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Development of the Swept Twist Adaptive Rotor (STAR) Blade

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Abstract

The Low Wind Speed Technology (LWST) project seeks to develop technology that will allow wind systems to provide reduced energy costs in regions where wind speeds average around 5.8 m/s, so-called "low wind speed sites." As part of LWST, Sandia National Laboratories contracted with Knight & Carver to develop a sweep-twist adaptive blade to passively reduce operating loads, thereby allowing for a larger, more productive rotor and ultimately reducing the cost-of-energy. After design and fabrication of a 27.1 m STAR blade, static and fatigue laboratory tests were successfully carried out. Full flight testing on a Zond 750 test turbine verified the predicted performance and operating loads. The STAR blade exceeded the project goal of improving annual energy capture over the baseline by producing 10-12 % more energy.

I. Introduction

The United States Department of Energy (DOE) Wind and Water Program has sponsored an effort to develop wind technology that will allow wind systems to compete in regions of low wind speed. The Low Wind Speed Technology (LWST) project targets sites that have annual average wind speeds of 5.8 m/s, measured at 10 meter height. Such sites are abundant in the U.S. and would increase the available land area which can be economically developed by twenty-fold. DOE estimated that new technology produced by LWST could result in 35 to 45 GW of additional wind capacity being installed by 2020.

In late 2004, as part of LWST's Phase II Component Development undertaking, Knight & Carver (K&C) was contracted by Sandia National Laboratories (SNL) to develop a sweep-twist adaptive blade that would passively reduce operating loads and thereby allow for a larger, more productive rotor. Such a design would use outer blade sweep to create bend-twist coupling rather than by an alternate method that incorporates off-axis carbon fiber, a concept developed by SNL [Ref. 1]. The feasibility of using geometric sweep to reduce fatigue loads has also been established in previous work at SNL [Ref. 2, 3]. Reduced fatigue loads will allow for a longer blade for the same fatigue load spectrum; thus the rotor swept area grows and more energy is captured. After design and fabrication of the Sweep-Twist Adaptive Rotor (STAR) blade, laboratory testing including static, fatigue and modal was successfully completed. Full flight testing recently has verified the predicted performance and operating loads. The STAR blade significantly exceeded the primary project goal by improving annual energy capture over the baseline by 10-12% while keeping critical loads at the same levels.

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II. Parametric Studies and Design of STAR Blade

The STAR blade project was initiated in late 2004 and advanced in several phases. The first year was a design stage used to complete parametric and concept studies, preliminary designs and analyses, and a final design, termed the STAR7. This work resulted in a prototype blade specification that was released in the spring of 2005. The manufacturing/test stage began with the successful fabrication of the first blade in early 2006. The static test immediately followed. Based on results of this test, modifications to the blade design were implemented. Four prototype blades were then fabricated in the fall of 2007. After three blades were installed on the test turbine in Tehachapi, California during the winter of 2007, field testing began in April 2008 and was completed that summer. Fatigue testing of the remaining blade was started at NREL in the summer of 2008 and completed early in 2009. The final report for the STAR project is being published by Sandia National Laboratories in January 2010 [Ref. 4]. This report provides much more detail about the project and a down-loadable version will be posted in the publication list at www.sandia.gov/wind. The rest of this section overviews the design stage while Section III is a discussion of STAR fabrication and test results.

The design began with a series of parametric and concept studies performed to determine the best options of manufacturing process and composite materials to use for this project. The Zond 750 and its 24.5 m blade were chosen as baselines. Concept studies considered variation on degrees of sweep and airfoil composition to determine the most desirable combinations (Figs. 1 and 2). The methodology of incorporating sweep is documented in Zuteck's Sandia National Laboratories report of 2002 [Ref. 3] and further discussed in Ref. 2.

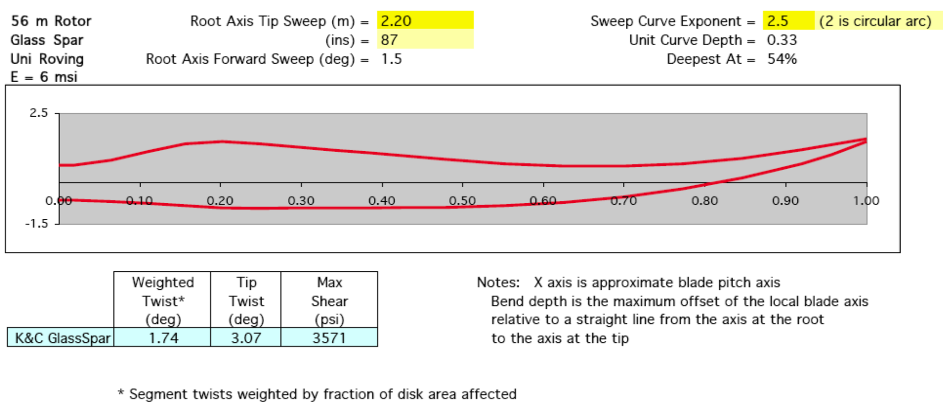

Figure 1. Concept Design

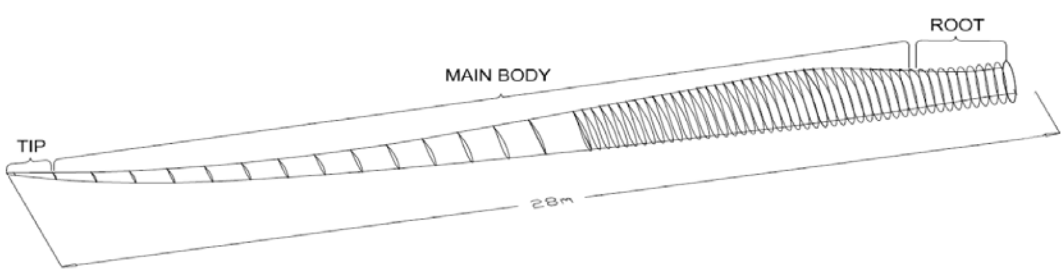

Figure 2. Design Planform and Airfoil Stations

Very early in the design stage, blade requirements were defined. These were complicated by the fact that the STAR blade is a retrofit to an existing machine, the baseline Zond 750 turbine. The following are conditions considered and design parameters optimized for:

1. General parameters defined upfront:
   - Rotor speed (RPM)
   - Blade stiffness (EI)
   - Span-wise mass
   - Chord-wise mass
   - Maximum blade sweep
   - Operational window of Z-750 baseline
   - Analytical calculations to use FAST, ADAMS, CFD, ABAQUS
   - Longer blade on same rotor
2. Design parameters for optimization
   - Planform (airfoils)
   - Airfoil thickness vs. span
   - Sweep magnitude & curve
   - Spar cap position & sizing
   - Airfoil structural geometry
   - Materials & process
   - Root forward sweep
   - Reduction of loads or same loads with larger rotor
3. Design for practicality
   - Sweep curve to minimize skin curvature
   - Sweep to allow for 3 blades on trailer
   - Exotic/expensive materials to be avoided
   - Existing root mold to be used for in-board 50% of blade
   - Moments to be similar to those of existing blades

The final STAR7 configuration met the major design requirements with a few examples shown below:

	Target	STAR7 Design
• Axis mass moment (kg-m)	19,661	20,000
• Deflection at Max Power	56.6”	56”
• Flatwise frequency	3.75p	> 3p
• Edgewise frequency	4.57p	> 4p
• Flatwise loads		Similar to existing
• Pitch moment		Similar to existing
• Materials		Fiberglass/epoxy

A series of airfoils were developed for this project (led by Case Van Dam of UC Davis) to provide the initial section shapes for the blade. These airfoils are derived from those designed by Wortmann in the late 1970s and compiled by Althaus [Ref. 5]. The geometries of these airfoils were changed and renamed a new designation of STAR-xxxx-yyyy where xxxx represents the maximum thickness to chord ratio t/c × 100% and yyyy the trailing edge thickness to chord ratio $t_{te}/c \times 100\%$. (Note: Ultimately, the inboard 50% of the prototype blade incorporated airfoils based upon the DU airfoil series used in the Euros EU-51 blade.)

The STAR series airfoil family was prepared especially for this blade project. Seven airfoil sections from the STAR series are shown in Fig. 3. The tip airfoil STAR-1520-0018 has a t/c = 15.2% and a t_{te}/c = 0.18% and was derived from the sharp trailing edge FX79-W-151a. The main outboard airfoil STAR-1700-0021 has a t/c = 17.0% and a t_{te}/c = 0.21% and was derived from the STAR-1520-0018. The mid airfoil STAR-2615-0123 has a t/c = 26.15% and a t_{te}/c = 1.23% and was derived from the FX77-W-258. The inboard airfoils STAR-3500-0545 (t/c = 35.0% and a t_{te}/c = 5.45%) and STAR-4000-0621 (t/c = 40.0% and a t_{te}/c = 6.21%) were derived from the FX77-W-270.

The simulations for the STAR airfoil series were performed with the viscous-inviscid airfoil analysis method MSES [Ref. 6, 7]. The airfoil lift characteristics of the STAR airfoils were estimated for free and fixed transition using representative Reynolds numbers. Lift, drag, and pitching moment coefficients were calculated at a variety of angles of attack. In Ref. 4 these data are summarized in tabular form as a function of thickness ratio for free transition (clean airfoil) and fixed transition (soiled airfoil).

The lift characteristics of the STAR airfoils are insensitive to the effects of roughness up to thickness ratios of 20%. These airfoil sections also have desirable structural and manufacturing characteristics.

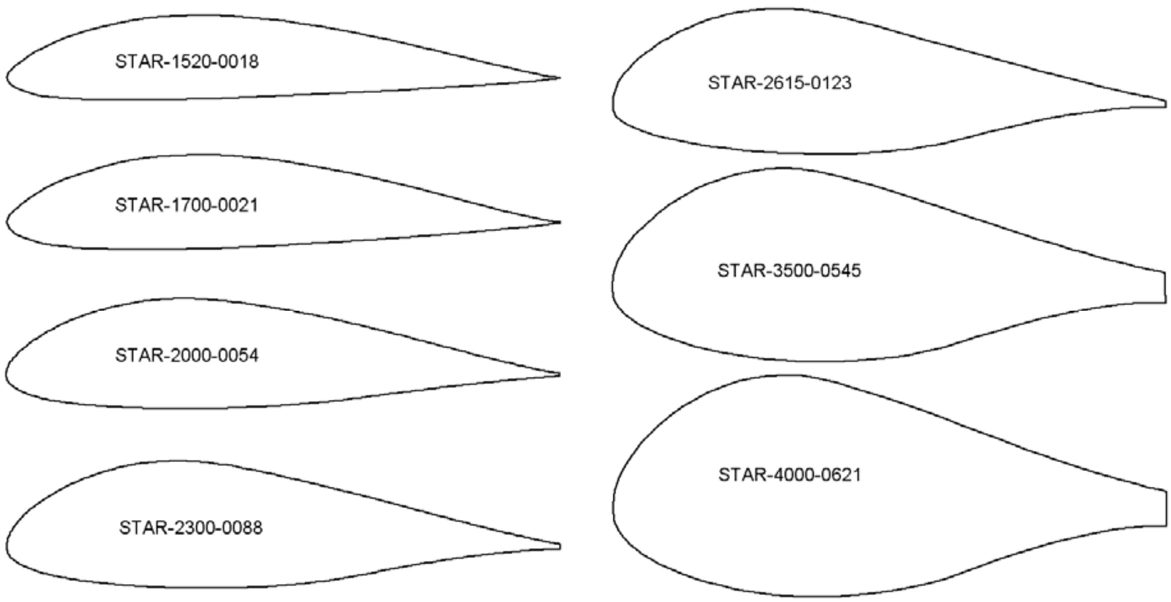

Figure 3. STAR Series Airfoil Family

Once the planform with airfoils was laid out, full system simulations and detailed structural design took place. Figure 4 shows the ABAQUS finite element mesh generated to study detailed stresses and perform a buckling analysis. Figure 5 shows the design drawing of a typical outboard cross-section of the blade.

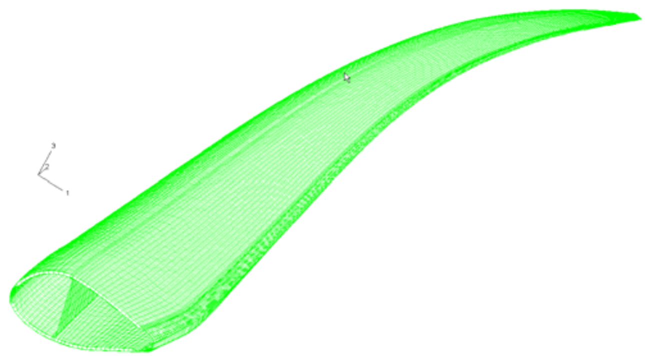

Figure 4. Finite Element Mesh Created During Design

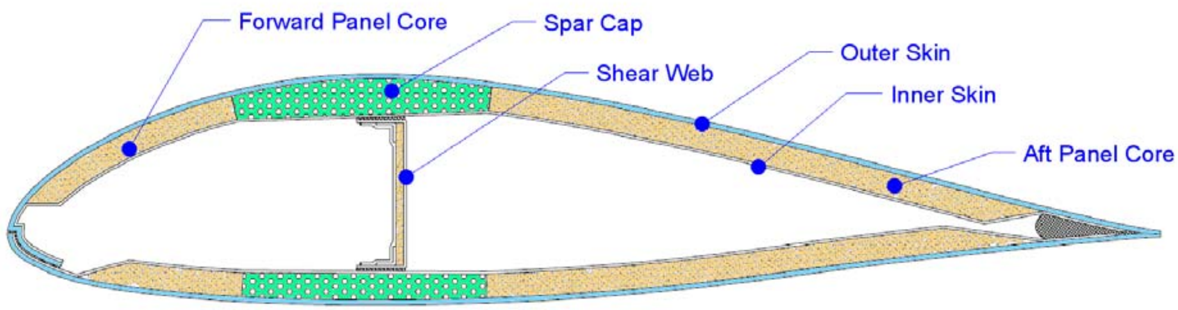

Figure 5. Cross-Section of Blade Outboard

Full system analyses were carried out using a combination of NREL's FAST and MSC's ADAMS codes, both of which are mated to the NREL aerodynamics package AeroDyn for wind loading inputs. For the analyses, several of the most severe IEC load cases were used. Figures 6 and 7 show PSD's of root moment and pitch moment. Adding 10% length to the baseline with no sweep grows the loads significantly (comparing EU51 to BASE6 curves in Fig. 6). Adding sweep reduces the loads back to similar values as the original baseline (comparing BASE6 to STAR7d curves in Fig. 6). Maximum pitch moments are reduced by STAR7 compared to baseline (Fig. 7). The bottom line is that the increased length implemented in the STAR blade (27.1 m) was predicted to have the same or reduced load distributions as the smaller straight baseline (24.5 m).

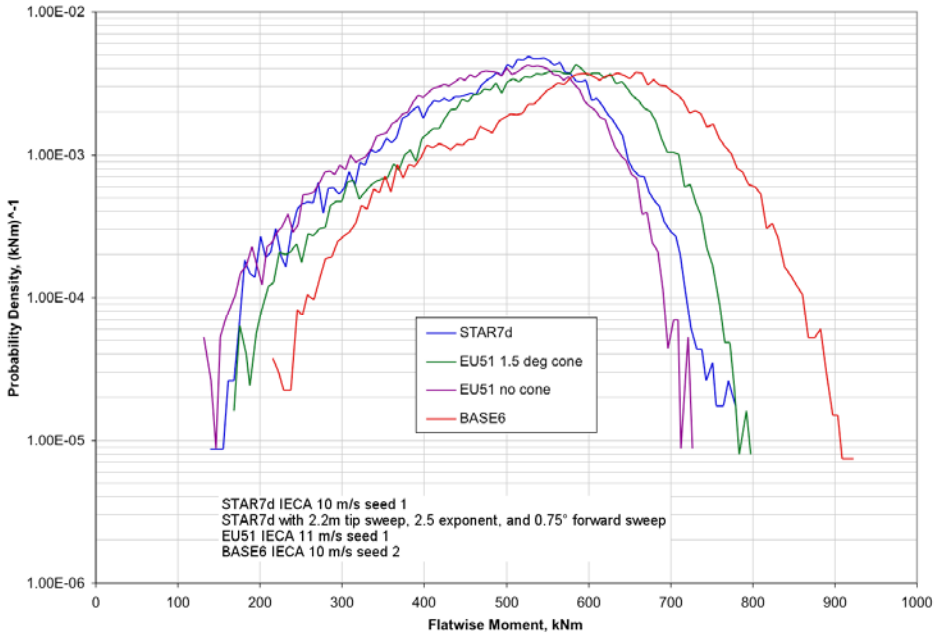

Figure 6. Flatwise Root Moment

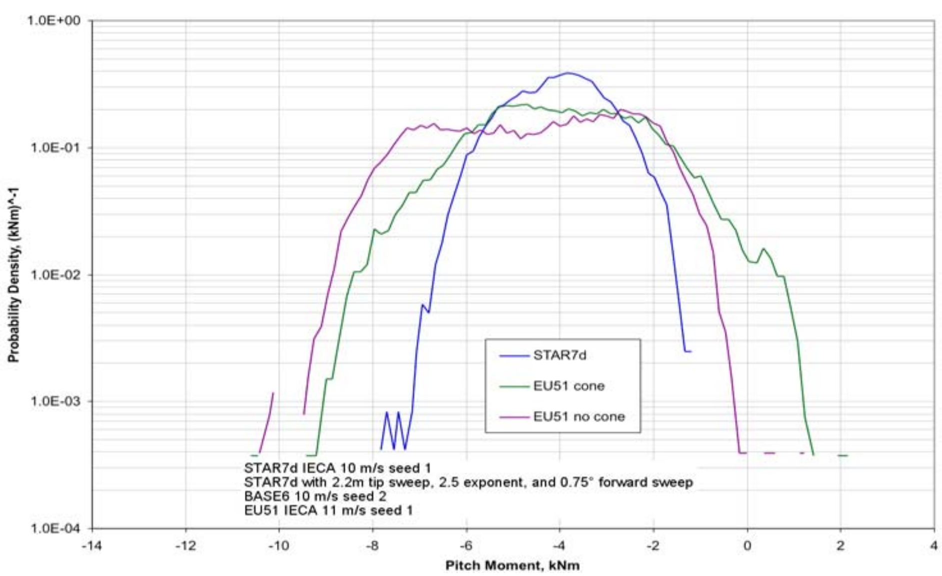

Figure 7. Pitch Moment

Predicted power curves, Fig. 8, shows the significant amount of increased power captured in winds below rated (12 m/s) when the STAR blades are incorporated.

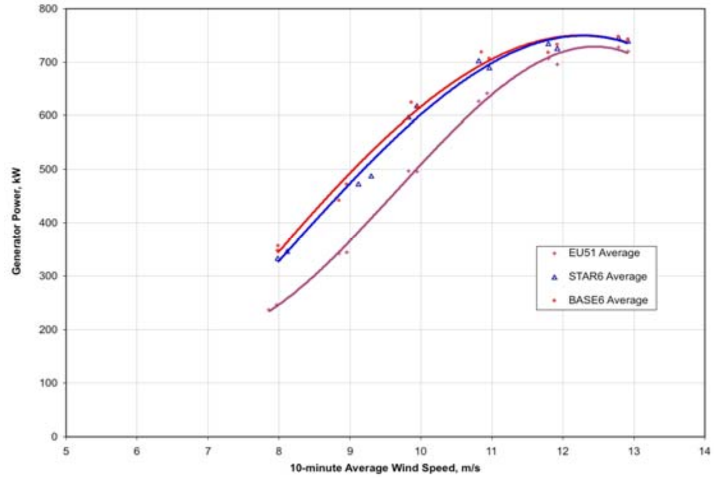

Figure 8. Predicted Generator Power, STAR vs. Baseline

III. Fabrication and Testing of STAR Blade

A. Fabrication.

The plug for the STAR blade was created using airfoil templates connected by wooden battens as shown in Fig. 9. The space between the battens was filled and sanded to a smooth surface. Skin molds were then formed over the plug. Figure 10 shows the lay-up of the first blade in one skin mold, and Fig. 11 the completed blade after being pulled from the mold. Knight & Carver employed a factory-controlled wet impregnation process for fabricating the blade skins and a wet pultrusion process for the spar cap. These processes are effective in holding the curve due to sweep during fabrication.

B. Testing.

1) Static. The first blade was tested statically in the flatwise direction at K&C facilities at three load levels – 50% and 100% of maximum operating load and proof load. Figures 12 and 13 show the static test arrangement including the unique barrel-type loading configuration (barrels were filled with water to different levels to produce desired load inputs). Both flatwise and twist deflections were carefully measured resulting in the verification of the predicted twist response expected by the swept nature of the blade.

Figure 9. Fabrication of STAR Plug

Figure 10. Lay-up of STAR Blade

Figure 11. Fabrication of 1st STAR Blade

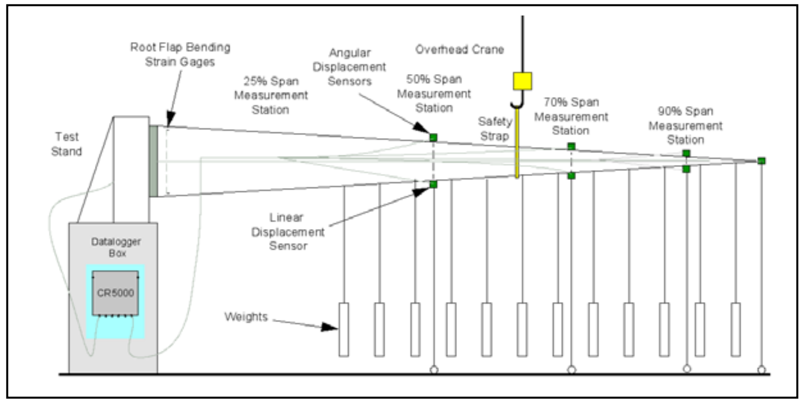

Figure 12. Static Test Layout

Figure 13. Static Testing of 1st STAR Blade

Figure 14. STAR prototype blade in NREL test stand with loading saddles.

2) Fatigue Test. The first STAR blade produced in Knight & Carver's new Howard, South Dakota factory was chosen for the NREL fatigue test. The fatigue blade was built in October of 2007 and shipped to NREL in January of 2008. It included modifications to the shear web and spar cap that were made based on the static test.

The loading was applied primarily in the flatwise direction to allow for the simultaneous testing of flatwise bending and torsional twisting to determine the amount of the bend-twist coupling achieved. The first phase of testing was designed to test the outboard portion of the blade where the bend-twist response is greatest. Figure 14 shows the blade in the test stand with the primary loading and load trimming saddles in position. Loads were applied through a pair of saddles centered on the 11 m station, and the load distribution was adjusted via two additional saddles at the 18 m and 23 m stations, which were weighted to achieve the desired load profile. This choice placed the loading saddles away from the 12–13 m region where inner skin crazing had been noted in the earlier static test, and the region near 15 m where peak torsional shears were expected to occur.

The initial loading phase tested the blade outboard of the 13 m station to at least a full 20 year equivalent life. The second phase of testing increased the blade loading in the inner region so that portion of the blade could be more thoroughly tested. Cycling resumed until a full 20 year lifetime equivalent damage load was obtained for all blade stations outboard of 5 m. The test was stopped with 2,660K cycles and much of the blade having been exercised to about three times the target 20 year equivalent life. Strain and stiffness data were essentially unchanged since the test began.

3) Field Testing. The primary goal of field testing was to measure blade loads for the STAR rotor and compare them to the representative loads for the turbine. A secondary goal was to compare the performance of the STAR rotor to reference turbines operating under similar conditions.

The field test turbine was a Zond 750 (Z48) turbine which operates at a rated speed of 34.4 rpm and originally had a 48 meter rotor with 23.5 m long blades. The STAR field testing used a two channel sensor system, which has proven to be successful on prior projects. Strain gages were used to measure blade root bending moments on the Z48 turbine equipped with the longer STAR prototype blades (26.1 m) and a 54 meter diameter rotor. The team led by Kevin Jackson of Dynamic Design had previously used a similar approach to measure data on Zond 750 kW turbines with conventional blades at two sites in Iowa and Minnesota. This approach provided a broad comparison of actual operating loads between the STAR rotor and other Z750 turbines in a range of configurations and environments.

The test site was located in the Tehachapi Mountain wind resource area of California. The test turbine is located within an existing wind plant several miles southeast of the town of Tehachapi, California. The elevation of the test site is approximately 4920 feet and the hub height is slightly more than 5000 feet above sea level. Wind conditions at the site are within the IEC Class II designation.

Field test data were initially collected using natural wind excitation with the turbine not operating. These data were used to determine the natural frequencies of the STAR blade when installed on the test turbine. Results were that the non-rotating frequency of the first blade flatwise mode (1.83 Hz) was slightly lower than the predicted value (1.98 Hz), while the measured blade edgewise frequency (2.6 Hz) was somewhat higher than the calculated value (2.43 Hz). The measured system natural frequencies were well placed between operating harmonics and dynamic amplification through resonance was ruled out as a concern prior to operation of the turbine.

Rank-ordered maximum flatwise and edgewise bending moments are compared to the certification design loads in Fig. 15. These data show that the STAR rotor operated safely below the design maximum operating load for the Z750 turbine.

Comparisons between measured loads for the STAR 54 rotor and the baseline Zond 48 rotor are presented in Figs. 16 and 17. A conventional 54 meter diameter rotor would have increased blade root bending moment by 80% as compared to the baseline. These results show that measured blade root bending moments for the STAR 54 rotor are comparable to loads measured on the baseline Z48 and no significant increase in loading occurred. The STAR rotor operated in the field as expected and successfully sheds high blade root bending loads through dynamically adaptive twisting.

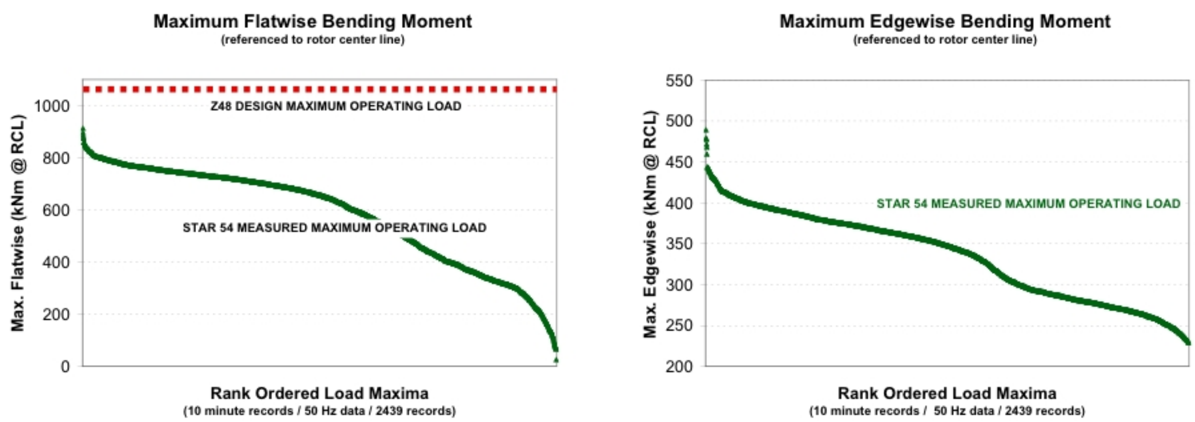

Figure 15. Rank ordered STAR 54 root bending moment maxima compared to the Z48 design.

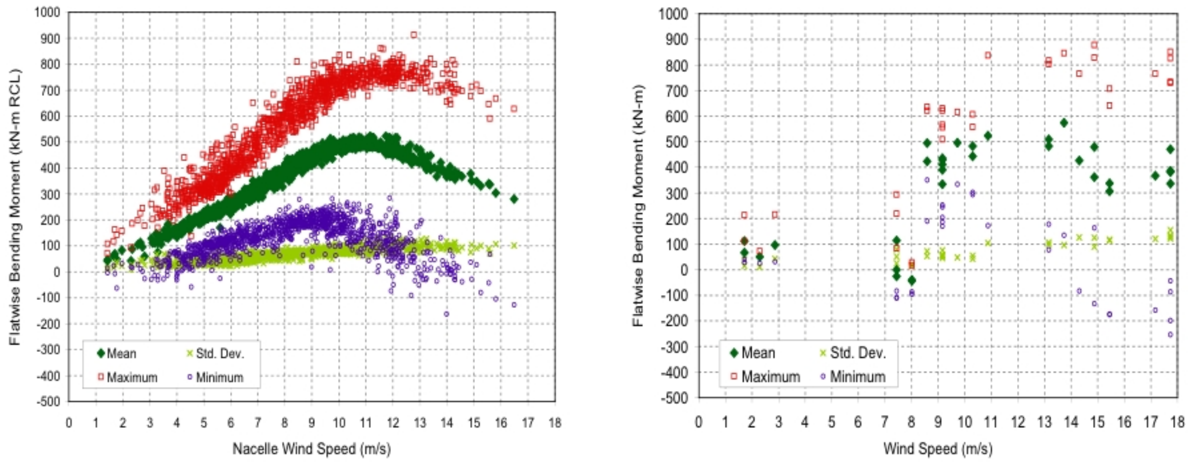

Figure 16. Measured flatwise bending moments - STAR 54 (left) and baseline Z48 (right).

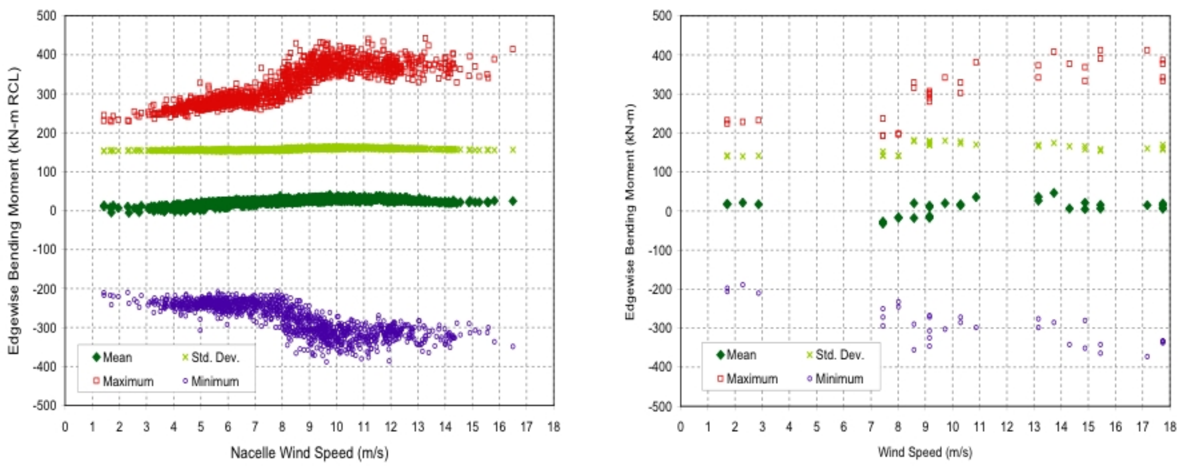

Figure 17. Measured edgewise bending moments - STAR 54 (left) and baseline Z48 (right).

Power curves were prepared for each of the seven standard Zond 48 turbines operating at the Tehachipi site. Four of the turbines (RP-01, RP-02, RP-04, and RP-08) were located on the ridgeline and have similar behavior to the STAR 54 prototype turbine. These four turbines represented the most productive of the baseline turbines operating and were designated as Group 1. Three turbines (RP-05, RP-06, and RP-07) were located at a lower elevation upwind from the main ridgeline and were designated as Group 2. Group 2 turbines have a lower energy capture as compared to Group 1 turbines and appear to have lower average wind speed and turbulence.

Lower turbulence levels found at Group 2 turbine sites resulted in power curves that had less scatter and were better for comparing with model predictions. Sets of power curves for both Groups 1 and 2 were generated by selecting the best performance from any turbine in the group for each wind bin, as shown in Fig. 18. This data showed that Group 2 was well matched to the performance model for the 48-m rotor. Figure 19 compares STAR 54 and the best of the low turbulence (Group 2) turbines to their respective models, showing good results. Data for the STAR 54 rotor are somewhat less well correlated to the 54-m model than Group 2 is to the 48-m model as a result of the relatively high wind speed and turbulence of the STAR 54 test turbine site.

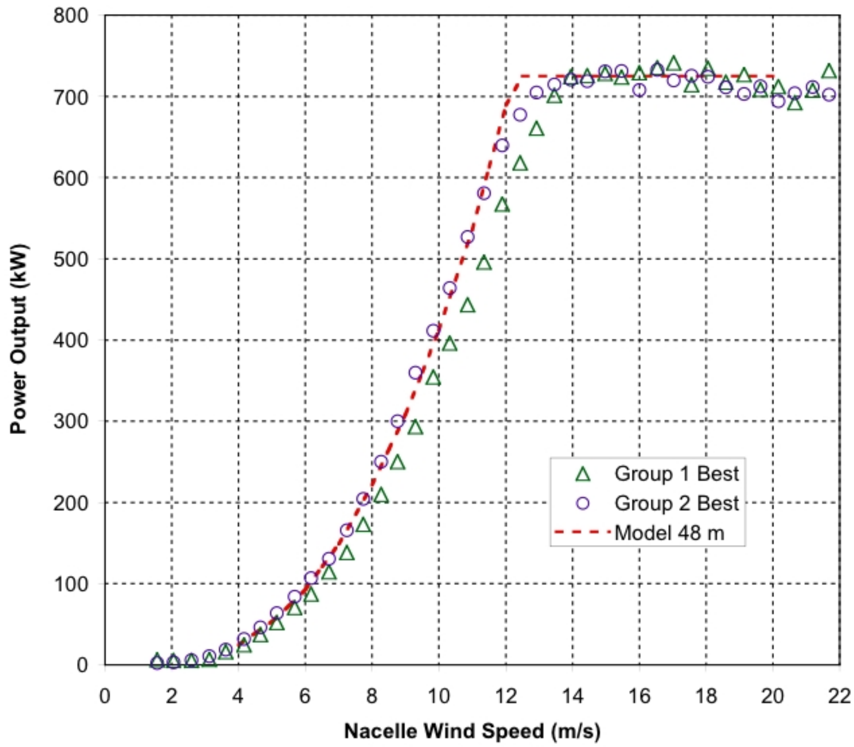

Figure 18. Best of group 1 and group 2 power output compared to 48-m rotor model.

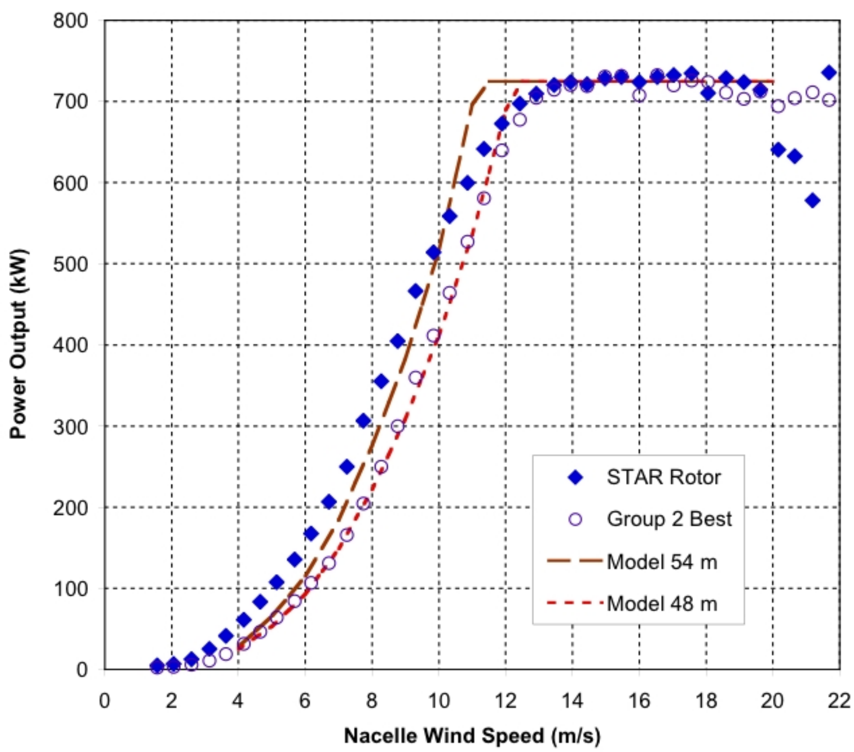

Figure 19. STAR and best of group 2 power output compared to 54-m and 48-m models.

The sorted data were used to calculate the average energy capture for each of the groups over the online period, which is summarized in Table 1. Group 1 consisted of 3322 10 minute data points, when all five turbines (STAR 54, RP-01, RP-02, RP-04, and RP-08) were simultaneously producing power. Group 2 was based on 2524 data points, because RP-07 had a considerable period of missing data. The group analysis shows that energy capture for the STAR rotor was approximately 12% better than the Group 1 turbines and about 36% better than the Group 2 machines.

Table 1. Comparison in energy capture for Group 1 and Group 2 with turbines online.

Turbine Group 1	Energy (kWh)	Compare	Turbine Group 2	Energy (kWh)	Compare
RP-01	243009	101%	RP-05	144456	99%
RP-02	236301	99%	RP-06	145654	100%
RP-04	237148	99%	RP-07	146298	101%
RP-08	242496	101%			
Average	239738	100%	Average	145469	100%
STAR	268711	112%	STAR	197147	136%

Measured moments at the blade root were compared to predictions from the ADAMS model for the STAR 54 rotor operating on a Z-48 turbine. The air density in the ADAMS model assumed an elevation of 5000 feet above sea level, which matched the turbine site altitude. Data records were processed to generate 10 minute statistics for wind speed, power output, and root moments. The binned data from 1128 records are summarized and compared against ADAMS predictions. The predicted flatwise moments were in good agreement with the ADAMS model predictions as shown in Figs. 20 and 21. Mean flatwise loads compared closely to predictions, and maximum flatwise moments were somewhat lower than those calculated by the ADAMS model, which is a positive aspect.

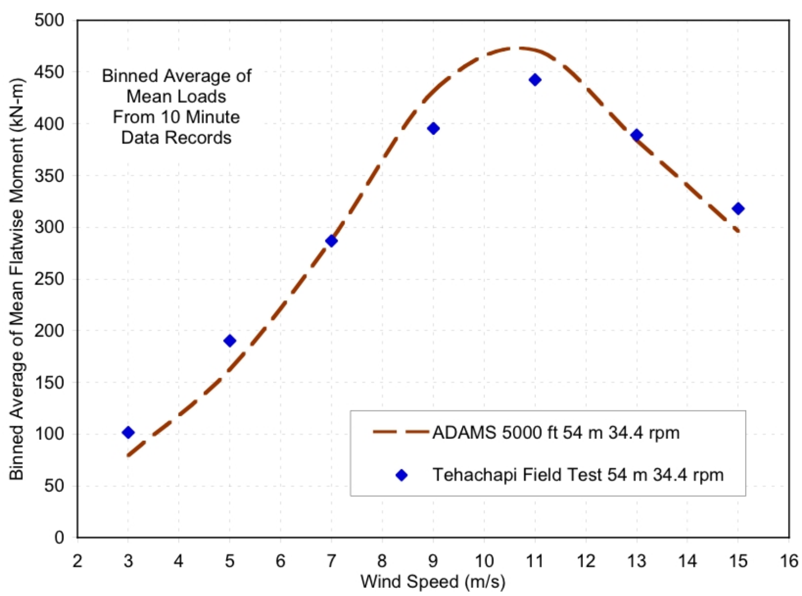

Figure 20. Comparison of measured binned average flatwise moments to the ADAMS model.

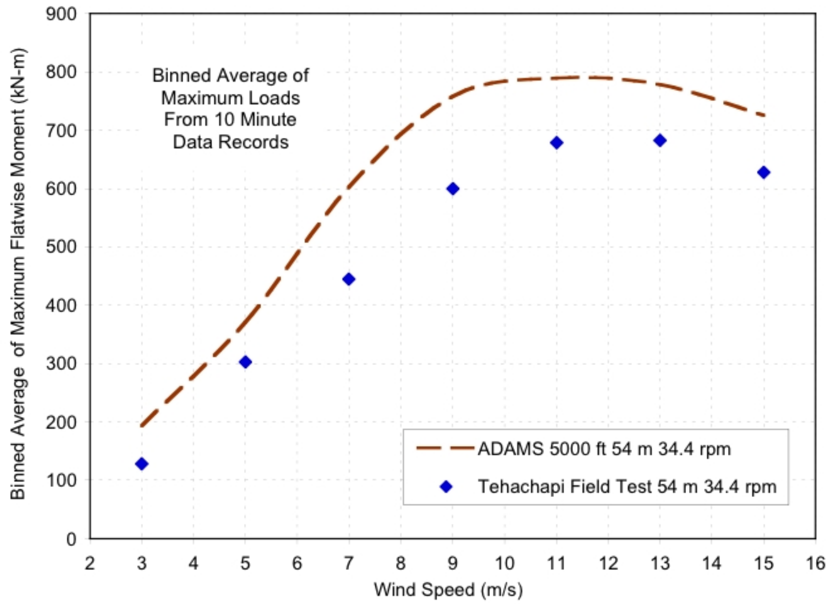

Figure 21. Comparison of measured binned maximum flatwise moments to the ADAMS model.

Measured mean edgewise moments were not in as good agreement with the ADAMS predictions. This is most likely due to strain gage thermal drift errors, which have a much increased impact on the relatively low mean edgewise loads. The maximum edgewise moments were somewhat higher than ADAMS calculations, which is probably due to less edgewise damping in the field as compared to the model. Figure 22 shows STAR blades mounted on the baseline Z-750 baseline turbine.

Figure 22. STAR Blades Mounted for Flight Testing

SUMMARY

A 27-m swept blade (termed the STAR blade) has been designed and several fabricated. Static, fatigue and full-flight testing are now complete. Major items of accomplishment are:

- The STAR project resulted in the successful design, fabrication and testing of this innovative blade that incorporates bend-twist coupling to lower loads at wind speeds above rated power.
- The STAR blade was tested in Tehachapi, California during the spring of 2008 and a large data set was collected to support engineering and commercial development of the technology. Field testing demonstrated that the turbine with STAR blades significantly exceeded the project goal of 5-8% greater energy capture without higher operating loads on the turbine.

- The maximum blade moments recorded during testing were well below the design value used to certify the Zond Z48 turbine. The measured moments were equivalent to those measured on other Zond turbines at sites in Minnesota and Iowa.
- The power performance improvement of the STAR rotor was somewhat greater than predicted by the increase in the swept area alone.
- The STAR rotor increased average energy capture **by 10-12%** as compared to baseline Z48 turbines.
- Laboratory fatigue testing exercised the STAR blade structure to loads representative of a full design operating lifetime. Much of the blade was exercised to about three times the target 20 year equivalent life.

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Kevin Jackson, Principal Investigator, Dynamic Design Engineering
Mike Zuteck, Principal Investigator, MDZ Consulting
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D.M. Hoyt, Finite Element Structural Analysis, NSE Composites
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Manny Buenrostro, Prototype Blade Fabrication, Knight & Carver
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Paul McGrew, Field Testing, Terra Gen Power
Dean Landon, Field Testing, Terra Gen Power
Darren Kelly, Field Testing, Terra Gen Power
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