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Technical Report

Evaluation of RCAS Inflow Models for Wind Turbine Analysis

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Contents

Figures

Tables

Executive Summary

The finite element structural modeling in the Rotorcraft Comprehensive Analysis System (RCAS) provides a state-of-the-art approach to aeroelastic analysis. This, coupled with its ability to model all turbine components, results in a methodology that can simulate complex system interactions characteristic of large wind. In addition, RCAS is uniquely capable of modeling advanced control algorithms and the resulting dynamic responses.

The aerodynamic inflow models in RCAS have been formulated for helicopter analysis. These models needed to be evaluated for wind turbine analysis to determine whether they included features that accurately predict the inflow for steady state, quasi-steady state, and unsteady operating conditions of wind turbines. The aerodynamic inflow models include the generalized dynamic inflow model, the equilibrium-based blade element momentum (BEM) theory, a prescribed vortex wake, and a free vortex wake. The four inflow methods in RCAS are listed in order of increasing complexity and computational time. The inflow models in RCAS were evaluated by comparing their predicted angles of attack for steady and quasi steady operating conditions with other wind industry aerodynamic models such as WT_Perf (BEM), AeroDyn (BEM and generalized dynamic wake), and LSWT (lifting surface prescribed wake).

Momentum theory or the generalized dynamic-wake theory should be selected for most applications because both are simple and have rapid computational times. For unsteady inflow conditions the generalized dynamic wake inflow model is preferred because of its noniterative time domain formulation. The use of momentum theory in RCAS will depend on successful implementation of the Prandtl tip/hub loss model, induced swirl effects, and the Glauert approximation. Both the prescribed and free vortex wake options require exponential increases in computational time and use a basic lifting line blade representation. In unsteady inflow conditions these inflow models are less compatible with dynamic perturbations because of their discretized blade and wake vortex models. The prescribed and free wake vortex models are better suited for steady-state, axis-symmetric performance prediction. However, for the prescribed and free wake vortex models, a lifting surface blade representation is preferred over a lifting line.

Background

The Rotorcraft Comprehensive Analysis System (RCAS) is a state-of-the-art computational analysis system for modeling rotorcraft [1–4]. It can model a complete range of rotorcraft configurations in hover, forward-flight, and maneuvering flight conditions. RCAS can perform a variety of engineering calculations, including vehicle performance, aerodynamics and rotor loads, vehicle vibration, flight-control analysis, aeroelastic stability, flight dynamics, and flight simulation. Analysis features in RCAS include trim, maneuver, and stability.

Structural modeling in RCAS uses a finite element approach for the various rotorcraft components. A helicopter model can include a conventional or multi-rotor configuration along with the fuselage, engine/drivetrain model, and control system. This structural modeling provides the capability for accurate dynamic simulation that includes the interaction between all system components. The rotorcraft system structural modeling capability can be adapted to model wind turbine systems, which would include the rotor, generator/drivetrain, nacelle, tower, and control system. Because wind turbines are becoming larger and more dynamically active, a comprehensive system dynamic simulation is more critical.

Aerodynamic modeling in RCAS includes all rotorcraft system components such as rotors, wings, and fuselage. Two-dimensional airloads are used for blade and wing segments, three-dimensional airloads for the fuselage, and disc inflow models for the rotor. The resulting induced velocities and airloads are modeled separately for each component and collected in an aerodynamic library. RCAS includes four aerodynamic models that have been tailored for helicopter analysis to calculate the rotor's induced inflow. Aerodynamic inflow models include the generalized dynamic wake theory [5], blade element momentum (BEM), prescribed wake, and free wake. These inflow methods are listed in order of increasing computational time and complexity. The Beddoes-Leishman dynamic stall model [6] can be used with all inflow models. The generalized dynamic wake theory or BEM should be selected for most applications because they are simple and have rapid computational times. Both the prescribed and free vortex wake options result in exponential increases in computational time and use the basic lifting line blade representation rather than a lifting surface.

The focus of this study was the aerodynamic modeling of the rotor in RCAS and assessing the suitability of the inflow models for predicting wind turbine blade loads and performance. Evaluation of the RCAS inflow models consisted of comparing their angle-of-attack predictions to similar inflow models used in-house and in the wind industry. These models include WT_Perf [7], AeroDyn [8,9] and LSWT (Lifting-Surface Prescribed-Wake code) [10]. Both WT_Perf and AeroDyn have a BEM inflow model to predict rotor performance. In addition, AeroDyn includes the generalized dynamic wake inflow model and the Beddoes-Leishman dynamic stall model. Both codes can be used to predict steady state axis-symmetric performance and quasi steady state, yawed rotor performance. RCAS and AeroDyn, with the generalized dynamic wake theory can be used for unsteady performance prediction. The LSWT performance prediction code uses a prescribed, expanding-wake, inflow model. The code uses a lifting surface blade representation for blade geometry optimization and can also be used to predict steady-state, axis-symmetric performance and quasi-steady-state, yawed rotor performance. The comparison in this report included exercising all the inflow options in RCAS relative to those in NREL's in-house performance prediction codes WT_Perf, AeroDyn, and LSWT. This was done using the UAE (unsteady aerodynamic experiment) two bladed, rotor geometry [11] and S809 [12] airfoil characteristics.

Objective

The objective of this study was to evaluate the aerodynamic inflow options in RCAS. To accomplish this objective, predicted angle of attack distributions obtained from RCAS were compared with industry-accepted aerodynamic codes that included WT_Perf, AeroDyn, and LSWT. The project scope was limited to axis-symmetric and yawed-flow, steady state operation with no structural degrees of freedom.

Approach

The UAE Phase VI wind turbine was selected for this code comparison. The upwind configuration of this two-bladed, horizontal-axis turbine has been the subject of several past studies. Consequently, input data for this turbine were available and results from this study will provide a baseline for future comparisons with UAE test data from the NASA Ames 80-ft by 120-ft (24.5-m by 36.5-m) wind tunnel. This 10-m (33-ft) rotor has tapered, twisted blades that use the NREL S809 airfoil profile from blade root to blade tip. S809 2-D airfoil data, from the Delft low turbulence wind tunnel, was used for calculating angle of attack distributions in RCAS, WT_Perf, AeroDyn, and LSWT. Operating cases included steady state axis-symmetric operation and quasi-steady state yawed flow operation.

Aerodynamic Inflow Models

RCAS, WT_Perf, and AeroDyn all employ the BEM inflow option for modeling wind turbine aerodynamics (see Table 1). In addition, RCAS and AeroDyn include a dynamic inflow option that minimizes computational time. For stall and post-stall calculations the prescribed wake inflow approach in LSWT and RCAS have the potential to more accurately predict the angle of attack. The free wake option in RCAS provides further flexibility to accommodate more inflow conditions at the expense of excessive computer time. Detailed descriptions of the theories each code employs can be found in their user and theory manuals.

Table 1: Program and Inflow Models Used in this Study

RCAS 1.9.5a	BEM, Dynamic Inflow, Prescribed Wake, Free Wake
WT_Perf 2.2	BEM
AeroDyn 12.50	BEM, Dynamic Inflow
LSWT 1.2	Prescribed Wake

Blade Element Momentum Theory

Below stall, BEM theory predicts reasonable angle-of-attack distributions for steady-state, axis-symmetric inflow conditions. Under stalled airfoil conditions, normally at high wind speeds, BEM over predicts the angle-of-attack distribution [13]. The over prediction is largely the result of two simplifying assumptions inherent in BEM. The "uniform inflow around the annulus" assumption leads to an over prediction of the angle of attack with the onset of stalled rotor conditions. The "no interaction between annuluses" assumption does not recognize the strong induced effect of trailing vorticity on the angle of attack distribution and resulting load distribution.

For helicopter analysis, RCAS uses an effective-radius tip-loss model with no hub loss model. Typically, an effective radius input of 0.98 is used for helicopters, which means the blade radius is reduced by 2%. For wind turbines, the shorter radius from this tip loss model results in a larger blade pitch angle to achieve the designated thrust and power. Because the effective radius tip loss model has little effect on the blade load distribution it is not appropriate for wind turbine calculations. The Prandtl tip and hub loss models favorably decrease the tip and root loading and should be implemented in RCAS for use with the BEM inflow option.

RCAS was formulated primarily for helicopter forward flight calculations, in which the axial induction factor is important and the swirl induction factor is insignificant. However, for wind turbine calculations the induced swirl is significant and results in a lower angle of attack distribution toward the blade root region. The induced swirl should be implemented in RCAS to improve accuracy and to provide results comparable with other wind turbine codes that include the induced swirl.

For wind turbines, the Glauert empirical approximation improves accuracy at low wind speeds, high tip speed ratios, and high axial induction factors. The Glauert empirical approximation (also known as the windmill brake state model) calculates higher power coefficients than the classical momentum method at non-optimum pitch angles toward feather. This empirical approximation should be included in RCAS.

Generalized Dynamic Wake Theory

The generalized dynamic wake model is based on incompressible, potential flow, and small disturbance theory. This inviscid, non-interative, three-dimensional unsteady induced-flow theory is based on the unsteady theory of Peters and He [4]. The time domain model uses acceleration potential with a skewed cylindrical wake. This method calculates only the dynamic inflow perpendicular to the rotor disc as a function of the disc loading and air mass dynamic force. Wake induced swirl in the rotor plane, which is not important to helicopter analysis, is not calculated. The method implicitly includes Theodorsen and Loewy induced inflow effects from the shed wake as well as Prandtl-Goldstein tip losses caused by the trailing wake. This inflow method is useful in analyzing skewed wake effects when operating off the wind axis. For helicopters, the method provides good correlation of the inflow relative to measurements, except near the blade tip. For yawed-flow calculations the method approximates the time lag between the initiation of a load disturbance and when it is felt at some other point in the flow field. Of all the inflow models it is best suited for aeroelasticity analysis, aeroelasticity tailoring, and higher harmonic control. It can also be applied to investigate coupled blade flap, lead-lag, and torsional stability.

Prescribed Vortex Wake Theory

Simplifying assumptions associated with blade element momentum and the generalized dynamic wake theories are largely eliminated through the use of a prescribed vortex wake. The method is better suited for axis-symmetric, blade geometry and performance optimization than either BEM or generalized dynamic wake theory, since it includes wake distortion and wake rollup. However, vortex wake inflow methods lend themselves to steady and quasi-steady analysis but are not well suited for unsteady aeroelasticity analysis. This drawback relates to the discretization of both the blade and wake vortex model, which tends to be less compatible with dynamic perturbations. The wake inflow model would likely need five inflow points per half cycle for the highest frequency of interest. Such a fine inflow resolution would lead to excessive computer time and frequent numerical instabilities. The RCAS prescribed wake model is based on helicopter contracting, prescribed wake equations that are limited to a constant diameter wake equal to the rotor diameter. Expanding wake prescribed equations, similar to those used in LSWT, are needed for this option to be viable for wind turbine analysis. In addition, the RCAS prescribed wake is used with a lifting line blade representation, whereas the expanding prescribed wake equations in LSWT are used with a lifting surface blade representation that includes induced effects for as many as five chordwise panels. Lacking the correct wind turbine prescribed wake equations, the RCAS prescribed wake model resulted in excessively high angle of attack predictions.

Free Wake Theory

A free wake inflow model is unencumbered by the use of prescribed wake equations and can accommodate a broader range of operating conditions. Several free wake formulations differ primarily in their numerical methods. The Leishman and Bhagwat free-vortex wake is the newest free wake option to be used in RCAS. For this wake model, the tip region trailing vorticity is truncated into a discrete tip vortex 15°–45° behind the blade. The free wake extends one and a half radii below the blade. The bottom of free wake is stabilized by evolutions of prescribed wake resulting from previous free wake iterations. Like the prescribed wake, the free wake is not well suited for unsteady aeroelasticity analysis because of wake discretization. Attempts to run the free wake for the UAE wind turbine rotor were not successful. The input data set included a large number of wake geometry input parameters that will require some trial and error to find a suitable combination.

Dynamic Stall Model

Dynamic stall behavior is characterized using the Beddoes-Leishman dynamic stall model with any of the RCAS inflow models. AeroDyn also uses the same dynamic stall model. The dynamic stall model is most compatible with the time domain based, generalized dynamic wake inflow model in RCAS and AeroDyn. In RCAS, the dynamic stall model is airfoil dependent and numerous airfoil specific input based to 2-D unsteady tests are required. Airfoil specific inputs in RCAS are defined only for the symmetric NACA 0012 airfoil and the SC1095 cambered airfoil. Only the cambered airfoil should be used in wind turbine analysis. In AeroDyn no airfoil inputs are required since the dynamic stall model is hard wired for a generic cambered airfoil.

Turbine Description

The UAE turbine geometry and aerodynamic information were obtained for the Phase VI UAE Rotor [10]. A summary of the turbine design properties for this two-bladed, upwind, horizontal-axis wind turbine appears in Table 2.

Table 2: Summary of Baseline Turbine Design Properties

Rotor Diameter	10.06 m
Hub Height	12.2 m
Rotor Precone	0°
Shaft Tilt	0°
Rotor Speed	72 rpm
Tip Speed Ratio for Maximum Power Coefficient	7.0

The UAE rotor blade geometry is shown in Figure 1. The blade uses the S809 airfoil from root to tip. Performance characteristics for the S809 airfoil, acquired in the Delft wind tunnel, are shown in Figure 2. For simplicity, the lift and drag data for a Reynolds number of 1,000,000 were used from blade root to tip in WT_Perf, AeroDyn, LSWT, and RCAS.

The airfoil data input format for RCAS is derived from a Bell Helicopter's dynamics code, "C81", which was tailored for helicopter analysis. Each angle of attack in the data table is listed for multiple Mach numbers. For each Mach number, lift, drag, and moment coefficient are given. For wind turbines, compressibility effects are negligible and the airfoil characteristics can be held constant with Mach number. An example of a wind turbine airfoil input data set (S809.C81) with the S809 airfoil is shown in the Appendix. A simpler format is desired for wind turbine analysis.

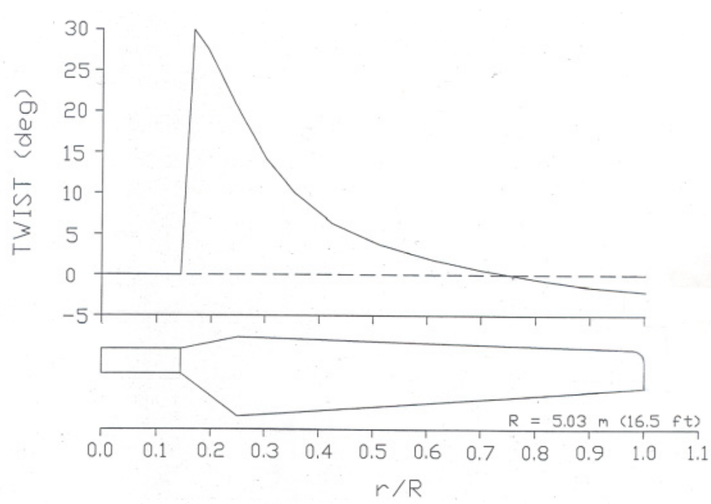

Figure 1. UAE rotor blade geometry.

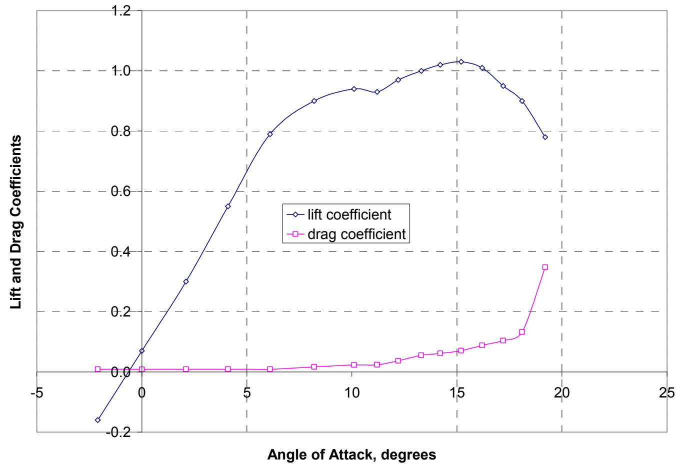

Figure 2. S809 Delft wind tunnel data.

Predicted Angle of Attack

Steady State Axis Symmetric Results

The BEM inflow option in RCAS neglects several options—induced swirl, the Prandtl tip loss option, and the Glauert approximation—important to wind turbine analysis. NREL's in-house BEM code, WT_Perf was used to illustrate the influence of the induced swirl and Prandtl tip loss option on the predicted angle of attack. Figure 3 shows the predicted angle of attack for the UAE two-bladed rotor at 7 m/s when no stall is present along the blade. Induced swirl, which adds to the local rotational speed, is greatest over the inboard portion of the blade and decreases with radius. Consequently, the inclusion of swirl decreases the angle of attack inboard by about 1° with almost no effect toward the tip. The Prandtl tip loss reduced the angle of attack by about 2° toward the tip. The Prandtl hub loss results in a fraction of a degree reduction toward the blade root. The Glauert approximation has little influence on the angle of attack distribution for optimum blade pitch.

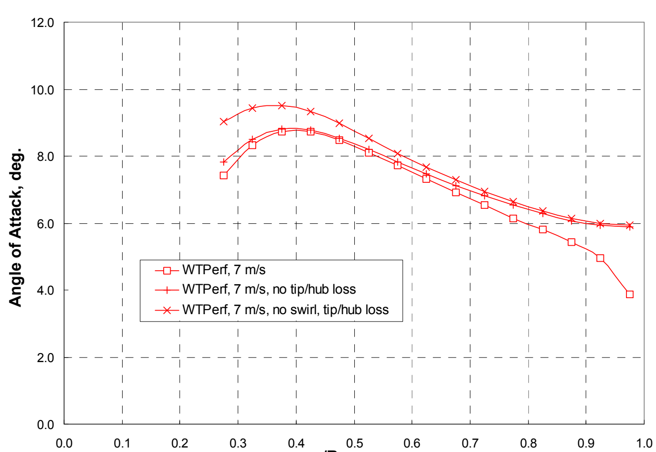

Figure 3. Effect of Prandtl tip/hub loss and induced swirl in WT_Perf.

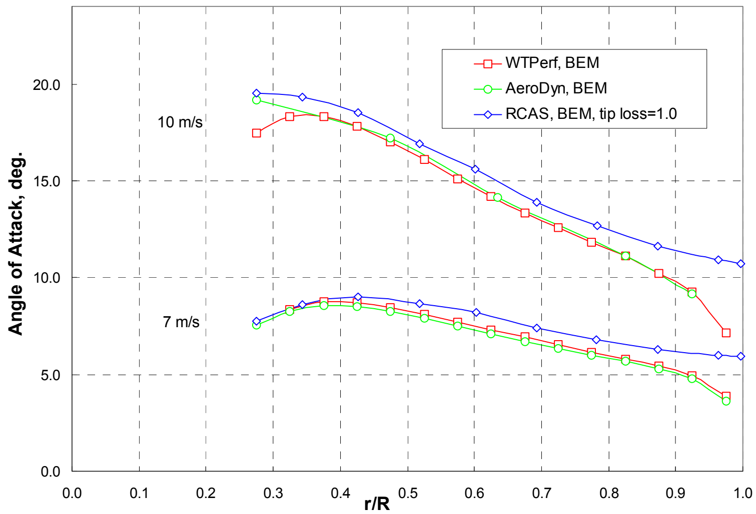

Figure 4. Angle of attack comparison of WT_Perf, AeroDyn, and RCAS.

The BEM inflow option was used to show a comparison of the predicted angle of attack for WT_Perf, AeroDyn, and RCAS for wind speeds of 7 and 10 m/s (Figure 4). Close agreement is seen for WT_Perf and AeroDyn, both of which include the induced swirl, Prandtl tip loss, and Glauert approximation. WT_Perf also includes the Prandtl hub loss that is omitted in this version of AeroDyn. The higher blade root angle of attack is attributed to this omission. For both wind speeds, RCAS predicts noticeably higher angle of attack distributions by not including these inflow options.

The dynamic wake inflow option [4] in RCAS provided better agreement with WT_Perf and LSWT over the outboard part of the blade (see Figure 5). For comparison, the RCAS BEM inflow option, with the over-predicted angle of attack is also shown. Both the BEM method WT_Perf and the prescribed wake method LSWT are in close agreement at 7 m/s, except for the root region where LSWT has a lower angle of attack as a result of greater induced root inflow. The dynamic inflow option of RCAS over predicts the tip and hub region angle of attack even though the method implicitly includes the Prandtl-Goldstein tip losses. Also unusual is the lower angle of attack (around 50% radius) when induced swirl effects are not included in the dynamic wake inflow option.

Further comparison of the RCAS dynamic wake inflow option is shown in Figure 6 for wind speeds of 5, 7, and 10 m/s. The dynamic inflow option tends to under predict the angle of attack distribution with increasing wind speeds, except for the immediate tip and hub region. Also, WT_Perf over predicts the angle of attack with increasing wind speed as a result of the uniform inflow assumption around the annulus and the assumption of no interaction between annuli.

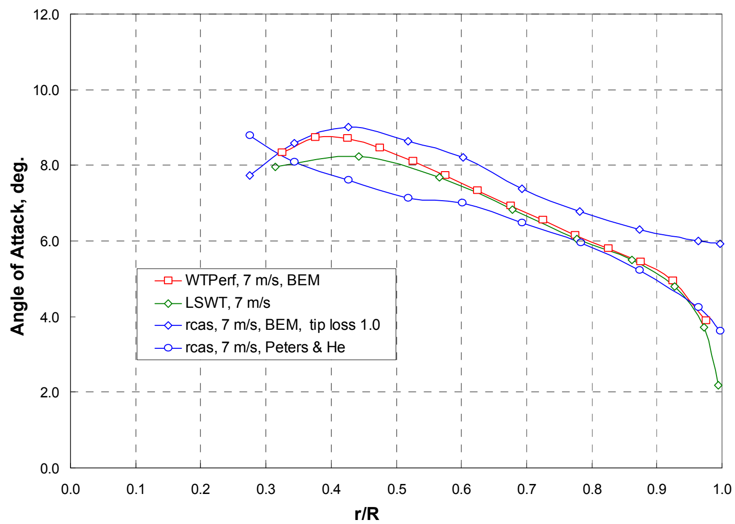

Figure 5. Angle of attack comparison with generalized dynamic wake [4].

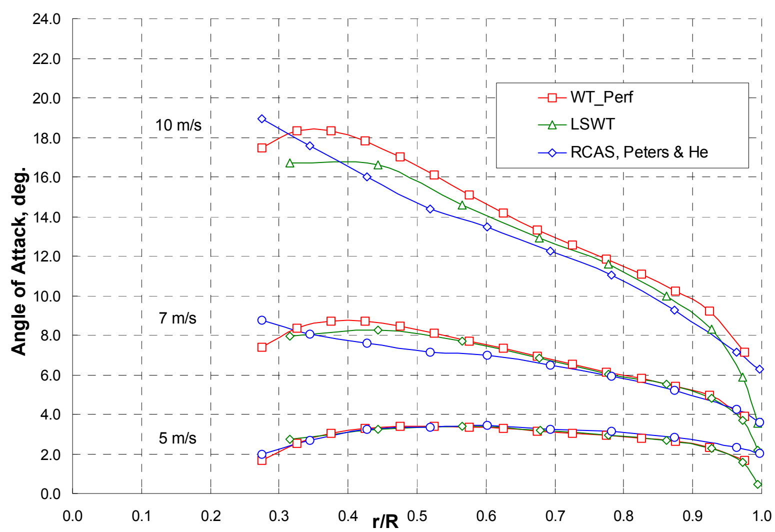

Figure 6. Angle of attack comparison for several wind speeds.

Quasi-Steady State Results

Angle of attack predictions at 10 m/s were generated for yaw angles of 10° and 30° at three blade radial stations (r/R=0.42, 0.87, and 0.97). The dynamic wake inflow model was used for RCAS because it is more accurate than the other inflow models. AeroDynAeroDyn comparisons are also provided with its dynamic wake inflow model. The comparisons show angle of attack versus blade azimuth. Zero blade azimuth is with the blade at the top of the rotor disc advancing into the wind. The advancing blade half of the disc would be 270°–90°; the retreating half would be 90°–270°.

For a yaw angle of 10°, a comparison of angle of attack distribution versus blade azimuth is shown in Figure 7. At r/R=0.97, RCAS, AeroDyn, and LSWT all agree with

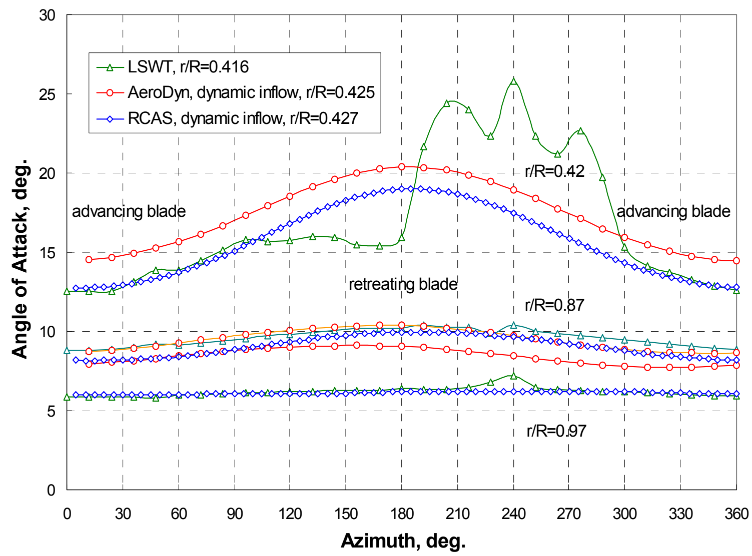

Figure 7. Yawed flow of 10° at a wind speed of 10 m/s.

an angle of attack slightly higher than 6°. Moving inboard to r/R=0.87, the angle of attack phasing is somewhat different even though both RCAS and AeroDyn use a dynamic inflow formulation. LSWT appears to be in better agreement with RCAS. Also in the root region RCAS and LSWT are in good agreement except for a large blade/vortex interaction on the retreating blade. In the root region AeroDyn predicts an angle of attack several degrees higher than the other two methods. For higher yaw angles LSWT would not converge because of numerical problems resulting from a lack of a finite vortex core model that would limit extremely high induced velocities resulting from blade/vortex interactions.

At a yaw angle of 30°, a similar comparison of RCAS and AeroDyn was done with the dynamic wake inflow models (see Figure 8). Also shown for comparison is a WT_Perf prediction with BEM inflow. Toward the tip, WT_Perf predicts a lower angle of attack. The dynamic inflow model in RCAS and AeroDyn results in an angle of attack several degrees higher. Again, RCAS and AeroDyn exhibit an unexplained magnitude and phasing shift of the angle of attack relative to one another. At r/R=0.87 the differences between the three methods are much smaller. Blade root region differences become more significant; most noticeable are the previously mentioned angle of attack phase shifts between RCAS and AeroDyn. The angle of attack distribution of AeroDyn is slightly less symmetrical or biased to the right.

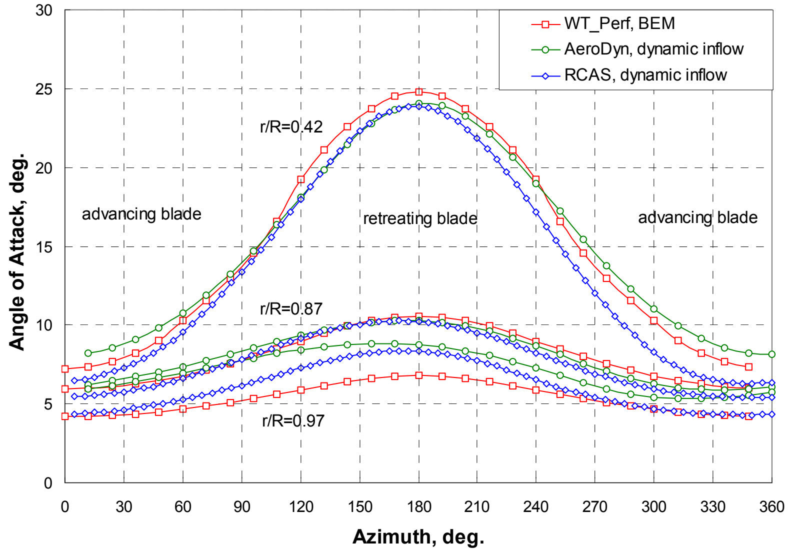

Figure 8. Yawed flow of 30° at a wind speed of 10 m/s.

The dynamic stall option in RCAS was turned on for comparative purposes. Dynamic stall, option 5, was used and is considered to be the most rigorous option. The dynamic stall model requires airfoil specific inputs for the S809 airfoil. Similar airfoil inputs from the program's cambered SC 1098 airfoil, used on the Blackhawk helicopter, were chosen since S809 inputs were not available. With dynamic stall turned on, the primary change is a decrease in angle of attack and a phase shift to the right (see Figure 9). With the dynamic stall model turned on in AeroDyn, a similar change is observed (Figure 10). Dynamic stall models in both AeroDyn and RCAS are based on the Leishmann-Beddoes method, but AeroDyn has the airfoil inputs hardwired with no user-selected inputs. An overlay of the dynamic stall predicted angle of attack distributions for RCAS and AeroDyn is shown in Figure 11. AeroDyn

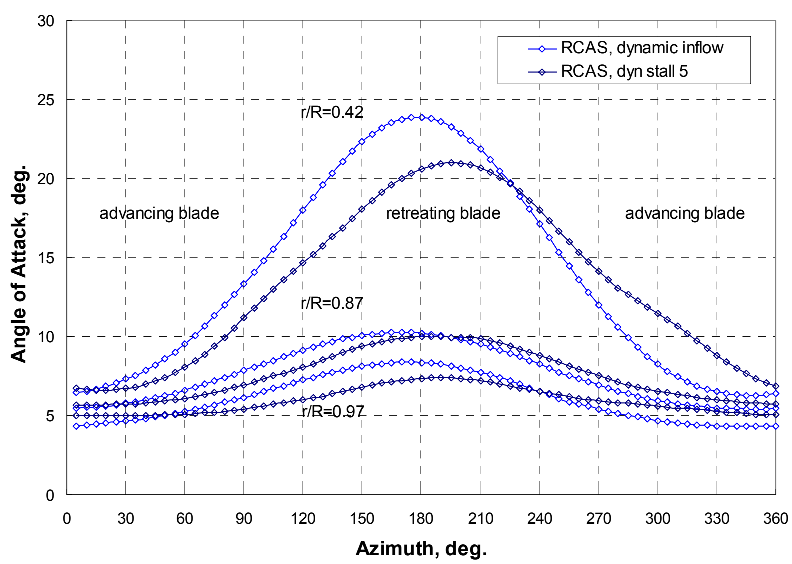

Figure 9. RCAS dynamic stall for 30 degrees yaw at a wind speed of 10 m/s.

predicts a higher angle of attack peak than RCAS. For AeroDyn, toward the blade root, the angle of attack distribution is several degrees greater from a blade azimuth of 180°–90°. This increase may not be related to the difference in dynamic stall models but to shift without the dynamic stall model.

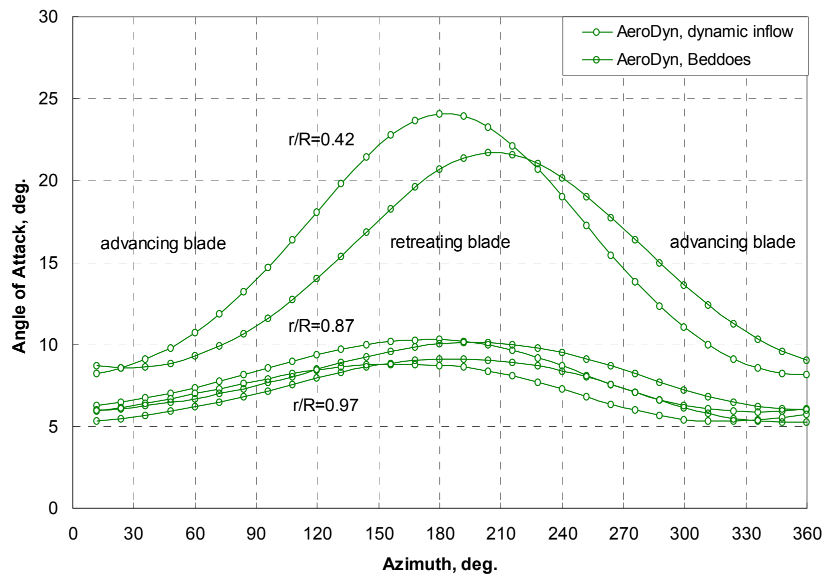

Figure 10. AeroDyn dynamic stall for 30° yaw at a wind speed of 10 m/s.

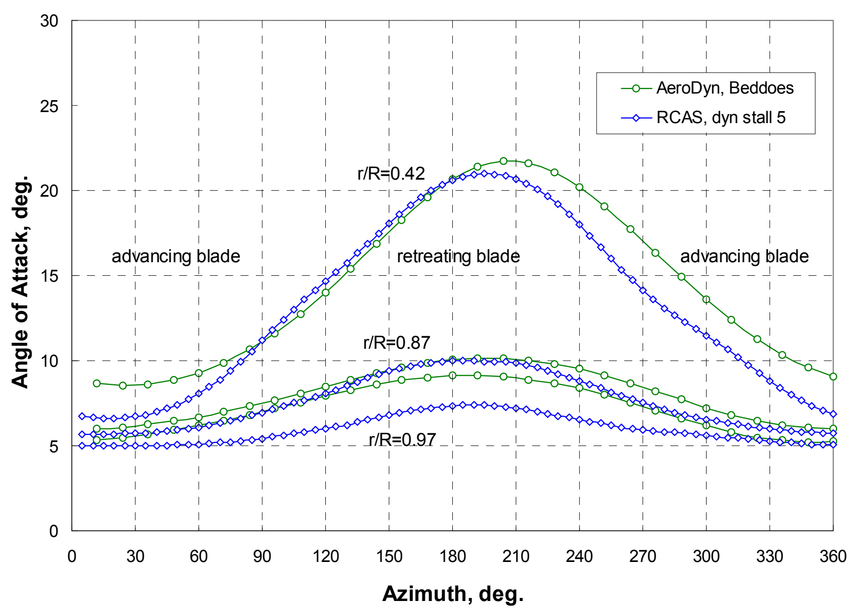

Figure 11. RCAS/AeroDyn dynamic stall, 30° yaw at a wind speed of 10 m/s.

Conclusions

Evaluation of the four aerodynamic inflow models in RCAS resulted in the following findings. BEM, which is used for most codes, lacks several features—Prandtl tip and hub loss model, induced swirl calculations, and the Glauert approximation for use at high thrust coefficients—needed for wind turbine analysis. Without these features, the BEM inflow option in RCAS over predicts the angle of attack distribution. The generalized dynamic wake inflow option in RCAS provided a reasonable prediction of the angle of attack distribution. Inherent in this model is a Prandtl-Goldstein based tip loss correction. Even with the tip loss correction, the local tip angle of attack is over predicted relative to BEM and LSWT theories. The wake inflow option does not include induced swirl effects. This does not appear to be a significant impediment, since the angle of attack distribution toward the blade root where the angle is reduced by swirl is already under predicted. Being a time domain, noniterative inflow model, the generalized dynamic wake is the only inflow model practical for unsteady inflow and aeroelasticity calculations. This model will also provide the lowest computational time of the four inflow models. The prescribed and free-wake inflow options are not as well suited for unsteady flow conditions because both the blade and wake vortex model, which are less compatible with dynamic perturbations, are discretized. The prescribed and free-wake inflow options are better used for axis-symmetric performance prediction and blade geometry optimization. They both use a basic lifting-line blade representation and the prescribed wake method lacks equations to simulate an expanding wind turbine wake. For axis-symmetric performance predictions, the LSWT is currently a better choice since it is tailored for wind turbine analysis.

Recommendations

Once the Prandtl tip/hub loss model, induced swirl, and with the Glauert approximation are implemented in RCAS, further validation of the BEM inflow option is needed to verify the angle of attack distributions. A more conventional airfoil data input format is needed in RCAS for wind turbine analysis. A wind turbine user's manual with examples is needed to minimize confusion. Wind turbine prescribed wake equations are necessary for the prescribed-wake inflow option. The free-wake inflow option should be further explored to determine what combinations of wake parameters are suitable for wind turbine analysis. A dynamic stall input file is needed for a generic wind turbine airfoil.

Currently the lack of a comprehensive wind turbine user's manual makes RCAS difficult to use and results in a long and expensive learning curve. A wind turbine user's manual should include several well-documented wind turbine examples along with their input and output files.

In AeroDyn, for yawed flow conditions, the angle of attack asymmetry versus blade azimuth relative to RCAS should be investigated. In LSWT, for yawed flow conditions, a vortex core model is needed to limit the maximum induced velocity generated by a vortex filament. This should be complemented with a dynamic stall subroutine. Finally, predicted results should be compared with actual UAE data for the operating conditions investigated in this report.

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Appendix: Sample Input Files

RCAS Airfoil Data Set (S809.C81)

```
180.   0.     0.     0.     0.     0.     0.     0.
-172.5 .78    .78    .78    .78    .78    .78    .78
-161.  .62    .62    .62    .62    .62    .62    .62
-147.  1.     1.     1.     1.     1.     1.     1.
-129.  1.     1.     1.     1.     1.     1.     1.
-49.   -1.18  -1.18  -1.18  -1.18  -1.18  -1.18  -1.18
-39.   -1.18  -1.18  -1.18  -1.18  -1.18  -1.18  -1.18
-21.   -.8    -.8    -.81   -.83   -.85   -.85   -.85
-16.5  -1.007 -1.007 -.944  -.96   -.965  -.965  -.965
-15.   -1.19  -1.19  -1.09  -1.055 -.99   -.98   -.98
-14.   -1.333 -1.333 -1.22  -1.096 -1.    -.97   -.97
-13.   -1.334 -1.334 -1.28  -1.12  -1.    -.96   -.96
-12.   -1.255 -1.255 -1.26  -1.13  -1.    -.947  -.94
-11.   -1.161 -1.161 -1.19  -1.12  -.994  -.93   -.923
-10.   -1.055 -1.055 -1.01  -1.082 -.985  -.91   -.90
-8.    -.844  -.844  -.88   -.907  -.922  -.87   -.84
-6.    -.633  -.633  -.66   -.684  -.741  -.77   -.75
-4.1   -.4    -.4    -.4    -.4    -.4    -.4    -.4
-2.1   -.16   -.16   -.16   -.16   -.16   -.16   -.16
0.     0.07   0.07   0.07   0.07   0.07   0.07   0.07
2.1    .30    .30    .30    .30    .30    .30    .30
4.1    .55    .55    .55    .55    .55    .55    .55
6.1    .79    .79    .79    .79    .79    .79    .79
8.2    .90    .90    .90    .90    .90    .90    .90
10.1   .94    .94    .94    .94    .94    .94    .94
11.2   .93    .93    .93    .93    .93    .93    .93
12.2   .97    .97    .97    .97    .97    .97    .97
13.3   1.0    1.0    1.0    1.0    1.0    1.0    1.0
14.2   1.02   1.02   1.02   1.02   1.02   1.02   1.02
15.2   1.03   1.03   1.03   1.03   1.03   1.03   1.03
16.2   1.01   1.01   1.01   1.01   1.01   1.01   1.01
18.1   .9     .9     .9     .9     .9     .9     .9
19.2   .78    .78    .78    .78    .78    .78    .78
30.0   1.0    1.0    1.0    1.0    1.0    1.0    1.0
```

129.	-1.	-1.	-1.	-1.	-1.	-1.	-1.
147.	-1.	-1.	-1.	-1.	-1.	-1.	-1.
161.	-.62	-.62	-.62	-.62	-.62	-.62	-.62
172.5	-.78	-.78	-.78	-.78	-.78	-.78	-.78
180.	0.	0.	0.	0.	0.	0.	0.
	0.	.18	.28	.38	.48	.62	.72
-180.	.022	.022	.022	.022	.022	.022	.022
-175.	.062	.062	.062	.062	.062	.062	.062
-170.	.132	.132	.132	.132	.132	.132	.132
-165.	.242	.242	.242	.242	.242	.242	.242
-160.	.302	.302	.302	.302	.302	.302	.302
-140.	1.042	1.042	1.042	1.042	1.042	1.042	1.042
-120.	1.652	1.652	1.652	1.652	1.652	1.652	1.652
-110.	1.852	1.852	1.852	1.852	1.852	1.852	1.852
-100.	2.022	2.022	2.022	2.022	2.022	2.022	2.022
-90.	2.022	2.022	2.022	2.022	2.022	2.022	2.022
-80.	1.962	1.962	1.962	1.962	1.962	1.962	1.962
-70.	1.842	1.842	1.842	1.842	1.842	1.842	1.842
-60.	1.662	1.662	1.662	1.662	1.662	1.662	1.662
-50.	1.392	1.392	1.392	1.392	1.392	1.399	1.392
-30.	.562	.562	.562	.562	.562	.562	.562
-21.	.332	.332	.332	.332	.332	.332	.332
-16.	.155	.155	.181	.207	.235	.257	.274
-15.	.102	.102	.148	.181	.209	.233	.252
-14.	.038	.038	.099	.146	.180	.212	.233
-13.	.0264	.0264	.0455	.094	.148	.191	.216
-12.	.022	.022	.030	.06	.111	.164	.198
-11.	.0196	.0196	.0232	.038	.078	.135	.17
-10.	.0174	.0174	.0189	.0259	.053	.105	.145
-9.	.0154	.0154	.0159	.0187	.0351	.077	.122
-8.	.0138	.0138	.0138	.0147	.0220	.053	.101
-7.	.0122	.0122	.0122	.0123	.0141	.035	.082
-6.	.011	.011	.011	.011	.011	.0212	.0615
-5.	.01	.01	.01	.01	.01	.0132	.038
-4.1	.0127	.0127	.0127	.0127	.0127	.0127	.0127
-2.1	.009	.009	.009	.009	.009	.009	.009
0.	.0085	.0085	.0085	.0085	.0085	.0085	.0085
2.1	.0088	.0088	.0088	.0088	.0088	.0088	.0088
4.1	.0088	.0088	.0088	.0088	.0088	.0088	.0088
6.1	.009	.009	.009	.009	.009	.009	.009
8.2	.0167	.0167	.0167	.0167	.0167	.0167	.0167
10.2	.0231	.0231	.0231	.0231	.0231	.0231	.0231
11.2	.0236	.0236	.0236	.0236	.0236	.0236	.0236
12.2	.0368	.0368	.0368	.0368	.0368	.0368	.0368
13.3	.0551	.0551	.0551	.0551	.0551	.0551	.0551
14.2	.0618	.0618	.0618	.0618	.0618	.0618	.0618
15.2	.0705	.0705	.0705	.0705	.0705	.0705	.0705
16.2	.088	.088	.088	.088	.088	.088	.088
18.1	.1325	.1325	.1325	.1325	.1325	.1325	.1325
19.2	.3474	.3474	.3474	.3474	.3474	.3474	.3474
30.	.500	.500	.500	.500	.500	.500	.500
50.	1.392	1.392	1.392	1.392	1.392	1.392	1.392
60.	1.662	1.662	1.662	1.662	1.662	1.662	1.662
70.	1.842	1.842	1.842	1.842	1.842	1.842	1.842
80.	1.962	1.962	1.962	1.962	1.962	1.962	1.962
90.	2.022	2.022	2.022	2.022	2.022	2.022	2.022
100.	2.022	2.022	2.022	2.022	2.022	2.022	2.022

110.	1.852	1.852	1.852	1.852	1.852	1.852	1.852		
120.	1.652	1.652	1.652	1.652	1.652	1.652	1.652		
140.	1.042	1.042	1.042	1.042	1.042	1.042	1.042		
160.	.302	.302	.302	.302	.302	.302	.302		
165.	.242	.242	.242	.242	.242	.242	.242		
170.	.132	.132	.132	.132	.132	.132	.132		
175.	.062	.062	.062	.062	.062	.062	.062		
180.	.022	.022	.022	.022	.022	.022	.022		
	.20	.30	.40	.50	.6	.7	.75	.8	.9
-180.	0.	0.	0.	0.	0.	0.	0.	0.	0.
-170.	.4	.4	.4	.4	.4	.4	.4	.4	.4
-165.	.3	.3	.3	.3	.3	.3	.3	.3	.3
-160.	.3	.3	.3	.3	.3	.3	.3	.3	.3
-135.	.5	.5	.5	.5	.5	.5	.5	.5	.5
-90.	.5	.5	.5	.5	.5	.5	.5	.5	.5
-30.	.174	.184	.196	.214	.235	.25	.264	.277	.298
-23.	.112	.118	.128	.144	.157	.171	.183	.206	.232
-16.	.073	.078	.086	.097	.108	.117	.137	.176	.200
-15.	.054	.065	.073	.084	.097	.111	.133	.173	.195
-14.	0.	.027	.054	.068	.086	.103	.127	.167	.189
-13.	0.	.0015	.025	.05	.074	.093	.122	.163	.184
-12.	0.	0.	.002	.03	.06	.083	.116	.157	.176
-11.	0.	0.	-.003	.014	.046	.074	.108	.149	.17
-10.	0.	0.	-.0015	.002	.032	.065	.10	.142	.163
-9.	0.	0.	0.	-.003	.016	.054	.089	.132	.154
-8.	0.	0.	0.	-.004	.005	.041	.082	.123	.145
-7.	0.	0.	0.	0.	-.004	.0275	.072	.1125	.136
-6.	0.	0.	0.	0.	-.003	.016	.0625	.10	.125
-4.	0.	0.	0.	0.	0.	.005	.04	.076	.102
-3.	0.	0.	0.	0.	0.	-.0025	.026	.0665	.087
-2.	0.	0.	0.	0.	0.	0.	.013	.053	.07
-1.	0.	0.	0.	0.	0.	0.	.0035	.033	.045
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1.	0.	0.	0.	0.	0.	0.	-.0035	-.033	-.045
2.	0.	0.	0.	0.	0.	0.	-.013	-.053	-.07
3.	0.	0.	0.	0.	0.	.0025	-.026	-.0665	-.087
4.	0.	0.	0.	0.	0.	-.005	-.04	-.076	-.102
6.	0.	0.	0.	0.	.003	-.016	-.0625	-.1	-.125
7.	0.	0.	0.	0.	.004	-.0275	-.072	-.1125	-.136
8.	0.	0.	0.	.004	-.005	-.041	-.082	-.123	-.145
9.	0.	0.	0.	.003	-.016	-.054	-.089	-.132	-.154
10.	0.	0.	.0015	-.002	-.032	-.065	-.1	-.142	-.163
11.	0.	0.	.003	-.014	-.046	-.074	-.108	-.149	-.17
12.	0.	0.	-.002	-.03	-.06	-.083	-.116	-.157	-.176
13.	0.	-.0015	-.025	-.05	-.074	-.093	-.122	-.163	-.184
14.	0.	-.027	-.054	-.068	-.086	-.103	-.127	-.167	-.189
15.	-.054	-.065	-.073	-.084	-.097	-.111	-.133	-.173	-.195
16.	-.073	-.078	-.086	-.097	-.108	-.117	-.137	-.176	-.20
23.	-.112	-.118	-.128	-.144	-.157	-.171	-.183	-.206	-.232
30.	-.174	-.184	-.196	-.214	-.235	-.250	-.264	-.277	-.298
90.	-.5	-.5	-.5	-.5	-.5	-.5	-.5	-.5	-.5
135.	-.5	-.5	-.5	-.5	-.5	-.5	-.5	-.5	-.5
160.	-.3	-.3	-.3	-.3	-.3	-.3	-.3	-.3	-.3
165.	-.3	-.3	-.3	-.3	-.3	-.3	-.3	-.3	-.3
170.	-.4	-.4	-.4	-.4	-.4	-.4	-.4	-.4	-.4
180.	0.	0.	0.	0.	0.	0.	0.	0.	0.

```
NACA0012 for Puma
from Bousman, US Army, October 1988

corrected cd typo at alpha=-10; October 1988
```

RCAS Input File

```
!            *********************************************
!            ***      Rotor of CER Wind Turbine         ***
!            ***             English Units              ***
!            ***          2 Rigid blades                ***
!            ***           0.0 deg precone              ***
!            ***       Table lookup aerodynamics        ***
!            ***        no dynamic Inflow               ***
!            ***          Steady state                  ***
!            *********************************************
!

 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    ENGLISH

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

S SUBSYSIDS
! List subsystem IDs which must be unique; one ID per row.
a   rotorss

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    rotorss          dtrain        51        0  0  0        0  0  0

S SSORIGIN
!  Subsystem              Origin Coordinates
```

```
!    Name           x            y            z
a  rotorss          0            0            0

S SSORIENT
!  Subsystem     rotation 1        rotation 2        rotation 3
!    Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a   rotorss       2      90         0       0         0       0

S CONTROLMIXER
!                              Bedplate Control
! Cont.  Control   ------- Coefficients for Pilot Control --------
!  ID     bias      Coll.      Lat.     Long.      Pedal     Throt
!         val0    b1_pitch   b2_pitch  b3_pitch    cont4     cont5
a   1      0       .017453      0          0          0         0
a   2      0          0      .017453      0          0         0
!======================================================================
!============================ 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      dtrain
a      blade1
a      blade2

S CORNODE
! identify center node for the rotor subsystem
! Prim_str_ID     Node_ID
a   dtrain          51

S BLADECOMP
! Blade                 Primitive Structure Name(s)
! Index     1         2       3        4       5       6       7
a  1       blade1     --      --       --      --      --      --
a  2       blade2     --      --       --      --      --      --

S PSORIGIN
! Primitive       Primitive Origin Offset
!   Name          x            y            z
a  dtrain         0            0            0
a  blade1         0            0            0
a  blade2         0            0            0

S PSORIENT
```

```
! Primitive    rotation 1        rotation 2        rotation 3
!  Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a dtrain       3       0         0       0         0       0
a blade1       3       0         2       0         0       0
a blade2       3    -180         2       0         0       0

S ROTORPARAM
!  Rotor Rotational Speed (rad/sec)
a         7.5372E-00

!======================================================================
!======================== PRIMITIVE STRUCTURE ========================
!                             dtrain
!======================================================================

S PRIMITIVEID
! Select a primitive structure
! Primitive structure_id
a    dtrain

S ELDATASETID
! Select an element property data set.
! Data set_id
a   wtprop

S FENODE
! Specify the node ID and its coordinates wrt Prim. Structure
!   Node              Node Coordinates
!    ID        x        y        z
a    51        0        0        0   !  Base of the lss
a    57        0        0        0   !  hub node
a    61        0        0        0   !  dummy node

S RIGIDBAR
!  Element  Node1  Node2      Center of gravity offset
!    ID      ID     ID       X            Y            Z
a     1      51     57       0            0            0

! dummy dof
!At least 1 dof is needed throughout the system
S SLIDE
! Elem.  Node1  Node2   Slide   Free or      Spring        Damper
!  ID     ID     ID     Axis   Controlled   Constant      Constant
a  15     51     61      x        0           .01            .14

S RBMELE
! Element  Node     Property
!   ID      ID        ID
a   16      61        61   !dummy mass ( 1.e-4 slug )

!======================================================================
!======================== PRIMITIVE STRUCTURE ========================
!                          WIND TURBINE BLADE 1
!======================================================================

S PRIMITIVEID
! Select a primitive structure
```

```
! Primitive structure_id
a     blade1

S ELDATASETID
! Select an element property data set.
! Data set_id
a    wtprop

S FENODE
! Specify the node ID and its coordinates wrt PS
!   Node              Node Coordinates (feet)
!    ID             x       y     z
a       1         0.000     0     0   ! Blade root Node
a       2         1.381     0     0   ! Hinge offset
a       3         1.381     0     0   ! Pitch hinge /bearing
a      20         16.5      0     0   ! Blade tip node

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID         X     Y     Z
a     1       1      2         0     0     0 ! Hinge offset
a     2       3     20         7     0     0 ! rigid blade
N
!  Element  Element                         Inertia Terms
!    ID      Mass     Ixx   Ixy  Ixz   Iyy   Iyz    Izz
a     2       50      10     0    0   10000   0    10010 ! blade prop

S HINGE
! Elem.  Node1  Node2   Hinge   Free or    Spring     Damper
!  ID     ID     ID     Type   Controlled  Constant  Constant
a  20      2      3       P       1           0        0   !Control br.

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/MLD ...)    or ACP ID
a    1       DIRECT        0.0           HIN                 20

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

S CONNCONST
! constraint ID, DOFL( PS name, node ID ), DOFR( PS name, node ID)
a      1              blade1       1           dtrain      57
a      2              blade2       1           dtrain      57
!======================================================================
!======================== Copy Primitives =============================
!                           blade1 to blade2
!======================================================================

S PRIMIT
! Copy primitive structures
a 1   blade1   blade2

EXIT

COMMAND
```

```
copyprimstruct

!=======================================================================
!======================== PRIMITIVE STRUCTURE =======================
!                          WIND TURBINE BLADE 2
!=======================================================================

S PRIMITIVEID
! Select a primitive structure
! Primitive Structure Name(s)
c          BLADE2

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               20

======================================================================
!======================== STRUCTURAL PROPERTIES =======================
!                               ROTORSS
!=======================================================================

S ELEPROPID
! List the names of element property data sets.
! element_prop_ID
a   wtprop

S RBMPRP
! Prop   mass,   cg offset                    Moment of Inertia
!  ID            x,  y,  z      Ixx,   Ixy,  Ixz,    Iyy,   Iyz,  Izz
a  61    .0001   0   0   0       0      0     0       0      0     0
!dummy


!=======================================================================
!============================ Airfoil Data ===========================
!=======================================================================

S AIRFOIL
!   Airfoil             Quasi Steady Airloads
!     ID                 2D Table File Name
a  bladeaf                   S809.C81
a  bladeaf2                  S809.C81

N
!  Airfoil   -- Linear Airfoil Coefficients --     Zero Lift Angle
!    ID      C_radial    CL_a      CD       CM     of Attack (rad)
a  bladeaf      0        6.28     0.01    -0.01        3.0
a  bladeaf2     0        5.78     0.008    0.0         0.0

!=======================================================================
!======================== Aerodynamic model ==========================
!=======================================================================

S AEROMODCOMP
```

```
! List of Supercomponent of the system
a   rotorsc

S SCORIGIN
!  Supercomponent          Origin Coordinates
!      Name          x            y            z
a     rotorsc        0            0            0

S SCORIENT
! Supercomponent    rotation 1        rotation 2        rotation 3
!    Name         axis angle(deg)   axis angle(deg)   axis angle(deg)
a  rotorsc          2      90         0       0         0       0

!======================================================================
!======================= Rotor Aerodynamic model ======================
!                             Wind Turbine
!======================================================================

S AEROSUPCOMPID
! Supercomponent name to be define or modified
a    rotorsc

S SUPCMPTYP
! 1 => rotor, 2 => wing, 3 => body, 4=> aux rotor
a 1

S COMPID
! List the Components which comprise the Supercomponent
! Component     Primitive   CP Root   Blade tip
!  Name(s)      Structure    El_id     node_id
a adblade1      blade1        0           20
a adblade2      blade2        0           20

S CPORIGIN
! Component         Component Origin Offset
!   Name           x            y            z
a adblade1         0            0            0
a adblade2         0            0            0

S CPORIENT
! Component     rotation 1       rotation 2        rotation 3
!    Name      axis angle(deg)  axis angle(deg)   axis angle(deg)
a adblade1       3      0         2        0        0       0
a adblade2       3   -180         2        0        0       0

S INFLOW
! 0. No inflow (wings).
! 1. Uniform momentum inflow (half wings and rotors)
! 2. Uniform momentum inflow (full wings)
! 3  Peters and He inflow model (rotors only).
! 5. Alternate Prescribed vortex wake ( only rotors).
! 6. Free vortex Wake (Only Rotor)
a     7

S AEROPTION
!  Yawed    Tip      Linear          Nonlinear         Linear
Compress
```

```
!  Flow     Loss    Unsteady    Unsteady/Dyn Stall     Airfoil  -
ibility
! Effects  Option   Effects    Leishman-beddos/Onera   Coeffs   Effects
!  (0:1)    (0:1)    (0:1)           (0:6)             (0:1)     (0:1)
a    0        1        0                0                 0         0

S TIPLOSS
!        Radial Location
!         for Zero Lift
!           (nondim)
a             1.00
S THRUSTAVE
! thrust ave option, no. time steps, initial thrust, no. Revs for TPP
averaging
a         2                72            500                   72

S SUPCMPTOSS
! Subsystem name for the current supercomponent
a         rotorss

!=======================================================================
!==================== Aerodynamic Component ===========================
!                             ADBLADE1
!=======================================================================

S AEROCOMPID
! Component name for defining or modifying
a   adblade1

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1

S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs       x         y       z
a  1    0.0000e+00   0.0000e+00   0.0000e+00
a  2    2.9000e+00   0.0000e+00   0.0000e+00
a  3    3.5000e+00   0.0000e+00   0.0000e+00
a  4    4.1200e+00   0.0000e+00   0.0000e+00
a  5    4.9500e+00   0.0000e+00   0.0000e+00
a  6    6.4000e+00   0.0000e+00   0.0000e+00
a  7    7.6900e+00   0.0000e+00   0.0000e+00
a  8    9.4100e+00   0.0000e+00   0.0000e+00
a  9    1.0450e+01   0.0000e+00   0.0000e+00
a 10    1.2410e+01   0.0000e+00   0.0000e+00
a 11    1.3410e+01   0.0000e+00   0.0000e+00
a 12    1.5410e+01   0.0000e+00   0.0000e+00
a 13    1.6410e+01   0.0000e+00   0.0000e+00
a 14    1.6500e+01   0.0000e+00   0.0000e+00

S AEROSEG
! Seg.   Aerodyn Node IDs    Chord       Airfoil  ELment   Twist
! ID   (Inboard)(Outboard)   (ft)          ID       ID      (rad)
a  1       2        3      1.0240e+00    bladeaf    0     -8.6400e-01
a  2       3        4      1.9330e+00    bladeaf    0     -2.6130e-01
a  3       4        5      2.3760e+00    bladeaf    0     -2.9960e-01
```

```
a  4       5        6      2.2590e+00    bladeaf    0     -1.9430e-01
a  5       6        7      2.1210e+00    bladeaf    0     -1.1080e-01
a  6       7        8      1.9700e+00    bladeaf    0     -5.9300e-02
a  7       8        9      1.8310e+00    bladeaf    0     -2.7900e-02
a  8       9       10      1.6800e+00    bladeaf    0     -1.0100e-02
a  9      10       11      1.5310e+00    bladeaf    0      4.3600e-03
a 10      11       12      1.3780e+00    bladeaf    0      1.5970e-02
a 11      12       13      1.2260e+00    bladeaf    0      2.7310e-02
a 12      13       14      1.1710e+00    bladeaf    0      3.1240e-02

!=======================================================================
!===================== Copy Aero components ==========================
!                          blade1 to blade2
!=======================================================================
S AEROCO
! Copy ID,    source component, destination component
a    1             adblade1           adblade2

EXIT

COMMAND

copyaerocomp

!=======================================================================
!=======================================================================
!                        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         2      0      0      S                 NO

N
! Case_id            Case Title
a    01               example5

S INITCOND
! Initial Pilot Controls
!  collective,    lateral,  longitudinal,    pedal,      throttle
!  b1_pitch        b2_pitch   b3_pitch       cont4       cont5
a    -4.8          -4.8       -4.8            0.0         0.0

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

S AEROSTATCONST
! Define aerostatic conditions for standard sea level
! Spec-type, altitude, temp, air density, sound velocity
```

```
a       0        0       0       0              0

S CONSTWIND
! Constant Wind velocity with respect to I frame in I coord.
!     Vx,       Vy,       Vz
a   22.97        0         0      ! ft/second

!=======================================================================
!==================== TRIM/PERIODIC SOLUTION  DATA ====================
!=======================================================================

S CONVERGETOL
!# of  # of  # of   -Displacement Tolerance-    --Velocity Tolerance-
Min.
!Trim  PSol  Time    translation   rotation     translation rotation
# of
!Iter  Iter  Step      (ft)          (rad)        (ft/sec)   (rad/sec)
PS Rev
a 10    25    72      0.001         0.001           1          0.5
5

S INTEGPARAM
!No. of| Newmark Constants|  HHT    | Displace.  | Velocity  | Relax.
!Iter. | Alpha  |  Delta  | Param   |   Tol      |   Tol     | Factor
a 20      .25       .5      -.03       1.e-5      1.e-4       1.0

!=======================================================================
!========================= STABILITY DATA =============================
!=======================================================================

S LINEAROPTION
!  Perturb.   Number of  Control  Gust  Identical  Reduction  Averaging
!   Delta     Azim/Rev   Option   opt   Blade Opt.  Option     Option
a  0.001         1          0       0       0          0          0

S CCEANALYSIS
!Eigenanalysis  Number of    Transient      Frequency     Mean Squared
!   Option       Modes     Response Opt.  Response Opt.  Random
Response
a      1           0           0              0                0

S PERIODICOUTPUT
!  Row   Subsystem   Prim. Struc.           output
!  ID      Name        Name                category
a   1      all         all               internal.loads
a   2      all         all               airloads
a   3      all         all               sys_dyn_resp

!S SAVESC
!!     Form of SC Data             Directory and File Name
!!      (RDB or FILES)                  for SC Data
!a       RDB                            NASA2bld.sav

!S RUNALLCASES
!!    Run All Cases Flag (0/1)
!a              1
```

```
EXIT

COMMAND

MENU RUNANALYSIS
```

WT_Perf Input File

```
WT_Perf        v2.2 input file:

-----  Job Title (one line)  ---------------------------------------------------
WT_Perf        test input file.  CER/NASA Phase 4 turbine.  Delft wind tunnel data.

-----  Input   Configuration  ---------------------------------------------------
TRUE           ECHO_INP:   Echo input parameters to echo.out?
FALSE                  DIMEN:      Turbine parameters are dimensional?
FALSE                  METRIC:     Turbine parameters are metric (MKS vs FPS]?

-----  Output Configuration  ---------------------------------------------------
TRUE           TABDELIM:   Make output tab-delimited (fixed-width otherwise).
TRUE           WRITE_BE:   Write out blade element data to bladelem.dat?
3              PAR_ROW:    Row parameter    (1-rpm, 2-pitch, 3-tsr/speed).
2              PAR_COL:    Column parameter (1-rpm, 2-pitch, 3-tsr/speed).
1              PAR_SHT:    Sheet parameter  (1-rpm, 2-pitch, 3-tsr/speed).
TRUE           OUT_PWR:    Request output of rotor power?
TRUE           OUT_CP:     Request output of Cp?
TRUE           OUT_TRQ:    Request output of shaft torque?
FALSE                  OUT_FLP:    Request output of flap bending moment?
TRUE           OUT_THR:    Request output of rotor thrust?

-----  Model  Configuration  ---------------------------------------------------
20             N_SEG:      Number of blade segments (entire rotor radius).
5              SEG_FRST:   First segment used in the analysis.
20             SEG_LAST:   Last segment used in the analysis.
1              N_SECT:     Number of circumferential sectors.
50             MAX_ITER:   Max number of iterations for induction factor.

-----  Algorithm Configuration  ------------------------------------------------
TRUE           VITERNA:    Use Viterna post stall instead of flat plate?
TRUE           TIP_LOSS:   Use the Prandtl tip loss model?
TRUE           HUB_LOSS:   Use the Prandtl hub loss model?
TRUE           SWIRL:      Include swirl effects?
TRUE           ADV_BRK:    Use the advanced brake-state model?
FALSE                  ADD_3D:     Add ECN's 3D effects to Cl and Cd?

-----  Parametric Analysis Configuration  --------------------------------------
4.8, 4.8, 0    PIT_ST, PIT_END, PIT_DEL:  First, last, delta blade pitch (deg).
```

72, 72, 0 OMG_ST, OMG_END, OMG_DEL: First, last, delta rotor speed.
FALSE INP_TSR: Input speeds as TSRs?
5, 20, 1 SPD_ST, SPD_END, SPD_DEL: First, last, delta speeds.
mps UNITS: Wind speed units (mps, fps, mph).

----- Turbine Data ---
2 NUM_BL: Number of blades.
16.5 ROT_RAD: Rotor radius [length].
-1.63 0.0 TIPTWIST: Angle between tip chordline and rotor plane [deg].
0.04 0.21 0.0 CHORD, THICK, TWIST: N_SEG lines of Chord [length or
0.04 0.21 0.0 div by radius], Thickness [length
0.04 0.21 0.0 or div by chord], and Twist [deg].
0.04 0.21 6.0
0.10657 0.21 13.4
0.144 0.21 17.0
0.13894 0.21 12.2
0.13389 0.21 8.7
0.12883 0.21 6.18
0.12378 0.21 4.36
0.11872 0.21 3.03
0.11367 0.21 2.04
0.10861 0.21 1.27
0.10356 0.21 0.66
0.0985 0.21 0.16
0.09345 0.21 -0.26
0.08839 0.21 -0.62
0.08334 0.21 -0.94
0.07828 0.21 -1.26
0.07323 0.21 -1.63
0.144 HUB_RAD: Hub radius [length or div by radius].
0.0 PRECONE: Precone angle, positive downwind [deg].
0.0 TILT: Shaft tilt (can be used as yaw if shear is zero).
3.3333 HUB_HT: Hub height [length or div by radius].

----- Aerodynamic Data --
0.002378 RHO: Air density [mass/volume].
0.0 SHR_EXP: Wind shear exponent (1/7 law = 0.143).
FALSE SEP_TABL: Are Cd and Cl tables separate?
1, 24, 24 SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
15.24 ALF_STAL: Stall angle of attack (deg). Peak of CL curve?
1 I_SHFT: For 3D, index of Cl curve where we depart from linear.
-1.04 0.019 0.0095 CL, CL, CD: NCL lines of Alpha (deg), Cl, and Cd.
-0.01 0.139 0.0094
1.02 0.258 0.0096
2.05 0.378 0.0099

```
3.07    0.497   0.01
4.1     0.617   0.01
5.13    0.736   0.0097
6.16    0.851   0.0095
7.18    0.913   0.0127
8.2     0.952   0.0169
9.21    0.973   0.0247
10.2    0.952   0.0375
11.21   0.947   0.0725
12.23   1.007   0.0636
13.22   1.031   0.0703
14.23   1.055   0.0828
15.23   1.062   0.1081
16.22   1.043   0.1425
20.00   0.700   0.3
30      1       0.580
45      1       1
90      0.1     1.6
2, 0, 1   SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
3, 0, 1   SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
4, 0, 1   SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
5, 0, 1   SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
7, 0, 1   SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
8, 0, 1   SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
9, 0, 1   SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
10, 0, 1  SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
11, 0, 1  SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
12, 0, 1  SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
13, 0, 1  SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
14, 0, 1  SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
15, 0, 1  SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
16, 0, 1  SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
17, 0, 1  SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
18, 0, 1  SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
19, 0, 1  SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
20, 0, 1  SEG, NCL, NCD: Segment#, #CLs, #CDs (Reuse segment NCD if NCL=0).
```

AeroDyn/YawDyn Input File

```
Combined Experiment Baseline for YawDyn version 12.1
ENGLISH       Units for input and output [SI or ENGlish]
STEADY        Dynamic stall model [BEDDOES or STEADY]
NO_CM         Aerodynamic pitching moment model [USE_CM or NO_CM]
EQUILInflow model [DYNIN or EQUIL]
SWIRL         Induction factor model [NONE or WAKE or SWIRL]
5.0000E-03    Convergence tolerance for induction factor
```

PRAND Tip-loss model (EQUIL only) [PRANdtl, GTECH, or NONE]
PRAND Hub-loss model (EQUIL only) [PRANdtl or NONE]
"STEADYtt.wnd" Hub-height steady wind file
55.0 Wind reference (hub) height.
0.0 Tower shadow centerline velocity deficit.
1.0 Tower shadow half width.
0.0 Tower shadow reference point.
2.3870E-03 Air density.
1.625e-4 KinVisc - Kinematic air viscosity
1.0000E-03 Time interval for aerodynamic calculations.
1 Number of airfoil files used. Files listed below:
"S809d_Cln.dat"
20 Number of blade elements per blade
RELM and Twist ignored by ADAMS (but placeholders must be present)

RELM	Twist	DR	Chord	File ID	Elem Data
0.4125	0	0.825	0.66	1	
1.2375	0	0.825	0.66	1	
2.0625	0	0.825	0.66	1	
2.8875	6	0.825	0.66	1	
3.7125	13.4	0.825	1.7584	1	
4.5375	17.	0.825	2.376	1	PRINT
5.3625	12.2	0.825	2.2925	1	PRINT
6.1875	8.7	0.825	2.2092	1	PRINT
7.0125	6.18	0.825	2.1257	1	PRINT
7.8375	4.36	0.825	2.0424	1	PRINT
8.6625	3.03	0.825	1.9589	1	PRINT
9.4875	2.04	0.825	1.8756	1	PRINT
10.3125	1.27	0.825	1.7921	1	PRINT
11.1375	0.66	0.825	1.7087	1	PRINT
11.9625	0.16	0.825	1.6253	1	PRINT
12.7875	-0.26	0.825	1.5419	1	PRINT
13.6125	-0.62	0.825	1.4584	1	PRINT
14.4375	-0.94	0.825	1.3751	1	PRINT
15.2625	-1.26	0.825	1.2916	1	PRINT
16.0875	-1.63	0.825	1.2083	1	PRINT

Combined Experiment Baseline in ENGLISH units for AeroDyn version 12.1
6.0 Time duration of the simulation (sec)
60.0 Number of azimuth sectors used for integration
2 Decimation factor for output printing
1.0000E-02 TOLER, Trim solution tolerance (deg)
2 Number of blades
4.8 4.8 4.8 Initial pitch angles (deg)
4.0 Rotor hub sling (distance from yaw axis to hub; positive downwind) (ft)
0.0 Shaft tilt angle (deg)

0.0 Rotor precone angle (deg)
72.0 RPM, rotor speed in revolutions per minute
0.0 PsiInit, Initial rotor position (zero for Blade 1 down) (deg)
FIXED Yaw Model: FREE or FIXED yaw system
0.0 Initial yaw angle (deg)
0.0 Initial yaw rate (deg/sec)
1000.0 Mass moment of inertia about yaw axis (slug-ft^2)
0.0 YawStiff, stiffness of yaw spring (lb-ft/rad)
0.0 YawDamp, yaw damping coefficient (lb-ft-sec)
0.0 YawFriction, constant friction moment at yaw axis (lb-ft)
RIGID Hub model: HINGE, TEETER or RIGID
0.0 0.0 0.0 Initial flap angles (deg)
0.0 0.0 0.0 Initial flap rates (deg/sec)
0.0 RHinge, radius of rotor hub (ft)
5.44 RBar, distance from hinge to blade c.g. (ft)
3.34 Mass of one blade (slug)
178.0 Mass moment of inertia of blade about hinge axis (slug-ft^2)
1.5500E+05 Torsional stiffness of blade root spring (lbf-ft/rad)
0.0 Teeter sling distance of teeter axis upwind of rotor apex (m)
0.0 Free teeter angle (deg)
0.0 Teeter stiffness, first or linear coeff. (lbf-ft/rad)
0.0 Teeter stiffness, coeff. of deflection (lbf-ft/rad^2)
0.0 Teeter damping coefficient (lbf-ft-sec)
1,2,5
1 = Horizontal wind speed at hub center, len/s. [HHWSpeed]
2 = Horizontal wind direction at hub center, deg. [HHWDir]
3 = Nacelle yaw angle, deg. [YawAng]
4 = Nacelle yaw rate, deg/sec. [YawRate]
5 = Blade azimuth angle (0 when blade 1 down), deg. [AzimAngB1D]
6 = Blade azimuth angle (0 when blade 1 up), deg. [AzimAngB1U]
7 = Teeter angle, deg. [TeeterAng]
8 = Teeter rate, deg/sec. [TeeterRate]
10 = Blade 1 flap angle, deg. [FlapAng1]
11 = Blade 1 flap rate, deg/sec. [FlapRate1]
12 = Blade 2 flap angle, deg. [FlapAng2]
13 = Blade 2 flap rate, deg/sec. [FlapRate2]
14 = Blade 3 flap angle, deg. [FlapAng3]
15 = Blade 3 flap rate, deg/sec. [FlapRate3]
16 = Rotor power, kW. [Power]
17 = Rotor torque, force*len. [Torque]
20 = Nacelle yaw moment, force*len. [YawMom]
21 = Nacelle yaw moment, kiloforce*len. [YawMomK]
22 = Hub moment, force*len. [HubMom]
23 = Hub moment, kiloforce*len. [HubMomK]
24 = Rotor thrust, force. [Thrust]
25 = Rotor thrust, kiloforce. [ThrustK]

26 = Lateral hub force, force. [HForceY]
27 = Lateral hub force, kiloforce. [HForceYK]
28 = Vertical hub force, force. [HForceZ]
29 = Vertical hub force, kiloforce. [HForceZK]
30 = Out-of-plane bending moment for blade 1, force*len. [OutPlMom1]
31 = Out-of-plane bending moment for blade 2, force*len. [OutPlMom2]
32 = Out-of-plane bending moment for blade 3, force*len. [OutPlMom3]
33 = In-plane bending moment for blade 1, force*len. [InPlMom1]
34 = In-plane bending moment for blade 2, force*len. [InPlMom2]
35 = In-plane bending moment for blade 3, force*len. [InPlMom3]
36 = Pitching moment for blade 1, force*len. [PitchMom1]
37 = Pitching moment for blade 2, force*len. [PitchMom2]
38 = Pitching moment for blade 3, force*len. [PitchMom3]
40 = Out-of-plane bending moment for blade 1, kiloforce*len. [OutPlMom1K]
41 = Out-of-plane bending moment for blade 2, kiloforce*len. [OutPlMom2K]
42 = Out-of-plane bending moment for blade 3, kiloforce*len. [OutPlMom3K]
43 = In-plane bending moment for blade 1, kiloforce*len. [InPlMom1K]
44 = In-plane bending moment for blade 2, kiloforce*len. [InPlMom2K]
45 = In-plane bending moment for blade 3, kiloforce*len. [InPlMom3K]
46 = Pitching moment for blade 1, kiloforce*len. [PitchMom1K]
47 = Pitching moment for blade 2, kiloforce*len. [PitchMom2K]
48 = Pitching moment for blade 3, kiloforce*len. [PitchMom3K]

S809 Airfoil, Delft data at Re=1.0 Million, Clean no roughness
NREL/TP-442-7817 Appendix B, Viterna used aspect ratio=11
1 Number of airfoil tables in this file
.00 Table ID parameter
15.30 Stall angle (deg)
.00 No longer used, enter zero
.00 No longer used, enter zero
.00 No longer used, enter zero
-.38 Zero lift angle of attack (deg)
7.12499 Cn slope for zero lift (dimensionless)
1.9408 Cn at stall value for positive angle of attack
-.8000 Cn at stall value for negative angle of attack
2.0000 Angle of attack for minimum CD (deg)
.0116 Minimum CD value

-180.00	.000	.1748	.0000	
-170.00	.230	.2116	.4000	
-160.00	.460	.3172	.1018	
-150.00	.494	.4784	.1333	
-140.00	.510	.6743	.1727	
-130.00	.486	.8799	.2132	
-120.00	.415	1.0684		.2498
-110.00	.302	1.2148		.2779
-100.00	.159	1.2989		.2933

-90.00	.000	1.3080		.2936
-80.00	-.159	1.2989		.2933
-70.00	-.302	1.2148		.2779
-60.00	-.415	1.0684		.2498
-50.00	-.486	.8799	.2132	
-40.00	-.510	.6743	.1727	
-30.00	-.494	.4784	.1333	
-20.10	-.560	.3027	.0612	
-18.10	-.670	.3069	.0904	
-16.10	-.790	.1928	.0293	
-14.20	-.840	.0898	-.0090	
-12.20	-.700	.0553	-.0045	
-10.10	-.630	.0390	-.0044	
-8.20	-.560	.0233	-.0051	
-6.10	-.640	.0131	.0018	
-4.10	-.420	.0134	-.0216	
-2.10	-.160	.0090	-.0282	
-1.04	0.019	0.0095	-.0346	
-0.01	0.139	0.0094	-.0405	
1.02	0.258	0.0096	-.0455	
2.05	0.378	0.0099	-.0507	
3.07	0.497	0.01	-.0404	
4.10	0.617	0.01	-.0321	
5.13	0.736	0.0097	-.0281	
6.16	0.851	0.0095	-.0284	
7.18	0.913	0.0127	-.0322	
8.2	0.952	0.0169	-.0361	
9.21	0.973	0.0247	-.0363	
10.2	0.952	0.0375	-.0393	
11.21	0.947	0.0725	-.0398	
12.23	1.007	0.0636	-.0983	
13.22	1.031	0.0703	-.1242	
14.23	1.055	0.0828	-.1155	
15.23	1.062	0.1081	-.2459	
16.22	1.043	0.1425	-.2813	
20.00	0.700	0.30	-.3134	
30.00	.705	.4784	-.2459	
40.00	.729	.6743	-.2813	
50.00	.694	.8799	-.3134	
60.00	.593	1.0684		-.3388
70.00	.432	1.2148		-.3557
80.00	.227	1.2989		-.3630
90.00	.000	1.3080		-.3604
100.00	-.159	1.2989		-.3600
110.00	-.302	1.2148		-.3446
120.00	-.415	1.0684		-.3166

130.00	-.486	.8799	-.2800
140.00	-.510	.6743	-.2394
150.00	-.494	.4784	-.2001
160.00	-.460	.3172	-.1685
170.00	-.230	.2116	-.5000
180.00	.000	.1748	.0000

! Steady wind file for 30 fps (or m/s) wind speed for AeroDyn

! Time	Wind	Wind	Vert.	Horiz.	Vert.	LinV	Gust
!	Speed	Dir	Speed	Shear	Shear	Shear	Speed
0.0	22.97	0.0	0	0.0	0.0	0	0

LSWT Input File

```
2 BLADED NREL/NASA COMBINED EXPERIMENT ROTOR  (cer4816D.ipt)
3.0       0.0       2.0       0.0       2.0       2.0       1.0
1.0
0.0       0.0       0.0
0.0       0.0       0.0       0.0
0.0       72.0      1.0       1.0
5.0       1.0       16.0      1.0
-4.8      1.0       1.0       300.0
2.0       2.0       2.0       16.5
2.0       12.0      1.0       180       30.0      1.0
0.0       0.0       1.0       10.0      11.0      13.0
2.0       3.0       0.25      2.90      4.12
0.0       0.0       0.0       0.0       0.0       0.0
12.0
2.90      3.50      4.12      4.95      6.40      7.69      9.41
10.45     12.41     13.41     15.41     16.41
0.600     1.447     2.418     2.333     2.185     2.057     1.883
1.778     1.581     1.480     1.276     1.175
12.0
2.90      3.50      4.12      4.95      6.40      7.69      9.41
10.45     12.41     13.41     15.41     16.41
0.0       -9.9      -20.04    -14.29    -7.98     -4.72     -2.08
-1.12     0.02      0.48      1.35      1.78
12.0
2.90      3.50      4.12      4.95      6.40      7.69      9.41
10.45     12.41     13.41     15.41     16.41
0.0       0.0       0.0       0.0       0.0       0.0       0.0
0.0       0.0       0.0       0.0       0.0
11.0
001.0     2.90      3.50
001.0     3.50      4.12
001.0     4.12      4.95
001.0     4.95      6.40
001.0     6.40      7.69
001.0     7.69      9.41
001.0     9.41      10.45
001.0     10.45     12.41
001.0     12.41     13.41
001.0     13.41     15.41
001.0     15.41     16.41
```

```
9.0       4.0       0.25      4.12      16.50
0.0       0.0       0.0       0.0       0.0       0.0
12.0
2.90      3.50      4.12      4.95      6.40      7.69      9.41
10.45     12.41     13.41     15.41     16.41
0.600     1.447     2.418     2.333     2.185     2.057     1.883
1.778     1.581     1.480     1.276     1.175
12.0
2.90      3.50      4.12      4.95      6.40      7.69      9.41
10.45     12.41     13.41     15.41     16.41
0.0       -9.9      -20.04    -14.29    -7.98     -4.72     -2.08
-1.12     0.02      0.48      1.35      1.78
12.0
2.90      3.50      4.12      4.95      6.40      7.69      9.41
10.45     12.41     13.41     15.41     16.41
0.0       0.0       0.0       0.0       0.0       0.0       0.0
0.0       0.0       0.0       0.0       0.0
11.0
001.0     2.90      3.50
001.0     3.50      4.12
001.0     4.12      4.95
001.0     4.95      6.40
001.0     6.40      7.69
001.0     7.69      9.41
001.0     9.41      10.45
001.0     10.45     12.41
001.0     12.41     13.41
001.0     13.41     15.41
001.0     15.41     16.41
1.0       0.0
001.0     Blade Station 1 to 11  (stalled flat plate model)
1.0       20.0      1.0       20.0      1.0       2.0
0.21
          1.0
-0.01     0.139
1.02      0.258
2.05      0.378
3.07      0.497
4.1       0.617
5.13      0.736
6.16      0.851
7.18      0.913
8.2       0.952
9.21      0.973
10.2      0.952
11.21     0.947
12.23     1.007
13.22     1.031
14.23     1.055
15.23     1.062
16.22     1.043
30.0      1.0
45.0      1.0
90.0      0.1
          1.0
-0.01     0.0094
1.02      0.0096
```

2.05	0.0099
3.07	0.01
4.1	0.01
5.13	0.0097
6.16	0.0095
7.18	0.0127
8.2	0.0169
9.21	0.0247
10.2	0.0375
11.21	0.0725
12.23	0.0636
13.22	0.0703
14.23	0.0828
15.23	0.1081
16.22	0.1425
30.0	0.5
45.0	1.0
90.0	1.6
	0.0
-180.0	0.0
180.0	0.0

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14. ABSTRACT

The finite element structural modeling in the Rotorcraft Comprehensive Analysis System (RCAS) provides a state-of-the-art approach to aeroelastic analysis. This, coupled with its ability to model all turbine components, results in a methodology that can simulate complex system interactions characteristic of large wind. In addition, RCAS is uniquely capable of modeling advanced control algorithms and the resulting dynamic responses.

15. SUBJECT TERMS

wind energy; wind turbines; RCAS; aeroelastic analysis

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