,   .000E+00,   .879E+07,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .107E+07,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .879E+07,   .000E+00,   .125E+08,   .000E+00
,   .000E+00,  -.232E+08,   .000E+00,   .000E+00,   .000E+00,   .743E+08
,LENGTH=  2.0001,0,0,0,0,0, CRATIO=.0005000
!
MARKER/20660,PART=20600
,QP=0.0,  -.2080,   .0000
,REULER=   .68D,  -.59D,0.0D
!
MARKER/20750,PART=20700
,QP=0.0,  -.1843,   .0000
,REULER=   .68D,  -.59D,0.0D
!
GRAPHIC/20600,OUTLINE=20600,20700
!
GRAPHIC/20601,OUTLINE=20700,20702
!
MARKER/20702, PART=20700, QP=0.0, -1.1428,   .0040
!
FIELD/20700,I=20850,J=20760,KMATRIX=   .376E+09
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .157E+08,   .000E+00,   .000E+00,   .000E+00,  -.153E+08
,   .000E+00,   .000E+00,   .495E+07,   .000E+00,   .440E+07,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .514E+06,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .440E+07,   .000E+00,   .587E+07,   .000E+00
,   .000E+00,  -.153E+08,   .000E+00,   .000E+00,   .000E+00,   .411E+08
,LENGTH=  2.0001,0,0,0,0,0, CRATIO=.0005000
!
MARKER/20760,PART=20700
,QP=0.0,  -.1843,   .0000
,REULER=   .68D,   .23D,0.0D
!
```

```
MARKER/20850,PART=20800
,QP=0.0,  -.1607,   .0000
,REULER=   .68D,   .23D,0.0D
!
GRAPHIC/20700,OUTLINE=20700,20800
!
GRAPHIC/20701,OUTLINE=20800,20802
!
MARKER/20802, PART=20800, QP=0.0, -1.0152,  -.0121
!
FIELD/20800,I=20950,J=20860,KMATRIX=   .257E+09
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .101E+08,   .000E+00,   .000E+00,   .000E+00,  -.989E+07
,   .000E+00,   .000E+00,   .219E+07,   .000E+00,   .192E+07,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .217E+06,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .192E+07,   .000E+00,   .246E+07,   .000E+00
,   .000E+00,  -.989E+07,   .000E+00,   .000E+00,   .000E+00,   .232E+08
,LENGTH=  2.0001,0,0,0,0,0, CRATIO=.0005000
!
MARKER/20860,PART=20800
,QP=0.0,  -.1607,   .0000
,REULER=   .68D,  1.28D,0.0D
!
MARKER/20950,PART=20900
,QP=0.0,  -.1371,   .0000
,REULER=   .68D,  1.28D,0.0D
!
GRAPHIC/20800,OUTLINE=20800,20900
!
GRAPHIC/20801,OUTLINE=20900,20902
!
MARKER/20902, PART=20900, QP=0.0,  -.8872,  -.0325
!
FIELD/20900,I=21050,J=20960,KMATRIX=   .200E+09
,   .000E+00,   .000E+00,   .000E+00,   .000E+00,   .000E+00
,   .000E+00,   .741E+07,   .000E+00,   .000E+00,   .000E+00,  -.709E+07
,   .000E+00,   .000E+00,   .928E+06,   .000E+00,   .759E+06,   .000E+00
,   .000E+00,   .000E+00,   .000E+00,   .830E+05,   .000E+00,   .000E+00
,   .000E+00,   .000E+00,   .759E+06,   .000E+00,   .907E+06,   .000E+00
,   .000E+00,  -.709E+07,   .000E+00,   .000E+00,   .000E+00,   .149E+08
,LENGTH=  1.9551,0,0,0,0,0, CRATIO=.0005000
!
MARKER/20960,PART=20900
,QP=0.0,  -.1371,   .0000
,REULER=   .68D,  2.59D,0.0D
!
MARKER/21050,PART=21000
,QP=0.0,  -.1140,   .0000
,REULER=   .68D,  2.59D,0.0D
!
GRAPHIC/20900,OUTLINE=20900,21000
!
GRAPHIC/20901,OUTLINE=21000,21002
!
MARKER/21002, PART=21000, QP=0.0,  -.7620,  -.0577
!
!
!  revolute joints at blade roots for pitching
!
MARKER/ 4109, PART= 4100, REU=90D,90.0D,90D
!
MARKER/ 5109, PART= 5100, REU=90D,90D,90D
!
JOINT/ 4109,I= 5109, J= 4109,  REVOLUTE
!
MARKER/ 4209, PART= 4200, REU=90D,90.0D,90D
!
MARKER/ 5209, PART= 5200, REU=90D,90D,90D
!
JOINT/ 4209, I= 5209, J= 4209, REVOLUTE
!
```

```
!  couple the pitch of blades #1 and #2 together
!
COUPLER/100, JOINTS=4109,4209, TYPE=R:R, SCALES=1,-1
!
!                                rpm
VARIABLE/3000
,  FUNCTION = WZ(3106,2006,2006)*30/PI
!
!      VARIABLE definitions of masses
!
ARRAY/ 5100, IC, NUMBERS =  257.45
ARRAY/10100, IC, NUMBERS =  386.70
ARRAY/10200, IC, NUMBERS =  322.89
ARRAY/10300, IC, NUMBERS =  270.03
ARRAY/10400, IC, NUMBERS =  220.66
ARRAY/10500, IC, NUMBERS =  174.85
ARRAY/10600, IC, NUMBERS =  131.83
ARRAY/10700, IC, NUMBERS =   94.06
ARRAY/10800, IC, NUMBERS =   62.72
ARRAY/10900, IC, NUMBERS =   44.07
ARRAY/11000, IC, NUMBERS =   18.03
ARRAY/ 5200, IC, NUMBERS =  257.45
ARRAY/20100, IC, NUMBERS =  386.70
ARRAY/20200, IC, NUMBERS =  322.89
ARRAY/20300, IC, NUMBERS =  270.03
ARRAY/20400, IC, NUMBERS =  220.66
ARRAY/20500, IC, NUMBERS =  174.85
ARRAY/20600, IC, NUMBERS =  131.83
ARRAY/20700, IC, NUMBERS =   94.06
ARRAY/20800, IC, NUMBERS =   62.72
ARRAY/20900, IC, NUMBERS =   44.07
ARRAY/21000, IC, NUMBERS =   18.03
ARRAY/ 4100, IC, NUMBERS = 1368.00
ARRAY/ 4200, IC, NUMBERS = 1368.00
ARRAY/ 4000, IC, NUMBERS = 2736.00
!
!          ***** CONSTRAINTS *****
!
!
JOINT/2000              ! yaw bearing
,  I=1953, J=2003,REVOLUTE
!
!                         adams_view_name='teeter_hinge'
JOINT/4
, REVOLUTE
, I = 3502
, J = 4090
!
MARKER/3502, PART=3500                  !marker for connection to hub
,   QP=0.000,0.0,0.0,   REU= 0D, -90D , 0D        ! delta_3 = -00 deg
!
!                        ! marker for connection to shaft
MARKER/4090, PART = 4000
, QP = 0.000,0.0,0.0, REULER =0D,  -90D, 0D        ! delta_3 = -00 deg
!
!
!                         adams_view_name='shaft_nacelle_hinge'
JOINT/3
, REVOLUTE
, I = 3001
, J = 2501
!
!                             adams_view_name='SPR2'
SPRINGDAMPER/4
, I = 3502, J = 4090
, ROTATION, KT = 1.0E3, CT=1.0E1
!
!                             adams_view_name='SPR2000'
SPRINGDAMPER/2000
, I = 1953, J = 2003
, ROTATION, KT = 1.0E4, CT=1.0E1
```

```
!
!                  rotation change damper
!
SFORCE/2501, I=3001, J=2501, ROTATION
,  FUNCTION=-2.E4*WDTZ(3001,2501,2501)!*STEP(TIME,8.0,1.0,9.0,0.0)
!
VARIABLE/4001                        ! beta
,   FUNCTION= AZ(4090,3502)*57.3
VARIABLE/4002                              ! beta_dot
,   FUNCTION= WZ(4090,3502,3502)*57.3
VARIABLE/4003            ! moment = 44000 + 15200(angle-2)
,  FUNCTION=  (ABS(VARVAL(4001))-6)*1E6  + 50000
VARIABLE/4004
, FUNCTION = 25000                         ! peak value at 10 degrees
VARIABLE/4005
,  FUNCTION=IF(ABS(VARVAL(4001))-7.0:VARVAL(4003),VARVAL(4003),VARVAL(4003))
VARIABLE/4006
, FUNCTION=VARVAL(4005)*STEP(VARVAL(4002),0,0,1.00,-1.0)*VARVAL(4008)
VARIABLE/4007
, FUNCTION=VARVAL(4005)*STEP(VARVAL(4002),-1.00,1.0,0,0)*VARVAL(4008)
VARIABLE/4008
, FUNCTION=STEP(ABS(VARVAL(4001))-6.0,0,0,0.25,1.0)
!
!                               generator model
!
VARIABLE/3002, FUNCTION = 1-WM(3106,2006)/4.398
!
VARIABLE/3001
,  FUNCTION=(1000*VARVAL(3002)/(0.02428*VARVAL(3002)**2
,   +0.00106*VARVAL(3002)+0.000200))
,  *(STEP(VARVAL(3002),0,0,0.001,1.0) + STEP(-VARVAL(3002),0,0,0.001,1.0))
!
!                               start-up
!
SFORCE/2001, ROTATION
,   I=3106, J=2006
,  FUNCTION = VARVAL(3001)
!
REQUEST/1000,F1=TZ(5109,4109,4109)\F2=TZ(2003,1953,1953)\
,  F3=VARVAL(1111)\TITLE=PTCHMT:YAWMT:VAR1111
!
!                            pitch control system
!
!  current power (Watts)
!
VARIABLE/100, FUNCTION = WZ(3001,2501,2501)*TZ(2501,3001,2501)
!
!  set desired/max power level(Watt)
!
ARRAY/300, IC, SIZE=1, NUMBERS= 650000.0
!
!  current blade #1 pitch angle and rate (degrees- aero convention)
!
VARIABLE/101, FUNCTION =-AZ(5109,4109)*57.3
!
VARIABLE/103, FUNCTION = -WZ(5109,4109,4109)*57.3
!
!  current blade #2 pitch angle  (degrees- aero convention)
!
VARIABLE/201, FUNCTION =-AZ(5209,4209)*57.3
!
!  desired pitch setting blade #1, from  varsub
!
VARIABLE/111, FUNCTION = 0.0
!
!  pitch error, blade #1, = (desired - actual) degrees- aero convention
!
VARIABLE/102, FUNCTION = (VARVAL(111) - VARVAL(101))*STEP(TIME,14.9,0,15.0,1.0)
!
!  apply  torque to blade #1
!
```

```
SFORCE/5100, ROTATION, I=5109, J=4109
,  FUNCTION =  (-1600.*VARVAL(102))*STEP(TIME,15,0,15.1,1.0)
,  + VARVAL(103)*2000*STEP(TIME,15,0,15.1,1.0)
!
!  initial motion to apply minimum pitch angle
!
MOTION/5100, JOINT= 4109
, FUNCTION =-2.0/57.3*STEP(TIME,5.,00,6.00,1.0)
!
!                             yaw control system
!
! call varsub - return the yaw error = (wind_dir) - (yaw_dir) [using yawdyn convention]
!
VARIABLE/1111, FUNCTION = 0.0
!
MOTION/2000,JOINT=2000, ROTATION, VELOCITY
, FUNCTION = IF(ABS(VARVAL(1111))-0.5:0,0,
,    IF(VARVAL(1111): -0.5/57.3, 0, +0.5/57.3))
!
END
```

Appendix D: Listing of Tuned ADAMS Model Dataset

```
MODEL #8 of the CART (Controls Advanced Research Turbine, NWTC) for model tuning
! Prepared by MATLAB script code
! K. Stol
!

!
!             ground definition.  global z axis vertical
!
PART/1,GROUND
MARKER/1, PART = 1             IGRND
MARKER/10, PART=1,QP=0,0,-00.000
!             marker oriented with x axis vertical
MARKER/11, PART=1,QP=0,0,0.0,REU=90D,90D,90D
!

!           tower parts
!

!           tower part #1110
PART/1110, MASS=5101.1, CM=1110
,   IP= 19123.3, 14722.3, 14722.3
,   QG= 0, 0, 1.709, REU=90D,90D,90D
MARKER/1110, PART=1110
GRAPHIC/1110, OUTLINE=11,1110

FIELD/1110, I=1110, J=11, KMATRIX= 2.1242e+010
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 1.7519e+011, 0.0000e+000, 0.0000e+000, 0.0000e+000, -1.4278e+011
, 0.0000e+000, 0.0000e+000, 1.7519e+011, 0.0000e+000, 1.4278e+011, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.5699e+010, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 1.4278e+011, 0.0000e+000, 1.5875e+011, 0.0000e+000
, 0.0000e+000, -1.4278e+011, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.5875e+011
,LENGTH= 1.709,0,0,0,0,0, CRATIO=0.0005
!           tower part #1120
PART/1120, MASS=4882.5, CM=1120
,   IP= 11482.4, 10685.8, 10685.8
,   QG= 0, 0, 5.238, REU=90D,90D,90D
MARKER/1120, PART=1120
GRAPHIC/1120, OUTLINE=1110,1120

FIELD/1120, I=1120, J=1110, KMATRIX= 9.7645e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 1.3996e+010, 0.0000e+000, 0.0000e+000, 0.0000e+000, -2.2851e+010
, 0.0000e+000, 0.0000e+000, 1.3996e+010, 0.0000e+000, 2.2851e+010, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 5.3344e+009, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 2.2851e+010, 0.0000e+000, 5.1589e+010, 0.0000e+000
, 0.0000e+000, -2.2851e+010, 0.0000e+000, 0.0000e+000, 0.0000e+000, 5.1589e+010
,LENGTH= 3.529,0,0,0,0,0, CRATIO=0.0005
!           tower part #1130
PART/1130, MASS=4764.9, CM=1130
,   IP= 6952.3, 8299.4, 8299.4
,   QG= 0, 0, 8.692, REU=90D,90D,90D
MARKER/1130, PART=1130
GRAPHIC/1130, OUTLINE=1120,1130

FIELD/1130, I=1130, J=1120, KMATRIX= 9.6995e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 8.7902e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, -1.3568e+010
, 0.0000e+000, 0.0000e+000, 8.7902e+009, 0.0000e+000, 1.3568e+010, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 3.1980e+009, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 1.3568e+010, 0.0000e+000, 2.9382e+010, 0.0000e+000
, 0.0000e+000, -1.3568e+010, 0.0000e+000, 0.0000e+000, 0.0000e+000, 2.9382e+010
,LENGTH= 3.454,0,0,0,0,0, CRATIO=0.0005
!           tower part #1140
PART/1140, MASS=4570.4, CM=1140
,   IP= 5173.5, 7215.7, 7215.7
,   QG= 0, 0, 12.202, REU=90D,90D,90D
```

```
MARKER/1140, PART=1140
GRAPHIC/1140, OUTLINE=1130,1140

FIELD/1140, I=1140, J=1130, KMATRIX= 9.2020e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 5.3514e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, -9.1832e+009
, 0.0000e+000, 0.0000e+000, 5.3514e+009, 0.0000e+000, 9.1832e+009, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 2.0059e+009, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 9.1832e+009, 0.0000e+000, 2.1245e+010, 0.0000e+000
, 0.0000e+000, -9.1832e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, 2.1245e+010
,LENGTH= 3.510,0,0,0,0,0, CRATIO=0.0005
!           tower part #1150
PART/1150, MASS=3939.1, CM=1150
,   IP= 4415.3, 6163.0, 6163.0
,   QG= 0, 0, 15.595, REU=90D,90D,90D
MARKER/1150, PART=1150
GRAPHIC/1150, OUTLINE=1140,1150

FIELD/1150, I=1150, J=1140, KMATRIX= 9.0964e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 5.3278e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, -8.9249e+009
, 0.0000e+000, 0.0000e+000, 5.3278e+009, 0.0000e+000, 8.9249e+009, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.8660e+009, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 8.9249e+009, 0.0000e+000, 2.0060e+010, 0.0000e+000
, 0.0000e+000, -8.9249e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, 2.0060e+010
,LENGTH= 3.393,0,0,0,0,0, CRATIO=0.0005
!           tower part #1160
PART/1160, MASS=3184.3, CM=1160
,   IP= 3508.9, 4977.9, 4977.9
,   QG= 0, 0, 19.152, REU=90D,90D,90D
MARKER/1160, PART=1160
GRAPHIC/1160, OUTLINE=1150,1160

FIELD/1160, I=1160, J=1150, KMATRIX= 7.1454e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 3.7853e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, -6.3376e+009
, 0.0000e+000, 0.0000e+000, 3.7853e+009, 0.0000e+000, 6.3376e+009, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.4582e+009, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 6.3376e+009, 0.0000e+000, 1.4560e+010, 0.0000e+000
, 0.0000e+000, -6.3376e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.4560e+010
,LENGTH= 3.557,0,0,0,0,0, CRATIO=0.0005
!           tower part #1170
PART/1170, MASS=3050.1, CM=1170
,   IP= 3348.0, 4763.1, 4763.1
,   QG= 0, 0, 22.658, REU=90D,90D,90D
MARKER/1170, PART=1170
GRAPHIC/1170, OUTLINE=1160,1170

FIELD/1170, I=1170, J=1160, KMATRIX= 6.0171e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 3.2560e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, -5.7088e+009
, 0.0000e+000, 0.0000e+000, 3.2560e+009, 0.0000e+000, 5.7088e+009, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.2205e+009, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 5.7088e+009, 0.0000e+000, 1.3346e+010, 0.0000e+000
, 0.0000e+000, -5.7088e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.3346e+010
,LENGTH= 3.506,0,0,0,0,0, CRATIO=0.0005
!           tower part #1180
PART/1180, MASS=2563.8, CM=1180
,   IP= 2772.7, 3953.2, 3953.2
,   QG= 0, 0, 26.039, REU=90D,90D,90D
MARKER/1180, PART=1180
GRAPHIC/1180, OUTLINE=1170,1180

FIELD/1180, I=1180, J=1170, KMATRIX= 5.6195e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 3.2669e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, -5.3147e+009
, 0.0000e+000, 0.0000e+000, 3.2669e+009, 0.0000e+000, 5.3147e+009, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.1391e+009, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 5.3147e+009, 0.0000e+000, 1.1744e+010, 0.0000e+000
, 0.0000e+000, -5.3147e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.1744e+010
,LENGTH= 3.381,0,0,0,0,0, CRATIO=0.0005
```

```
!           tower part #1190
PART/1190, MASS=2362.4, CM=1190
,   IP= 2537.6, 3650.7, 3650.7
,   QG= 0, 0, 29.700, REU=90D,90D,90D
MARKER/1190, PART=1190
GRAPHIC/1190, OUTLINE=1180,1190

FIELD/1190, I=1190, J=1180, KMATRIX= 4.2051e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 2.0760e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, -3.6750e+009
, 0.0000e+000, 0.0000e+000, 2.0760e+009, 0.0000e+000, 3.6750e+009, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 8.5091e+008, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 3.6750e+009, 0.0000e+000, 8.8173e+009, 0.0000e+000
, 0.0000e+000, -3.6750e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, 8.8173e+009
,LENGTH= 3.661,0,0,0,0,0, CRATIO=0.0005
!           tower part #1200
PART/1200, MASS=3603.5, CM=1200
,   IP= 4019.2, 5571.6, 5571.6
,   QG= 0, 0, 33.275, REU=90D,90D,90D
MARKER/1200, PART=1200
GRAPHIC/1200, OUTLINE=1190,1200

FIELD/1200, I=1200, J=1190, KMATRIX= 6.0847e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 3.1891e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, -6.4026e+009
, 0.0000e+000, 0.0000e+000, 3.1891e+009, 0.0000e+000, 6.4026e+009, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.2423e+009, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 6.4026e+009, 0.0000e+000, 1.6095e+010, 0.0000e+000
, 0.0000e+000, -6.4026e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.6095e+010
,LENGTH= 3.575,0,0,0,0,0, CRATIO=0.0005
!           tower top, part #1500

PART/1500, MASS=1610.0, CM=1500         ! concentrated tower-top mass
,   IP= 0.1, 0.1, 0.1
,   QG= 0, 0, 34.862, REU=90D,90D,90D
MARKER/1500, PART=1500
GRAPHIC/1500, OUTLINE=1500, 1200

FIELD/1500, I=1500, J=1200, KMATRIX= 1.9406e+010
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 5.1963e+010, 0.0000e+000, 0.0000e+000, 0.0000e+000, -4.1782e+010
, 0.0000e+000, 0.0000e+000, 5.1963e+010, 0.0000e+000, 4.1782e+010, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 3.9824e+009, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 4.1782e+010, 0.0000e+000, 4.4499e+010, 0.0000e+000
, 0.0000e+000, -4.1782e+010, 0.0000e+000, 0.0000e+000, 0.0000e+000, 4.4499e+010
,LENGTH= 1.587,0,0,0,0,0, CRATIO=0.0005
MARKER/1010, PART=1500, QP=0.437,0,0, REU=90D,-90D,-90D    ! yaw marker on tower (also ITOWER for AeroDyn)
GRAPHIC/1010, OUTLINE=1010, 1500

!           nacelle
!

PART/2000, MASS=23228.0, CM=2000
,   IP= 1.200e+003, 3.659e+004, 3.659e+004
,   QG= 0, 0, 36.59600
,   REU= 90D, 90D, 90D
MARKER/2000, PART=2000, QP= 0.02643, 0, -0.40113    ! cg marker
,   REU= 90D, 86.23D, 90D

MARKER/2010, PART=2000, QP= -1.29700, 0, 0       ! yaw marker on nacelle (also IYBRG for AeroDyn)
,   REU= 90D, -90D, -90D
MARKER/2050, PART=2000, QP= 0.16563, 0, -2.51355    ! rotation marker on nacelle (also IPSINAC for AeroDyn)
,   REU= 90D, -3.77D, 90D

MARKER/2001, PART=2000                        ! marker for graphics
GRAPHIC/2001, OUTLINE=2001, 2010
JOINT/2000, FIXED, I=1010, J=2010             ! yaw bearing

!           HSS + generator
```

```
!

PART/3000, MASS=0.1, CM=3000
,   IP= 6.410e+004, 1.000e-001, 1.000e-001
,   QG= -1.49675, 0, 36.69463, REU= 90.00D, 93.77D, 90.00D
MARKER/3000, PART=3000                        ! cg marker
,   REU = 90D, 90D, 90D

MARKER/3051, PART=3000,                       ! (Ipsib1 for AeroDyn)
,   QP= 0, 0, -1.01900
MARKER/3052, PART=3000,                       ! rotation marker on HSS (also Ipsib2 for AeroDyn)
,   QP= 0, 0, -1.01900, REU = 180D, 0, 0
MARKER/3010, PART=3000, QP= 0, 0, -1.01900        ! LSS end marker on HSS
,   REU= 90D, 90D, 90D

GRAPHIC/3000, OUTLINE=3010, 2001
JOINT/3000, FIXED, I=3052, J=2050             ! rotation joint

!           LSS
!

BEAM/3100, I=3010, J=3510
,   LENGTH= 0.68800, IXX= 2.388e-004, IYY= 2.388e-004, IZZ = 2.388e-004
,   A= 7.596e-002, E= 2.000e+011, G= 7.752e+010
,   ASY= 1.111, ASZ= 1.111, CRATIO=0.0005
GRAPHIC/3100, OUTLINE=3010, 3510
!           teeter yoke
!

PART/3500, MASS=5885.0, CM=3500
,   IP= 1.000e-001, 1.000e-001, 1.000e-001
,   QG= -3.85863, 0, 36.85026, REU= 90.00D, 93.77D, 90.00D
MARKER/3500, PART=3500                    ! cg marker
,   REU= 0, 90D, 0D

MARKER/3510, PART=3500, QP= 0, 0, 0.66000    ! LSS end marker on yoke
,   REU= 90D, 90D, 90D

GRAPHIC/3500, OUTLINE=3500, 3510
!           hub spindle
!

PART/4000, MASS=5852.0, CM=4000
,   IP= 1.000e-001, 1.500e+004, 1.500e+004
,   QG= -3.85863, 0, 36.85026, REU= 90.00D, 93.77D, 90.00D
MARKER/4000, PART=4000                    ! cg marker
,   REU= 0, 90D, 0D

MARKER/4109, PART=4000,                   ! blade #1 pitch marker on hub
,   QP= 1.38100, 0, 0, REU= 90D, 90D, 90D
MARKER/4191, PART=4000,                   ! (Ipitchb1 for AeroDyn)
,   QP= 1.38100, 0, 0, REU= 0, -90D, 0
GRAPHIC/4109, OUTLINE=4109, 4000
MARKER/4209, PART=4000,                   ! blade #2 pitch marker on hub
,   QP= -1.38100, 0, 0, REU= -90D, 90D, 90D

MARKER/4291, PART=4000,                   ! (Ipitchb2 for AeroDyn)
,   QP= -1.38100, 0, 0, REU= 180D, -90D, 0
GRAPHIC/4209, OUTLINE=4209, 4000
JOINT/4000, FIXED, I=4000, J=3500         ! teeter joint


!
!           parts for blade #1
!

!           dummy part for blade root
PART/5100, MASS=0.1, CM=5100
,   IP= 0.1, 0.1, 0.1
,   QG= -3.7678, 0, 38.2283, REU= 90D, 93.770D, 90.000D
MARKER/5100, PART=5100, QP= 0, -0.0898, 0.0054    ! cg marker
```

```
,   REU = 0, -93.440D, 0
MARKER/5105, PART=5100, QP= 0, 0.0080, -0.0005    ! ea marker
,   REU= 0, -93.440D, 0
MARKER/5109, PART=5100, REU= 90D, 90D, 90D    ! pitch marker on blade

JOINT/4109, FIXED, I= 4109, J= 5109             ! pitch joint

!           blade part #10100

PART/10100, MASS=497.0, CM=10100,   IP= 82.9, 225.7, 184.3
,   QG= -3.7052, 0, 39.1788, REU= 90D, 93.770D, 90.000D
MARKER/10100, PART=10100, QP= 0, -0.1514, 0.0087       ! cg marker
,   REU= 0, -93.289D, 0
MARKER/10105, PART=10100, QP= 0, -0.0500, 0.0029       ! ea marker
,   REU= 0, -93.289D, 0
MARKER/10101, PART=10100, QP= -0.4537, -0.0167, 0.0010    ! aero marker 1
,   REU= 0, -93.362D, 0
MARKER/10201, PART=10100, QP= 0.5441, -0.0129, 0.0007    ! aero marker 2
,   REU= 0, -93.202D, 0
GRAPHIC/10101, OUTLINE=5100,10100
FIELD/10100, I=10105, J=5105, KMATRIX= 5.0387e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 2.1538e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, -1.0041e+009
, 0.0000e+000, 0.0000e+000, 4.2296e+009, 0.0000e+000, 2.0622e+009, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 4.2078e+007, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 2.0622e+009, 0.0000e+000, 1.3247e+009, 0.0000e+000
, 0.0000e+000, -1.0041e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, 6.3070e+008
,   LENGTH= 0.9530,0.0001,-0.0581, 0.151D,0,0, CRATIO=0.0005

!           blade part #10200

PART/10200, MASS=393.8, CM=10200,   IP= 81.7, 198.2, 143.6
,   QG= -3.5730, 0, 41.1849, REU= 90D, 93.770D, 90.000D
MARKER/10200, PART=10200, QP= 0, -0.2776, 0.0144       ! cg marker
,   REU= 0, -92.968D, 0
MARKER/10205, PART=10200, QP= 0, -0.1723, 0.0089       ! ea marker
,   REU= 0, -92.968D, 0
MARKER/10301, PART=10200, QP= -0.4687, -0.0104, 0.0006    ! aero marker 1
,   REU= 0, -93.044D, 0
MARKER/10401, PART=10200, QP= 0.5290, -0.0080, 0.0004    ! aero marker 2
,   REU= 0, -92.881D, 0
GRAPHIC/10201, OUTLINE=10100,10200
FIELD/10200, I=10205, J=10105, KMATRIX= 1.9831e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 1.7168e+008, 0.0000e+000, 0.0000e+000, 0.0000e+000, -1.5823e+008
, 0.0000e+000, 0.0000e+000, 4.8129e+008, 0.0000e+000, 4.8364e+008, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.5951e+007, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 4.8364e+008, 0.0000e+000, 6.4812e+008, 0.0000e+000
, 0.0000e+000, -1.5823e+008, 0.0000e+000, 0.0000e+000, 0.0000e+000, 2.0247e+008
,   LENGTH= 2.0100,0.0010,-0.1225, 0.321D,0,0, CRATIO=0.0005

!           blade part #10300

PART/10300, MASS=328.0, CM=10300,   IP= 73.1, 172.9, 117.1
,   QG= -3.4418, 0, 43.1757, REU= 90D, 93.770D, 90.000D
MARKER/10300, PART=10300, QP= 0, -0.3544, 0.0163       ! cg marker
,   REU= 0, -92.632D, 0
MARKER/10305, PART=10300, QP= 0, -0.2527, 0.0116       ! ea marker
,   REU= 0, -92.632D, 0
MARKER/10501, PART=10300, QP= -0.4683, -0.0064, 0.0003    ! aero marker 1
,   REU= 0, -92.725D, 0
MARKER/10601, PART=10300, QP= 0.5294, -0.0042, 0.0002    ! aero marker 2
,   REU= 0, -92.544D, 0
GRAPHIC/10301, OUTLINE=10200,10300
FIELD/10300, I=10305, J=10205, KMATRIX= 1.5487e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 1.0866e+008, 0.0000e+000, 0.0000e+000, 0.0000e+000, -1.0068e+008
, 0.0000e+000, 0.0000e+000, 4.9512e+008, 0.0000e+000, 4.9495e+008, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.0338e+007, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 4.9495e+008, 0.0000e+000, 6.5901e+008, 0.0000e+000
, 0.0000e+000, -1.0068e+008, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.2878e+008
```

```
,   LENGTH= 1.9950,0.0015,-0.0804, 0.336D,0,0, CRATIO=0.0005

!           blade part #10400

PART/10400, MASS=269.6, CM=10400,   IP= 55.1, 138.6, 94.6
,   QG= -3.3109, 0, 45.1625, REU= 90D, 93.770D, 90.000D
MARKER/10400, PART=10400, QP= 0, -0.3634, 0.0143       ! cg marker
,   REU= 0, -92.251D, 0
MARKER/10405, PART=10400, QP= 0, -0.2640, 0.0104       ! ea marker
,   REU= 0, -92.251D, 0
MARKER/10701, PART=10400, QP= -0.4640, -0.0018, 0.0001    ! aero marker 1
,   REU= 0, -92.355D, 0
MARKER/10801, PART=10400, QP= 0.5338, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -92.156D, 0
GRAPHIC/10401, OUTLINE=10300,10400
FIELD/10400, I=10405, J=10305, KMATRIX= 1.3202e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 7.0972e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, -6.5678e+007
, 0.0000e+000, 0.0000e+000, 4.3826e+008, 0.0000e+000, 4.1541e+008, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 6.6475e+006, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 4.1541e+008, 0.0000e+000, 5.3755e+008, 0.0000e+000
, 0.0000e+000, -6.5678e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, 8.3878e+007
,   LENGTH= 1.9910,0.0018,-0.0112, 0.380D,0,0, CRATIO=0.0005

!           blade part #10500

PART/10500, MASS=214.7, CM=10500,   IP= 37.7, 105.1, 74.3
,   QG= -3.1801, 0, 47.1473, REU= 90D, 93.770D, 90.000D
MARKER/10500, PART=10500, QP= 0, -0.3452, 0.0109       ! cg marker
,   REU= 0, -91.807D, 0
MARKER/10505, PART=10500, QP= 0, -0.2442, 0.0077       ! ea marker
,   REU= 0, -91.807D, 0
MARKER/10901, PART=10500, QP= -0.4576, 0.0000, 0.0000    ! aero marker 1
,   REU= 0, -91.920D, 0
MARKER/11001, PART=10500, QP= 0.5401, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -91.685D, 0
GRAPHIC/10501, OUTLINE=10400,10500
FIELD/10500, I=10505, J=10405, KMATRIX= 1.0753e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 4.5365e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, -4.1547e+007
, 0.0000e+000, 0.0000e+000, 3.0934e+008, 0.0000e+000, 2.8543e+008, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 4.2996e+006, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 2.8543e+008, 0.0000e+000, 3.6376e+008, 0.0000e+000
, 0.0000e+000, -4.1547e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, 5.2727e+007
,   LENGTH= 1.9890,0.0019,0.0199, 0.444D,0,0, CRATIO=0.0005

!           blade part #10600

PART/10600, MASS=162.8, CM=10600,   IP= 23.8, 75.4, 55.5
,   QG= -3.0496, 0, 49.1281, REU= 90D, 93.770D, 90.000D
MARKER/10600, PART=10600, QP= 0, -0.3163, 0.0071       ! cg marker
,   REU= 0, -91.278D, 0
MARKER/10605, PART=10600, QP= 0, -0.2206, 0.0049       ! ea marker
,   REU= 0, -91.278D, 0
MARKER/11101, PART=10600, QP= -0.4472, 0.0000, 0.0000    ! aero marker 1
,   REU= 0, -91.411D, 0
MARKER/11201, PART=10600, QP= 0.5505, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -91.118D, 0
GRAPHIC/10601, OUTLINE=10500,10600
FIELD/10600, I=10605, J=10505, KMATRIX= 8.4118e+008
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 2.7316e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, -2.4634e+007
, 0.0000e+000, 0.0000e+000, 1.9775e+008, 0.0000e+000, 1.8104e+008, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 2.6424e+006, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 1.8104e+008, 0.0000e+000, 2.2951e+008, 0.0000e+000
, 0.0000e+000, -2.4634e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, 3.0960e+007
,   LENGTH= 1.9850,0.0020,0.0237, 0.530D,0,0, CRATIO=0.0005

!           blade part #10700

PART/10700, MASS=114.8, CM=10700,   IP= 13.7, 50.2, 38.6
```

```
,   QG= -2.9193, 0, 51.1055, REU= 90D, 93.770D, 90.000D
MARKER/10700, PART=10700, QP= 0, -0.2815, 0.0031       ! cg marker
,   REU= 0, -90.628D, 0
MARKER/10705, PART=10700, QP= 0, -0.1973, 0.0022       ! ea marker
,   REU= 0, -90.628D, 0
MARKER/11301, PART=10700, QP= -0.4334, 0.0000, 0.0000    ! aero marker 1
,   REU= 0, -90.808D, 0
MARKER/11401, PART=10700, QP= 0.5644, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -90.431D, 0
GRAPHIC/10701, OUTLINE=10600,10700
FIELD/10700, I=10705, J=10605, KMATRIX= 6.4385e+008
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 1.5223e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, -1.3529e+007
, 0.0000e+000, 0.0000e+000, 1.2322e+008, 0.0000e+000, 1.1242e+008, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.5168e+006, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 1.1242e+008, 0.0000e+000, 1.4212e+008, 0.0000e+000
, 0.0000e+000, -1.3529e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.6847e+007
,   LENGTH= 1.9820,0.0022,0.0234, 0.650D,0,0, CRATIO=0.0005

!           blade part #10800

PART/10800, MASS=72.9, CM=10800,   IP= 7.1, 30.2, 24.1
,   QG= -2.7896, 0, 53.0737, REU= 90D, 93.770D, 90.000D
MARKER/10800, PART=10800, QP= 0, -0.2492, -0.0008       ! cg marker
,   REU= 0, -89.822D, 0
MARKER/10805, PART=10800, QP= 0, -0.1740, -0.0005       ! ea marker
,   REU= 0, -89.822D, 0
MARKER/11501, PART=10800, QP= -0.4104, 0.0000, 0.0000    ! aero marker 1
,   REU= 0, -90.047D, 0
MARKER/11601, PART=10800, QP= 0.5873, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -89.583D, 0
GRAPHIC/10801, OUTLINE=10700,10800
FIELD/10800, I=10805, J=10705, KMATRIX= 4.7422e+008
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 7.6902e+006, 0.0000e+000, 0.0000e+000, 0.0000e+000, -6.6072e+006
, 0.0000e+000, 0.0000e+000, 7.3081e+007, 0.0000e+000, 6.4793e+007, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 7.9462e+005, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 6.4793e+007, 0.0000e+000, 8.0415e+007, 0.0000e+000
, 0.0000e+000, -6.6072e+006, 0.0000e+000, 0.0000e+000, 0.0000e+000, 8.0459e+006
,   LENGTH= 1.9730,0.0024,0.0233, 0.805D,0,0, CRATIO=0.0005

!           blade part #10900

PART/10900, MASS=40.5, CM=10900,   IP= 3.5, 16.3, 13.1
,   QG= -2.6596, 0, 55.0463, REU= 90D, 93.770D, 90.000D
MARKER/10900, PART=10900, QP= 0, -0.2194, -0.0046       ! cg marker
,   REU= 0, -88.808D, 0
MARKER/10905, PART=10900, QP= 0, -0.1506, -0.0031       ! ea marker
,   REU= 0, -88.808D, 0
MARKER/11701, PART=10900, QP= -0.3918, 0.0000, 0.0000    ! aero marker 1
,   REU= 0, -89.065D, 0
MARKER/11801, PART=10900, QP= 0.6060, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -88.536D, 0
GRAPHIC/10901, OUTLINE=10800,10900
FIELD/10900, I=10905, J=10805, KMATRIX= 3.2430e+008
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 3.2750e+006, 0.0000e+000, 0.0000e+000, 0.0000e+000, -2.7721e+006
, 0.0000e+000, 0.0000e+000, 3.7449e+007, 0.0000e+000, 3.2685e+007, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 3.6362e+005, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 3.2685e+007, 0.0000e+000, 4.0221e+007, 0.0000e+000
, 0.0000e+000, -2.7721e+006, 0.0000e+000, 0.0000e+000, 0.0000e+000, 3.3469e+006
,   LENGTH= 1.9760,0.0027,0.0234, 1.015D,0,0, CRATIO=0.0005

!           blade part #11000

PART/11000, MASS=19.7, CM=11000,   IP= 1.9, 8.1, 6.3
,   QG= -2.5299, 0, 57.0146, REU= 90D, 93.770D, 90.000D
MARKER/11000, PART=11000, QP= 0, -0.1892, -0.0082       ! cg marker
,   REU= 0, -87.525D, 0
MARKER/11005, PART=11000, QP= 0, -0.1272, -0.0055       ! ea marker
,   REU= 0, -87.525D, 0
```

```
MARKER/11901, PART=11000, QP= -0.3689, 0.0000, 0.0000    ! aero marker 1
,   REU= 0, -87.798D, 0
MARKER/12001, PART=11000, QP= 0.6289, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -87.059D, 0
GRAPHIC/11001, OUTLINE=10900,11000
FIELD/11000, I=11005, J=10905, KMATRIX= 2.2852e+008
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 1.2811e+006, 0.0000e+000, 0.0000e+000, 0.0000e+000, -1.0680e+006
, 0.0000e+000, 0.0000e+000, 1.8971e+007, 0.0000e+000, 1.6904e+007, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.4884e+005, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 1.6904e+007, 0.0000e+000, 2.1043e+007, 0.0000e+000
, 0.0000e+000, -1.0680e+006, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.2759e+006
,   LENGTH= 1.9730,0.0029,0.0233, 1.283D,0,0, CRATIO=0.0005

!    Blade Tip Marker
MARKER/13000, PART=11000, QP= 1.1277, -0.1718, -0.0074
,   REU = 0, 0, 0
GRAPHIC/13000, OUTLINE=13000,11000

!
!           parts for blade #2
!

!           dummy part for blade root
PART/5200, MASS=0.1, CM=5200
,   IP= 0.1, 0.1, 0.1
,   QG= -3.9494, 0, 35.4722, REU= 90D, 93.770D, -90.000D
MARKER/5200, PART=5200, QP= 0, -0.0898, 0.0054    ! cg marker
,   REU = 0, -93.440D, 0
MARKER/5205, PART=5200, QP= 0, 0.0080, -0.0005    ! ea marker
,   REU= 0, -93.440D, 0
MARKER/5209, PART=5200, REU= 90D, 90D, 90D    ! pitch marker on blade

JOINT/4209, FIXED, I= 4209, J= 5209             ! pitch joint

!           blade part #20100

PART/20100, MASS=497.0, CM=20100,   IP= 82.9, 225.7, 184.3
,   QG= -4.0121, 0, 34.5218, REU= 90D, 93.770D, -90.000D
MARKER/20100, PART=20100, QP= 0, -0.1514, 0.0087       ! cg marker
,   REU= 0, -93.289D, 0
MARKER/20105, PART=20100, QP= 0, -0.0500, 0.0029       ! ea marker
,   REU= 0, -93.289D, 0
MARKER/20101, PART=20100, QP= -0.4537, -0.0167, 0.0010    ! aero marker 1
,   REU= 0, -93.362D, 0
MARKER/20201, PART=20100, QP= 0.5441, -0.0129, 0.0007    ! aero marker 2
,   REU= 0, -93.202D, 0
GRAPHIC/20101, OUTLINE=5200,20100
FIELD/20100, I=20105, J=5205, KMATRIX= 5.0387e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 2.1538e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, -1.0041e+009
, 0.0000e+000, 0.0000e+000, 4.2296e+009, 0.0000e+000, 2.0622e+009, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 4.2078e+007, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 2.0622e+009, 0.0000e+000, 1.3247e+009, 0.0000e+000
, 0.0000e+000, -1.0041e+009, 0.0000e+000, 0.0000e+000, 0.0000e+000, 6.3070e+008
,   LENGTH= 0.9530,0.0001,-0.0581, 0.151D,0,0, CRATIO=0.0005

!           blade part #20200

PART/20200, MASS=393.8, CM=20200,   IP= 81.7, 198.2, 143.6
,   QG= -4.1443, 0, 32.5156, REU= 90D, 93.770D, -90.000D
MARKER/20200, PART=20200, QP= 0, -0.2776, 0.0144       ! cg marker
,   REU= 0, -92.968D, 0
MARKER/20205, PART=20200, QP= 0, -0.1723, 0.0089       ! ea marker
,   REU= 0, -92.968D, 0
MARKER/20301, PART=20200, QP= -0.4687, -0.0104, 0.0006    ! aero marker 1
,   REU= 0, -93.044D, 0
MARKER/20401, PART=20200, QP= 0.5290, -0.0080, 0.0004    ! aero marker 2
,   REU= 0, -92.881D, 0
GRAPHIC/20201, OUTLINE=20100,20200
FIELD/20200, I=20205, J=20105, KMATRIX= 1.9831e+009
```

```
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 1.7168e+008, 0.0000e+000, 0.0000e+000, 0.0000e+000, -1.5823e+008
, 0.0000e+000, 0.0000e+000, 4.8129e+008, 0.0000e+000, 4.8364e+008, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.5951e+007, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 4.8364e+008, 0.0000e+000, 6.4812e+008, 0.0000e+000
, 0.0000e+000, -1.5823e+008, 0.0000e+000, 0.0000e+000, 0.0000e+000, 2.0247e+008
,   LENGTH= 2.0100,0.0010,-0.1225, 0.321D,0,0, CRATIO=0.0005

!           blade part #20300

PART/20300, MASS=328.0, CM=20300,   IP= 73.1, 172.9, 117.1
,   QG= -4.2754, 0, 30.5248, REU= 90D, 93.770D, -90.000D
MARKER/20300, PART=20300, QP= 0, -0.3544, 0.0163       ! cg marker
,   REU= 0, -92.632D, 0
MARKER/20305, PART=20300, QP= 0, -0.2527, 0.0116       ! ea marker
,   REU= 0, -92.632D, 0
MARKER/20501, PART=20300, QP= -0.4683, -0.0064, 0.0003    ! aero marker 1
,   REU= 0, -92.725D, 0
MARKER/20601, PART=20300, QP= 0.5294, -0.0042, 0.0002    ! aero marker 2
,   REU= 0, -92.544D, 0
GRAPHIC/20301, OUTLINE=20200,20300
FIELD/20300, I=20305, J=20205, KMATRIX= 1.5487e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 1.0866e+008, 0.0000e+000, 0.0000e+000, 0.0000e+000, -1.0068e+008
, 0.0000e+000, 0.0000e+000, 4.9512e+008, 0.0000e+000, 4.9495e+008, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.0338e+007, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 4.9495e+008, 0.0000e+000, 6.5901e+008, 0.0000e+000
, 0.0000e+000, -1.0068e+008, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.2878e+008
,   LENGTH= 1.9950,0.0015,-0.0804, 0.336D,0,0, CRATIO=0.0005

!           blade part #20400

PART/20400, MASS=269.6, CM=20400,   IP= 55.1, 138.6, 94.6
,   QG= -4.4064, 0, 28.5380, REU= 90D, 93.770D, -90.000D
MARKER/20400, PART=20400, QP= 0, -0.3634, 0.0143       ! cg marker
,   REU= 0, -92.251D, 0
MARKER/20405, PART=20400, QP= 0, -0.2640, 0.0104       ! ea marker
,   REU= 0, -92.251D, 0
MARKER/20701, PART=20400, QP= -0.4640, -0.0018, 0.0001    ! aero marker 1
,   REU= 0, -92.355D, 0
MARKER/20801, PART=20400, QP= 0.5338, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -92.156D, 0
GRAPHIC/20401, OUTLINE=20300,20400
FIELD/20400, I=20405, J=20305, KMATRIX= 1.3202e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 7.0972e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, -6.5678e+007
, 0.0000e+000, 0.0000e+000, 4.3826e+008, 0.0000e+000, 4.1541e+008, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 6.6475e+006, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 4.1541e+008, 0.0000e+000, 5.3755e+008, 0.0000e+000
, 0.0000e+000, -6.5678e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, 8.3878e+007
,   LENGTH= 1.9910,0.0018,-0.0112, 0.380D,0,0, CRATIO=0.0005

!           blade part #20500

PART/20500, MASS=214.7, CM=20500,   IP= 37.7, 105.1, 74.3
,   QG= -4.5371, 0, 26.5532, REU= 90D, 93.770D, -90.000D
MARKER/20500, PART=20500, QP= 0, -0.3452, 0.0109       ! cg marker
,   REU= 0, -91.807D, 0
MARKER/20505, PART=20500, QP= 0, -0.2442, 0.0077       ! ea marker
,   REU= 0, -91.807D, 0
MARKER/20901, PART=20500, QP= -0.4576, 0.0000, 0.0000    ! aero marker 1
,   REU= 0, -91.920D, 0
MARKER/21001, PART=20500, QP= 0.5401, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -91.685D, 0
GRAPHIC/20501, OUTLINE=20400,20500
FIELD/20500, I=20505, J=20405, KMATRIX= 1.0753e+009
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 4.5365e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, -4.1547e+007
, 0.0000e+000, 0.0000e+000, 3.0934e+008, 0.0000e+000, 2.8543e+008, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 4.2996e+006, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 2.8543e+008, 0.0000e+000, 3.6376e+008, 0.0000e+000
```

```
, 0.0000e+000, -4.1547e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, 5.2727e+007
,   LENGTH= 1.9890,0.0019,0.0199, 0.444D,0,0, CRATIO=0.0005

!           blade part #20600

PART/20600, MASS=162.8, CM=20600,   IP= 23.8, 75.4, 55.5
,   QG= -4.6677, 0, 24.5724, REU= 90D, 93.770D, -90.000D
MARKER/20600, PART=20600, QP= 0, -0.3163, 0.0071       ! cg marker
,   REU= 0, -91.278D, 0
MARKER/20605, PART=20600, QP= 0, -0.2206, 0.0049       ! ea marker
,   REU= 0, -91.278D, 0
MARKER/21101, PART=20600, QP= -0.4472, 0.0000, 0.0000    ! aero marker 1
,   REU= 0, -91.411D, 0
MARKER/21201, PART=20600, QP= 0.5505, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -91.118D, 0
GRAPHIC/20601, OUTLINE=20500,20600
FIELD/20600, I=20605, J=20505, KMATRIX= 8.4118e+008
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 2.7316e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, -2.4634e+007
, 0.0000e+000, 0.0000e+000, 1.9775e+008, 0.0000e+000, 1.8104e+008, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 2.6424e+006, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 1.8104e+008, 0.0000e+000, 2.2951e+008, 0.0000e+000
, 0.0000e+000, -2.4634e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, 3.0960e+007
,   LENGTH= 1.9850,0.0020,0.0237, 0.530D,0,0, CRATIO=0.0005

!           blade part #20700

PART/20700, MASS=114.8, CM=20700,   IP= 13.7, 50.2, 38.6
,   QG= -4.7980, 0, 22.5951, REU= 90D, 93.770D, -90.000D
MARKER/20700, PART=20700, QP= 0, -0.2815, 0.0031       ! cg marker
,   REU= 0, -90.628D, 0
MARKER/20705, PART=20700, QP= 0, -0.1973, 0.0022       ! ea marker
,   REU= 0, -90.628D, 0
MARKER/21301, PART=20700, QP= -0.4334, 0.0000, 0.0000    ! aero marker 1
,   REU= 0, -90.808D, 0
MARKER/21401, PART=20700, QP= 0.5644, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -90.431D, 0
GRAPHIC/20701, OUTLINE=20600,20700
FIELD/20700, I=20705, J=20605, KMATRIX= 6.4385e+008
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 1.5223e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, -1.3529e+007
, 0.0000e+000, 0.0000e+000, 1.2322e+008, 0.0000e+000, 1.1242e+008, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.5168e+006, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 1.1242e+008, 0.0000e+000, 1.4212e+008, 0.0000e+000
, 0.0000e+000, -1.3529e+007, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.6847e+007
,   LENGTH= 1.9820,0.0022,0.0234, 0.650D,0,0, CRATIO=0.0005

!           blade part #20800

PART/20800, MASS=72.9, CM=20800,   IP= 7.1, 30.2, 24.1
,   QG= -4.9277, 0, 20.6268, REU= 90D, 93.770D, -90.000D
MARKER/20800, PART=20800, QP= 0, -0.2492, -0.0008       ! cg marker
,   REU= 0, -89.822D, 0
MARKER/20805, PART=20800, QP= 0, -0.1740, -0.0005       ! ea marker
,   REU= 0, -89.822D, 0
MARKER/21501, PART=20800, QP= -0.4104, 0.0000, 0.0000    ! aero marker 1
,   REU= 0, -90.047D, 0
MARKER/21601, PART=20800, QP= 0.5873, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -89.583D, 0
GRAPHIC/20801, OUTLINE=20700,20800
FIELD/20800, I=20805, J=20705, KMATRIX= 4.7422e+008
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 7.6902e+006, 0.0000e+000, 0.0000e+000, 0.0000e+000, -6.6072e+006
, 0.0000e+000, 0.0000e+000, 7.3081e+007, 0.0000e+000, 6.4793e+007, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 7.9462e+005, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 6.4793e+007, 0.0000e+000, 8.0415e+007, 0.0000e+000
, 0.0000e+000, -6.6072e+006, 0.0000e+000, 0.0000e+000, 0.0000e+000, 8.0459e+006
,   LENGTH= 1.9730,0.0024,0.0233, 0.805D,0,0, CRATIO=0.0005

!           blade part #20900
```

```
PART/20900, MASS=40.5, CM=20900,   IP= 3.5, 16.3, 13.1
,   QG= -5.0576, 0, 18.6542, REU= 90D, 93.770D, -90.000D
MARKER/20900, PART=20900, QP= 0, -0.2194, -0.0046       ! cg marker
,   REU= 0, -88.808D, 0
MARKER/20905, PART=20900, QP= 0, -0.1506, -0.0031       ! ea marker
,   REU= 0, -88.808D, 0
MARKER/21701, PART=20900, QP= -0.3918, 0.0000, 0.0000    ! aero marker 1
,   REU= 0, -89.065D, 0
MARKER/21801, PART=20900, QP= 0.6060, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -88.536D, 0
GRAPHIC/20901, OUTLINE=20800,20900
FIELD/20900, I=20905, J=20805, KMATRIX= 3.2430e+008
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 3.2750e+006, 0.0000e+000, 0.0000e+000, 0.0000e+000, -2.7721e+006
, 0.0000e+000, 0.0000e+000, 3.7449e+007, 0.0000e+000, 3.2685e+007, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 3.6362e+005, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 3.2685e+007, 0.0000e+000, 4.0221e+007, 0.0000e+000
, 0.0000e+000, -2.7721e+006, 0.0000e+000, 0.0000e+000, 0.0000e+000, 3.3469e+006
,   LENGTH= 1.9760,0.0027,0.0234, 1.015D,0,0, CRATIO=0.0005

!           blade part #21000

PART/21000, MASS=19.7, CM=21000,   IP= 1.9, 8.1, 6.3
,   QG= -5.1873, 0, 16.6859, REU= 90D, 93.770D, -90.000D
MARKER/21000, PART=21000, QP= 0, -0.1892, -0.0082       ! cg marker
,   REU= 0, -87.525D, 0
MARKER/21005, PART=21000, QP= 0, -0.1272, -0.0055       ! ea marker
,   REU= 0, -87.525D, 0
MARKER/21901, PART=21000, QP= -0.3689, 0.0000, 0.0000    ! aero marker 1
,   REU= 0, -87.798D, 0
MARKER/22001, PART=21000, QP= 0.6289, 0.0000, 0.0000    ! aero marker 2
,   REU= 0, -87.059D, 0
GRAPHIC/21001, OUTLINE=20900,21000
FIELD/21000, I=21005, J=20905, KMATRIX= 2.2852e+008
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 1.2811e+006, 0.0000e+000, 0.0000e+000, 0.0000e+000, -1.0680e+006
, 0.0000e+000, 0.0000e+000, 1.8971e+007, 0.0000e+000, 1.6904e+007, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.4884e+005, 0.0000e+000, 0.0000e+000
, 0.0000e+000, 0.0000e+000, 1.6904e+007, 0.0000e+000, 2.1043e+007, 0.0000e+000
, 0.0000e+000, -1.0680e+006, 0.0000e+000, 0.0000e+000, 0.0000e+000, 1.2759e+006
,   LENGTH= 1.9730,0.0029,0.0233, 1.283D,0,0, CRATIO=0.0005

!    Blade Tip Marker
MARKER/23000, PART=21000, QP= 1.1277, -0.1718, -0.0074
,   REU = 0, 0, 0
GRAPHIC/23000, OUTLINE=23000,21000

!
! gravity and inertial constants
!  units: m, kg, s, Newtons
!
UNITS/SYSTEM=MKS
ACCGRAV/KGRAV=-9.80665

END
```

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
September 2004

2. REPORT TYPE
Subcontract Report

3. DATES COVERED *(From - To)*
August 25 - November 30, 2003

4. TITLE AND SUBTITLE
Geometry and Structural Properties for the Controls Advanced Research Turbine (CART) from Model Tuning

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
K.A. Stol

5d. PROJECT NUMBER
NREL/SR-500-32087

5e. TASK NUMBER
WER43301

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Auckland
Private Bag 92019
Auckland, New Zealand

8. PERFORMING ORGANIZATION REPORT NUMBER
AAM-3-33231-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
NREL/SR-500-32087

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES
NREL Technical Monitor: A. Wright

14. ABSTRACT *(Maximum 200 Words)*

The Controls Advanced Research Turbine (CART) is a modified Westinghouse WWG-0600 machine rated at 600 kW. It is located at the National Wind Technology Center (NWTC) in Boulder, Colorado, and has been installed to test new control schemes for power and load regulation. In its original configuration, the WWG-0600 uses a synchronous generator, fluid coupling, and hydraulic collective pitch actuation. However, the CART is fitted with an induction generator, rigid coupling, and individual electromechanical pitch actuators. The rotor runs upwind of the tower and consists of two blades and a teetering hub.In order to design advanced control schemes for the CART, representative computational models are essential.

15. SUBJECT TERMS
CART; ADAMS models; distributed mass; stiffness; low-speed shaft;

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		19b. TELEPONE NUMBER *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1146-E(05/2004)