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Technical Report

A Demonstration of the Ability of RCAS to Model Wind Turbines

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Executive Summary

In recent years, the wind industry has sponsored the development, verification, and validation of comprehensive aeroelastic simulators, which are used by industry, academia, and government entities for wind turbine design, certification, and research. Unfortunately, as wind turbines continue to grow in size, become more flexible, are augmented with sophisticated controllers, and sometimes exhibit unconventional design characteristics, the existing codes do not always support the additional analysis features required for proper design. Examples of analysis options not supported by most wind turbine design codes include aeroelastic stability, a wide variety of aerodynamic modeling options, well-integrated control implementation, modal reduction, and others. These limitations and the increasing need to perform more advanced analyses are motivating the wind industry to search for new and improved analysis tools.

The development history, functionality, and advanced nature of RCAS (Rotorcraft Comprehensive Analysis System) make this code a sensible option. RCAS is an aeroelastic simulator developed over a 4-year cooperative effort among the U.S. Army's Aeroflightdynamics Directorate, Advanced Rotorcraft Technology (ART), Inc., and the helicopter industry. An additional 14 years were spent developing its predecessor. As its name suggests, RCAS was created for the rotorcraft industry but developed as a general purpose code for modeling the aerodynamic and structural response of any system with rotating and nonrotating subsystems (such as wind turbines). RCAS employs the finite element method (FEM) modeling approach. It includes nonlinear beam "elements" capable of modeling important centrifugal, gyroscopic, large-deflection, and pretwist effects needed for accurate rotor blade modeling. Several rotary aerodynamic modules are available, including blade-element-momentum (BEM), lifting line, prescribed wake, free wake, and the capability of modeling aerodynamic interactions among the rotor, nacelle, and tower. RCAS is easily integrated with advanced controls in a familiar Simulink®-style environment, and it incorporates many features not available in existing wind turbine analysis codes, including aeroelastic stability analysis, modal reduction, and periodic Floquet analysis.

To demonstrate that RCAS can analyze wind turbines, models of a conventional, 1.5-MW, 3-bladed, upwind, horizontal axis wind turbine (HAWT) are created in RCAS and wind-industry-accepted wind turbine analysis codes FAST (Fatigue, Aerodynamics, Structures, and Turbulence) and ADAMS (Automatic Dynamic Analysis of Mechanical Systems). Using these models, a side-by-side comparison of structural response predictions is performed under several test scenarios. The project scope is limited to a high-level comparison of the systems responses under a few, typical wind turbine analysis conditions; a detailed verification of low-level element responses is not developed. Furthermore, the study does not attempt to demonstrate the diverse functionality of RCAS; only the basic structural dynamic features are employed.

All three codes employ different modeling techniques. Nevertheless, comparisons of response predictions among the codes show excellent agreement and do not expose any glaring inaccuracies in RCAS. For example, modal analyses of the ADAMS and RCAS models show that the predicted full-system natural frequencies are within 2% of each other for at least the first 15 modes. Regions where the different response predictions do not exactly coalesce are attributed to differences in modeling techniques, such as integration methods and the differences between the FEM (RCAS), assumed modes (FAST), and lumped-properties (ADAMS) structural dynamics modeling approaches.

The wind industry's acceptance and acquisition of RCAS are not without obstacles, however. RCAS's inherent complexity is a mixed blessing, and its user interface is somewhat lacking. The learning curve is also steep. Nevertheless, the user-friendliness will naturally improve in time as the code and its user's manuals are upgraded. In the end, the wind industry must decide whether the gains accrued from RCAS's enhanced functionality relative to existing wind turbine analysis tools outweigh the costs of adopting this new code.

Background

Over the past decade, the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) has sponsored the development, verification, and validation of comprehensive aeroelastic simulators capable of predicting both the extreme loads and the fatigue life of wind turbines. These simulation tools, also known as design codes, are used by industry, academia, and government entities for wind turbine design, certification, and research. In general, these design codes enable a user to (1) define an aerodynamic and structural model of a wind turbine given the turbine geometry and aerodynamic and mechanical properties of its members, and (2) simulate the wind turbine's aerodynamic and structural response by imposing complex, virtual wind-inflow conditions. Outputs of the simulations include time-series data on the loads and deflections of the structural members of the wind turbine. Post-processing codes are then used to analyze these data.

In many respects, design codes bridge the gap between theorized predictions and experimental and/or observable measurements. Design codes enable virtual experiments capable of yielding load analysis results quickly and cheaply. In many situations, virtual experimentation offers the only practical method of research and testing.

FAST [1] and ADAMS® [2] are two of the most sophisticated codes used by the U.S. wind industry and the two most promoted by NREL's National Wind Technology Center (NWTC). ADAMS is a commercially available, general purpose, multibody-dynamics code from MSC.Software Corporation that is adaptable for modeling wind turbines. FAST is a structural-response, wind-turbine-specific code originally developed by Oregon State University and the University of Utah for the NWTC. Both FAST and ADAMS use Windward Engineering LLC's AeroDyn aerodynamic subroutine package for calculating aerodynamic forces [3].

Unfortunately, as wind turbines continue to grow in size, become more flexible, are augmented with sophisticated controllers, and sometimes exhibit unconventional design characteristics, the existing codes do not always support the additional features required for proper design. Examples of options not supported by most wind turbine design codes (including FAST and ADAMS) include aeroelastic stability, multiple aerodynamic modeling options, well-integrated control implementation, modal reduction, and others.

The RCAS aeroelastic code [4], [5], [6], the successor of the Second Generation Comprehensive Helicopter Analysis System (2GCHAS), has the potential to fill this void. This code is a result of a 4-year cooperative effort among the U.S. Army's Aeroflightdynamics Directorate, Advanced Rotorcraft Technology (ART), Inc., and the helicopter industry. An additional 14 years were spent developing 2GCHAS. RCAS was created for the rotorcraft industry but developed as a general purpose code for modeling the aerodynamic and structural response of any system with rotating and nonrotating subsystems (such as wind turbines).

There are many motivations for exploring the potential to use RCAS for analyzing wind turbines. It is the most advanced aeroelastics code available for analyzing rotorcraft technology, with almost 20 years of development history. It includes nonlinear beam elements capable of modeling important centrifugal, gyroscopic, large-deflection, and pretwist effects needed for accurate rotor blade modeling. The code is flexible enough to model unconventional, precurved blades, rotors with teeter and delta-3, and complex linkages for blade collective pitch control. Several rotary aerodynamic modules are available, including blade-element-momentum (BEM), lifting line, prescribed wake, free wake, and the capability of modeling aerodynamic interactions among the rotor, nacelle, and tower. RCAS is easily integrated with advanced controls in a familiar Simulink®-style environment, and it incorporates many features not available in existing wind turbine analysis codes, including aeroelastic stability analysis, modal reduction, and periodic Floquet analysis. Finally, RCAS is free to U.S. industries, unlike many commercial codes (such as ADAMS), which require expensive licensing fees.

Objective

The objective of this study is to demonstrate that RCAS can analyze wind turbines through a side-by-side comparison of response predictions obtained using RCAS and the industry-accepted wind turbine analysis codes FAST and ADAMS. The project scope is limited to a high-level comparison of the systems responses under a few, typical wind turbine analysis conditions; a detailed verification of low-level element responses is not developed herein. Furthermore, the study does not attempt to demonstrate the diverse functionality of RCAS; only the basic structural dynamic features are employed.

Approach

A conventional, 1.5-MW, 3-bladed, upwind, horizontal-axis wind turbine is selected for the side-by-side comparison. Models of this turbine are created using RCAS and the industry-accepted wind turbine analysis codes FAST and ADAMS. Operating cases are chosen to demonstrate that RCAS can be applied to analyze wind turbines, and the results are compared in a side-by-side fashion.

Description of Codes

FAST, ADAMS, and RCAS all employ different techniques of modeling wind turbine structural dynamics. This section documents the general class of modeling techniques employed in the various codes. For a more detailed description of the structural dynamic theories each code employs, please refer to their respective user's guides and theory manuals [1], [2], [4], [5], [6]. Modeling tools continue to be upgraded and versions of the codes become outdated; for reference, Table 1 lists the programs and version numbers used in this study.

Table 1: Program Versions Used in this Study

Program	Version
FAST	4.10 (not yet released to public), AeroDyn 12.51
ADAMS	12.0.0, AeroDyn 12.51
RCAS	1.9.5a

FAST is the simplest of the three codes used in this study and was developed specifically for modeling horizontal-axis wind turbines [1]. It has a limited number of degrees of freedom (DOFs) but can model most common wind turbine configurations and control scenarios. FAST models the blades and tower as individual flexible elements using a modal representation. The flexibility characteristics of these members are determined by specifying distributed stiffness and mass properties along the span of the members and by prescribing their mode shapes through equivalent polynomial coefficients. Flexibility in the drive train is modeled using an equivalent linear spring and damper model. The high-speed shaft (HSS) inertias and torques are cast to the low-speed shaft (LSS) through appropriate multiplications and divisions with the gearbox ratio, so the HSS is, in essence, not modeled independently of the LSS. The nacelle and hub are modeled in FAST as rigid bodies with appropriate mass and inertia terms. Time marching of the equations of motion (EoM) is performed using a constant-time-step, Adams-Bashforth-Adams-Moulton, predictor-corrector integration scheme.

The structural dynamics models of ADAMS are more sophisticated, permitting virtually an unlimited combination of model configurations and DOFs [2]. It is not a wind-turbine-specific code and is routinely used by members of the automotive, aerospace, and robotics industries. Flexible members, such as the blades and tower of a wind turbine, are modeled in ADAMS using a series of lumped masses connected by flexible "fields" akin to multidimensional spring dampers. ADAMS can model the drive train through a similar series of lumped masses and flexible fields or through a simple, single-DOF hinge/spring/damper element. As in FAST, the nacelle and hub are usually modeled using rigid bodies with lumped mass and inertia properties but can be modeled with flexibility. ADAMS incorporates a similar time-marching integration scheme as the one in FAST, except that the ADAMS scheme incorporates a variable time step algorithm.

RCAS is the most complex of the three codes, employing the FEM approach [4], [5], [6]. Instead of an assumed-modes or lumped-mass approach, flexible members in RCAS are modeled as fully flexible beam elements with fully distributed mass and stiffness properties. As in typical FEM work, the model is assembled by defining "nodes," which are then interconnected by "elements." The types of "elements" range from the trivial single-DOF hinge/spring/damper element to the complex, fully flexible, nine-DOF nonlinear beam element[†]. The nonlinear

[†] To be precise, the nonlinear beam element actually has 15 DOF if it is not cantilevered to a parent element.

beam element takes into account important centrifugal, gyroscopic, and large-deflection effects needed for accurate rotor blade modeling. The flexibility characteristics of the nonlinear beam elements are determined by prescribing distributed stiffness and mass properties along the span of the elements, similar to the input format used to define a FAST model; these are then integrated along the beam elements using Gaussian Quadrature integration techniques. Time marching of the EoM is achieved using a constant time step, Hilber-Hughes-Taylor (HHT) integration scheme, which is based on the Newmark-Beta integration method.

Both FAST and ADAMS use the AeroDyn aerodynamic subroutine package for computing aerodynamic forces [3]. This aerodynamic module package models wind turbine aerodynamics using the classic, equilibrium-based, BEM theory or by using a generalized dynamic inflow model, both of which include the effects of axial and tangential induction and tip and hub losses as characterized by Prandtl. Dynamic stall behavior is characterized using the Beddoes-Leishman dynamic stall model.

Previous comparisons among FAST (previously known as FAST_AD in some literature), ADAMS, and other industry-accepted wind turbine analysis codes show excellent agreement between FAST and ADAMS response predictions [7], [8], [9]. RCAS is just recently entering the validation phase. Some initial findings associated with the structural mechanics and dynamics of rotor blades show excellent promise [10]. RCAS's predecessor 2GCHAS has also been extensively validated.

Turbine Description

The turbine geometry, mechanical properties, and aerodynamic information were obtained from the baseline turbine in the Wind Partnership for Advanced Component Technologies (WindPACT) Turbine Rotor Design Study [11]. The WindPACT Rotor Design Study was performed by Global Energy Concepts and Windward Engineering Inc. to identify technology improvements that will enable the cost of energy from wind turbines to fall to a target of 3.0¢/kWh in low-wind-speed sites.

The WindPACT baseline turbine was created by surveying modern wind turbines. It represents a conventional, 1.5-MW, 3-bladed, upwind, horizontal-axis wind turbine. Table 2 contains a summary of the turbine design properties.

Table 2: Summary of Baseline Turbine Design Properties

Rotor Diameter	70 m
Hub Height	84 m
Hub Overhang	3.3 m
Rotor Precone	0°
Shaft Tilt	5°
Tower Base Diameter	5.663 m
Max Rotor Speed	20.5 rpm
Tip Speed Ratio for Maximum Power Coefficient	7.0

A working ADAMS model of the WindPACT baseline turbine was obtained from Windward Engineering Inc. This ADAMS model was used to verify the NREL FAST and ADAMS models used in this study through a side-by-side comparison of response predictions. In performing this model comparison, several differences and a few errors were discovered in Windward Engineering's original model. Although the results of this model comparison are not documented in this report, three small errors in Windward Engineering's model are reported here to assist others who might wish to use the Windward Engineering WindPACT baseline model. Two of the errors concern the blade and tower inertias. On the blade, the distributed flap and edge inertias are switched. On the tower, the distributed tower inertia is twice that indicated in the turbine description. The third error is that each blade mass is 1000 kg heavier in Windward Engineering's ADAMS model than stated in the turbine description. This is due to poor interpolation of the distributed blade mass near the blade root section.

Description of Models

The FAST code can model a three-bladed HAWT with a maximum of 17 DOFs. All DOFs but the nacelle tilt and free yaw are enabled in the FAST model used in this study. These include blade flexibility (two flap and one edge mode for each independent blade), tower flexibility (two fore-aft and two side-to-side modes), and drive train torsion. The generator side of the shaft compliance is forced to spin at a constant rate (removing an additional available DOF), eliminating the need to implement electrical generator models, which are deemed unnecessary for the comparison of the various code's structural response predictions. A program entitled "Modes" [12] is used to generate the mode shapes for the assumed modes of the flexible blades and tower. An example set of FAST input files are given in Appendix A for the turbine spinning in a vacuum.

As alluded to in Table 1, a recently updated version of FAST, which has not yet been released to the public, is used in this study. This version of FAST has the capability of extracting "equivalent" ADAMS wind turbine datasets from the turbine properties specified in the FAST input file(s). That is, this new version of FAST has the functionality of acting like an ADAMS-preprocessor capable of creating ADAMS datasets of wind turbine models through FAST's simple property-input-style interface. The main advantages of using FAST to create the ADAMS model are to ensure consistency between the FAST and ADAMS models and to facilitate quick and easy creation of the ADAMS datasets.

The ADAMS datasets extracted from FAST contain most of the functionality and usability associated with the FAST model, while bypassing some of FAST's limitations. For example, instead of applying the assumed-mode characteristics of FAST's flexible members, the blades and tower of the extracted ADAMS model are developed from FAST's distributed mass and stiffness inputs using ADAMS' conventional approach of a series of lumped masses, connected by stiffness and damping fields. Additionally, several characteristics not implemented in the FAST model are incorporated into the extracted ADAMS model. Two notable examples are the distributed blade mass and elastic offsets. These offsets are incorporated into the ADAMS blade model, whereas the FAST model assumes the center of mass (c.m.) and elastic axes to be coincident with the collective pitch axis.

Like the FAST model, the yaw and tilt DOFs are disabled in the ADAMS model and the generator (cast to the LSS) is forced to rotate at a constant speed (though drive train torsion compliance is included). Tower flexibility is modeled in ADAMS using 10 equally spaced lumped masses (plus a yaw bearing mass) interconnected by 11 linear stiffness and damping fields. Similarly, each blade is modeled using 15 equally spaced lumped masses (plus a tip mass) interconnected by 16 linear stiffness and damping fields. The total number of structural DOFs in the ADAMS model is 355.

The RCAS model is developed so as to replicate the ADAMS model as close as possible (which, in turn, replicates the FAST model as close as possible). To do this, mass, stiffness, and geometrical properties are prescribed identically among all three models. Also, the nodes of the RCAS model are located where the lumped masses are positioned in the ADAMS model. In the RCAS blade models, these nodes are interconnected by 16 nonlinear beam elements, similar to the 16 ADAMS stiffness and damping fields. In the RCAS tower model, the nodes are interconnected by 11 nonlinear beam elements, similar to the 11 ADAMS stiffness and damping fields. The three internal nodes of each nonlinear beam element used in the RCAS model are disabled. Drive train compliance is modeled in RCAS using a single-DOF hinge/spring/damper element, and the generator is again cast to the LSS. Control hinges are implemented at the three blade collective pitch bearings and the nacelle yaw bearing so that motions of these hinges could easily be prescribed during the analysis phase. Like ADAMS, the RCAS model has 355 DOFs.

Regardless of the analysis type, all models are created so that their simulations begin with no initial deflection of their flexible members. This should be evident in the response comparisons documented in the following section, but it is constructive to reiterate this point: The simulations do not begin at static or dynamic equilibrium. In FAST, this is intrinsic, as the model begins with all DOFs zero-valued at time zero (unless initial conditions are prescribed otherwise in FAST's primary input file). In ADAMS, this is achieved by "locking" all DOFs over the first integration time step. In RCAS, this is achieved by prescribing all DOFs and their derivatives to equal zero before the time-series analysis (known as a "maneuver" analysis in RCAS) is initiated.

Simulation Results

The code demonstration consisted of five analyses: 1) parked turbine modal analysis, 2) spinning in a vacuum, 3) spinning and yawing in a vacuum, 4) steady loads, and 5) sinusoidal loads. Figure 1 depicts these analyses. In the last two analyses, point loads in two directions (normal and tangential) are applied to all 15 of the blade nodes in ADAMS and RCAS to simulate the effect of aerodynamic loads and associated responses. FAST results are not included for the last three analyses, due to the inherent difficulty in performing these types of analyses in FAST.

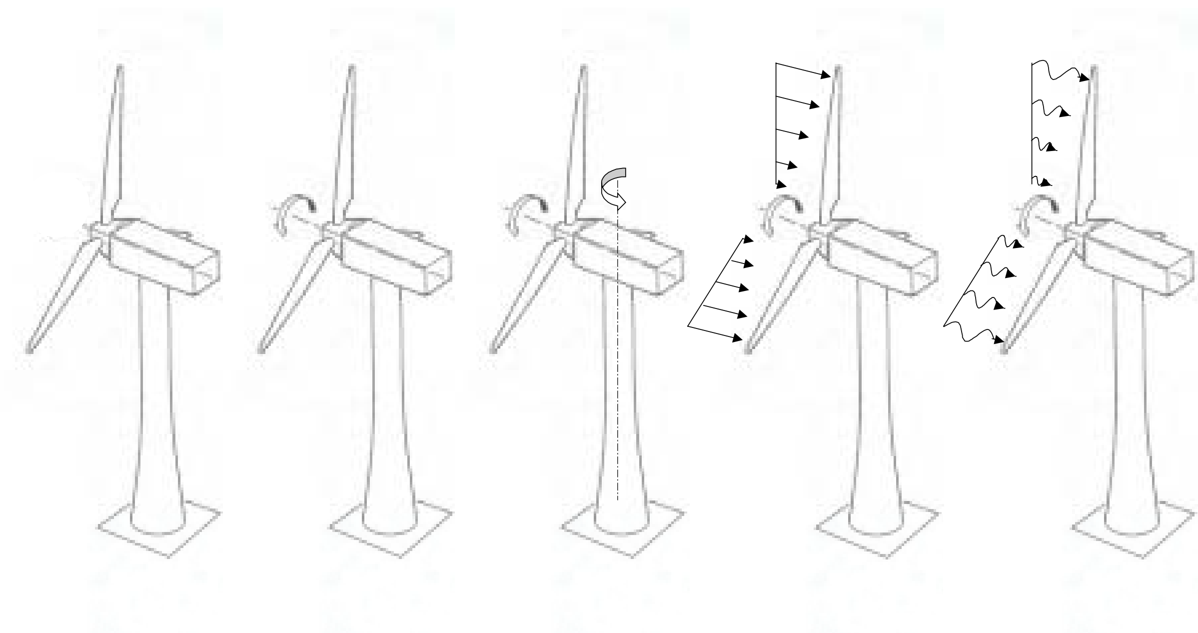

Figure 1: Graphical representation of analyses performed in the code demonstration.

Parked Turbine Modal Analysis

The modal analysis is performed on a stationary turbine (not spinning) and ignores gravitational and aerodynamic loads and structural damping. The blade collective pitch angle of all three blades is set at 2.6°, which corresponds with the minimum set position. The first 15 full system natural frequencies and mode shapes are examined. The resulting frequencies are listed in Table 3 along with a description of the corresponding modes. In ADAMS, these are obtained by invoking an ADAMS "LINEAR/EIGENSOL" command, which linearizes the complete ADAMS model and computes eigendata. In RCAS, a similar solution procedure is invoked using a stability analysis. For the FAST model, only independent system natural frequencies (i.e., tower alone or blade alone) are available outputs due to current limitations in the code. These frequencies are compared to the closest matching full system modes from ADAMS and RCAS in Table 3 for reference only. The types of the modes were established by viewing animations of the modes in ADAMS/View and verifying them against deflection shapes available in an RCAS postprocessor.

Table 3: Non-Rotating Full System Natural Frequencies

Mode	FAST†	ADAMS	RCAS	Description
1	0.421	0.408	0.405	1st tower side-to-side
2	0.421	0.409	0.407	1st tower fore-aft
3	-	1.151	1.154	1st blade axisymmetric flap (2 and 3 out of phase, 1 stationary)
4	1.236	1.203	1.206	1st blade axisymmetric flap (2 and 3 in phase, 1 out of phase)
5	-	1.256	1.259	1st blade symmetric flap
6	-	1.598	1.618	1st blade symmetric edge
7	1.878	1.824	1.860	1st blade axisymmetric edge (2 and 3 out of phase, 1 stationary)
8	-	1.852	1.888	1st blade axisymmertic edge (2 and 3 in phase, 1 out of phase)
9	-	2.824	2.832	1st blade 1 flap / tower fore-aft coupling
10	-	2.987	2.999	Complicated blade flap and edge / tower coupling
11	-	3.262	3.278	2nd blade axisymmetric flap (2 and 3 out of phase, 1 stationary)
12	3.722	3.642	3.680	2nd blade axisymmetric flap (2 and 3 in phase, 1 out of phase)
13	-	3.730	3.766	2nd blade symmetric flap
14	-	5.557	5.578	2nd blade symmetric edge
15	-	5.992	6.026	Complicated blade flap and edge / tower coupling
†Single system natural frequencies (i.e., tower alone or blade alone); compared with the closest matching full system mode				

In general, the predictions of full system natural frequencies agree very well among the models. The RCAS frequencies are within 2% of the ADAMS frequencies. These slight discrepancies are most likely due to differences in the models caused by the methods of integration and interpolation to find the blade and tower stiffness properties (more evidence of this will be demonstrated later). The FAST frequencies are within 3.2% of the ADAMS frequencies. These larger discrepancies result from modeling components decoupled (not integrated with the complete system) and don't characterize the full system responses that will result from a time-series analysis.

Spinning in a Vacuum

This analysis considers the turbine spinning in a vacuum (no aerodynamic effects) loaded only by gravity. The turbine is simulated running at rated speed (20.463 rpm, 2.14288 rad/sec) for a number of fixed blade collective pitch angles. From each simulation, 34 output responses are examined (see Table 4). Selected responses when all three blades have 2.6° collective pitch angle are plotted in Figure 5. In general, very good agreement exists among the results from the three codes.

Table 4: Output Responses Examined

Response	Number of Components
Hub-height wind speed and direction	2
Blade 1 tip deflections	2
Blade 1 collective pitch angle	1
Blade 1 root loads	6
Rotor azimuth angle and speed	2
Shaft loads at hub (includes rotor torque and thrust)	6
Yaw position	1
Tower-top deflections at yaw bearing	2
Tower-top loads at yaw bearing	6
Tower-base loads	6

Figure 2 is a plot of the radial blade root forces for each code. Centrifugal forces of the rotating blade bring about the mean load, and the oscillating component is driven by gravity. Variations in the first couple of seconds of the simulation are attributed to the different simulation approaches and associated start-up transients†. These are not of particular concern since most analysts avoid recording data associated with simulation start-up transients. Beyond the first 2 seconds, the FAST and ADAMS responses are nearly indistinguishable. The RCAS response has a slightly larger amplitude and mean than FAST and ADAMS. This response suggests that RCAS has internally computed a larger blade mass than FAST and ADAMS. This is understandable because RCAS's Gaussian Quadrature integration approach is more accurate at capturing the large mass density gradient at the inboard portion

† The large fluctuation in RCAS's response is most likely due to the HHT time-marching algorithm, which acts to remove high-frequency transients at the simulation start-up.

of the blade than FAST's and ADAMS' linear interpolation/integration techniques. More evidence of this blade mass discrepancy can be found by examining the yaw bearing tilt moments and tower-top fore/aft deflections in Figure 5. The magnitudes of the tilt moment and fore-aft tower deflections in the RCAS model are larger than in the other two codes, indicating a heavier rotor. This is also consistent with the slightly larger oscillatory period of the tower fore-aft deflections in Figure 5 and the slightly lower tower fore-aft frequency seen in Table 3.

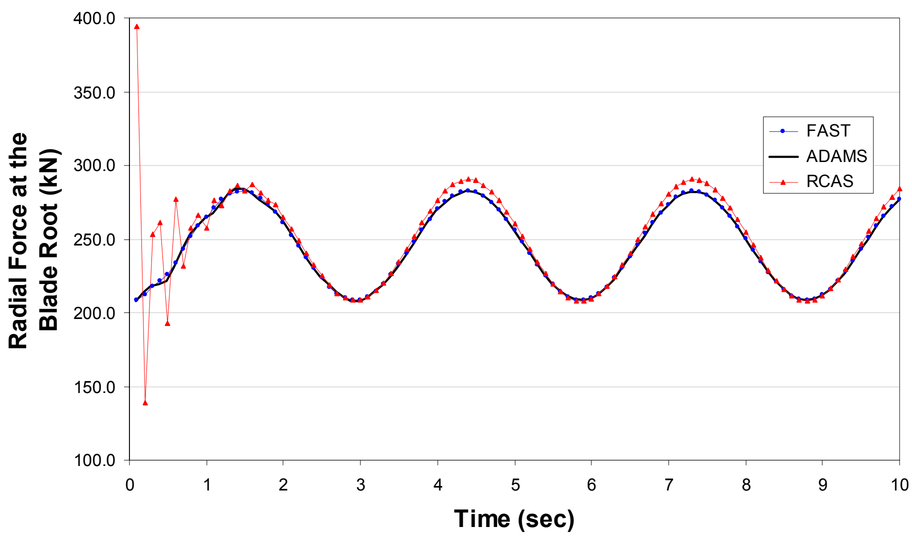

Figure 2: Radial blade root forces for the turbine spinning in a vacuum.

As discussed earlier in the description of models section of this report, the ADAMS and RCAS models include distributed elastic and center of gravity offsets in the blades, whereas these features are not available in FAST. The out-of-plane tip deflections in Figure 5 illustrate the effect that this limitation has on the FAST responses. The lower fidelity FAST model does not capture the resonances caused by these offsets.

Spinning and Yawing in a Vacuum

This analysis is identical to the previous one (spinning in a vacuum) except the nacelle and rotor are yawed at a rate of 0.75 deg/sec in the clockwise direction (looking downward) after an initial 10-second lapse in which the yaw angle is held fixed. The yaw angle as a function of time is plotted for each code in Figure 3. This case is run so that gyroscopically induced loads and deflections can be compared among the models.

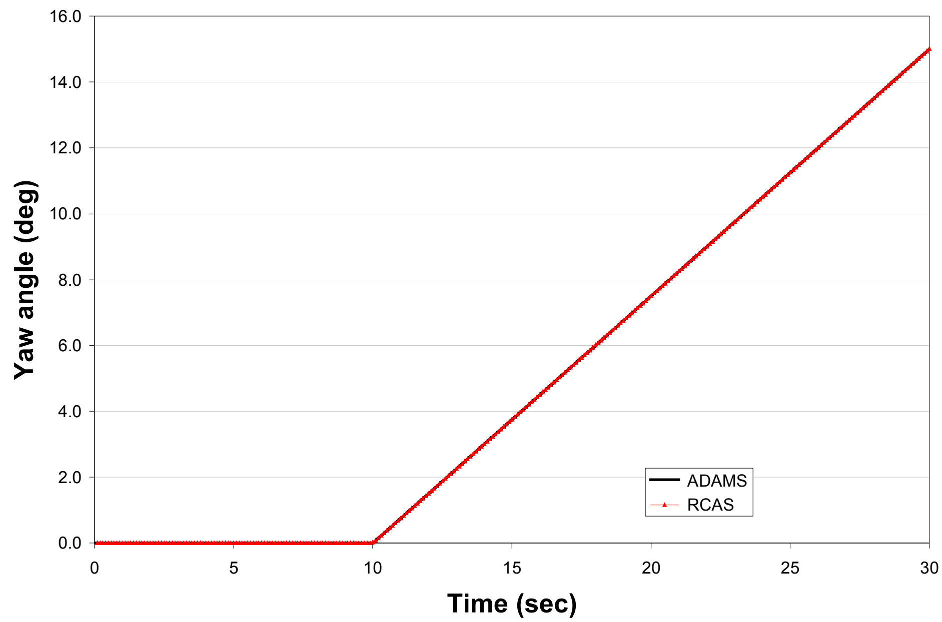

Figure 3: Output yaw angle for the turbine spinning and yawing in a vacuum analysis.

Selected responses are plotted in Figure 6. In general, there is good agreement between the RCAS and ADAMS response predictions, both before and after the nacelle yaw motion is initiated. Of particular interest in this case is the response of each code at the initiation of the yaw motion. The yaw motion is prescribed in ADAMS using a "MOTION" statement, which specifies the yaw rotation angular displacement as a function of time. When specifying a MOTION statement that prescribes a displacement in ADAMS, the code realizes that there must be an associated velocity and acceleration, and it applies appropriate time-derivates in the model accordingly. This approach results in an acceleration impulse at the instant the yaw motion begins (time = 10 seconds) because the prescribed yaw position is not "smoothed out" at this point. This acceleration impulse "kicks" the system, which is evident in the tower-top yaw moment response of 10 seconds (Figure 4).

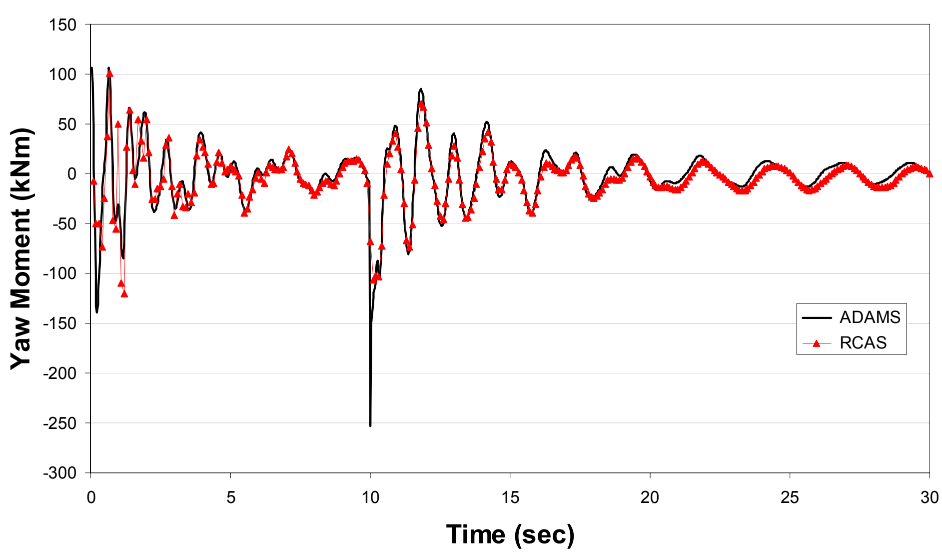

Figure 4: Yaw moment for the turbine spinning and yawing in a vacuum.

This "kick" is not evident in the RCAS response, which is explained as follows. Since the yaw bearing is modeled as a control hinge in RCAS (as discussed earlier in the description of models section of this report), the yaw motion in RCAS is prescribed through a time-varying control input in SCREEN "MANEUVERINPUT". The RCAS theory manual [4] clearly states that time-derivates of control inputs are *not* internally computed by RCAS, meaning in this case, that the yaw motion has no associated velocity, acceleration, or gyroscopically induced loads and deflections. Therefore, the responses would not correlate well between ADAMS and RCAS. To bypass these limitations, the yaw angle control input is passed through a second order actuator "element," which invokes RCAS to solve a differential equation for the yaw position, velocity, and acceleration that is forced by the desired control input yaw position. This results in a yaw response with appropriate velocity and acceleration that is a lagged and "smoothed" version of the desired control input. The "smoothed" behavior is evident in the lack of "kick" seen in Figure 4. The response lag is avoided for the side-by-side comparisons given in Figure 3, Figure 4, and Figure 6 by initiating the controlled yaw event earlier in RCAS than in ADAMS. An alternative method for modeling this situation in RCAS would be to specify not only the time-varying position of the yaw motion, but also the velocity and acceleration. The implementation of this alternative method is not included in this report.

Steady Loads Analysis

In this analysis, steady point loads are applied to all blade nodes in ADAMS and RCAS to simulate the effect of aerodynamic loads and associated responses. The point loads are applied to the ADAMS model via "GFORCE" statements. In RCAS, point loads are applied by adding mechanical load "elements" to the model (via SCREEN MECHLOAD). To obtain values for these loads, the FAST model (with AeroDyn) is run using a uniform, 12 m/s, steady wind input with no shear, turbulence, or yaw misalignment. The resulting normal and tangential forces in the AeroDyn output are averaged to determine the steady loads to apply at each node in the ADAMS and RCAS models.

Selected results are presented in Figure 7. As in previous cases, a very good agreement exists between the ADAMS and RCAS results. Slight variations in the results are attributed to the discrepancies in the blade mass and full system modal frequencies, as discussed earlier.

Sinusoidal Loads Analysis

This analysis expands on the steady load analysis by including the oscillatory components of the normal and tangential aerodynamic forces. The normal and tangential aerodynamic forces are oscillatory since the shaft tilt causes a periodic variation in the blade angle of attack as the blades advance and retreat relative to the wind. To obtain values for the point loads, amplitudes and means of the normal and tangential forces are computed at each node from the AeroDyn output of the FAST simulation with 12 m/s winds. The phase angle of the normal component of the load at each node is also computed. For simplicity, the tangential components of the forces are assumed to oscillate in phase with the normal components. The amplitude, mean, and phase of each normal and tangential force at each node are then used to construct equivalent, harmonic point loads.

Selected results are presented in Figure 8. Again, the agreement between ADAMS and RCAS is very good. Moreover, there is little difference between these responses and those obtained from the steady point load analysis (Figure 7) because the oscillating component of the load is generally small relative to the mean component of the load. For example, the amplitude of the normal component is typically only 1% to 5% of the mean.

A Critique of RCAS's Usability and Applicability in the Wind Industry

The results illustrated above demonstrate that RCAS has the ability to model wind turbine structures as accurately as other industry-accepted codes do. Certainly, the response comparisons do not highlight any glaring weaknesses or inadequacies. However, the ability to obtain the "correct" results is not the only factor considered when adopting a new analysis tool. Factors such as code complexity, user friendliness, and code flexibility and functionality are equally important and will determine whether RCAS is accepted for use by the wind industry.

In terms of code complexity, RCAS is equally as complex as ADAMS. This is a direct result of RCAS's flexibility and implementation of the FEM modeling approach. In addition, RCAS is currently only in an alpha stage of development; little attention has been given to the graphical user interface. RCAS's input prompt-style interface and poor 3D-graphics capabilities also contribute to the code complexity, though the input prompt-style interface is somewhat bypassed through the use of script files and the 3D graphics capabilities will most likely improve with code upgrades in time. Nevertheless, first-time users of RCAS should expect a steep learning curve, just as they would for ADAMS. Background experience in structural dynamics analysis and the FEM modeling approach is a necessity. Programming experience with Fortran, C, and MATLAB are also important because the code is developed in these programming languages and because it is necessary to develop scripts in these languages (especially MATLAB) if one is to exploit the diverse functionality of RCAS[†].

With regard to user-friendliness and everyday usability, RCAS has both advantages and disadvantages when compared to ADAMS. RCAS's comparative advantages include a method for directly inputting distributed mass and inertia properties for determination of blade and tower flexibility, easy methods for implementing control paradigms, and its open source code, allowing for custom-tailoring by its users to suit their needs. One disadvantage is that the code was developed originally for the rotorcraft industry, and as such, the code utilizes sign conventions and terminology that are not always consistent with wind turbine lingo. This might bring about modeling mishaps if users trying to model wind turbines are not careful. Other drawbacks include the complicated interface, as discussed in the previous paragraph, and the fact that RCAS must be run on a Linux platform instead of on Windows. In general, the usability of RCAS in the wind industry may be improved upon by developing a wind-turbine-specific front end for the code.

One important weakness of the RCAS code, as noticed during this study, is the processing speed for a time-series response analysis. Time-series analyses using RCAS take roughly one order of magnitude longer than similar analyses in ADAMS for models with an identical number of DOF and time step size. This is most likely due to the sophisticated finite element methodology used in RCAS, as contrasted to the lumped-properties approach used in ADAMS. This may not be a serious limitation because FEM is considerably more accurate than the lumped method, and fewer DOFs in an RCAS model may suffice to yield a desired accuracy—thereby drastically reducing the process speed of an RCAS analysis. For example, users may be able to deactivate various states of individual nonlinear beam elements or use fewer elements if they are not important for the problem at hand.

Code functionality is another factor affecting the code's acceptance by the wind industry. RCAS's diverse capabilities, many of which are listed in the background section of this report, are one motivation for this study. One feature not yet available is bending-torsion coupling in the blades. This limitation may be important, as passive load control is currently an active research topic in the wind industry. However, with RCAS's open source format and custom-tailoring potential, this limitation may be remedied with some work. In fact, ART Inc. currently plans to introduce anisotropic composite beam elements into the code. Integration of RCAS with a wind-industry-accepted aerodynamics modeling package, such as AeroDyn, is another limitation that can be eliminated with some work.

Conclusions

Limitations in the existing design codes and the increasing need to perform more advanced analyses motivate the wind industry to search for new and improved analysis tools. The development history, functionality, and advanced-nature of RCAS make this code a sensible option. To demonstrate that RCAS can be applied to analyze wind turbine structures, a side-by-side comparison is performed of response predictions obtained using RCAS and industry-accepted wind turbine analysis codes FAST and ADAMS. All three codes employ different modeling techniques. Nevertheless, comparisons of response predictions between the codes show excellent agreement and do not expose any glaring inaccuracies in RCAS. Regions where the different response predictions do not exactly coalesce are attributed to differences in the models techniques, such as integration methods and the differences between the FEM, assumed-modes, and lumped-properties modeling approaches.

The wind industry's acceptance and acquisition of RCAS is not without obstacles, however. RCAS's inherent complexity is a mixed blessing, and its user interface is somewhat lacking. The learning curve is also steep.

[†] To be precise, much of RCAS is written in script files that closely resemble "m-files" used in MATLAB, and a large portion of RCAS's user environment behaves similarly to the MATLAB-style environment. However, in RCAS, this environment is called RSCOPE, which is a custom-designed environment and programming language developed by ART Inc. There is no association between RCAS and MATLAB.

Nevertheless, the user-friendliness will naturally improve in time as the code and its user's manuals are upgraded. In the end, the wind industry must decide whether the gains accrued from RCAS's enhanced functionality relative to existing wind turbine analysis tools outweigh the costs of adopting this new code.

Acknowledgements

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References

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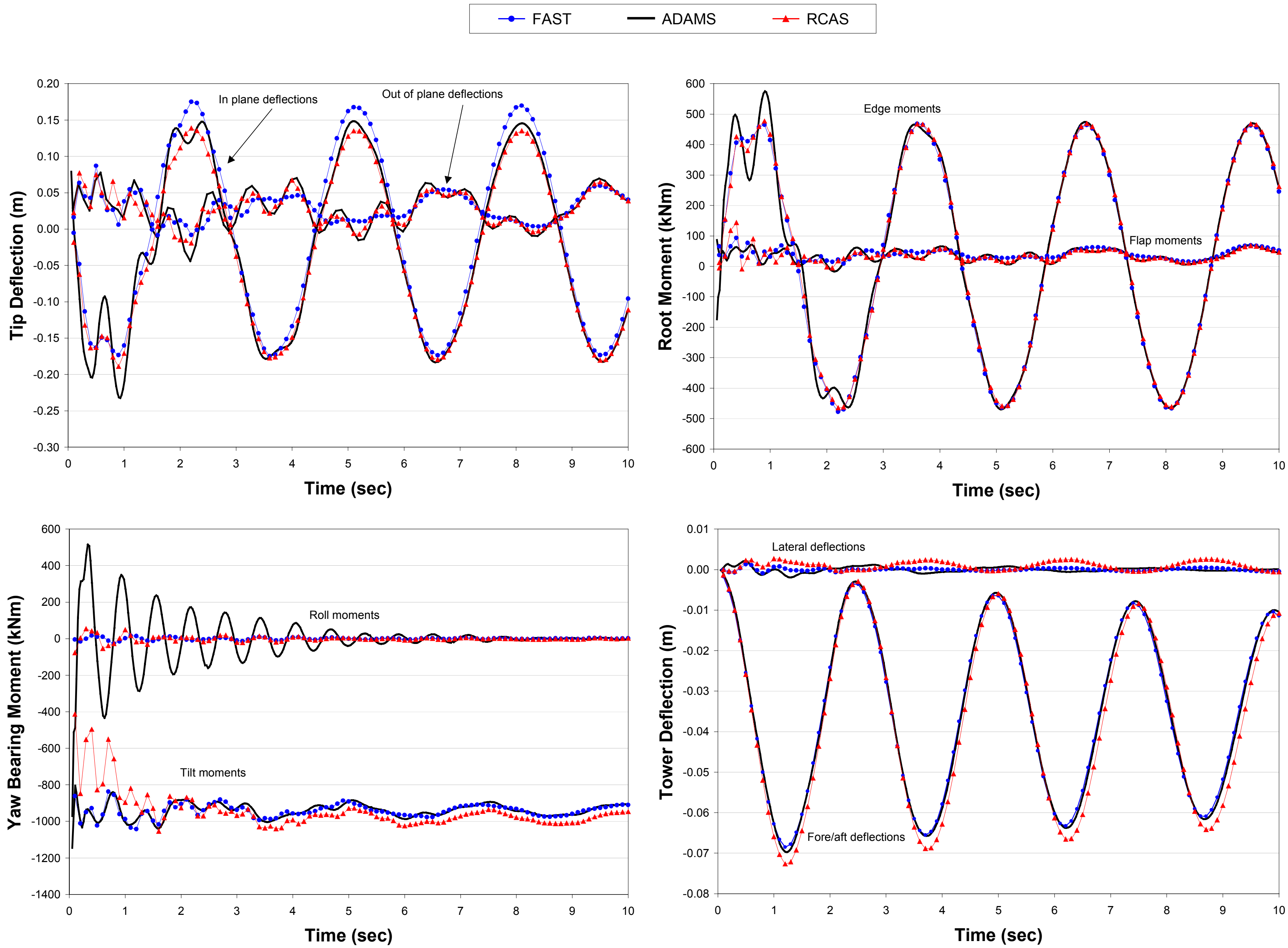

Figure 5: Selected responses for the turbine spinning in a vacuum.

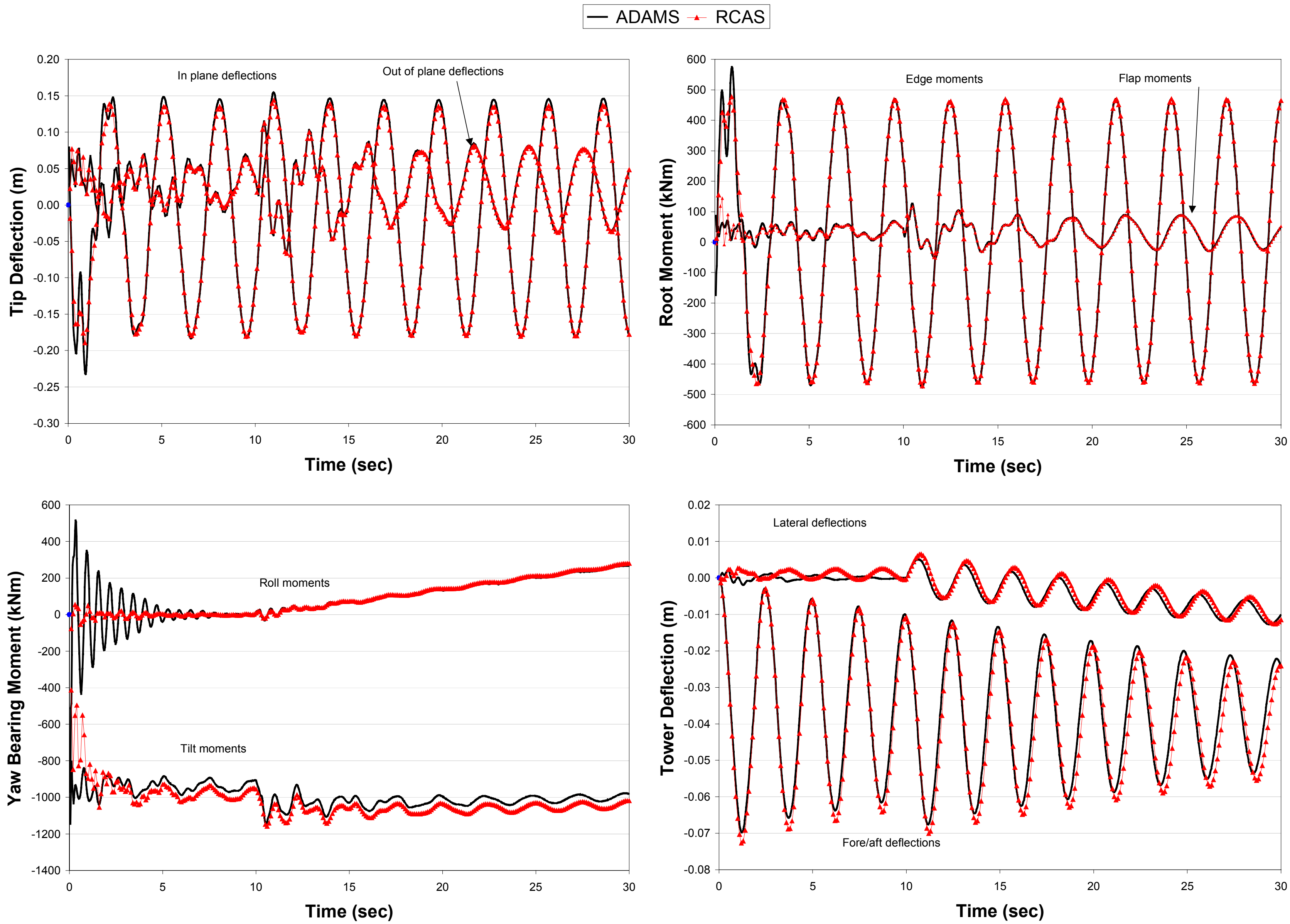

Figure 6: Selected responses for the turbine spinning and yawing in a vacuum.

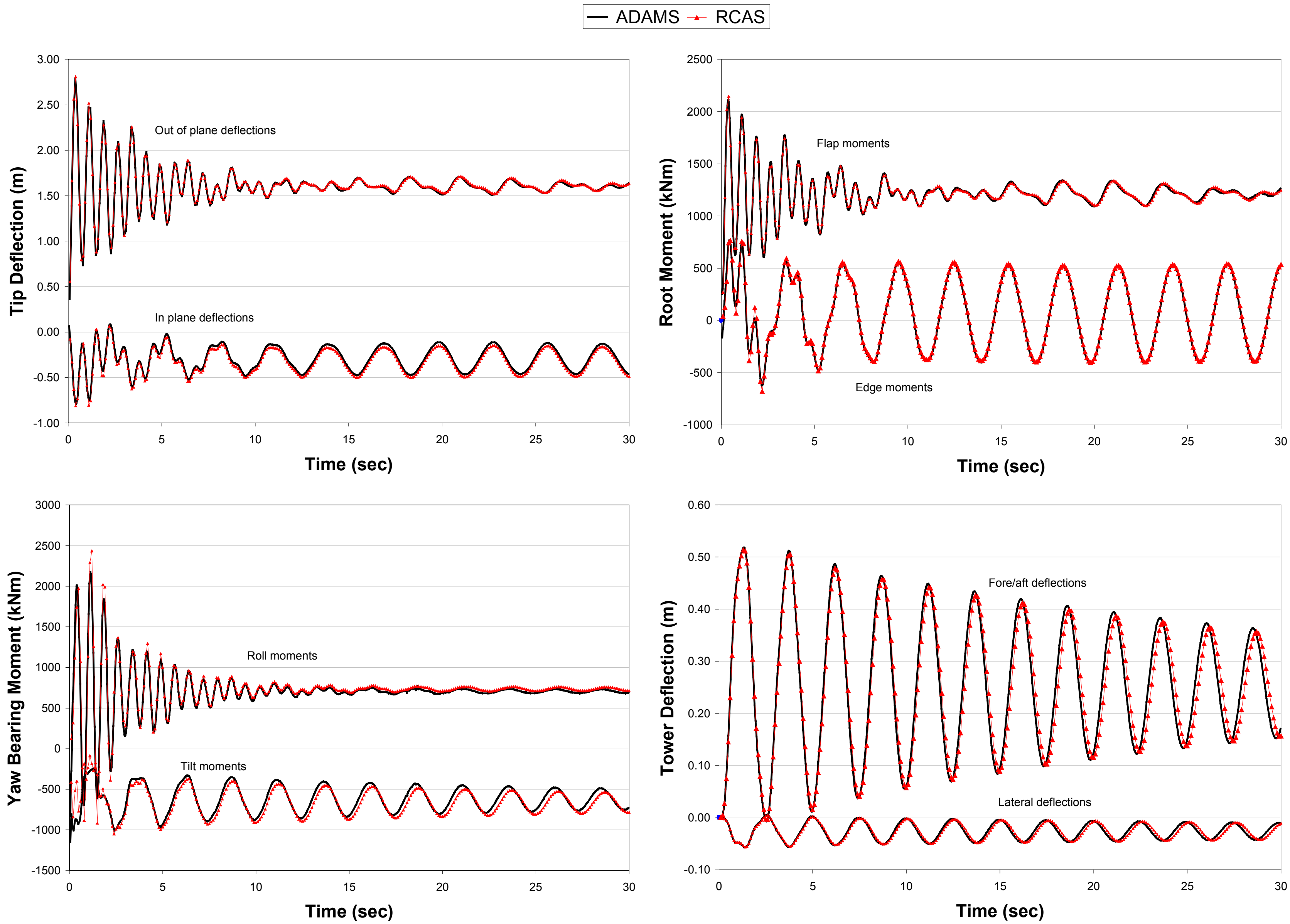

Figure 7: Selected responses for 12 m/s steady loads applied to the turbine.

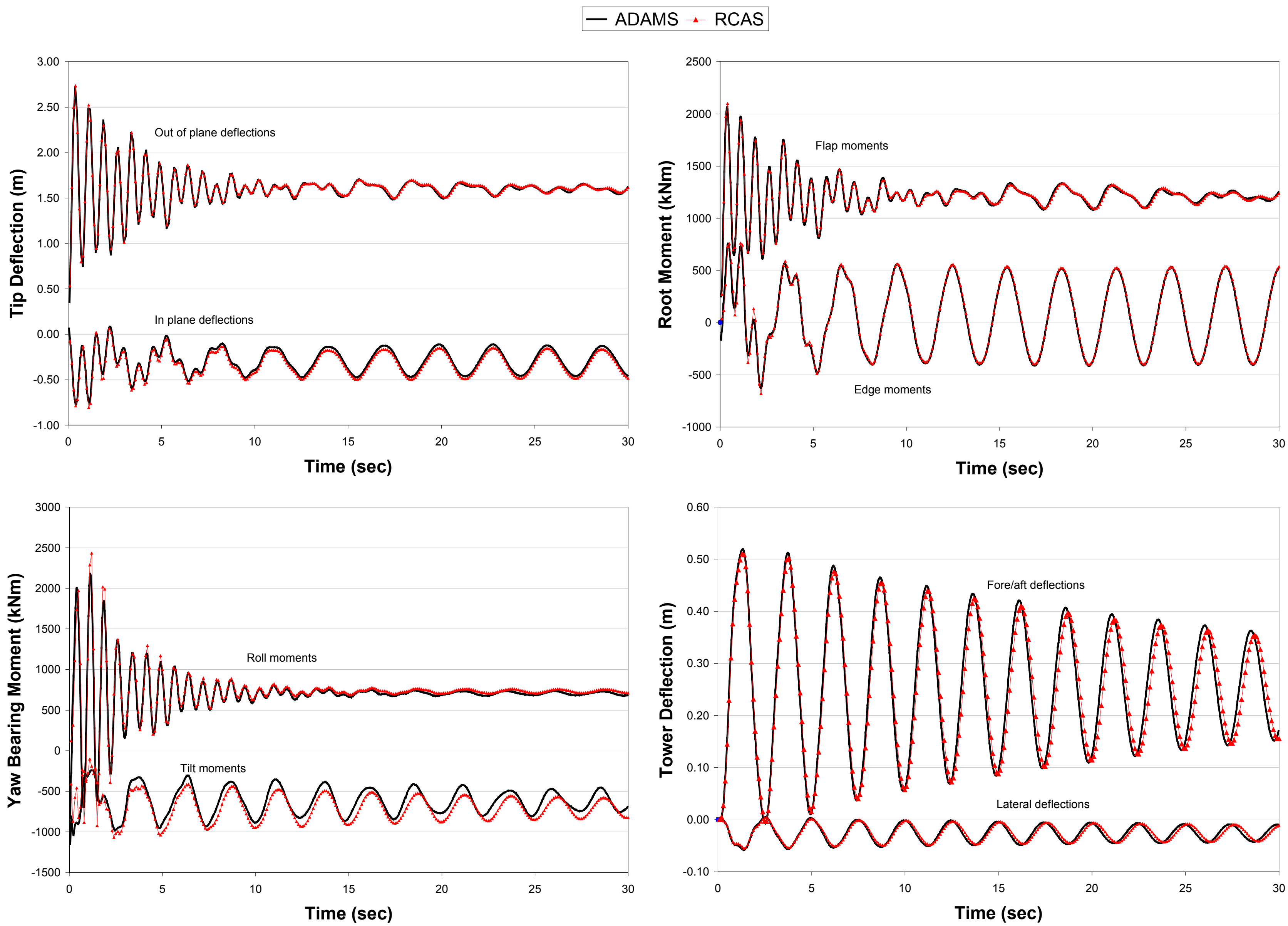

Figure 8: Selected responses for 12 m/s sinusoidal loads applied to the turbine.

Appendix: Sample Input Files

This appendix includes sample FAST and RCAS input files for the turbine spinning in a vacuum. The ADAMS Solver dataset is not included due to its length; it is available from the authors upon request.

FAST Input File for the Turbine Spinning in a Vacuum

```
--------------------------------------------------------------------------------
------- FAST INPUT FILE --------------------------------------------------------
FAST model of a 1.5 MW, 3-bladed, upwind, baseline turbine used for RCAS validation.
Model properties from "InputData1.5A08V07adm.xls" (from C. Hansen) with bugs removed.  Compatible with FAST v4.1.
---------------------- SIMULATION CONTROL --------------------------------------
False          Echo        - Echo input data to "echo.out" (switch)
3              ADAMSPrep   - ADAMS preprocessor mode {1: Run FAST, 2: use FAST as a preprocessor to create an ADAMS model, 3: do both}
(switch)
3              NumBl       - Number of blades (-)
10.0           TMax        - Total run time (s)
0.005          DT          - Integration time step (s)
---------------------- TURBINE CONTROL -----------------------------------------
0              PCMode      - Pitch control mode {0: none, 1: power control, 2: speed control} (switch)
9999.9         TPCOn       - Time to enable active pitch control (s)
0              VSContrl    - Variable-speed control {0: none, 1: simple VS, 2: user-defined VS}  (switch)
9999.9         RatGenSp    - Rated generator speed for simple variable-speed generator control (HSS side) (rpm) [used only when
VSContrl=1]
9999.9         Reg2TCon    - Torque constant for simple variable-speed generator control in Region 2 (HSS side) (N-m/rpm^2) [used only
when VSContrl=1]
1              GenModel    - Generator model {1: Simple, 2: Thevenin, 3: User Defined} (-)
True           GenTiStr    - Method to start the generator {T: timed using TimGenOn, F: generator speed using SpdGenOn} (switch)
True           GenTiStp    - Method to stop the generator {T: timed using TimGenOf, F: when generator power = 0} (switch)
9999.9         SpdGenOn    - Generator speed to turn on the generator for a start-up (HSS speed) (rpm)
0.0            TimGenOn    - Time to turn on the generator for a start-up (s)
9999.9         TimGenOf    - Time to turn off the generator (s)
9999.9         THSSBrDp    - Time to initiate deployment of the HSS brake (s)
9999.9         TiDynBrk    - Time to initiate deployment of the dynamic generator brake [CURRENTLY IGNORED] (s)
9999.9         TTpBrDp(1)  - Time to initiate deployment of tip brake 1 (s)
9999.9         TTpBrDp(2)  - Time to initiate deployment of tip brake 2 (s)
9999.9         TTpBrDp(3)  - Time to initiate deployment of tip brake 3 (s) [unused for 2 blades]
9999.9         TBDepISp(1) - Deployment-initiation speed for the tip brake on blade 1 (rpm)
9999.9         TBDepISp(2) - Deployment-initiation speed for the tip brake on blade 2 (rpm)
9999.9         TBDepISp(3) - Deployment-initiation speed for the tip brake on blade 3 (rpm) [unused for 2 blades]
9999.9         TPitManS(1) - Time to start override pitch maneuver for blade 1 and end standard pitch control (s)
9999.9         TPitManS(2) - Time to start override pitch maneuver for blade 2 and end standard pitch control (s)
9999.9         TPitManS(3) - Time to start override pitch maneuver for blade 3 and end standard pitch control (s) [unused for 2
blades]
9999.9         TPitManE(1) - Time at which override pitch maneuver for blade 1 reaches final pitch (s)
9999.9         TPitManE(2) - Time at which override pitch maneuver for blade 2 reaches final pitch (s)
9999.9         TPitManE(3) - Time at which override pitch maneuver for blade 3 reaches final pitch (s) [unused for 2 blades]
2.6            B1Pitch(1)  - Blade 1 initial pitch (degrees)
2.6            B1Pitch(2)  - Blade 2 initial pitch (degrees)
2.6            B1Pitch(3)  - Blade 3 initial pitch (degrees) [unused for 2 blades]
```

```
2.6            B1PitchF(1) - Blade 1 final pitch for pitch maneuvers (degrees)
2.6            B1PitchF(2) - Blade 2 final pitch for pitch maneuvers (degrees)
2.6            B1PitchF(3) - Blade 3 final pitch for pitch maneuvers (degrees) [unused for 2 blades]
---------------------- ENVIRONMENTAL CONDITIONS --------------------------------
9.80665        Gravity     - Gravitational acceleration (m/s^2)
---------------------- FEATURE SWITCHES ----------------------------------------
True           FlapDOF1    - First flapwise blade mode DOF (switch)
True           FlapDOF2    - Second flapwise blade mode DOF (switch)
True           EdgeDOF     - First edgewise blade mode DOF (switch)
False          TeetDOF     - Rotor-teeter DOF (switch) [unused for 3 blades]
True           DrTrDOF     - Drivetrain rotational-flexibility DOF (switch)
False          GenDOF      - Generator DOF (switch)
False          TiltDOF     - Nacelle-tilt DOF (switch)
False          YawDOF      - Yaw DOF (switch)
True           TwFADOF1    - First fore-aft tower bending-mode DOF (switch)
True           TwFADOF2    - Second fore-aft tower bending-mode DOF (switch)
True           TTwSSDOF1    - First side-to-side tower bending-mode DOF (switch)
True           TwSSDOF2    - Second side-to-side tower bending-mode DOF (switch)
False          CompAero    - Compute aerodynamic forces (switch)
---------------------- INITIAL CONDITIONS --------------------------------------
0.0            OoPDefl     - Initial out-of-plane blade-tip displacement, (meters)
0.0            IPDefl      - Initial in-plane blade-tip deflection, (meters)
0.0            TeetDefl    - Initial or fixed teeter angle (degrees) [unused for 3 blades]
0.0            Azimuth     - Initial azimuth angle for blade 1 (degrees)
20.463         RotSpeed    - Initial or fixed rotor speed (rpm)
-5.0           NacTilt     - Initial or fixed nacelle-tilt angle (degrees)
0.0            NacYaw      - Initial or fixed nacelle-yaw angle (degrees)
0.0            TTDspFA     - Initial fore-aft tower-top displacement (meters)
0.0            TTDspSS     - Initial side-to-side tower-top displacement (meters)
---------------------- TURBINE CONFIGURATION -----------------------------------
35.0           TipRad      - The distance from the rotor apex to the blade tip (meters)
1.75           HubRad      - The distance from the rotor apex to the blade root (meters)
1              PSpnElN     - Number of the innermost blade element which is still part of the pitchable portion of the blade for
partial-span pitch control [1 to BldNodes] [CURRENTLY IGNORED] (-)
0.0            UndSling    - Undersling length [distance from teeter pin to the rotor apex] (meters) [unused for 3 blades]
0.0            HubCM       - Distance from rotor apex to hub mass [positive downwind] (meters)
-3.3           OverHang    - Distance from yaw axis to rotor apex [3 blades] or teeter pin [2 blades] (meters)
-0.1251        ParaDNM     - Distance parallel to shaft from yaw axis to nacelle CM (meters)
-0.2328        PerpDNM     - Perpendicular distance from shaft to nacelle CM (meters)
82.39          TowerHt     - Height of tower above ground level (meters)
1.61           Twr2Shft    - Vertical distance from the tower top to the yaw/shaft intersection (meters)
0.0            TwrRBHt     - Tower rigid base height (meters)
0.0            Delta3      - Delta-3 angle for teetering rotors (degrees) [unused for 3 blades]
0.0            PreCone(1)  - Blade 1 cone angle (degrees)
0.0            PreCone(2)  - Blade 2 cone angle (degrees)
0.0            PreCone(3)  - Blade 3 cone angle (degrees) [unused for 2 blades]
0.0            AzimB1Up    - Azimuth value to use for I/O when blade 1 points up (degrees)
---------------------- MASS AND INERTIA ----------------------------------------
51170.0        NacMass     - Nacelle mass (kg)
15148.0        HubMass     - Hub mass (kg)
0.0            TipMass(1)  - Tip-brake mass, blade 1 (kg)
```

```
0.0            TipMass(2)  - Tip-brake mass, blade 2 (kg)
0.0            TipMass(3)  - Tip-brake mass, blade 3 (kg) [unused for 2 blades]
49130.0        NacYIner    - Nacelle inertia about yaw axis (kg m^2)
58720.0        NacTIner    - Nacelle inertia about tilt axis (kg m^2)
53.036         GenIner     - Generator inertia about HSS (kg m^2)
34600.0        HubIner     - Hub inertia about teeter axis (kg m^2) [unused for 3 blades]
---------------------- DRIVETRAIN ---------------------------------------------
100.0          GBoxEff     - Gearbox efficiency (%)
95.0           GenEff      - Generator efficiency [ignored by the Thevenin and user-defined generator models] (%)
87.965         GBRatio     - Gearbox ratio (-)
False          GBRevers    - Gearbox reversal {T: if rotor and generator rotate in opposite directions} (switch)
9999.9         HSSBrTqF    - Fully deployed HSS-brake torque (N-m)
9999.9         HSSBrDt     - Time for HSS-brake to reach full deployment once initiated (sec)
"DynBrk.dat"   DynBrkFi    - File containing a mech-gen-torque vs HSS-speed curve for a dynamic brake [CURRENTLY IGNORED] (quoted
string)
5.6E9          DTTorSpr    - Drivetrain torsional spring (N-m/rad)
0.0            DTTorDmp    - Drivetrain torsional damper (N-m/s)
---------------------- SIMPLE INDUCTION GENERATOR ------------------------------
1.0            SIG_SlPc    - Rated generator slip percentage [>0] (%)              Now HSS side!
1800.0         SIG_SySp    - Synchronous (zero-torque) generator speed [>0] (rpm)  Now HSS side!
7879.0         SIG_RtTq    - Rated torque [>0] (N-m)                               Now HSS side!
2.0            SIG_PORt    - Pull-out ratio (Tpullout/Trated) [>1] (-)
---------------------- THEVENIN-EQUIVALENT INDUCTION GENERATOR -----------------
9999.9         TEC_Freq    - Line frequency [50 or 60] (Hz)
9998           TEC_NPol    - Number of poles [even integer > 0] (-)
9999.9         TEC_SRes    - Stator resistance [>0] (ohms)
9999.9         TEC_RRes    - Rotor resistance [>0] (ohms)
9999.9         TEC_VLL     - Line-to-line RMS voltage (volts)
9999.9         TEC_SLR     - Stator leakage reactance (ohms)
9999.9         TEC_RLR     - Rotor leakage reactance (ohms)
9999.9         TEC_MR      - Magnetizing reactance (ohms)
---------------------- TOWER ---------------------------------------------------
10             TwrNodes    - Number of tower nodes used for analysis (-)
"../Baseline_Tower.dat"       TwrFile - Name of file containing tower properties (quoted string)
---------------------- NACELLE-YAW ---------------------------------------------
0.0            YawSpr      - Nacelle-yaw spring constant (N-m/rad)
0.0            YawDamp     - Nacelle-yaw constant (N-m/rad/s)
0.0            YawNeut     - Neutral yaw position--yaw spring force is zero at this yaw (degrees)
---------------------- NACELLE-TILT --------------------------------------------
0.0            TiltSpr     - Nacelle-tilt linear-spring constant (N-m/rad)
0.0            TiltDamp    - Nacelle-tilt damping constant (N-m/rad/s)
0.0            TiltSStP    - Nacelle-tilt soft-stop position (degrees)
0.0            TiltHStP    - Nacelle-tilt hard-stop position (degrees)
0.0            TiltSSSp    - Nacelle-tilt soft-stop linear-spring constant (N-m/rad)
0.0            TiltHSSp    - Nacelle-tilt hard-stop linear-spring constant (N-m/rad)
---------------------- ROTOR-TEETER --------------------------------------------
0              TeetDMod    - Rotor-teeter damper model (0: none, 1: linear, 2: user-defined) (switch) [unused for 3 blades]
0.0            TeetDmpP    - Rotor-teeter damper position (degrees) [unused for 3 blades]
0.0            TeetDmp     - Rotor-teeter damping constant (N-m/rad/s) [unused for 3 blades]
0.0            TeetCDmp    - Rotor-teeter rate-independent Coulomb-damping moment (N-m) [unused for 3 blades]
0.0            TeetSStP    - Rotor-teeter soft-stop position (degrees) [unused for 3 blades]
```

```
0.0            TeetHStP    - Rotor-teeter hard-stop position (degrees) [unused for 3 blades]
0.0            TeetSSSp    - Rotor-teeter soft-stop linear-spring constant (N-m/rad) [unused for 3 blades]
0.0            TeetHSSp    - Rotor-teeter hard-stop linear-spring constant (N-m/rad) [unused for 3 blades]
---------------------- TIP-BRAKE ------------------------------------------------
0.0            TBDrConN    - Tip-brake drag constant during normal operation, Cd*Area (m^2)
0.0            TBDrConD    - Tip-brake drag constant during fully-deployed operation, Cd*Area (m^2)
9999.9         TpBrDT      - Time for tip-brake to reach full deployment once released (sec)
---------------------- BLADE ----------------------------------------------------
"../Baseline_Blade.dat"       BldFile(1) - Name of file containing properties for blade 1 (quoted string)
"../Baseline_Blade.dat"       BldFile(2) - Name of file containing properties for blade 2 (quoted string)
"../Baseline_Blade.dat"       BldFile(3) - Name of file containing properties for blade 3 (quoted string) [unused for 2 blades]
---------------------- AERODYN --------------------------------------------------
"AeroDyn.ipt"  ADFile  - Name of file containing AeroDyn input parameters (quoted string)
---------------------- OUTPUT ---------------------------------------------------
True           SumPrint    - Print summary data to "<RootName>.fsm" (switch)
True           TabDelim    - Generate a tab-delimited tabular output file. (switch)
"ES10.3E2"     OutFmt      - Format used for tabular output except time.  Resulting field should be 10 characters. (quoted string)
[not checked for validity!]
0.0            TStart      - Time to begin tabular output (s)
5              DecFact     - Decimation factor for tabular output [1: output every time step] (-)
1.0            SttsTime    - Amount of time between screen status messages (sec)
0.99           ShftGagL    - Distance from rotor apex [3 blades] or teeter pin [2 blades] to shaft strain gages [positive for upwind
rotors] (meters)
0              NBlGages    - Number of blade nodes that have strain gages for output [0 to 5] (-)
2,4,8,12       BldGagNd    - List of blade nodes that have strain gages [1 to BldNodes] (-)
               OutList     - The next line(s) contains a list of output parameters.  See OutList.txt for a listing of available output
channels, (-)
"WindVxt, HorWndDir"                   ! Wind speed and direction
"OoPDefl1, IPDefl1"                    ! OoP and IP blade 1 tip deflections
"BldPitch1"                            ! Blade 1 pitch angle
"RootFxb1, RootFyb1, RootFzb1"         ! Blade 1 root forces
"RootMxb1, RootMyb1, RootMzb1"         ! Blade 1 root moments
"Azimuth, RotSpeed"                    ! Rotor azimuth and speed
"RotThrust, LSShftFya, LSShftFza"      ! Rotor thrust and rotating LSS shear forces
"RotTorq, LSSTipMya, LSSTipMza"        ! Rotor torque and rotating LSS bending moments at the shaft tip
"NacYaw"                               ! Nacelle yaw angle
"TTDspFA, TTDspSS"                     ! FA and SS tower-top deflections
"YawBrFxp, YawBrFyp, YawBrFzp"         ! Tower-top / yaw bearing axial and shear forces
"YawBrMxp, YawBrMyp, YawBrMzp"         ! Tower-top / yaw bearing roll, pitch, and yaw moments
"TwrBsFxt, TwrBsFyt, TwrBsFzt"         ! Tower base axial and shear forces
"TwrBsMxt, TwrBsMyt, TwrBsMzt"         ! Tower base roll, pitch, and yaw moments
END of FAST input file (the word "END" must appear in the first 3 columns of this last line).
---------------------------------------------------------------------------------
```

FAST Blade Input File

```
------------------------------------------------------------------------------
---------------------- FAST INDIVIDUAL BLADE FILE -----------------------------
1.5 MW baseline blade model properties from "InputData1.5A08V07adm.xls" (from C. Hansen) with bugs removed.
---------------------- BLADE PARAMETERS ---------------------------------------
21             NBlInpSt    - Number of blade input stations (-)
False          CalcBMode   - Calculate blade mode shapes internally {T: ignore mode shapes from below, F: use mode shapes from below}
[CURRENTLY IGNORED] (switch)
3.882          BldFlDmp(1) - Blade flap mode #1 structural damping in percent of critical (%)
3.882          BldFlDmp(2) - Blade flap mode #2 structural damping in percent of critical (%)
5.900          BldEdDmp(1) - Blade edge mode #1 structural damping in percent of critical (%)
---------------------- BLADE ADJUSTMENT FACTORS -------------------------------
1.0            FlStTunr(1) - Blade flapwise modal stiffness tuner, 1st mode (-)
1.0            FlStTunr(2) - Blade flapwise modal stiffness tuner, 2nd mode (-)
1.0            AdjBlMs     - Factor to adjust blade mass density (-)
1.0            AdjFlSt     - Factor to adjust blade flap stiffness (-)
1.0            AdjEdSt     - Factor to adjust blade edge stiffness (-)
---------------------- DISTRIBUTED BLADE PROPERTIES ---------------------------
BlFract AeroCent StrcTwst BmassDen FlpStff     EdgStff     GJStff      EAStff      FlpIner EdgIner  FlpcgOf  EdgcgOf  FlpEAOf  EdgEAOf
(-)     (-)      (deg)    (kg/m)   (Nm^2)      (Nm^2)      (Nm^2)      (N)         (kg m)  (kg m)   (m)      (m)      (m)      (m)
0.00000 0.250    11.100   1447.607 7681.46E+06 7681.46E+06 2655.23E+06 17152.7E+06 646.044 646.044  0.000    0.000    0.000     0.000
0.02105 0.250    11.100    180.333 1169.87E+06 1169.87E+06  408.80E+06  2640.8E+06  80.480  80.480  0.000    0.000    0.000     0.000
0.05263 0.250    11.100    181.672 1020.62E+06 1092.28E+06  343.81E+06  2611.3E+06  68.241  80.113  0.000    0.032    0.000    -0.005
0.10526 0.250    11.100    183.905  771.88E+06  962.97E+06  235.50E+06  2562.1E+06  47.842  79.502  0.000    0.086    0.000    -0.014
0.15789 0.250    11.100    186.138  523.14E+06  833.66E+06  127.19E+06  2512.9E+06  27.444  78.892  0.000    0.140    0.000    -0.023
0.21053 0.250    11.100    188.370  274.40E+06  704.35E+06   18.87E+06  2463.6E+06   7.045  78.281  0.000    0.194    0.000    -0.032
0.26316 0.250     9.500    178.321  234.57E+06  614.65E+06   16.80E+06  2332.8E+06   5.963  68.302  0.000    0.188    0.000    -0.020
0.31579 0.250     7.900    168.271  194.74E+06  524.96E+06   14.72E+06  2202.0E+06   4.881  58.323  0.000    0.182    0.000    -0.007
0.36842 0.250     6.300    158.222  154.90E+06  435.26E+06   12.64E+06  2071.2E+06   3.799  48.344  0.000    0.176    0.000     0.005
0.42105 0.250     4.700    148.172  115.07E+06  345.57E+06   10.56E+06  1940.4E+06   2.717  38.366  0.000    0.170    0.000     0.018
0.47368 0.250     3.100    138.123   75.23E+06  255.87E+06    8.48E+06  1809.6E+06   1.635  28.387  0.000    0.164    0.000     0.030
0.52632 0.250     2.600    122.896   62.49E+06  217.87E+06    7.12E+06  1605.3E+06   1.367  24.050  0.000    0.168    0.000     0.038
0.57895 0.250     2.100    107.669   49.75E+06  179.86E+06    5.76E+06  1401.1E+06   1.099  19.714  0.000    0.172    0.000     0.047
0.63158 0.250     1.600     92.442   37.01E+06  141.86E+06    4.40E+06  1196.8E+06   0.831  15.377  0.000    0.176    0.000     0.055
0.68421 0.250     1.100     77.215   24.27E+06  103.85E+06    3.04E+06   992.6E+06   0.564  11.041  0.000    0.179    0.000     0.063
0.73684 0.250     0.600     61.988   11.53E+06   65.85E+06    1.68E+06   788.3E+06   0.296   6.704  0.000    0.183    0.000     0.071
0.78947 0.250     0.480     51.861    9.27E+06   54.25E+06    1.38E+06   654.3E+06   0.240   5.513  0.000    0.190    0.000     0.077
0.84211 0.250     0.360     41.734    7.01E+06   42.66E+06    1.08E+06   520.4E+06   0.185   4.322  0.000    0.198    0.000     0.082
0.89474 0.250     0.240     31.607    4.75E+06   31.06E+06    0.78E+06   386.4E+06   0.130   3.130  0.000    0.205    0.000     0.087
0.94737 0.250     0.120     21.480    2.49E+06   19.47E+06    0.48E+06   252.4E+06   0.074   1.939  0.000    0.212    0.000     0.092
1.00000 0.250     0.000     11.353    0.23E+06    7.87E+06    0.18E+06   118.5E+06   0.019   0.747  0.000    0.220    0.000     0.098
---------------------- BLADE MODE SHAPES---------------------------------------
 0.0838        BldFl1Sh(2) - Flap , coeff of x^2
 1.6525        BldFl1Sh(3) -      , coeff of x^3
-1.5682        BldFl1Sh(4) -      , coeff of x^4
 1.6947        BldFl1Sh(5) -      , coeff of x^5
-0.8628        BldFl1Sh(6) -      , coeff of x^6
-0.3008        BldFl2Sh(2) - Flap , coeff of x^2
-1.9968        BldFl2Sh(3) -      , coeff of x^3
-4.6564        BldFl2Sh(4) -      , coeff of x^4
```

```
16.9661        BldFl2Sh(5) -      , coeff of x^5
-9.0121        BldFl2Sh(6) -      , coeff of x^6
 0.3165        BldEdgSh(2) - Edge , coeff of x^2
 3.2618        BldEdgSh(3) -      , coeff of x^3
-6.4005        BldEdgSh(4) -      , coeff of x^4
 6.0367        BldEdgSh(5) -      , coeff of x^5
-2.2146        BldEdgSh(6) -      , coeff of x^6
```

FAST Tower Input File

```
--------------------------------------------------------------------------------
---------------------- FAST TOWER FILE -----------------------------------------
1.5 MW baseline tower model properties from "InputData1.5A08V07adm.xls" (from C. Hansen) with bugs removed.
---------------------- TOWER PARAMETERS ----------------------------------------
10             NTwInpSt    - Number of input stations to specify tower geometry
False          CalcTMode   - Calculate tower mode shapes internally {T: ignore mode shapes from below, F: use mode shapes from below}
[CURRENTLY IGNORED] (switch)
3.435          TwrFADmp(1) - Tower 1st fore-aft mode structural damping ratio (%)
3.435          TwrFADmp(2) - Tower 2nd fore-aft mode structural damping ratio (%)
3.435          TwrSSDmp(1) - Tower 1st side-to-side mode structural damping ratio (%)
3.435          TwrSSDmp(2) - Tower 2nd side-to-side mode structural damping ratio (%)
---------------------- TOWER ADJUSTMUNT FACTORS --------------------------------
1.0            FAStTunr(1) - Tower fore-aft modal stiffness tuner, 1st mode (-)
1.0            FAStTunr(2) - Tower fore-aft modal stiffness tuner, 2nd mode (-)
1.0            SSStTunr(1) - Tower side-to-side stiffness tuner, 1st mode (-)
1.0            SSStTunr(2) - Tower side-to-side stiffness tuner, 2nd mode (-)
1.0            AdjTwMa     - Factor to adjust tower mass density (-)
1.0            AdjFASt     - Factor to adjust tower fore-aft stiffness (-)
1.0            AdjSSSt     - Factor to adjust tower side-to-side stiffness (-)
---------------------- DISTRIBUTED TOWER PROPERTIES ----------------------------
HtFract  TMassDen     TwFAStif       TwSSStif       TwGJStif       TwEAStif       TwFAIner       TwSSIner       TwFAcgOf  TwSScgOf
(-)      (kg/m)       (Nm^2)         (Nm^2)         (Nm^2)         (N)            (kg m)         (kg m)         (m)       (m)
0.00000  2549.742     243.058E+9     243.058E+9     186.968E+9     61.868E+9      9540.03        9540.03        0.0       0.0
0.11111  2275.820     193.660E+9     193.660E+9     148.969E+9     55.222E+9      7601.16        7601.16        0.0       0.0
0.22222  2017.460     152.204E+9     152.204E+9     117.080E+9     48.953E+9      5974.02        5974.02        0.0       0.0
0.33333  1774.662     117.790E+9     117.790E+9      90.608E+9     43.061E+9      4623.25        4623.25        0.0       0.0
0.44444  1547.425      89.570E+9      89.570E+9      68.900E+9     37.548E+9      3515.63        3515.63        0.0       0.0
0.55556  1335.750      66.753E+9      66.753E+9      51.349E+9     32.411E+9      2620.07        2620.07        0.0       0.0
0.66667  1139.637      48.601E+9      48.601E+9      37.386E+9     27.653E+9      1907.59        1907.59        0.0       0.0
0.77778   959.085      34.430E+9      34.430E+9      26.485E+9     23.272E+9      1351.37        1351.37        0.0       0.0
0.88889   794.095      23.610E+9      23.610E+9      18.162E+9     19.268E+9       926.69         926.69        0.0       0.0
1.00000   644.666      15.566E+9      15.566E+9      11.974E+9     15.643E+9       610.96         610.96        0.0       0.0
---------------------- TOWER FORE-AFT MODE SHAPES ------------------------------
  0.7696       TwFAM1Sh(2) - Mode 1, coefficient of x^2 term
  0.4288       TwFAM1Sh(3) -       , coefficient of x^3 term
 -0.5376       TwFAM1Sh(4) -       , coefficient of x^4 term
  0.7678       TwFAM1Sh(5) -       , coefficient of x^5 term
 -0.4286       TwFAM1Sh(6) -       , coefficient of x^6 term
-26.0405       TwFAM2Sh(2) - Mode 2, coefficient of x^2 term
 13.6951       TwFAM2Sh(3) -       , coefficient of x^3 term
 -5.6458       TwFAM2Sh(4) -       , coefficient of x^4 term
 52.6424       TwFAM2Sh(5) -       , coefficient of x^5 term
-33.6512       TwFAM2Sh(6) -       , coefficient of x^6 term
---------------------- TOWER SIDE-TO-SIDE MODE SHAPES --------------------------
  0.7696       TwSSM1Sh(2) - Mode 1, coefficient of x^2 term
  0.4288       TwSSM1Sh(3) -       , coefficient of x^3 term
 -0.5376       TwSSM1Sh(4) -       , coefficient of x^4 term
  0.7678       TwSSM1Sh(5) -       , coefficient of x^5 term
```

```
  -0.4286       TwSSM1Sh(6) -       , coefficient of x^6 term
 -26.0405       TwSSM2Sh(2) - Mode 2, coefficient of x^2 term
  13.6951       TwSSM2Sh(3) -       , coefficient of x^3 term
  -5.6458       TwSSM2Sh(4) -       , coefficient of x^4 term
  52.6424       TwSSM2Sh(5) -       , coefficient of x^5 term
 -33.6512       TwSSM2Sh(6) -       , coefficient of x^6 term
```

FAST AeroDyn Input File

```
1.5 MW baseline aerodynamic parameters for FAST.
SI             SysUnits - System of units for used for input and output [must be SI for FAST] (unquoted string)
BEDDOES        StallMod - Dynamic stall included [BEDDOES or STEADY] (unquoted string)
NO_CM          UseCm    - Use aerodynamic pitching moment model? [USE_CM or NO_CM] (unquoted string)
DYNIN          InfModel - Inflow model [DYNIN or EQUIL] (unquoted string)
SWIRL          IndModel - Induction-factor model [NONE or WAKE or SWIRL] (unquoted string)
0.005          AToler   - Induction-factor tolerance (convergence criteria) (-)
PRANDtl        TLModel  - Tip-loss model (EQUIL only) [PRANDtl, GTECH, or NONE] (unquoted string)
PRANDtl        HLModel  - Hub-loss model (EQUIL only) [PRANdtl or NONE] (unquoted string)
"../../Wind/NoShr_12.wnd"     WindFile - Name of file containing wind data (quoted string)
84.2876        HH       - Wind reference (hub) height [TowerHt+Twr2Shft+OverHang*SIN(NacTilt)] (m)
0.0            TwrShad  - Tower-shadow velocity deficit (-)
9999.9         ShadHWid - Tower-shadow half width (m)
9999.9         T_Shad_Refpt - Tower-shadow reference point (m)
1.225          Rho      - Air density (kg/m^3)
1.4639e-5      KinVisc  - Kinematic air viscosity [CURRENTLY IGNORED] (m^2/sec)
0.004          DTAero   - Time interval for aerodynamic calculations (sec)
4              NumFoil  - Number of airfoil files (-)
"../../AeroData\cylinder.dat" FoilNm   - Names of the airfoil files [NumFoil lines] (quoted strings)
"../../AeroData\s818_2703.dat"
"../../AeroData\s825_2103.dat"
"../../AeroData\s826_1603.dat"
15             BldNodes - Number of blade nodes used for analysis (-)
RNodes         AeroTwst       DRNodes        Chord          NFoil   PrnElm
 2.85833       11.10          2.21667        1.949          1       PRINT
 5.07500       11.10          2.21667        2.269          2       PRINT
 7.29167       11.10          2.21667        2.589          2       PRINT
 9.50833       10.41          2.21667        2.743          2       PRINT
11.72500        8.38          2.21667        2.578          2       PRINT
13.94167        6.35          2.21667        2.412          2       PRINT
16.15833        4.33          2.21667        2.247          2       PRINT
18.37500        2.85          2.21667        2.082          3       PRINT
20.59167        2.22          2.21667        1.916          3       PRINT
22.80833        1.58          2.21667        1.751          3       PRINT
25.02500        0.95          2.21667        1.585          3       PRINT
27.24167        0.53          2.21667        1.427          3       PRINT
29.45833        0.38          2.21667        1.278          3       PRINT
31.67500        0.23          2.21667        1.129          4       PRINT
33.89167        0.08          2.21667        0.980          4       PRINT
```

RCAS Input File for the Turbine Spinning in a Vacuum

```
! RCAS model of 1.5 MW, 3-bladed, upwind, turbine used for RCAS validation.
! Model properties from "InputData1.5A08V07adm.xls" (from C. Hansen) with bugs removed.
!
!           ********************************************
!           ***      Wind Turbine Baseline Model       ***
!           ***             Elastic Tower              ***
!           ***        Linear Spring Driveshaft        ***
!           ***           3 Elastic Blades             ***
!           ***              Rigid hub                 ***
!           ***            0 deg Precone               ***
!           ***              No Aero                   ***
!           ***              SI Units                  ***
!           ********************************************
!

MENU RCASROOT
! Reinitialize/Clean RDB
11
E

! Initialize/Load screen  ...
1

! Return to command mode
COMMAND

!======================================================================
!============================ Unit System =============================
!======================================================================

S UNITSYSTEM
! Unity System Name
! ENGLISH, SI
A   SI                                                                   ! m, kg, N, sec

!======================================================================
!============================ MODEL ===================================
!======================================================================

S SUBSYSIDS
! List subsystem IDs which must be unique; one ID per row.
A   towerss                                                              ! tower and nacelle
A   rotorss                                                              ! hub, blades, and drivetrain

S GFRAMEORIG
! G frame origin of the  node to which the G frame is attached.
!                    Primitive            Active Degrees of Freedom
!   Subsystem        Structure     Node    Translational  Rotational
!     Name             Name         ID        X  Y  Z       X  Y  Z
```

```
A   towerss           towerps      1400       0  0  0       0  0  0    ! all locked; therefore, G and I frame are coincedental

S SSORIGIN
!  Subsystem             Origin Coordinates
!    Name          x            y            z
A   towerss       0.0          0.0          0.0                        ! tower base
A   rotorss       0.0          0.0        -84.0                        ! intersection of yaw and shaft axes

S SSORIENT
!  Subsystem     rotation 1        rotation 2        rotation 3
!    Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
A   towerss      2    90.0         0       0         0       0         ! x of towerss is along tower centerline
A   rotorss      2    85.0         0       0         0       0         ! z of rotorss is along shaft, directed nominally downwind (+
thrust)

S CONTROLMIXER
! Cont.  Bias      ------ Coefficients for Pilot Control --------
!  ID    Value     Coll.       Lat.         Long.     Pedal    Throt
A   1     0.0    -0.01745329  0.0          0.0        0.0        0.0    ! blade 1 pitch angle
A   2     0.0     0.0        -0.01745329  0.0        0.0        0.0    ! blade 2 pitch angle
A   3     0.0     0.0         0.0        -0.01745329 0.0        0.0    ! blade 3 pitch angle
A   4     0.0     0.0         0.0         0.0        0.01745329 0.0    ! nacelle yaw angle

S ACTUATORMODEL
!  Control    Actuator Cutoff     Actuator
!    ID         Frequency       Damping Ratio
A   4             10.0              0.7                                ! use a 2nd order actuator model b/n the nacelle yaw angle
control
                                                                       !   input and the actual yaw angle so that derivatives can be
calc.
                                                                       ! NOTE: if either are zero, no derivatives of control inputs
are calc.

!======================================================================
!=============================== Subsystem =============================
!                                towerss
!======================================================================

S SELSUBSYS
! Select a subsystem. Note that all the following data will pertain
! to this subsystem until another subsystem is selected.
A   towerss

S SUBSYSTYP
! Select subsystem type.
! 1=rotor, 2=fuselage, 3=control
A   2

S SUBSYSCOMP
! List the names of the primitive structures for the subsystem.
! primitive structure name
```

```
A   towerps
A   nacllps

S PSORIGIN
!   Primitive       Primitive Origin Offset
!   Name           x            y            z
A   towerps      0.0          0.0          0.0                           ! same origin as towerss
A   nacllps     84.0          0.0          0.0                           ! same origin as rotorss

S PSORIENT
!   Primitive     rotation 1        rotation 2        rotation 3
!     Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
A   towerps       0       0         0       0         0       0        ! same orientation as towerss
A   nacllps       2     -5.0        0       0         0       0        ! same orientation as rotorss

!======================================================================
!========================= PRIMITIVE STRUCTURE ========================
!                          PRIMITIVE FOR tower
!======================================================================

S PRIMITIVEID
! Select primitive to be defined
A   towerps

S ELDATASETID
! Select a property set
A   miscprop

S FENODE
!   node ID   X       Y       Z
A   1400     0.0000  0.0     0.0                                         ! tower base
A   1101     4.1195  0.0     0.0                                         ! lowermost tower analysis point/node
A   1102    12.3585  0.0     0.0
A   1103    20.5975  0.0     0.0
A   1104    28.8365  0.0     0.0
A   1105    37.0755  0.0     0.0
A   1106    45.3145  0.0     0.0
A   1107    53.5535  0.0     0.0
A   1108    61.7925  0.0     0.0
A   1109    70.0315  0.0     0.0
A   1110    78.2705  0.0     0.0                                         ! uppermost tower analysis point/node
A   1010    82.3900  0.0     0.0                                         ! yaw bearing/hinge bottom
A   2010    82.3900  0.0     0.0                                         ! yaw bearing/hinge top
A   2000    84.0000  0.0     0.0                                         ! intersection of yaw and shaft axes
A   1030    82.3900  0.0     0.0                                         ! node used for undeflected tower-top position

S NLBEAMDEF
! Elem  1st    2nd    Shape   NGauss  MatProp   End Node Active DOFs
!  ID   Node   Node  Func ID  Points    ID      ue v  w    phi w' v'
A   101 1400   1101     1       6       1       1  1  1     1  1  1    ! lowermost tower element
A   102 1101   1102     1       6       1       1  1  1     1  1  1
```

```
A   103 1102   1103     1       6       1       1  1  1     1  1  1
A   104 1103   1104     1       6       1       1  1  1     1  1  1
A   105 1104   1105     1       6       1       1  1  1     1  1  1
A   106 1105   1106     1       6       1       1  1  1     1  1  1
A   107 1106   1107     1       6       1       1  1  1     1  1  1
A   108 1107   1108     1       6       1       1  1  1     1  1  1
A   109 1108   1109     1       6       1       1  1  1     1  1  1
A   110 1109   1110     1       6       1       1  1  1     1  1  1
A   150 1110   1010     1       6       1       1  1  1     1  1  1    ! uppermost tower element

N
! Structural properties may be entered here, or in a table in next screen
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID,   STR-TWIST

N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A   101         0.0              ../BASELINE_TOWER.TAB
A   102         0.0              ../BASELINE_TOWER.TAB
A   103         0.0              ../BASELINE_TOWER.TAB
A   104         0.0              ../BASELINE_TOWER.TAB
A   105         0.0              ../BASELINE_TOWER.TAB
A   106         0.0              ../BASELINE_TOWER.TAB
A   107         0.0              ../BASELINE_TOWER.TAB
A   108         0.0              ../BASELINE_TOWER.TAB
A   109         0.0              ../BASELINE_TOWER.TAB
A   110         0.0              ../BASELINE_TOWER.TAB
A   150         0.0              ../BASELINE_TOWER.TAB

S PSMODALDAMP
!row index           mode number      Damping ratio
A   1                 1:9999           3.435E-02

S RIGIDBAR
!  Element  Node1  Node2    Center of gravity offset
!    ID      ID     ID       X        Y        Z
A   2100    2010   2000     0.0      0.0      0.0                      ! bed-plate
A   1030    1400   1030     0.0      0.0      0.0                      ! link from tower base to undeflected tower-top

N
!  Element  Element                         Inertia Terms
!    ID      Mass     Ixx   Ixy  Ixz   Iyy   Iyz    Izz
A   2100      0.0     0.0   0.0  0.0   0.0   0.0    0.0
A   1030      0.0     0.0   0.0  0.0   0.0   0.0    0.0

S HINGE
! Elem.  Node1  Node2  Hinge   Free or     Spring       Damper
!  ID     ID     ID    Type   Controlled  Constant     Constant
A   2010 1010   2010     P        1          0.0         0.0           ! yaw bearing/hinge
```

```
S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
A   4         DIRECT         0.0           HIN               2010

!=======================================================================
!========================= PRIMITIVE STRUCTURE ========================
!                          PRIMITIVE FOR nacelle
!=======================================================================

S PRIMITIVEID
! Select primitive to be defined
A   nacllps

S ELDATASETID
! Select a property set
A   miscprop

S FENODE
!   node ID   X       Y       Z
A   2130     0.0000  0.0     0.0                                     ! intersection of yaw and shaft axes
A   2001     1.0000  0.0     0.0                                     ! one unit above along local x-axis

S RIGIDBAR
!  Element  Node1  Node2    Center of gravity offset
!    ID      ID     ID       X        Y        Z
A   2000    2130   2001   -0.2328    0.0    -0.1251                  ! nacelle CM

N
!  Element  Element                         Inertia Terms
!    ID      Mass     Ixx    Ixy  Ixz   Iyy   Iyz    Izz
A   2000    51170.0 48329.19 0.0  0.0  55145.99 0.0   0.0            ! nacelle mass and inertia

!=======================================================================
!========================= Connect Primitives =========================
!=======================================================================

S CONNCONST
! constraint ID, DOFL( PS name, node ID ), DOFR( PS name, node ID)
A   1                  nacllps    2130          towerps   2000       ! connect tower and nacelle PSs together at node 2000
                                                                     !   (this effectively eliminates node 2130 from the model)

!=======================================================================
!============================ SUBSYSTEM ===============================
!                                ROTOR
!=======================================================================

S SELSUBSYS
! Select a subsystem. Note that all the following data will pertain
! to this subsystem until another subsystem is selected.
```

```
A   rotorss

S SUBSYSTYP
! Select subsystem type.
! 1=rotor, 2=fuselage, 3=control
A   1

S SUBSYSCOMP
! List the names of the primitive structures for the subsystem.
!   Primitive Structure
!       Name
A   lsshftps
A   blade1ps
A   blade2ps
A   blade3ps

S CORNODE
! identify center node for the rotor subsystem
! Prim_str_ID     Node_ID
A   lsshftps        3120

S BLADECOMP
! Blade                Primitive Structure Name(s)
! Index     1         2       3        4       5       6       7
A   1     blade1ps   --      --       --      --      --      --
A   2     blade2ps   --      --       --      --      --      --
A   3     blade3ps   --      --       --      --      --      --

S PSORIGIN
! Primitive       Primitive Origin Offset
!   Name           x            y            z
A   lsshftps     0.0          0.0          0.0                        ! intersection of yaw and shaft axes
A   blade1ps     0.0          0.0         -3.3                        ! hub center
A   blade2ps     0.0          0.0         -3.3                        ! hub center
A   blade3ps     0.0          0.0         -3.3                        ! hub center

S PSORIENT
! Primitive    rotation 1        rotation 2        rotation 3
!  Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
A   lsshftps   3       0.0       0       0         0       0           ! same orientation as rotorss
A   blade1ps   3       0.0       0       0         0       0           ! same orientation as rotorss; blade1 points up at zero azimuth
A   blade2ps   3     120.0       0       0         0       0           ! 120 deg ahead of blade1 about + azimuth rotation
A   blade3ps   3     240.0       0       0         0       0           ! 240 deg ahead of blade2 about + azimuth rotation

S ROTORPARAM
!  Rotor Rotational Speed (rad/sec)
A   2.14288                                                           ! 20.463 rpm

!======================================================================
!========================= PRIMITIVE STRUCTURE ========================
!                    PRIMITIVE FOR low speed shaft
```

```
!=======================================================================

S PRIMITIVEID
! Select primitive to be defined
A   lsshftps

S ELDATASETID
! Select a property set
A   miscprop

S FENODE
!   node ID   X       Y       Z
A   3120     0.0     0.0     0.0                                     ! LSS to HSS joint bottom (attached to HSS)
A   3020     0.0     0.0     0.0                                     ! LSS to HSS joint top    (attached to LSS)
A   3201     0.0     0.0     1.0                                     ! one unit along local z-axis (for generator)
A   4000     0.0     0.0    -3.3                                     ! hub center

S RIGIDBAR
!  Element  Node1  Node2    Center of gravity offset
!    ID      ID     ID       X        Y        Z
A   3200    3120   3201     0.0      0.0      0.0                    ! generator CM
A   4000    3020   4000     3.3      0.0      0.0                    ! hub CM

N
!  Element  Element                         Inertia Terms
!    ID      Mass     Ixx   Ixy  Ixz   Iyy   Iyz    Izz
A   3200      0.0 410284.1  0.0  0.0   0.0   0.0    0.0              ! generator mass and inertia (about LSS)
A   4000  15148.0      0.0  0.0  0.0   0.0   0.0    0.0              ! hub       mass and inertia

S HINGE
! Elem.  Node1  Node2  Hinge   Free or     Spring       Damper
!  ID     ID     ID    Type   Controlled  Constant     Constant
A   3020 3120   3020     L        0       5.6E+09         0.0        ! LSS to HSS connection/hinge and drivetrain spring / damper

!=======================================================================
!========================= PRIMITIVE STRUCTURE ========================
!                          PRIMITIVE FOR blade 1
!=======================================================================

S PRIMITIVEID
! Select primitive to be defined
A   blade1ps

S ELDATASETID
! Select a property set
A   miscprop

S FENODE
!   node ID   X       Y       Z
A   4001     0.00000 0.0     0.0                                     ! hub center
A   4010     1.75000 0.0     0.0                                     ! pitch bearing/hinge bottom
```

```
A    400     1.75000 0.0     0.0                                       ! pitch bearing/hinge top
A      1     2.85833 0.0     0.0                                       ! lowermost blade analysis point/node
A      2     5.07500 0.0     0.0
A      3     7.29167 0.0     0.0
A      4     9.50833 0.0     0.0
A      5    11.72500 0.0     0.0
A      6    13.94167 0.0     0.0
A      7    16.15833 0.0     0.0
A      8    18.37500 0.0     0.0
A      9    20.59167 0.0     0.0
A     10    22.80833 0.0     0.0
A     11    25.02500 0.0     0.0
A     12    27.24167 0.0     0.0
A     13    29.45833 0.0     0.0
A     14    31.67500 0.0     0.0
A     15    33.89167 0.0     0.0                                       ! uppermost blade analysis point/node
A    500    35.00000 0.0     0.0                                       ! blade tip
A   4030    35.00000 0.0     0.0                                       ! node used for the undeflected blade tip position

S NLBEAMDEF
! Elem  1st    2nd    Shape   NGauss  MatProp   End Node Active DOFs
!  ID   Node   Node  Func ID  Points    ID      ue v  w    phi w' v'
A    1  400      1       1       6       1       1  1  1     1  1  1    ! lowermost blade element
A    2    1      2       1       6       1       1  1  1     1  1  1
A    3    2      3       1       6       1       1  1  1     1  1  1
A    4    3      4       1       6       1       1  1  1     1  1  1
A    5    4      5       1       6       1       1  1  1     1  1  1
A    6    5      6       1       6       1       1  1  1     1  1  1
A    7    6      7       1       6       1       1  1  1     1  1  1
A    8    7      8       1       6       1       1  1  1     1  1  1
A    9    8      9       1       6       1       1  1  1     1  1  1
A   10    9     10       1       6       1       1  1  1     1  1  1
A   11   10     11       1       6       1       1  1  1     1  1  1
A   12   11     12       1       6       1       1  1  1     1  1  1
A   13   12     13       1       6       1       1  1  1     1  1  1
A   14   13     14       1       6       1       1  1  1     1  1  1
A   15   14     15       1       6       1       1  1  1     1  1  1
A   50   15    500       1       6       1       1  1  1     1  1  1    ! uppermost blade element

N
! Direct property input for NLB elements

N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A    1          1.75              ../BASELINE_BLADE.TAB
A    2          1.75              ../BASELINE_BLADE.TAB
A    3          1.75              ../BASELINE_BLADE.TAB
A    4          1.75              ../BASELINE_BLADE.TAB
A    5          1.75              ../BASELINE_BLADE.TAB
```

```
A    6          1.75               ../BASELINE_BLADE.TAB
A    7          1.75               ../BASELINE_BLADE.TAB
A    8          1.75               ../BASELINE_BLADE.TAB
A    9          1.75               ../BASELINE_BLADE.TAB
A   10          1.75               ../BASELINE_BLADE.TAB
A   11          1.75               ../BASELINE_BLADE.TAB
A   12          1.75               ../BASELINE_BLADE.TAB
A   13          1.75               ../BASELINE_BLADE.TAB
A   14          1.75               ../BASELINE_BLADE.TAB
A   15          1.75               ../BASELINE_BLADE.TAB
A   50          1.75               ../BASELINE_BLADE.TAB

S PSMODALDAMP
!row index           mode number      Damping ratio
A    1                 1               3.882E-02                      ! blade flap mode (obtained using ADAMS LIN anal. w/ only blade
DOFs)
A    2                 2               5.900E-02                      ! blade edge mode (")
A    3                 3               3.882E-02                      ! blade flap mode (")
A    4                 4               5.900E-02                      ! blade edge mode (")
A    5                 5               3.882E-02                      ! blade flap mode (")
A    6                 6               1.000E-02                      ! blade torional mode (")
A    7                 7               3.882E-02                      ! blade flap mode (")
A    8                 8               3.882E-02                      ! blade flap mode (")
A    9                 9               1.000E-02                      ! blade torsional mode (")
A   10                10               3.882E-02                      ! blade flap mode (")
A   11                11:9999          1.000E-02                      ! all other blade modes

S RIGIDBAR
!  Element  Node1  Node2    Center of gravity offset
!    ID      ID     ID       X        Y        Z
A   4020    4001   4010     0.0      0.0      0.0                     ! portion of hub for blade 1
A   4030    4001   4030     0.0      0.0      0.0                     ! link from hub to undeflected tip of blade 1

N
!  Element  Element                         Inertia Terms
!    ID      Mass     Ixx   Ixy  Ixz   Iyy   Iyz    Izz
A   4020      0.0     0.0   0.0  0.0   0.0   0.0    0.0
A   4030      0.0     0.0   0.0  0.0   0.0   0.0    0.0

S HINGE
! Elem. Node1 Node2  Hinge   Free or    Spring     Damper
!  ID    ID    ID    Type   Controlled  Constant  Constant
A   100 4010   400     P        1         0.0        0.0              ! pitch bearing/hinge

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
A   1         DIRECT        0.0            HIN               100

!=====================================================================
!========================= Copy Primitives ===========================
```

```
!======================================================================
S PRIMIT
! Row_id  Source_Prim_Str_id     Dest_Prim_Str_id
A   1          blade1ps              blade2ps
A   2          blade2ps              blade3ps

EXIT

COMMAND

copyprimstruct

!======================================================================
!========================= CONTROL CONNECTIONS ========================
!                         FOR blade 1 and blade 2
!======================================================================

S PRIMITIVEID
! Select primitive to be defined
C   blade2ps

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
D   1
A   2         DIRECT        0.0           HIN               100

S PRIMITIVEID
! Select primitive to be defined
C   blade3ps

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
D   1
A   3         DIRECT        0.0           HIN               100

!======================================================================
!========================= Connect Primitives =========================
!======================================================================

S CONNCONST
! constraint ID, DOFL( PS name, node ID ), DOFR( PS name, node ID)
A   1                 blade1ps    4001          lsshftps   4000        ! connect lss and blade PSs together at node 4000
A   2                 blade2ps    4001          lsshftps   4000        !   (this effectively eliminates node(s) 4001 from the model)
A   3                 blade3ps    4001          lsshftps   4000

!======================================================================
!========================= Connect Subsystems =========================
!======================================================================
```

```
S ROTNONCONST
!             Non-rotating                     Rotating
! Cnstr.  Subsystem Primitive  Node      Subsystem Primitive  Node
!  ID       Name      Name      ID         Name      Name      ID
A   1      towerss   towerps   2000       rotorss  lsshftps   3120     ! connect rotating and non-rotating subsystems
                                                                       !   at intersection of yaw and shaft axes

!======================================================================
!====================== MISCELLANEOUS PROPERTIES ======================
!======================================================================

S ELEPROPID
! List the names of element property data sets.
! element_prop_ID
A   miscprop

S NLBSHAPE
!  NLB Shape Function     ----- Shape Function Orders ----
!      Set ID             Axial       Bending      Torsion
A   1                       1           0            1                 ! linear for axial and torsional modes, default for bending
                                                                       !   (therefore, the NLB is effectively a linear beam model)

S MATPROPER
! Input material properties (E, G)
! material, Young's Modulus,  shear Modulus
! prop id   or scale factor  or scale factor
A   1            1.0            1.0                                    ! scaling factors for the input distributed elastic properties

!======================================================================
!======================================================================
!                       END OF MODEL DEFINITION
!======================================================================
!======================================================================

!======================================================================
!========================== ANALYSIS DATA =============================
!======================================================================

S SELANALYSIS
! Case      Trim   Mane   Stab   Init      ----- Scope Script -----
!  ID       (0:3)  (0:1)  (0:1)  Cond             File Name
A   01        0      1      0      D                 NO

N
! Case_id            Case Title
A   01                maneuver

S INITCOND
! Initial Pilot Controls
!  collective,    lateral,  longitudinal,    pedal,      throttle
```

```
A   2.6             2.6         2.6           0.0          0.0         ! initial blade 1-3 pitch angles (2.6 deg) and nacelle yaw
angle
                                                                       ! NOTE: the values from SCREEN MANEUVERINPUT add to these!

S SYSTEMFLAGS
! Global element formulation flags
! gravity, aero (1=Yes, 0=No)
A   1       0                                                          ! yes gravity, no aero

!=======================================================================
!========================= MANEUVER DATA ===============================
!=======================================================================
S MANEUVERINPUT
!  Number of Time        Time Step Size     Increment
!     Steps                  (sec)          for output
A   2000                     0.005              1

N
!   Row  Input  Step Number    Amp1       Amp2       Freq1      Freq2      Phase
!   ID    ID    Start  End                           (Hz)       (Hz)       (Deg)
A   1    coll      1  2000      0.0        0.0        0.0        0.0        0.0   ! no change to blade 1 pitch angle from initial
conditions
A   2    latc      1  2000      0.0        0.0        0.0        0.0        0.0   ! no change to blade 2 pitch angle from initial
conditions
A   3    lonc      1  2000      0.0        0.0        0.0        0.0        0.0   ! no change to blade 3 pitch angle from initial
conditions
A   4    pedal     1  2000      0.0        0.0        0.0        0.0        0.0   ! no change to nacelle yaw angle form initial
conditions
                                                                       ! NOTE: these values add to those specified in SCREEN INITCOND!

S INTEGPARAM
!No. of| Newmark Constants|  HHT    | Displace.  | Velocity  | Relax.
!Iter. | Alpha  |  Delta  | Param   |   Tol      |   Tol     | Factor
A   20    .25       .5      -.03       1.e-6       1.e-5       1.0

S MANEUVEROUTPUT
!  Row   Subsystem   Prim. Struc.            output
!  ID      Name        Name                category
A   1       all         all              internal.loads

!=======================================================================
!============================= WRAP UP =================================
!=======================================================================

S RUNALLCASES
!  Run All Cases Flag (0/1)
A   0                                                                  ! no

EXIT

COMMAND
```

```
MENU RUNANALYSIS
```

RCAS Blade Properties Input File

```
! 1.5 MW baseline blade model properties from "InputData1.5A08V07adm.xls" (from C. Hansen) with bugs removed.
! NOTE: "!M CatName" is a keyword telling RCAS that the next set of data to be read in is data for category "CatName".
!           Thus, the order of fields in this file is unimportant.

! Reference/flexible length of beam (m)
!M REFLENGTH
33.25

! Structural twist about X (rad)
!M BSTRUCTW
0.00000   -0.19373
0.02105   -0.19373
0.05263   -0.19373
0.10526   -0.19373
0.15789   -0.19373
0.21053   -0.19373
0.26316   -0.16581
0.31579   -0.13788
0.36842   -0.10996
0.42105   -0.08203
0.47368   -0.05411
0.52632   -0.04538
0.57895   -0.03665
0.63158   -0.02793
0.68421   -0.01920
0.73684   -0.01047
0.78947   -0.00838
0.84211   -0.00628
0.89474   -0.00419
0.94737   -0.00209
1.00000    0.00000

! Mass per unit length (kg/m)
!M BMPL
0.00000   1447.607
0.02105    180.333
0.05263    181.672
0.10526    183.905
0.15789    186.138
0.21053    188.370
0.26316    178.321
0.31579    168.271
0.36842    158.222
0.42105    148.172
0.47368    138.123
0.52632    122.896
0.57895    107.669
0.63158     92.442
0.68421     77.215
```

```
0.73684     61.988
0.78947     51.861
0.84211     41.734
0.89474     31.607
0.94737     21.480
1.00000     11.353

! EI stiffness about local Y (Nm^2)
!M BEIYY
0.00000   7681.46E+06
0.02105   1169.87E+06
0.05263   1020.62E+06
0.10526    771.88E+06
0.15789    523.14E+06
0.21053    274.40E+06
0.26316    234.57E+06
0.31579    194.74E+06
0.36842    154.90E+06
0.42105    115.07E+06
0.47368     75.23E+06
0.52632     62.49E+06
0.57895     49.75E+06
0.63158     37.01E+06
0.68421     24.27E+06
0.73684     11.53E+06
0.78947      9.27E+06
0.84211      7.01E+06
0.89474      4.75E+06
0.94737      2.49E+06
1.00000      0.23E+06

! EI stiffness about local Z (Nm^2)
!M BEIZZ
0.00000   7681.46E+06
0.02105   1169.87E+06
0.05263   1092.28E+06
0.10526    962.97E+06
0.15789    833.66E+06
0.21053    704.35E+06
0.26316    614.65E+06
0.31579    524.96E+06
0.36842    435.26E+06
0.42105    345.57E+06
0.47368    255.87E+06
0.52632    217.87E+06
0.57895    179.86E+06
0.63158    141.86E+06
0.68421    103.85E+06
0.73684     65.85E+06
0.78947     54.25E+06
0.84211     42.66E+06
```

```
0.89474     31.06E+06
0.94737     19.47E+06
1.00000      7.87E+06

! EI cross-stiffness (Nm^2)
!M BEIYZ
0.00000   0.0
1.00000   0.0

! GJ Stiffness about X (Nm^2)
!M BGJ
0.00000   2655.23E+06
0.02105    408.80E+06
0.05263    343.81E+06
0.10526    235.50E+06
0.15789    127.19E+06
0.21053     18.87E+06
0.26316     16.80E+06
0.31579     14.72E+06
0.36842     12.64E+06
0.42105     10.56E+06
0.47368      8.48E+06
0.52632      7.12E+06
0.57895      5.76E+06
0.63158      4.40E+06
0.68421      3.04E+06
0.73684      1.68E+06
0.78947      1.38E+06
0.84211      1.08E+06
0.89474      0.78E+06
0.94737      0.48E+06
1.00000      0.18E+06

! EA Stiffness along X (Nm^2)
!M BEA
0.00000   17152.7E+06
0.02105    2640.8E+06
0.05263    2611.3E+06
0.10526    2562.1E+06
0.15789    2512.9E+06
0.21053    2463.6E+06
0.26316    2332.8E+06
0.31579    2202.0E+06
0.36842    2071.2E+06
0.42105    1940.4E+06
0.47368    1809.6E+06
0.52632    1605.3E+06
0.57895    1401.1E+06
0.63158    1196.8E+06
0.68421     992.6E+06
0.73684     788.3E+06
```

```
0.78947     654.3E+06
0.84211     520.4E+06
0.89474     386.4E+06
0.94737     252.4E+06
1.00000     118.5E+06

! Radius of gyration about local Y (m)
!M BKMYY
0.00000   0.6680
0.02105   0.6680
0.05263   0.6129
0.10526   0.5100
0.15789   0.3840
0.21053   0.1934
0.26316   0.1829
0.31579   0.1703
0.36842   0.1550
0.42105   0.1354
0.47368   0.1088
0.52632   0.1055
0.57895   0.1010
0.63158   0.0948
0.68421   0.0855
0.73684   0.0691
0.78947   0.0680
0.84211   0.0666
0.89474   0.0641
0.94737   0.0587
1.00000   0.0409

! Radius of gyration about local Z (m)
!M BKMZZ
0.00000   0.6680
0.02105   0.6680
0.05263   0.6641
0.10526   0.6575
0.15789   0.6510
0.21053   0.6446
0.26316   0.6189
0.31579   0.5887
0.36842   0.5228
0.42105   0.5089
0.47368   0.4533
0.52632   0.4424
0.57895   0.4279
0.63158   0.4079
0.68421   0.3781
0.73684   0.3289
0.78947   0.3260
0.84211   0.3218
0.89474   0.3147
```

```
0.94737   0.3004
1.00000   0.2565

! Cross-radius of gyration (m)
!M BKMYZ
0.00000   0.0
1.00000   0.0

! CG offset along local Y (m)
!M BCGOFF
0.00000    0.000
0.02105    0.000
0.05263   -0.032
0.10526   -0.086
0.15789   -0.140
0.21053   -0.194
0.26316   -0.188
0.31579   -0.182
0.36842   -0.176
0.42105   -0.170
0.47368   -0.164
0.52632   -0.168
0.57895   -0.172
0.63158   -0.176
0.68421   -0.179
0.73684   -0.183
0.78947   -0.190
0.84211   -0.198
0.89474   -0.205
0.94737   -0.212
1.00000   -0.220

! CG offset along local Z (m)
!M BCGOFFZ
0.00000   0.0
1.00000   0.0

! Elastic/tension offset along local Y (m)
!M BTOFFY
0.00000    0.000
0.02105    0.000
0.05263    0.005
0.10526    0.014
0.15789    0.023
0.21053    0.032
0.26316    0.020
0.31579    0.007
0.36842   -0.005
0.42105   -0.018
0.47368   -0.030
0.52632   -0.038
```

```
0.57895   -0.047
0.63158   -0.055
0.68421   -0.063
0.73684   -0.071
0.78947   -0.077
0.84211   -0.082
0.89474   -0.087
0.94737   -0.092
1.00000   -0.098

! Elastic/tension offset along local Z (m)
!M BTOFFZ
0.00000   0.0
1.00000   0.0

!M BYMODUL
0.00000   1.0
1.00000   1.0

!M BSMODUL
0.00000   1.0
1.00000   1.0

!M BMISC
0 0 0 0 0 0 0 0
1 0 0 0 0 0 0 0
```

RCAS Tower Properties Input File

```
! 1.5 MW baseline tower model properties from "InputData1.5A08V07adm.xls" (from C. Hansen) with bugs removed.
! NOTE: "!M CatName" is a keyword telling RCAS that the next set of data to be read in is data for category "CatName".
!          Thus, the order of fields in this file is unimportant.

! Reference/flexible length of beam (m)
!M REFLENGTH
82.39

! Structural twist about X (rad)
!M BSTRUCTW
0.00000   0.0
1.00000   0.0

! Mass per unit length (kg/m)
!M BMPL
0.00000   2549.742
0.11111   2275.820
0.22222   2017.460
0.33333   1774.662
0.44444   1547.425
0.55556   1335.750
0.66667   1139.637
0.77778    959.085
0.88889    794.095
1.00000    644.666

! EI stiffness about local Y (Nm^2)
!M BEIYY
0.00000   243.058E+09
0.11111   193.660E+09
0.22222   152.204E+09
0.33333   117.790E+09
0.44444    89.570E+09
0.55556    66.753E+09
0.66667    48.601E+09
0.77778    34.430E+09
0.88889    23.610E+09
1.00000    15.566E+09

! EI stiffness about local Z (Nm^2)
!M BEIZZ
0.00000   243.058E+09
0.11111   193.660E+09
0.22222   152.204E+09
0.33333   117.790E+09
0.44444    89.570E+09
0.55556    66.753E+09
0.66667    48.601E+09
0.77778    34.430E+09
```

```
0.88889    23.610E+09
1.00000    15.566E+09

! EI cross-stiffness (Nm^2)
!M BEIYZ
0.00000   0.0
1.00000   0.0

! GJ Stiffness about X (Nm^2)
!M BGJ
0.00000   186.968E+09
0.11111   148.969E+09
0.22222   117.080E+09
0.33333    90.608E+09
0.44444    68.900E+09
0.55556    51.349E+09
0.66667    37.386E+09
0.77778    26.485E+09
0.88889    18.162E+09
1.00000    11.974E+09

! EA Stiffness along X (Nm^2)
!M BEA
0.00000    61.868E+09
0.11111    55.222E+09
0.22222    48.953E+09
0.33333    43.061E+09
0.44444    37.548E+09
0.55556    32.411E+09
0.66667    27.653E+09
0.77778    23.272E+09
0.88889    19.268E+09
1.00000    15.643E+09

! Radius of gyration about local Y (m)
!M BKMYY
0.00000   1.9343
0.11111   1.8276
0.22222   1.7208
0.33333   1.6140
0.44444   1.5073
0.55556   1.4005
0.66667   1.2938
0.77778   1.1870
0.88889   1.0803
1.00000   0.9735

! Radius of gyration about local Z (m)
!M BKMZZ
0.00000   1.9343
0.11111   1.8276
```

```
0.22222   1.7208
0.33333   1.6140
0.44444   1.5073
0.55556   1.4005
0.66667   1.2938
0.77778   1.1870
0.88889   1.0803
1.00000   0.9735

! Cross-radius of gyration (m)
!M BKMYZ
0.00000   0.0
1.00000   0.0

! CG offset along local Y (m)
!M BCGOFF
0.00000   0.0
1.00000   0.0

! CG offset along local Z (m)
!M BCGOFFZ
0.00000   0.0
1.00000   0.0

! Elastic/tension offset along local Y (m)
!M BTOFFY
0.00000   0.0
1.00000   0.0

! Elastic/tension offset along local Z (m)
!M BTOFFZ
0.00000   0.0
1.00000   0.0

!M BYMODUL
0.00000   1.0
1.00000   1.0

!M BSMODUL
0.00000   1.0
1.00000   1.0

!M BMISC
0 0 0 0 0 0 0 0
1 0 0 0 0 0 0 0
```

RCAS Output Data Extractor File

```
// This file extracts out useful information (loads and motions) from a maneuver, analysis event for the 15mwbaseline.scr models.


// Inform users we have arrived here:

DISP(" ");
DISP("Running user-defined RSCOPE script, '15mwbaselineoutputs.exc' written by J. Jonkman");
DISP(" ");


// Define some constants:

Pi       = 3.1415927;                              // pi
R2D      = 57.295780;                              // conversion from radians to degrees
RPS2RPM  = 9.5492966;                              // conversion form rad/sec to rpm


// Define some basic variables used for data extraction:

NSteps   = NTSTEPK;                                // the number of time steps analyzed
DecFact  = 1;                                      // the decimation factor for tabular output
NStepOut = NSteps/DecFact;                         // the number of time steps output
Index    = DecFact:DecFact:NSteps;                 // the array [ 1,  2,  3, ..., NSteps ] used as a decimation factor for output data
Index2   = 5:5:6000;                               // the array [ 5, 10, 15, ..., 6000   ] used as a decimation factor for output data


// Extract out useful loads and motions from ambiguous arrays (take data only every 5th time step):
// NOTE: the indices of these arrays where found using the DISP(@xxx) command in RSCOPE

Time        = TIMEVEC(Index);                      // extract out only every 5th component of time

WindVxt     = ZEROS(NStepOut,1);                   // horizontal wind speed, m/s
HorWndDir   = ZEROS(NStepOut,1);                   // wind direction, deg

Node500Pos  = OUTNDRPOS(  88: 90,Index)';          // 3 components (x,y,z) of position of node 500  (  deflected blade 1 tip) in
global CS
Node4030Pos = OUTNDRPOS(  94: 96,Index)';          // 3 components (x,y,z) of position of node 4030 (undeflected blade 1 tip) in
global CS
Node4030XFM = OUTNDRXFM( 280:288,Index)';          // 9 components of the transformation matrix of node 4030 relative to the global CS
                                                   //   as follows:
                                                   //      columns 1:3 of Node4030XFM represent the 1st column of [Tp/i] of node 4030,
                                                   //      columns 4:6 of Node4030XFM represent the 2nd column of [Tp/i] of node 4030,
and
                                                   //      columns 7:9 of Node4030XFM represent the 3rd column of [Tp/i] of node 4030

BldPitch1   = UTOT(Index2,1);                      // pitch angle of blade 1 (in degrees)
                                                   // NOTE: UTOT = <values from SCREEN INITCOND> + MANEUHIS

Node400Frc  = OUTINTLFRC(106:108,Index)';          // 3 components (x,y,z) of force  on node 400 (blade 1 root-blade side) in local
```

```
                                                    //   element CS
Node400Mom  = OUTINTLMOM(106:108,Index)';          // 3 components (x,y,z) of moment on node 400 (blade 1 root-blade side) in local
                                                    //   element CS

Node2130XFM = OUTNDRXFM( 136:144,Index)';          // 9 components of the transformation matrix of node 2130 relative to the global CS
                                                    //   as follows:
                                                    //      columns 1:3 of Node2130XFM represent the 1st column of [Tp/i] of node 2130,
                                                    //      columns 4:6 of Node2130XFM represent the 2nd column of [Tp/i] of node 2130,
and
                                                    //      columns 7:9 of Node2130XFM represent the 3rd column of [Tp/i] of node 2130
Node3020Omg = OUTNDROMG(      54,Index)';          // z-component of angular velocity of node 3020 (rotor end of LSS compliance) in
local
                                                    //   element CS
Node2130Omg = OUTNDROMG(      48,Index)';          // z-component of angular velocity of node 2130 (intersection of yaw and shaft
axes;
                                                    //   fixed in nacalle) in local element CS

Node3020Frc = OUTINTLFRC( 52: 54,Index)';          // 3 components (x,y,z) of force on node 3020 (rotor end of LSS compliance) in
local
                                                    //   element CS
Node4000Mom = OUTINTLMOM( 61: 63,Index)';          // 3 components (x,y,z) of moment on node 4000 (rotor / hub center) in local
element CS

Node2010XFM = OUTNDRXFM(  64: 72,Index)';          // 9 components of the transformation matrix of node 2010 relative to the global CS
                                                    //   as follows:
                                                    //      columns 1:3 of Node2010XFM represent the 1st column of [Tp/i] of node 2010,
                                                    //      columns 4:6 of Node2010XFM represent the 2nd column of [Tp/i] of node 2010,
and
                                                    //      columns 7:9 of Node2010XFM represent the 3rd column of [Tp/i] of node 2010
Node1010XFM = OUTNDRXFM( 100:108,Index)';          // 9 components of the transformation matrix of node 1010 relative to the global CS
                                                    //   as follows:
                                                    //      columns 1:3 of Node1010XFM represent the 1st column of [Tp/i] of node 1010,
                                                    //      columns 4:6 of Node1010XFM represent the 2nd column of [Tp/i] of node 1010,
and
                                                    //      columns 7:9 of Node1010XFM represent the 3rd column of [Tp/i] of node 1010

Node1010Pos = OUTNDRPOS(  34: 36,Index)';          // 3 components (x,y,z) of position of node 1010 (  deflected tower-top) in global
CS
Node1030Pos = OUTNDRPOS(   7:  9,Index)';          // 3 components (x,y,z) of position of node 1030 (undeflected tower-top) in global
CS

Node1010Frc = OUTINTLFRC( 34: 36,Index)';          // 3 components (x,y,z) of force  on node 1010 (yaw bearing) in local element CS
Node1010Mom = OUTINTLMOM( 34: 36,Index)';          // 3 components (x,y,z) of moment on node 1010 (yaw bearing) in local element CS

Node1400Frc = OUTINTLFRC( 40: 42,Index)';          // 3 components (x,y,z) of force  on node 1400 (tower base) in local element CS
Node1400Mom = OUTINTLMOM( 40: 42,Index)';          // 3 components (x,y,z) of moment on node 1400 (tower base) in local element CS


// Calculate the blade 1 tip deflection from the deflected and undeflected tip position:

Node500Defl = Node500Pos - Node4030Pos;            // 3 components (x,y,z) of the deflection of node 500 (blade 1 tip) in global CS
```

```
FOR i = 1:NStepOut,
   T4030piT(1,1:3) = Node4030XFM(i,1:3);           //
   T4030piT(2,1:3) = Node4030XFM(i,4:6);           // the transpose of transformation matrix [Tp/i] of node 4030
   T4030piT(3,1:3) = Node4030XFM(i,7:9);           //
   Node500Defl(i,:) = Node500Defl(i,:)*T4030piT;   // 3 components (x,y,z) of the deflection of node 500 (blade 1 tip) in blade1ps CS
END


// Calculate the rotor azimuth angle from the transformation matrices of nodes 4030 and 2130:

FOR i = 1:NStepOut,
   T4030piT(1,1:3) = Node4030XFM(i,1:3);           //
   T4030piT(2,1:3) = Node4030XFM(i,4:6);           // the transpose of transformation matrix [Tp/i] of node 4030
   T4030piT(3,1:3) = Node4030XFM(i,7:9);           //
   T2130piT(1,1:3) = Node2130XFM(i,1:3);           //
   T2130piT(2,1:3) = Node2130XFM(i,4:6);           // the transpose of transformation matrix [Tp/i] of node 2130
   T2130piT(3,1:3) = Node2130XFM(i,7:9);           //
        T4030p2130p = T4030piT'*T2130piT;               // the transformation matrix [Ta/b] of node 4130 (a) relative to node 2130 (b)
        Azimuth(i,1) = ACOS(T4030p2130p(1,1));          // use the inverse COS to obtain the rotor azimuth
   IF T4030p2130p(2,1) > 0.0,
      Azimuth(i,1) = 2.0*Pi - Azimuth(i,1);        // force rotor azimuth to belong in 0 <= azimuth < 360 deg
   END
END


// Calculate the rotor speed (relative to the nacalle, not the ground):

RotSpeed = Node3020Omg - Node2130Omg;              // rotor speed (LSS spd) relative to nacalle, not absolute


// Calculate the nacelle yaw angle from the transformation matrices of nodes 2010 and 1010:

FOR i = 1:NStepOut,
   T2010piT(1,1:3) = Node2010XFM(i,1:3);           //
   T2010piT(2,1:3) = Node2010XFM(i,4:6);           // the transpose of transformation matrix [Tp/i] of node 2010
   T2010piT(3,1:3) = Node2010XFM(i,7:9);           //
   T1010piT(1,1:3) = Node1010XFM(i,1:3);           //
   T1010piT(2,1:3) = Node1010XFM(i,4:6);           // the transpose of transformation matrix [Tp/i] of node 1010
   T1010piT(3,1:3) = Node1010XFM(i,7:9);           //
        T2010p1010p = T2010piT'*T1010piT;               // the transformation matrix [Ta/b] of node 2010 (a) relative to node 1010 (b)
        NacYaw(i,1) = REAL(ASIN(T2010p1010p(2,3)));     // use the inverse SIN to obtain the nacelle yaw angle
END


// Calculate the tower-top deflection from the deflected and undeflected tower-top position:

Node1010Defl = Node1010Pos - Node1030Pos;          // 3 components (x,y,z) of the deflection of node 1010 (yaw bearing) in global CS


// Convert the outputs to IEC-style coordinate systems:
```

```
Blade1psCS2Coned1CS  = [  0.0, 0.0, 1.0; 0.0, -1.0, 0.0; 1.0, 0.0,  0.0 ]; // transformation matrix to convert from blade1ps CS to the
coned
                                                                              //   CS of blade 1
Node400CS2Blade1CS   = [  0.0, 0.0, 1.0; 0.0, -1.0, 0.0; 1.0, 0.0,  0.0 ]; // transformation matrix to convert from local node 400 CS
to
                                                                              //   blade 1 CS
LSShftpsCS2AzimuthCS = [  0.0, 0.0  1.0; 0.0, -1.0, 0.0; 1.0, 0.0,  0.0 ]; // transformation matrix to convert from LSShftps CS to
azimuth CS
Node4000CS2AzimuthCS = [ -1.0, 0.0, 0.0; 0.0, -1.0, 0.0; 0.0, 0.0,  1.0 ]; // transformation matrix to convert from local node 4000 CS
to
                                                                              //   azimuth CS
GlobalCS2TwrBaseCS   = [  1.0, 0.0, 0.0; 0.0, -1.0, 0.0; 0.0, 0.0, -1.0 ]; // transformation matrix to convert from global CS to
                                                                              //   tower-base CS
Node1010CS2TwrTopCS  = [  0.0, 0.0, 1.0; 0.0, -1.0, 0.0; 1.0, 0.0,  0.0 ]; // transformation matrix to convert from local node 1010 CS
to
                                                                              //   tower-top / base-plate CS
TowerpsCS2TwrBaseCS  = [  0.0, 0.0, 1.0; 0.0, -1.0, 0.0; 1.0, 0.0,  0.0 ]; // transformation matrix to convert from towerps CS to
                                                                              //   tower-base CS

TipDefl1 = Node500Defl*Blade1psCS2Coned1CS;        // blade 1 tip deflections in the coned CS for blade 1
RootFb1  = Node400Frc*Node400CS2Blade1CS;          // blade 1 root forces in blade 1 CS
RootMb1  = Node400Mom*Node400CS2Blade1CS;          // root moments in blade 1 CS
LSShftF  = Node3020Frc*LSShftpsCS2AzimuthCS;       // rotor thrust and rotating LSS shear forces - NOTE: use the force on node 3020
instead
                                                   //   of the force on node 4000, since the force on node 4000 doesn't include the
effects
                                                   //   of the hub mass (I can use the force on node 3020 to represent the forces on
the
                                                   //   shaft tip since the thrust and shear forces are constant along the shaft).
LSSTipM  = Node4000Mom*Node4000CS2AzimuthCS;       // rotor torque and rotating LSS bending moments at the shaft tip
TTDsp    = Node1010Defl*GlobalCS2TwrBaseCS;        // tower-top deflection
YawBrF   = Node1010Frc*Node1010CS2TwrTopCS;        // tower-top / yaw bearing axial and shear forces
YawBrM   = Node1010Mom*Node1010CS2TwrTopCS;        // tower-top / yaw bearing roll, pitch, and yaw moments
TwrBsF   = Node1400Frc*TowerpsCS2TwrBaseCS;        // tower base axial and shear forces
TwrBsM   = Node1400Mom*TowerpsCS2TwrBaseCS;        // tower base roll, pitch, and yaw moments


// Split these into single column arrays with one array per output channel and covert units as appropriate:

OoPDefl1  = TipDefl1(:,1);                         // OoP blade 1 tip deflection
IPDefl1   = TipDefl1(:,2);                         // IP  blade 1 tip deflection
RootFxb1  = RootFb1(:,1)/1000.0;                   // x-component of blade 1 root force, kN
RootFyb1  = RootFb1(:,2)/1000.0;                   // y-component of blade 1 root force, kN
RootFzb1  = RootFb1(:,3)/1000.0;                   // z-component of blade 1 root force, kN
RootMxb1  = RootMb1(:,1)/1000.0;                   // x-component of blade 1 root moment, kN-m
RootMyb1  = RootMb1(:,2)/1000.0;                   // y-component of blade 1 root moment, kN-m
RootMzb1  = RootMb1(:,3)/1000.0;                   // z-component of blade 1 root moment, kN-m
Azimuth   = Azimuth*R2D;                           // rotor azimuth, deg
RotSpeed  = RotSpeed*RPS2RPM;                      // rotor speed, rpm
RotThrust = LSShftF(:,1)/1000.0;                   // rotor thrust, kN
```

```
LSShftFya = LSShftF(:,2)/1000.0;                    // y-component of rotating LSS shear force, kN
LSShftFza = LSShftF(:,3)/1000.0;                    // z-component of rotating LSS shear force, kN
RotTorq   = LSSTipM(:,1)/1000.0;                    // rotor torque, kN-m
LSSTipMya = LSSTipM(:,2)/1000.0;                    // y-component of rotating LSS bending moment at the shaft tip, kN-m
LSSTipMza = LSSTipM(:,3)/1000.0;                    // z-component of rotating LSS bending moment at the shaft tip, kN-m
NacYaw    = NacYaw*R2D;                             // nacelle yaw angle, deg
TTDspFA   = TTDsp(:,1);                             // FA tower-top deflection, m
TTDspSS   = TTDsp(:,2);                             // SS tower-top deflection, m
YawBrFxp  = YawBrF(:,1)/1000.0;                     // x-component of tower-top / yaw bearing shear force, kN
YawBrFyp  = YawBrF(:,2)/1000.0;                     // y-component of tower-top / yaw bearing shear force, kN
YawBrFzp  = YawBrF(:,3)/1000.0;                     // tower-top / yaw bearing axial force, kN
YawBrMxp  = YawBrM(:,1)/1000.0;                     // tower-top / yaw bearing roll  moment, kN-m
YawBrMyp  = YawBrM(:,2)/1000.0;                     // tower-top / yaw bearing pitch moment, kN-m
YawBrMzp  = YawBrM(:,3)/1000.0;                     // tower-top / yaw bearing yaw   moment, kN-m
TwrBsFxt  = TwrBsF(:,1)/1000.0;                     // x-component of tower base shear force, kN
TwrBsFyt  = TwrBsF(:,2)/1000.0;                     // y-component of tower base shear force, kN
TwrBsFzt  = TwrBsF(:,3)/1000.0;                     // tower base axial force, kN
TwrBsMxt  = TwrBsM(:,1)/1000.0;                     // tower base roll  moment, kN-m
TwrBsMyt  = TwrBsM(:,2)/1000.0;                     // tower base pitch moment, kN-m
TwrBsMzt  = TwrBsM(:,3)/1000.0;                     // tower base yaw   moment, kN-m


// Write the data to file "15mwbaseline.out":

SHORTE;                                             // use short, exponential format for outputs

PRINT( "15mwbaseline.out", Time, WindVxt, HorWndDir, OoPDefl1, IPDefl1, BldPitch1, RootFxb1, RootFyb1, RootFzb1, RootMxb1, RootMyb1,
RootMzb1, Azimuth, RotSpeed, RotThrust, LSShftFya, LSShftFza, RotTorq, LSSTipMya, LSSTipMza, NacYaw, TTDspFA, TTDspSS, YawBrFxp,
YawBrFyp, YawBrFzp, YawBrMxp, YawBrMyp, YawBrMzp, TwrBsFxt, TwrBsFyt, TwrBsFzt, TwrBsMxt, TwrBsMyt, TwrBsMzt );
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13. ABSTRACT *(Maximum 200 words)*
In recent years, the wind industry has sponsored the development, verification, and validation of comprehensive aeroelastic simulators, which are used for wind turbine design, certification, and research. Unfortunately, as wind turbines continue to grow in size and sometimes exhibit unconventional design characteristics, the existing codes do not always support the additional analysis features required for proper design. The development history, functionality, and advanced nature of RCAS (Rotorcraft Comprehensive Analysis System) make this code a sensible option. RCAS is an aeroelastic simulator developed over a 4-year cooperative effort amongst the U.S. Army's Aeroflightdynamics Directorate, Advanced Rotorcraft Technology (ART), Inc., and the helicopter industry. As its name suggests, RCAS was created for the rotorcraft industry but developed as a general purpose code for modeling the aerodynamic and structural response of any system with rotating and nonrotating subsystems (such as wind turbines). To demonstrate that RCAS can analyze wind turbines, models of a conventional, 1.5-MW, 3-bladed, upwind, horizontal axis wind turbine (HAWT) are created in RCAS and wind turbine analysis codes FAST (Fatigue, Aerodynamics, Structures, and Turbulence) and ADAMS (Automatic Dynamic Analysis of Mechanical Systems). Using these models, a side-by-side comparison of structural response predictions is performed under several test scenarios.

14. SUBJECT TERMS
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