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A Comparison of Wind Turbine Aeroelastic Codes Used for Certification

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A Comparison of Wind Turbine Aeroelastic Codes Used for Certification

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The National Renewable Energy Laboratory (NREL) has created aeroelastic simulators for horizontal-axis wind turbines. The U.S. wind energy industry often uses these codes to analyze its turbines, and manufacturers seeking type certification for their turbines need to use codes that certifying agencies will accept. NREL brokered an agreement with Germanischer Lloyd (GL) WindEnergie GmbH, the world's foremost certifying body for wind turbines, to participate in a comparison between its code and two of NREL's codes. After a variety of exercises, GL issued a statement that it is acceptable for manufacturers to use the NREL codes for on-shore wind turbine certification.

I. Introduction

THE National Renewable Energy Laboratory (NREL) and its academic and industry partners have created aeroelastic simulators for horizontal-axis wind turbines (HAWTs). Many members of the U.S. wind energy industry use these codes to estimate the design loads of their turbines. When manufacturers seek type certification for their turbines, they need to use codes that the certifying agencies will accept.

The world's foremost certifying body for wind turbines is Germanischer Lloyd (GL) WindEnergie GmbH, located in Hamburg, Germany. NREL and GL agreed to participate in a comparison of their codes. The goal of this agreement was for GL to test the accuracy of the NREL codes and, if found acceptable, issue a statement to that effect. After the comparison, GL issued this statement and a report on the study.[1]

FAST[2] (Fatigue, Aerodynamics, Structures, and Turbulence) is NREL's primary aeroelastic wind turbine simulator. It is a medium-complexity, turbine-specific code that models HAWTs with two or three blades. It uses NREL's AeroDyn[3,4] subroutine library of rotor-aerodynamics routines to compute the aerodynamic forces on the turbine blades.

MSC.Software developed ADAMS[5,6] (Automatic Dynamic Analysis of Mechanical Systems) as a commercial, multibody-dynamics code. Users can model a wide variety of structures with this code. NREL linked the AeroDyn[78] library with ADAMS to enable it to model HAWTs. By means of pre-processing logic, FAST generated the input files for the ADAMS models. These ADAMS models included features not available in FAST, even though FAST created them. One important additional feature is the blade torsion degree of freedom. NREL has made extensive comparisons[9–11] between FAST and ADAMS. Because they share aerodynamics routines, these studies mostly compared the structural response. In the most recent comparison, the two codes agree extremely well for a wide variety of turbines, from small to large. Differences appear when the ADAMS models use features not available in FAST, such as blade torsional flexibility.

GL's code is DHAT (Dynamic Analysis of Horizontal Axis Turbines). It, too, is a HAWT-specific code with a similar design philosophy to FAST.

To evaluate the NREL codes, NREL and GL agreed to model two turbines. Different types of turbines were required to exercise different features of the codes. To publish the results of the study without constraint, the participants chose two public domain turbine designs. The first turbine was the 10-m, two-bladed, stall-regulated turbine

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used in the NREL's Unsteady Aerodynamics Experiment (UAE) conducted in the NASA Ames 80'x120' wind tunnel. Although the UAE rotor is capable of teetering, this study used only the upwind configuration with locked teeter. The second turbine was a fictional concept turbine designed by Global Energy Concepts and Windward Engineering for NREL's WindPACT (Wind Partnership for Advanced Component Technologies) program. The WP 1.5 is a three-bladed, upwind turbine with a 70-m rotor with active pitch control and a variable-speed generator.

We started with existing FAST models of the two turbines. FAST's ADAMS preprocessor generated our ADAMS models from the FAST input files. GL used the properties in the FAST input files to create its DHAT model.

Although the project started with simple comparisons, it became more complex as the participants gained confidence that the codes used the same properties for their models. They compared aggregate properties such as mass, centers of mass, inertias, and natural frequencies. The first simulations were for rigid turbine models rotating in a vacuum. Other simulations were for fully flexible turbines that included an abrupt wind drop for parked turbines, yawing at a fixed rate with the rotor locked, unsheared gusts, and 10-minute simulations with full-field, stochastic turbulence.

The 1.5-MW WindPACT turbine, with its relatively low rigidity in blade torsion, showed the importance of being able to model that degree of freedom (DOF) and the blade center-of-mass offsets that help drive it. Another finding is the importance of applying the aerodynamic forces at the deflected orientations of the blades instead of the undeflected orientations.

The primary purpose of this study was to determine whether the NREL codes are accurate enough for use in turbine certification. Because of time and funding constraints, the project included only code-to-code comparisons, not validating comparisons to test data.

This paper will provide a detailed description of the aeroelastic simulators, the turbines modeled, and the procedures used in the project. It will include comparisons of key loads for the various simulations and illuminate the strengths and weaknesses of the various codes and the importance of modeling advanced blade properties.

II. The Codes

A. ADAMS

ADAMS is a sophisticated, commercial, multibody-dynamics simulator that can model virtually any turbine type if coupled with an appropriate fluid-dynamics model. MSC.Software develops and licenses it. We used ADAMS 2003 for this study. ADAMS is not a wind-turbine-specific code, and many use it to analyze other types of systems such as cars, robots, and spacecraft. It is a well tested program, and we believe the rigid-body predictions of this fully nonlinear code are very accurate. ADAMS uses lumped masses connected by flexible fields similar to multi-dimensional spring dampers to model flexible structures. The flexible fields use some approximations and are not as exact as the rigid-body portion of the simulator.

As distributed by MSC.Software, ADAMS has no built-in rotor-aerodynamics algorithms. However, it allows users to link their own routines with it. NREL links its AeroDyn aerodynamics module with ADAMS to model the propeller-type rotor aerodynamics.

ADAMS is a complex program, and it normally requires a large effort to model a wind turbine with it. To simplify and speed this process, NREL added ADAMS-preprocessing capabilities to FAST. We used the FAST-to-ADAMS preprocessor to construct all ADAMS models used in this study.

Because of the way ADAMS models flexible parts of the structure, it has capabilities unlike the other codes used in the study. Turbine-specific codes typically have just a few DOFs to model the blades and tower. ADAMS models usually use more than 100 DOFs for each flexible substructure. This includes not only bending modes but also torsional and extensional modes. ADAMS can model the low-speed shaft as a fully flexible structure to model rotor whirling motion, but we limited it to only a torsional DOF to mimic the other codes. ADAMS also allows users to specify the location of the elastic axis and the centers of mass of cross-sections. Results from this study show that these offsets and live twist are important in modeling flexible turbines.

B. DHAT

GL's DHAT code is a "traditional" wind-turbine-specific code. Its development began in the late 1980s as a quasi-stationary, rigid, structural analysis tool. With changing demands, the code evolved to include aeroelastic coupling and a better description of the wind turbine. The code is still under development to meet evolving needs.

The aerodynamics calculations in DHAT use the classic, blade-element/momentum (BEM) theory from Wilson or Politis[12,13] to compute induced velocities. Now dynamic and turbulent wake conditions,[14] as well as dynamic stall, are available options. The dynamic stall models used are from Stig Oye[15,16] or Goman and Khrabrov[17].

The code models blade, drive train torsion, and tower flexibility. Blade-bending flexibility through modal representation is independently analyzed for every blade and considers full edge-flap coupling. Up to six modes for every blade can be considered, but usually only the first two or three modes are used.

DHAT models the drive train as a simple two-mass spring-damper system with input torque from the hub and the generator. The generator can be asynchronous or fully controlled synchronous.

The yaw bearing is a brake, which can slip, and a spring damper system. The tower model used in this study considered only fore-aft and side-to-side bending, but a new version of DHAT in testing includes tower torsion, as well as the influence of linear springs at the different nodes to model guy wires.

A set of different parametric pitch-controller algorithms is available representing typical wind turbine controller designs that can be adjusted by a few parameters such as proportional-integral-derivative (PID) omega/pitch control and proportional-integral power/pitch control.

DHAT comes with a package of pre- and post-processing tools. The turbulent wind for the DHAT input is generated by a turbulence generator using an ESDU (modified von Karman) spectrum delivering a three-dimensional, three-component, and anisotropic wind field. Another tool computes the fatigue-analysis of calculated time series, a program using the rainflow counting method, including weighting of the results according to given wind distributions. Further, a huge number of statistical analysis functions are included within the tool, which cover the requirements of detailed load analysis and load assessment procedures.

We used DHAT v19 (Sept. 2001) for this study.

C. FAST

Like DHAT, FAST is a wind-turbine-specific code. Therefore, it has limited DOFs but can model many common turbine configurations. FAST also models flexible elements using modal representation. The reliability of this representation depends on the generation of accurate mode shapes, which are input into FAST. We used a program called Modes[18] to generate these shapes. Like FAST, Modes originally came from Oregon State University, but NREL rewrote most of it. The blade and tower models also use properties such as stiffness and mass per unit length to specify the flexibility characteristics. As with ADAMS, FAST uses the AeroDyn module of routines to model the rotor aerodynamics.

We used FAST v5.10 in this study and added a custom-written PID pitch controller for the WP 1.5 turbine. This version of FAST allows up to 18 DOFs. These DOFs include two blade-flap modes and one uncoupled blade-edge mode per blade. It also has two fore/aft and two side-to-side tower bending modes. It has drive train torsional flexibility similar to DHAT and a generator DOF with multiple models. We used the simplest model for the UAE turbine in this study. For the WP 1.5 turbine, the control system computed the desired generator torque, so we did not use any of the available generator models.

FAST has nacelle yaw, rotor teeter for two-bladed turbines, and hinges between the rotor and tower and between the tower and tail for furling turbines. Of this last group, we used only nacelle yaw in this study and for only one test case. For the yaw model, FAST can allow it to rotate freely or can apply a spring/damper. For most of this study, all the codes disabled the yaw DOF.

Comparisons between ADAMS and an earlier version of FAST (called FAST_AD) illuminated many weaknesses in FAST, so it received a major overhaul that began in 2002. The latest version of FAST shows excellent agreement with ADAMS.[11]

An attractive feature of FAST is that it is a public domain code freely available to anyone. Its distribution archive includes the full source code for the program. The source code allows users to know what the program is doing, and it allows them to modify the code to suit their needs.

D. AeroDyn

AeroDyn is part of a simple wind turbine aeroelastic simulator called YawDyn[19]. The University of Utah[‡] developed YawDyn under a subcontract with NREL. When NREL engineers started using ADAMS, they needed routines to compute aerodynamic forces to apply to the structure. NREL contracted with the Utah group to extract the aerodynamic routines from YawDyn so that ADAMS could use them. That effort resulted in the AeroDyn subroutine library.

[‡] The principals from the University of Utah formed an independent company called Windward Engineering, and that organization now supports AeroDyn and YawDyn for NREL.

AeroDyn is a library of subroutines that can be linked with structural codes to provide the lift, drag, and pitching-moment forces on the blade. To calculate the induced velocities, AeroDyn has two options: BEM theory based on the PROPX code[20] and generalized dynamic wake (GDW), which uses Peters and He's method.[21] The BEM induction can optionally include tip and hub losses based on Prandtl's work as described by Glauert.[22] AeroDyn also has an option to use dynamic stall based on the work of Leishman and Beddoes.[23-25] AeroDyn can excite the rotor structure with steady or turbulent, sheared, hub-height winds, or by using full-field stochastic winds. We used NREL's TurbSim[26] v1.00c-bjj to generate the full-field turbulent winds for the AeroDyn-based codes in this study.

The version of AeroDyn used in this study has a weakness in the GDW algorithm that causes numerical instabilities at low wind speeds when the induction is large (turbulent windmill state and vortex-ring state). Because of this, AeroDyn would automatically switch to BEM analysis whenever the mean wind speed of simulations using full-field turbulence was 8 m/s or less. The latest version of AeroDyn is numerically stable throughout the turbine operating range.

For this study, we linked AeroDyn v12.57 with FAST and with ADAMS to create their executable files.

III. The Turbines Modeled

A. Unsteady Aerodynamics Turbine

The first turbine to be modeled was used by NREL in the UAE tests performed in the NASA Ames 80'x120' wind tunnel in May 2000. Test engineers had the option to allow the two-bladed rotor for the UAE turbine to teeter or be locked. Almost all commercial turbines have three blades, and GL's DHAT has no teeter DOF, so we kept the UAE rotor rigid for this evaluation. The turbine also had the capability to run upwind with locked yaw or downwind with free yaw. Virtually all commercial turbines run upwind, so we modeled it this way in this study.

NREL designed the UAE turbine to be extremely stiff so that it could be used in the aerodynamics studies. Because it is so stiff, the blades twisted very little in the ADAMS model, so there was excellent agreement between the FAST and ADAMS predictions for the UAE turbine. Properties used for the UAE model came from the report documenting the wind tunnel test[27]. We list some of the more important properties in Table 1.

The UAE ADAMS model for cases with full flexibility used 21 analysis nodes for each of the two blades and for the tower. The blades used 21 flexible segments to join the nodes, which resulted in 126 (6x21) DOFs for each blade. The tower used 22 flexible segments to join the 21 nodes and the tower top, which resulted in 132 (6x22) DOFs. The model also included drive-train-torsion and generator DOFs. The full system had 386 DOFs.

Table 1. UAE Turbine Properties.

Number of Blades	2
Rotor Diameter	10 m
Hub Height	12.2 m
Rated Power	20 kW
Fixed Speed	72 rpm
Stall Control	
Upwind	
Fixed Yaw	
Rigid Hub	

B. WindPACT 1.5-MW Baseline Turbine

The other turbine we modeled was the baseline paper turbine used in NREL's WindPACT Turbine Rotor Design Study[28]. That fictional turbine is a typical, utility-scale turbine rated at 1.5 MW. We had originally intended to use a commercial turbine for the second turbine, but the logistics of passing proprietary data among all parties became onerous, and we abandoned that plan.

NREL attempted to replace the state-space pitch-control system previously used by NREL for this turbine with a simpler PID pitch-control system for the FAST and ADAMS models. However, after the completion of the study, NREL discovered that the control system was not a true PID pitch-control system. It was more of a pitch-rate control system, and it commanded the pitch change that would be accomplished in one time step at the desired pitch rate.

The FAST model had no pitch-actuator model, and it set the actual pitch angle to the commanded pitch angle. When FAST generated the WP 1.5 ADAMS model, it created an actuator model unlike the one used in the original WindPACT study. NREL found that tuning the spring and damping constants for the new WP 1.5 actuator model was problematic. GL used their built-in PID control system and tuned it to approximate the NREL control system. After a defined time lag, DHAT sets the pitch angle to the commanded pitch setting. For this turbine, we attribute many of the differences between the simulators to the differences in the control systems.

Because of some of the changes NREL made to the WP 1.5 control system, the models predicted a maximum power of 1.2 MW instead of the original 1.5 MW. In the interest of time, we decided to accept the lower maximum power as we were not comparing results to a real turbine.

Properties for the WP 1.5 model came from the FAST model used in the WindPACT study. We list some of the more important properties in Table 2.

The WP 1.5 ADAMS model for cases with full flexibility used 15 analysis nodes for each of the 3 blades and 10 nodes for the tower. The blades used 15 flexible segments to join the nodes, which resulted in 90 (6x15) DOFs for each blade. The tower used 11 flexible segments to join the 10 nodes and the tower top, which resulted in 66 (6x11) DOFs. The model also included drive train torsion and generator DOFs. The full system had 338 DOFs.

Table 2. WP 1.5 Turbine Properties.

Number of Blades	3
Rotor Diameter	70 m
Hub Height	84.3 m
Rated Power	1.5 MW
Variable Speed	Cut-in to rated wind speed
Variable Pitch	Rated to cut-out wind speed
Upwind	
Yaw Control	
Rigid Hub	

IV. Test Cases

A. Vacuum Cases

We used the first two tests to determine if we had correctly modeled the basic configuration and mass properties. For the first test, we disabled all but the yaw DOF and yawed the turbine at a steady rate in a vacuum. The rotor did not rotate during this test. In general, the agreement was quite good, and the differences were in the noise level.

For the second case, we enabled all DOFs but yaw while holding the rotor speed constant in a vacuum. See Fig. 1 for a UAE turbine example.

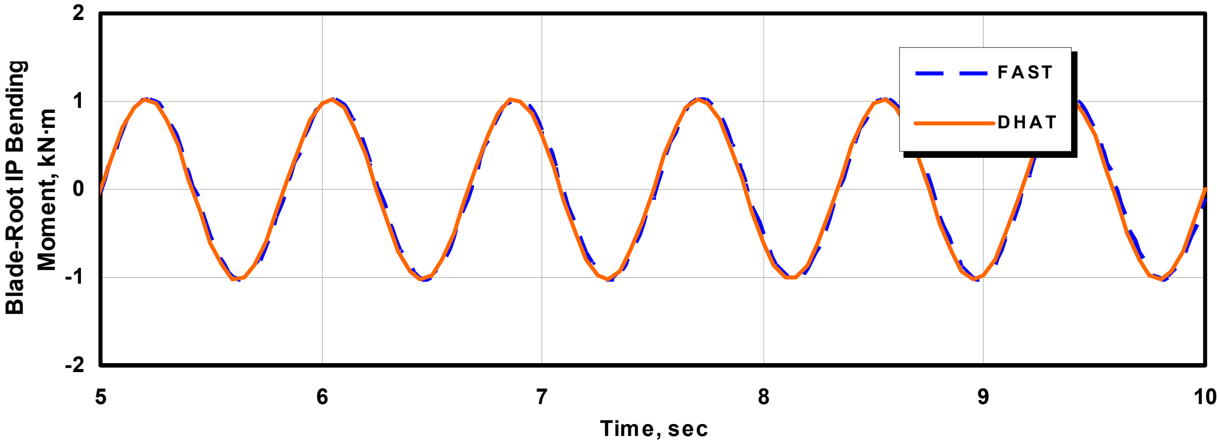

Figure 1. UAE blade-root in-plane bending moment for the case of a rigid, rotating rotor in a vacuum.

Because of a lack of aerodynamic damping, there was some oscillation of the flexible parts for the WP 1.5 turbine, which masked the comparisons. However, the load levels were in good agreement.

B. Abrupt Wind Drop

For this case, we modeled the turbines with full flexibility. We parked the rotor and locked the yaw. We set the blades so they were flat to the wind. This was the first case that included aerodynamics effects. We blew a steady, uniform 60 m/s wind on the turbines and then dropped the wind speed to zero instantaneously.

The WindPACT turbine has flexible blades. In this case, the wind bent the blades back quite dramatically by several meters. As seen in Fig. 2, all codes agreed. ADAMS and FAST agreed perfectly despite their fundamentally different methods of modeling flexibility. ADAMS uses the lumped mass method, while the other two codes use defined modes. ADAMS and FAST share identical aerodynamic routines, which eliminates a significant potential difference. The small differences to DHAT during wind load period are probably the result of differences in the aerodynamic routines.

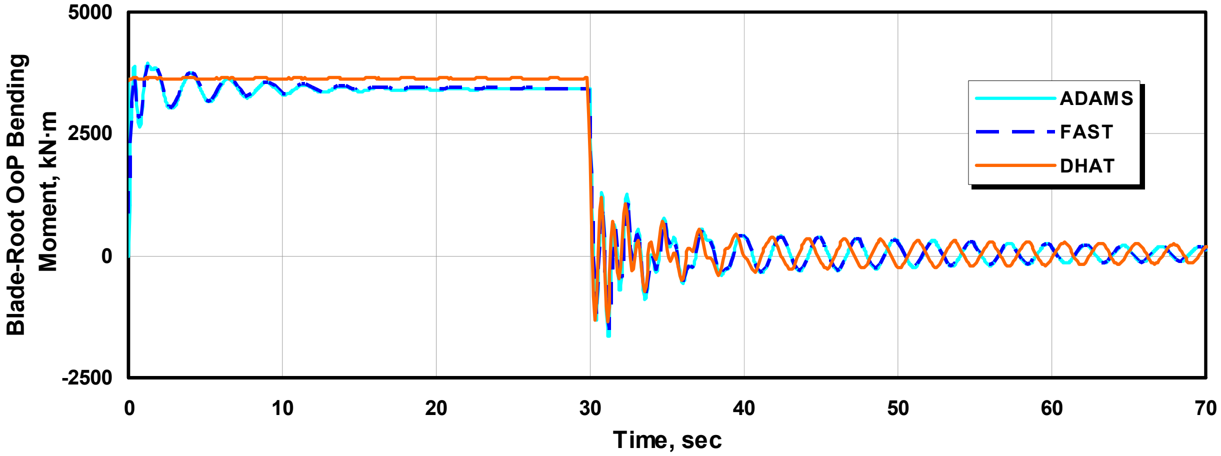

Figure 2. WP 1.5 blade-root out-of-plane bending moment for the Abrupt Wind Drop case.

This case illuminated a difference in the way aerodynamic loads are applied to the blades. All codes apply the aerodynamic forces at the deflected position of the blade. However, only ADAMS and FAST apply these forces in the deflected orientation (Fig. 3). In older-technology turbines with stiffer blades, this was not a modeling problem. However, as turbines become larger and more flexible, the deflected orientations become more important. This difference between modeling methods shows quite dramatically in the radial loads of the blade root, as one can see in Fig. 4. DHAT applies the aerodynamic forces perpendicular to the undeflected blades. Thus, the only axial force acting on the blade is gravity. This is probably the cause of the small differences in the out-of-plane bending moments seen in Fig. 2.

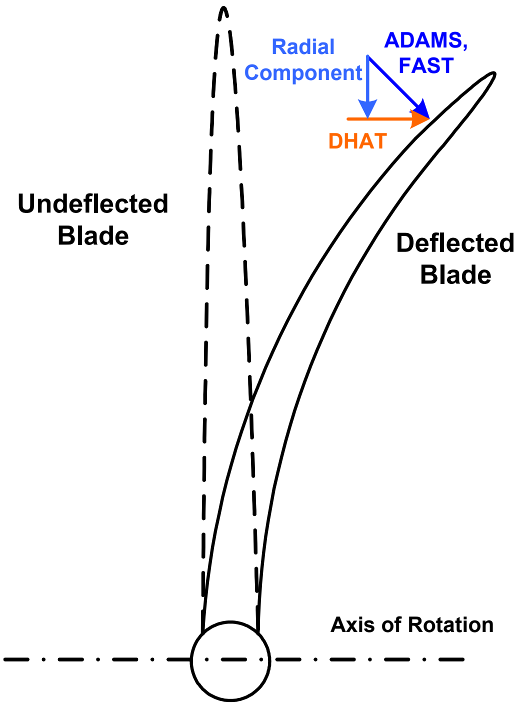

Figure 3. Application of aerodynamic forces to a bent blade.

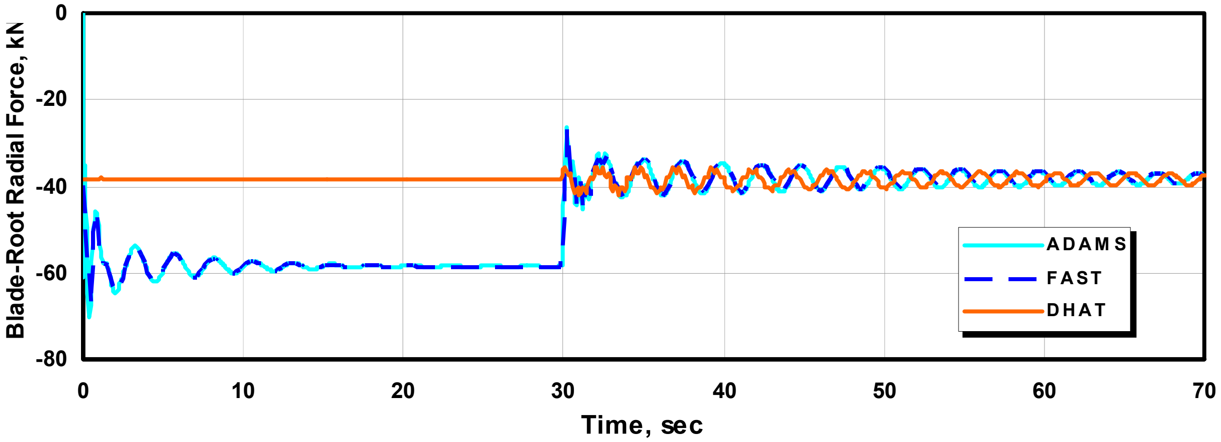

Figure 4. WP 1.5 blade-root radial force for the Abrupt Wind Drop case.

When we look at the yaw-bearing rolling moment (Fig. 5), we see that the ADAMS model gives much higher values when the wind is blowing. Because the rotor is not turning and the simulators used only simple aerodynamics, the likely cause of the difference is blade torsion. The tip rotation in the ADAMS model was over six degrees. Neither of the other codes has this DOF.

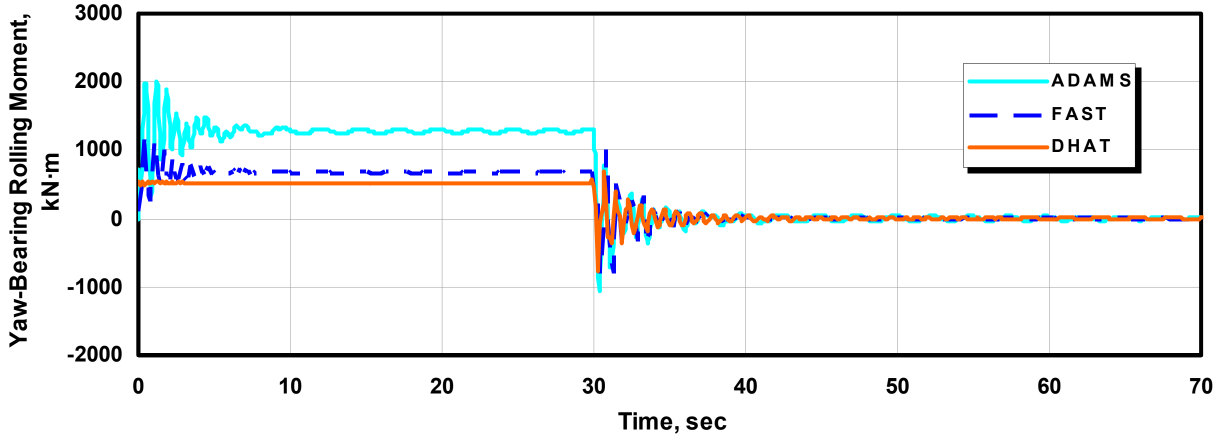

Figure 5. WP 1.5 yaw-bearing rolling moment for the Abrupt Wind Drop case.

Figure 6 shows the blade-root pitching moment. DHAT doesn't compute blade pitching moments nor account for the blade torsion due to aerodynamic and inertial forces acting on a bent blade, so it predicts a zero value. ADAMS and FAST are close, and their difference is likely due to blade twist.

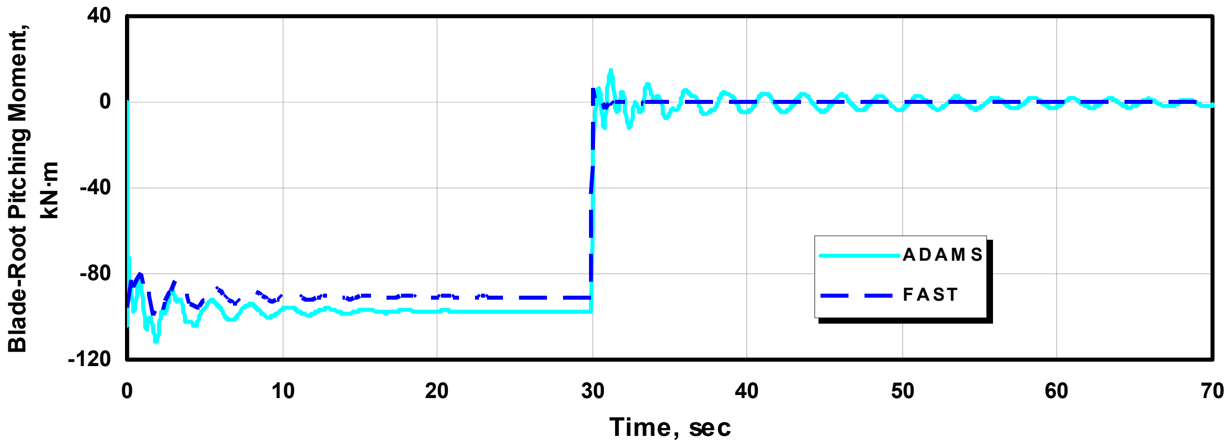

Figure 6. WP 1.5 blade-root pitching moment for the Abrupt Wind Drop case.

C. Uniform Gust

This case modeled the turbines with full flexibility. We superimposed a 10 m/s sinusoidal gust on a steady 15 m/s wind. There was no change in wind direction and no wind shear.

This case was the first to highlight a significant shortcoming in the way we modeled the WP 1.5 turbine with ADAMS. The FAST model included no pitch actuator model, and the actual pitch was set to the commanded pitch. The ADAMS model did include a pitch actuator, and the default values chosen prevented the blade pitch from slewing at even one deg/s (Fig. 7). We did not discover this problem until after we ran all the test cases and began writing the report. As can be seen in the plots of rotor power (Fig. 8), the slow pitch actuator had a significant effect on all system loads.

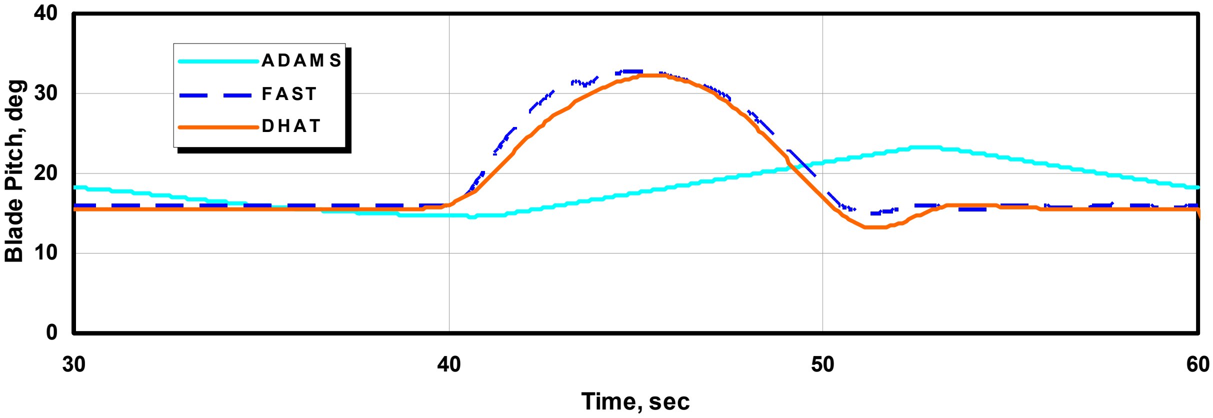

Figure 7. WP 1.5 blade pitch for the Uniform Gust case.

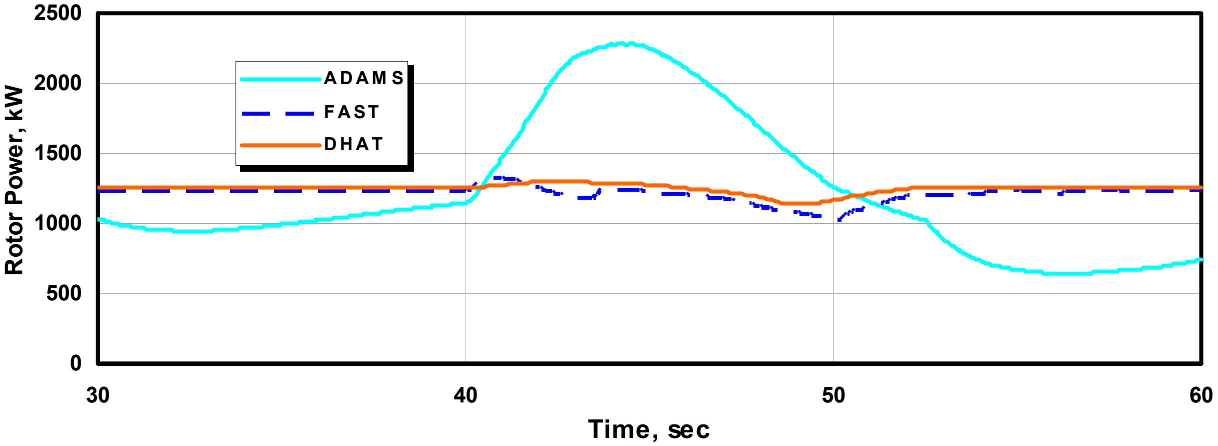

Figure 8. WP 1.5 rotor power for the Uniform Gust case.

D. Full Models Operating in Turbulent Wind

1. Description

The series of simulations used to model the turbines in normal operation with stochastic winds was the decisive test for the comparisons. We used mean wind speeds from 5–25 m/s in steps of 2 m/s. We used the IEC von Karman model with the "A" turbulence intensity as specified in the IEC standard.[29] The models we used for this series included all the appropriate DOFs, and the DHAT model used the 1.2-MW rated power for the WP 1.5 that the NREL codes used.

For this case, we not only compared time series, but we also calculated damage-equivalent loads (DELs) and cumulative fatigue spectra. To define the annual operation conditions, we used a Rayleigh wind-speed distribution with an 8.5 m/s mean wind speed and assumed a 20-year lifetime for the turbines. For the DEL calculations, we set the number of constant-load cycles to 10 million. We used an S/N slope of 10 for composite parts and 4 for steel parts.

2. UAE Results

For the UAE turbine, we documented only the resulting power curve from the series of simulations. We computed the mean rotor power for each case and plotted the results, which show that FAST and ADAMS agree exactly (Fig. 9). The fact that they share common aerodynamics routines from AeroDyn make such excellent agreement relatively easy to achieve. The structural theory base for the two codes is completely different, but it appears we have successfully represented the turbine in both simulators and that elastic deflections are not significant. The results of the DHAT model showed a small deviation from the other two codes. We suspect that the disagreement is inherent in the aerodynamics algorithms used by the codes. At low wind speeds, the NREL codes used BEM instead of GDW because of numerical instability problems in the GDW algorithm at low wind speeds. DHAT uses a different dynamic-stall model than AeroDyn, which probably leads to the deviation in post stall power production in turbulent wind.

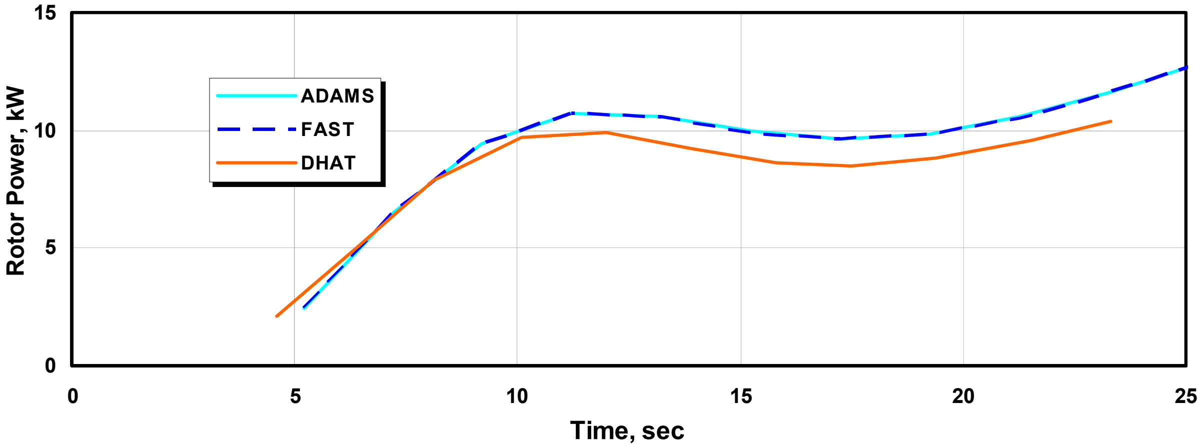

Figure 9. UAE rotor power curve.

3. WP 1.5 Results

At 9 m/s and below, ADAMS and FAST are in perfect agreement. However, above that point, the problems with the ADAMS pitch actuator cause ADAMS to diverge significantly from the FAST and DHAT results. Except for the difference at 9 m/s, DHAT and FAST agree quite well (Fig. 10).

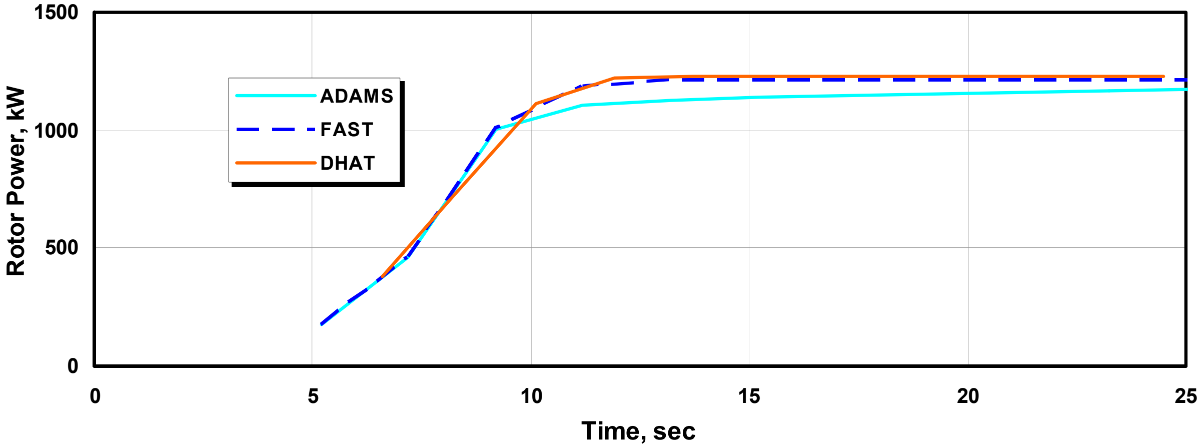

Figure 10. WP 1.5 rotor power curve.

We computed cumulative fatigue spectra for all loads channels. As seen in the comparison of flap-bending moments in Fig. 11, the three codes grouped quite nicely. The chart of root radial forces shows that FAST and DHAT agree well, while ADAMS predicts quite different results (Fig. 12). The difference is due to the low pitch rate available in the ADAMS model, which becomes a problem at higher wind speeds. The ADAMS model required about 50 s to reach the appropriate pitch setting of 30 deg (Fig. 13), so the loads were very high during the first part of the run. Once the pitch reached equilibrium, ADAMS agreed well with the other codes, which can be seen in the spectra above 3.0×10^5 load cycles.

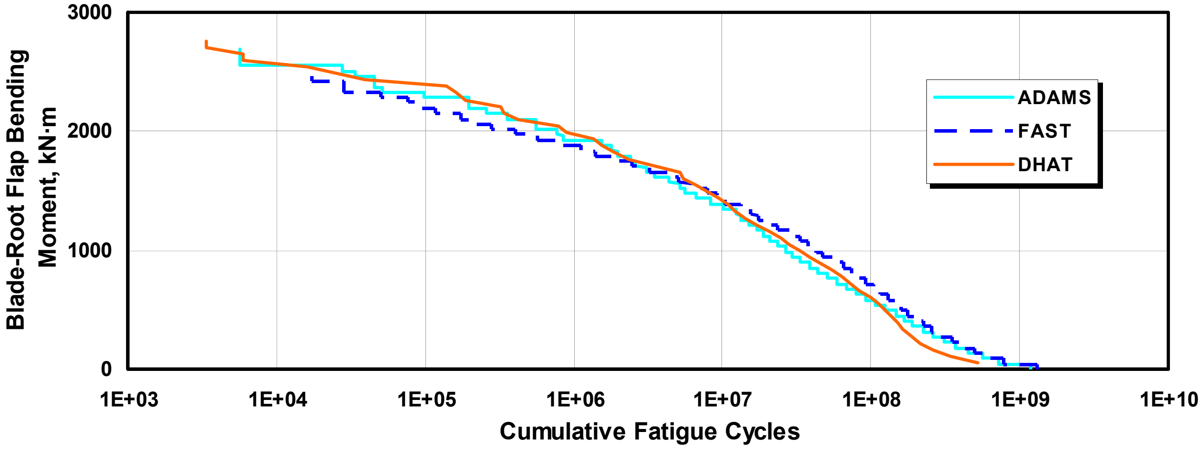

Figure 11. WP 1.5 blade-root flap bending moment cumulative spectra.

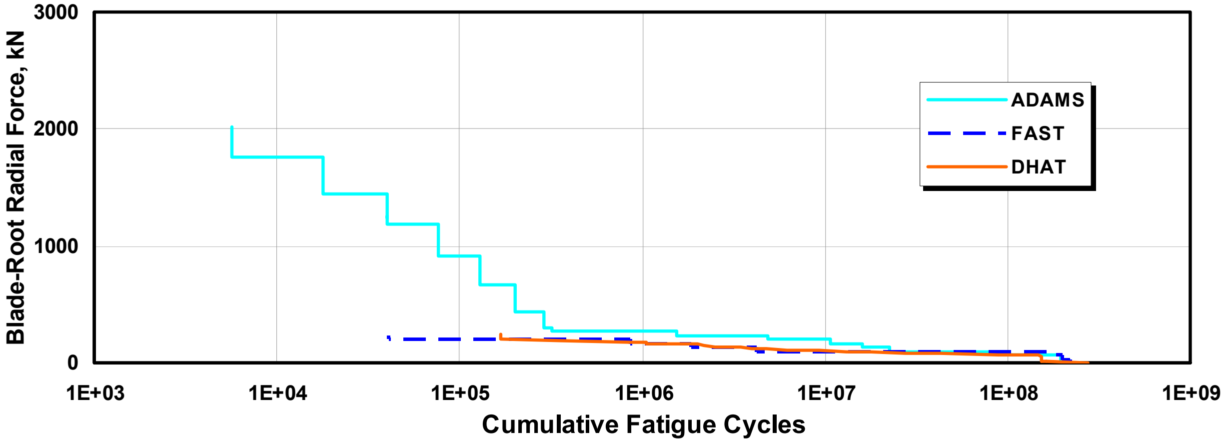

Figure 12. WP 1.5 blade-root radial force cumulative spectra.

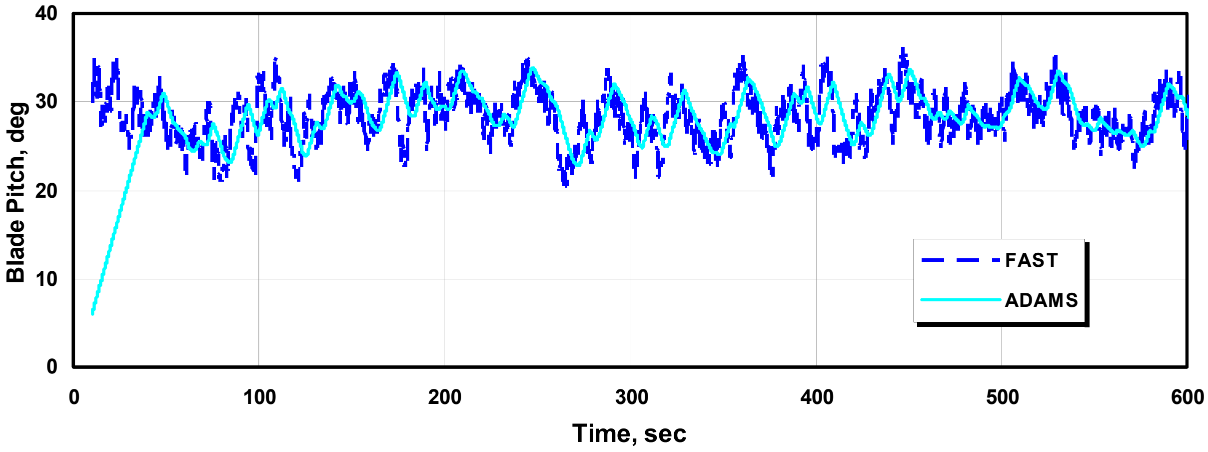

Figure 13. WP 1.5 blade pitch for 25 m/s mean wind speed.

There is a small difference in the curves for the shaft-bending moments in Fig. 14. Various channels tell similar tales. In general, the codes agree with each other. However, the downwind thrust on the yaw bearing (Fig. 15) reveals considerable discrepancies. When looking at the 25 m/s time series for the NREL codes, it is apparent that both codes had not reached equilibrium when the recording started at 10 s. This caused a huge jump in the cumulative spectra in the low-cycle region. A probable cause of the long startup transient is that AeroDyn uses BEM for the first second of a GDW simulation. NREL eliminated this use of BEM for 1 s in the latest version of AeroDyn. This switchover causes the blade pitch to be at the wrong setting when GDW takes over. It seems that the transient took longer than 9 s to die out. With the tower shaking back and forth violently during the transient, the combined rotor and nacelle mass (thrice that of the rotor) amplified the forces at the tower top more than it did at the rotor, so the difference is not so pronounced in the blade and rotor loads. DHAT's equation-of-motion solver generally finds an equilibrium within the first simulation steps, thus the transient period was much shorter compared to FAST and ADAMS. This explains the typical spectral differences seen for the rarer, low-cycle events.

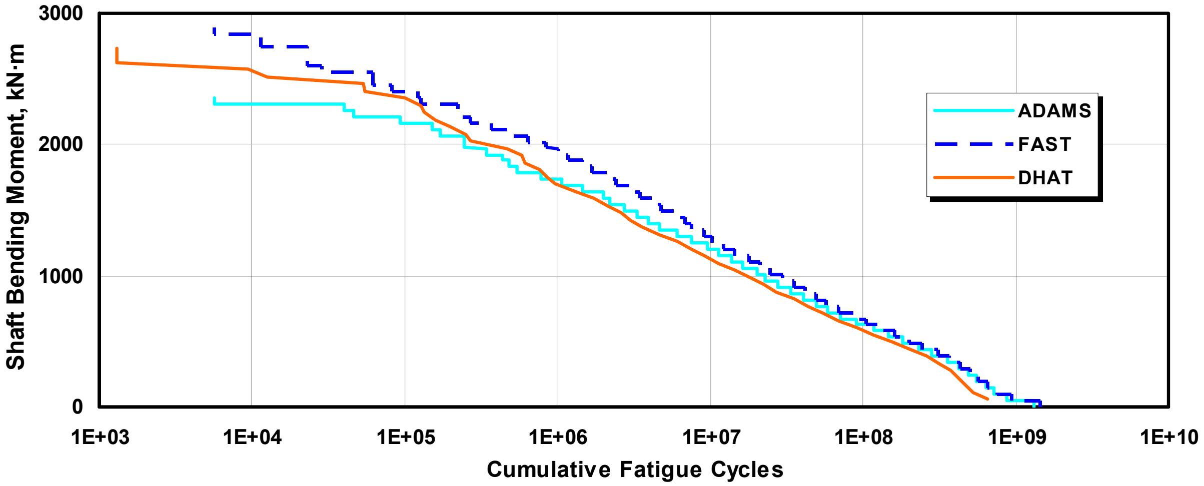

Figure 14. WP 1.5 shaft-bending moment cumulative spectra.

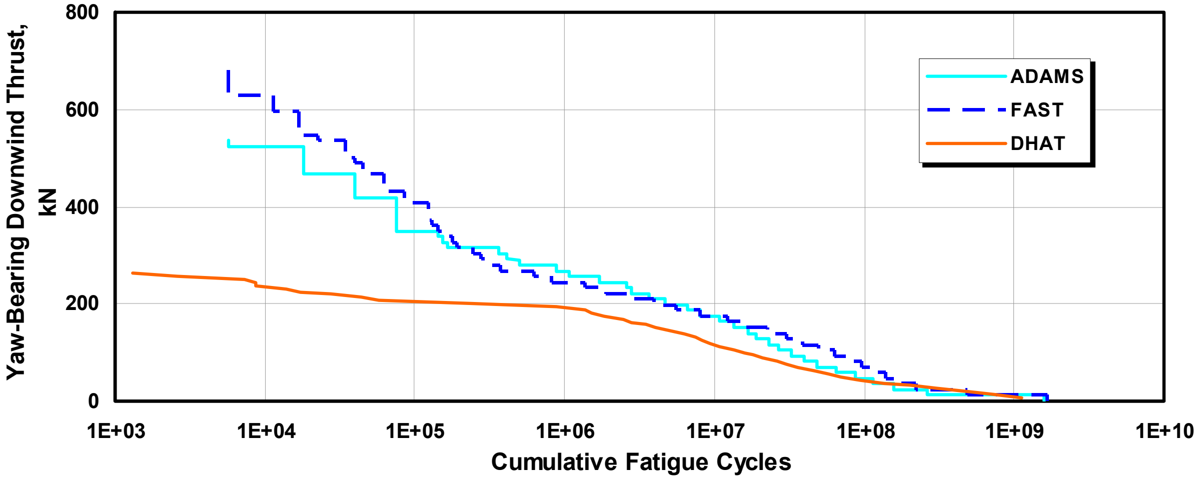

Figure 15. WP 1.5 yaw-bearing downwind force cumulative spectra.

Conclusion

This paper contains a small selection of results from the codes FAST, ADAMS, and DHAT. After a profound study of the comparisons between the codes based on all components relevant for wind turbine design and certification, GL decided that the differences in the predictions are within reason, so they issued a certificate of acceptability.

We believe that modeling errors, such as the pitch actuator used for ADAMS, caused many of the errors, but that differences in the feature sets of the various codes also had a significant impact. Only ADAMS has a blade torsional DOF, and it has full coupling between the flap, edge, and torsional modes. Another unique ADAMS feature is blade section center-of-mass offsets. FAST and ADAMS apply aerodynamic forces at the deflected orientations of the blades, while DHAT applies them in the original orientations. During normal operation when blade deflection is moderate, it is a reasonable compromise. However, for computing the extreme loads of a parked turbine, the approximation may not be valid for specific components.

All of these codes have strengths and weaknesses. A great benefit from studies such as this one is that they help us decide which features we want to work on next in the continual development of our codes. After a decade of code comparisons performed by NREL, much progress has been made on both sides of the Atlantic.

The comparisons have left some items still to be clarified and reveal the need for some additional effort. We would like to fix the modeling errors to help us isolate the real differences among the codes. We would try things such as setting the blade torsional stiffness much higher in ADAMS to determine whether that was the source of some of the differences. We would investigate setting the blade-section centers of mass to align with the pitch axis for the ADAMS models and observe that effect. Similarly, setting the aerodynamic centers to align with the pitch axis might tell us if those offsets caused some differences between NREL's codes and DHAT.

NREL hopes to work with GL to retest ADAMS, FAST, and AeroDyn every other year as they develop new versions of the codes. They plan to replace the UAE turbine with the NREL Offshore Baseline 5-MW turbine for the next comparison. Like the WP 1.5, it is a fictional turbine used by NREL for code-development efforts. By including an offshore turbine in the comparison, NREL hopes to convince GL that its codes are also acceptable for analysis of offshore turbines.

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NREL created aeroelastic simulators for horizontal-axis wind turbines accepted by Germanischer Lloyd (GL) WindEnergie GmbH for manufacturers to use for on-shore wind turbine certification.

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