DESIGN AND INITIAL PERFORMANCE OF A 500-KW VERTICAL-AXIS WIND TURBINE

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ABSTRACT

A large vertical-axis wind turbine which incorporates the latest technology from field experiments, wind tunnel models, and computer code simulations was erected at Bushland, TX. Testing began in 1988. The wind turbine was designed and built to examine aerodynamic, control, and structural dynamic strategies intended to improve the effectiveness of vertical-axis wind turbine systems. The turbine has a 34-m equatorial rotor diameter and is 50 m high. The rotor blades are each constructed in five sections with two different airfoil shapes and three sizes. Power from the rotor is transferred through a speed increasing transmission to a variable speed generator rated at 500 kW in a 12.5 m/s wind operating at 37.5 rpm.

Results from aerodynamic testing indicate the turbine's performance is slightly less than predicted but is much better than previous designs. Power per square meter of rotor area was measured at 40% greater than earlier systems. Using a Rayleigh windspeed distribution and an annual windspeed average of 6.3 m/s, the annual energy from the new wind turbine is projected to be 50% more per square meter of rotor area than the systems now used in wind farms. The structural measurements show that the measured gravity and centrifugal stresses were within 2% of the stresses predicted by the finite element model. Also the predicted modal frequencies for the first 11 modes were within 2% of the measured values. **KEYWORDS.** Wind turbine, Wind energy, Electrical generation, Windmills, Electric power.

INTRODUCTION

A large vertical-axis wind turbine which incorporates the latest technology from past field experiments, wind tunnel models, and computer code simulations was erected for research purposes. This versatile vertical-axis wind turbine was designed to examine aerodynamic, control, and structural dynamic strategies intended to improve the effectiveness of wind systems. These strategies include: multiple blade airfoil sections designed specifically for wind turbines; step-tapered discontinuous sloped blades to reduce stress; and variable-speed, constant-frequency generation capabilities. The Department of Energy authorized a cooperative research team composed of Sandia National Laboratories, Albuquerque, NM, and USDA-Agricultural Research Service, Bushland, TX, to design, construct, and test the new vertical-axis wind turbine. This machine was erected at the USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX, in 1988.

Existing vertical-axis research turbines were designed in the late 1970s and served as the basis for the commercial development during the early and mid 1980s. A new research machine was needed to adequately demonstrate the potential for reducing the cost of energy. This new system needed to be about twice the size of the existing 17-m research turbines to provide the benefits of higher rotor blade Reynolds numbers. High peak energy conversion efficiencies and decreased sensitivity to dynamic stall are benefits of increased Reynolds numbers. The use of step-tapered blades, with a longer chord near the tower and a smaller chord at the equator, maintains a more uniform Reynolds number over the entire blade length. Another benefit of a larger scale turbine was to convincingly demonstrate blade fabrication technology using large multiple aluminum extrusions.

A Test Plan was prepared to organize the experiments in sequences dictated by machine assembly, unknowns in performance and structural integrity, and new concepts (Stephenson, 1986). Phase I testing was primarily performed during the erection of the machine and included baseline measurements on instrumentation, machine sensors, and checks on the control system and brakes. Other Phase I testing included modal vibration evaluation of the blades, tower, and fully assembled rotor. The objective of Phase I testing was to define or characterize the turbine for proper inclusion in structural and performance models.

Phase II testing included resonance surveys, aerodynamic performance, structural performance, and correlation of windspeed with turbine performance using a horizontal plane array of anemometers. The objective of Phase II testing was to actually measure structural loads and performance, then compare measured and predicted values.

WIND TURBINE DESCRIPTION

This vertical-axis wind turbine has a 34-m equatorial rotor diameter with a height-to-diameter ratio of 1.25 and a total turbine height of 50 m. The swept rotor area is 955

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m^2. The top of the tower is supported by three sets of double guy cables, each 63.5 mm in diameter. The rotor is mounted on a 5.2 m tall stand weighing 17 200 kg. Figure 1 is a drawing of the turbine. The three guy cable tie-downs are blocks of reinforced concrete 4.3 m wide, 6.1 m long, and 4.3 m deep that are buried at equal elevations. The cable tie-downs were designed to resist uplift and sliding forces caused by the cable tension of 1290 kN and induced loads due to a 67 m/s wind. The rotor, through a 700 kW transmission, drives a variable speed synchronous motor and current source load commutated inverter. The turbine is rated at 500 kW in a 12.5 m/s wind.

Structural Design

The crucial item in the structural design is the rotor which consists of the blades and tower. The variable-speed nature of the rotor required that the turbine be designed so that none of the natural frequencies of the turbine create a resonance condition. The tower design was based on the requirement that it be very stiff both axially and in bending because of the unknown vibrational characteristics of potential future rotor blades.

Tower

The tower is an aluminum cylinder, 3.0 m in diameter, constructed of 13-mm rolled plates, butt-welded together. An aluminum tower was chosen over a steel tower because its light weight moved a major tower resonance above the desired operating range of 28 to 40 rpm. During construction, three 12.2 m tower sections were placed on saddle stands, trued, and bolted together with splice plates. The blade mounts were attached to the ends of the tower, and the cable tie-downs were assembled and attached to the top end of the tower. The total assembled weight of the tower assembly was 68 000 kg. The tower bearings were designed to carry the thrust loading as well as radial loading for operation with a single blade without counterweights.

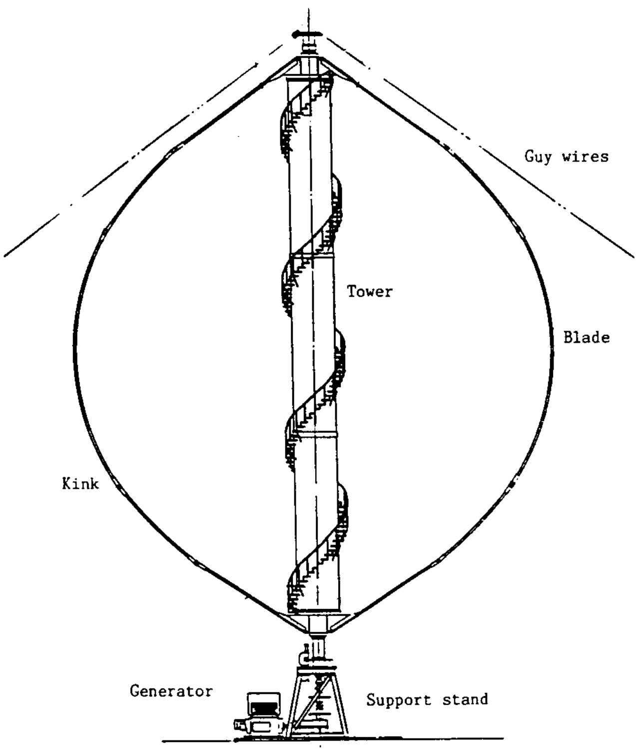

Figure 1–Drawing of 34-m vertical-axis wind turbine, Bushland, TX.

Rotor Blades

The turbine is powered by two curved blades which are shaped to a 37.5 rpm troposkien that contains slope discontinuities or "kinks" of 6 to 7° at the blade to blade joints. Using this improved troposkien approximation technique, the mean stresses were reduced from a peak of 58.6 MPa to 27.6 MPa in the blades (Ashwill and Leonard, 1986). This machine is the first vertical-axis wind turbine to feature blades which are multiple elemental airfoil sections and step-tapered. The elemental airfoil sections were designed specifically for the vertical-axis machine by Sandia National Laboratories and Ohio State University (Klimas, 1984). Each blade section was extruded from 6063-T6 aluminum and assembled with two or three single extrusions bolted together in the spanwise direction.

The curved equatorial section (center) features the SAND 0018/50 natural laminar flow profile with a 910-mm chord (fig. 2). The low drag at small angles-of-attack and sharp stall characteristics should contribute to high rotor power coefficients in modest winds and provide excellent stall regulation. The curved adjoining sections (transition) use a slightly modified version of this airfoil and have a 1070-mm chord. The straight portions which join the blade to the central column (root) use the NACA 0021 profile and have a 1220-mm chord. This profile was chosen for its gradual and gentle stall characteristics since these blade elements operate over the widest range of angle-of-attack.

Brakes

The brakes consist of four independently-controllable custom-designed calipers that apply torque to a 2.0 m diameter, 25 mm thick disc mounted to the tower just

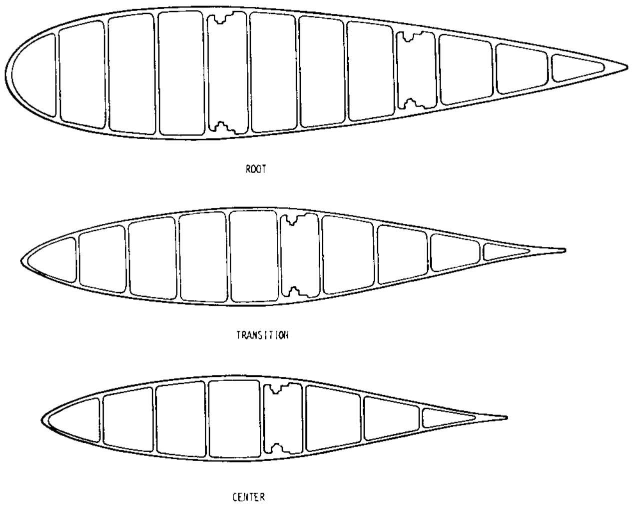

Figure 2–Cross-sections of the SAND 0018/50 airfoil used for the center and transition sections and the NACA 0021 used for the root section.

above the turbine support stand. The calipers are spring applied and hydraulically released, insuring braking action whenever hydraulic pressure is lost. Normal braking occurs in two steps: the generator slows the turbine to approximately 5 rpm, and then a pair of brake calipers are applied to completely stop the turbine. Under emergency stopping conditions, all four calipers are applied, creating a torque of 810 kN-m, enough to stop the turbine from 40 rpm in approximately 10 s with the wind blowing at 20 m/s (Ashwill, 1987).

GENERATOR

Electric power is produced by a variable-speed generator system with a nominal power rating of 500 kW. The generator is a 520 kW synchronous motor with a speed range of 275 to 1900 rpm, and is operated in the regenerative mode. A regenerative mode allows power from the output circuit to be used as feedback to the input circuit. The generator's speed and torque are controlled by a load commutated inverter (LCI) variable speed motor drive. The LCI and synchronous motor are standard production items and are normally used as a variable speed drive for fan and pump applications in power plants and factories. This variable-speed generator system allows for wind turbine rotor operation up to 40 rpm.

The variable-frequency power from the generator is converted to DC and then converted back to AC at the frequency of the utility. The utility side converter locks onto the utility system voltage while the generator side converter locks onto the generator voltage. The LCI controls the speed of the turbine by regulating the generator's current (Ralph, 1987). Increasing the excitation current to the generator will remove kinetic energy from the rotor and slow the turbine.

CONTROL SYSTEM

The control system was designed to monitor turbine aerodynamic performance and structural response at various windspeeds and turbine rotational speeds, and to validate constant speed and variable speed control algorithms. The control system is implemented on three microcomputers: a programmable logic controller (PLC), a personal computer (PC), and the variable speed LCI motor drive controller (fig. 3). The PLC is responsible for monitoring the turbine, generator system, wind, and utility system and implementing constant and variable speed control algorithms. The PC is utilized as an operator control station and to program the PLC. The LCI controller monitors the generator, LCI, and utility systems and regulates the speed of the turbine.

The PLC is the heart of the control system because it monitors several parameters and decides what control actions need to be taken. It is an industrial programmable controller that is commercially available and includes two input/output (I/O) racks and 8 K words of 16-bit RAM memory. Programs are developed and edited on the PC and then downloaded to the PLC. Examples of parameters monitored by the PLC are: brake status, guy cable tension, turbine speed, generator speed, tower vibration, windspeed, generator power output, generator winding temperature, and LCI alarm conditions.

In addition to using the PC to program the PLC, the PC is used to record and interpret the status of the turbine and control system for the operator. Important operating and maintenance information is logged on a printer, and the current turbine status is displayed on the PCs screen with selected information highlighted. The PC allows the operator to vary the speed of the turbine while the turbine is operating, or change operating parameters (i.e., the windspeed cutout set-points) when the turbine is stopped.

INSTRUMENTATION

The wind turbine and its environment have been equipped with a large array of sensors to monitor all aspects of performance. There is a large array of meteorological instruments to monitor windspeed, wind direction, air temperature, and barometric pressure. The sensors on the turbine itself measure strain, fatigue damage, rotational speed, blade rotational position, and vibration. Paired strain gauges have been positioned along both blades at the extreme edges of the chord to measure both flatwise and lead-lag response. Axial strain gauges are

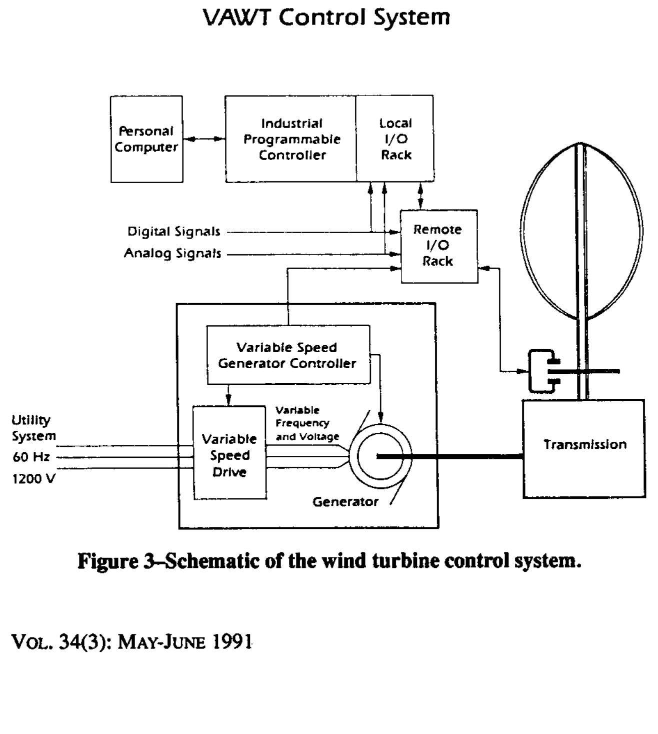

Figure 3–Schematic of the wind turbine control system.

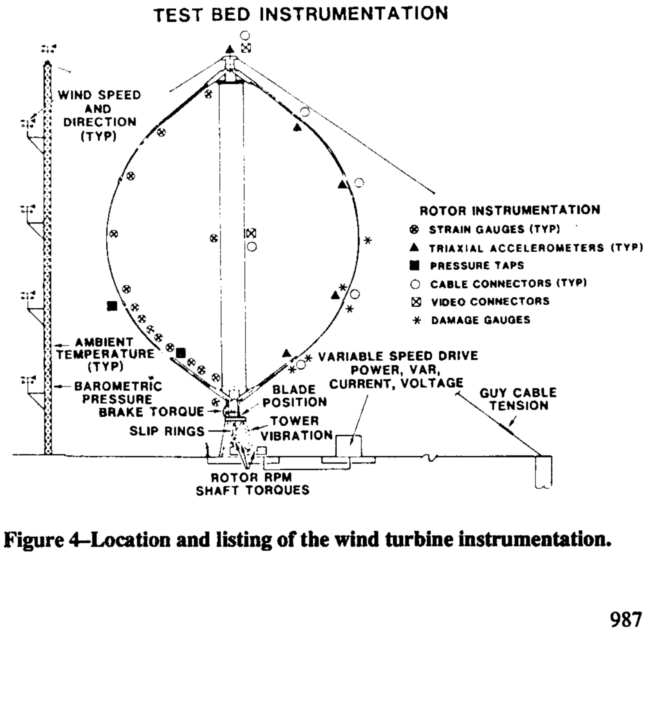

Figure 4–Location and listing of the wind turbine instrumentation.

also installed in several locations on the blades and tower to measure the axial response (fig. 4). One blade has been instrumented to investigate the detailed strain distribution, especially near the center and ends of each of the five blade sections. One blade-to-tower joint has been heavily instrumented so that the stress concentrations can be accurately determined. Gauges have also been installed on the tower to measure in-plane and out-of-plane bending (plane of the blades) and on the low speed shaft to measure torque.

Analog data from all of the rotor-mounted instrumentation are fed into a multiplexed 64-channel pulse-code modulated system and transferred through slip rings. This serial stream is passed through a fiber-optic link (for lightning protection) to the control building where it is converted back to analog form with a digital to analog converter. The analog channels of interest are routed to the appropriate data acquisition hardware; either the data acquisition and analysis system (DAAS), data logger, or turbine PLC. The data acquisition and analysis system is a minicomputer with 512 K words of high performance memory and operates as a concurrent tasking system.

Data are collected as time-series and can be stored as such or reduced by the method of bins. The method of bins is a data grouping technique where all data of a similar windspeed are grouped together for analysis. A bin width of 0.5 m/s was used. The system will simultaneously acquire, store, and reduce data from 60 channels at a rate of 50 Hz/s/channel or 30 channels at 100 Hz/s, etc. Selected time-series data can be displayed while data acquisition is in progress. All data can be collected, stored, and processed at the turbine control building.

Aerodynamic Performance

The wind turbine was first operated in a fixed-speed mode to determine the structural and performance characteristics of the machine. Since the variable speed operation was to be within the range of 26 to 40 rpm, 28, 34, and 38 rpm were chosen for the fixed speed tests. The shaft output power is shown in figure 5 for 28 and 34 rpm. The turbine started producing positive power at a windspeed slightly above 5 m/s. Peak power at 28 rpm was measured at about 14 m/s windspeed and power declined slightly in windspeeds above 14 m/s. This characteristic was encouraging because these new airfoils were designed to provide a flat power curve at high windspeeds in contrast to the continually increasing power curve for the more conventional airfoils.

When operated at 34 rpm, the turbine started producing power at almost the same windspeed and followed the same curve until a windspeed of 9 m/s. The 34 rpm power curve continued to climb and peaked at about 550 kW in a 16 m/s windspeed. The power appears to remain level at this windspeed indicating again that the rotor blades are regulating the power in high winds. Additional high windspeed data will be needed to determine the amount of power regulation.

The power curve for operation at 38 rpm is shown in figure 6. In this case, positive power is not produced until the windspeed reaches 6 m/s. Not enough high windspeed data have been collected to determine at what windspeed the peak power will occur and if aerodynamic stall will be effective. The last four data points in figure 6 show considerable scatter because they contain less than one hundred observations. Also these data show that the 500 kW rated power at 12.5 m/s windspeed was not achieved, but the 500 kW was reached at a windspeed of 14.5 m/s. Additional data have not been collected because the capacity of the generator is often exceeded.

The efficiency of the wind turbine while operating at 34 rpm is expressed in normalized form in figure 7. Coefficient of performance is calculated as measured

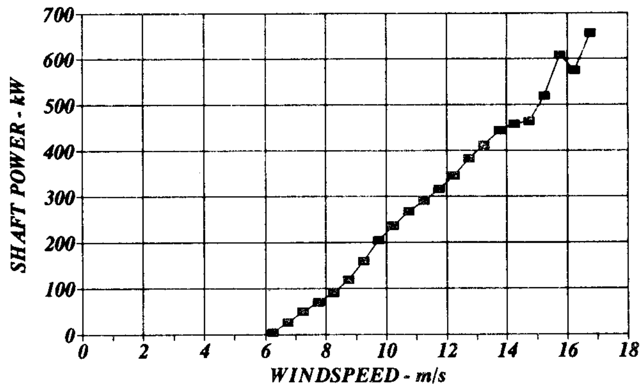

Figure 6–The aerodynamic performance of the 34-m wind turbine when operated at 38 rpm.

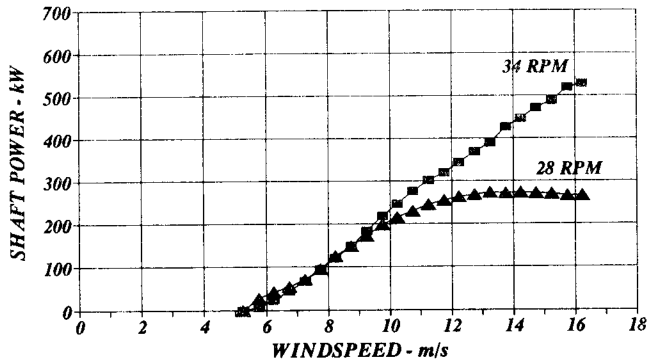

Figure 5–The aerodynamic performance of the 34-m wind turbine when operated at 28 and 34 rpm.

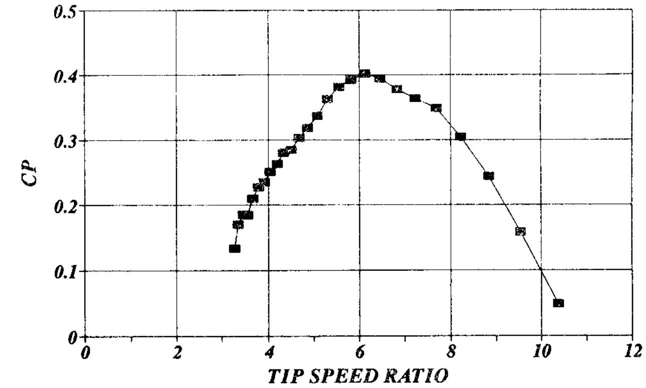

Figure 7–The efficiency or coefficient of performance (C_p) of the 34-m wind turbine as a function of the tip speed ratio.

power divided by theoretical power in the wind, and the tip speed ratio is the speed of the rotor blade at the rotor equator divided by the windspeed. The peak efficiency occurs at a tip speed ratio of 6. The measured peak performance coefficient of 0.40 is about 5% less than predicted by the simulation model. This difference is believed to be due to the unfaired blade-to-blade joints. The blade-to-blade joints have exposed bolt heads and a blunt connecting block that produces drag. Additional information on the aerodynamic performance has been reported by Berg et al. (1990).

The aerodynamic performance of these new airfoils was compared to the performance of airfoils used on an earlier vertical-axis wind turbine (Dodd, 1990). A 17-m vertical-axis wind turbine which used NACA 0015 airfoils was tested at Bushland in the early 1980s. The NACA 0015 is similar to the NACA 0021 shown in figure 2. Power per square m of swept area was determined for each turbine and compared for windspeeds between cut-in and 16 m/s as shown in figure 8. These data clearly show the improved performance of the new laminar airfoil design and the multiple section blades. The improvement is about 40% at a windspeed of 14 m/s. These data were used with a Rayleigh windspeed distribution to calculate a projected annual energy production for five annual average windspeeds (fig. 9). The measured performance of a 19-m vertical-axis wind turbine operated in the California wind farms was used to compare to the protected performance of the new turbine operating at 34 rpm and variable speed. For an

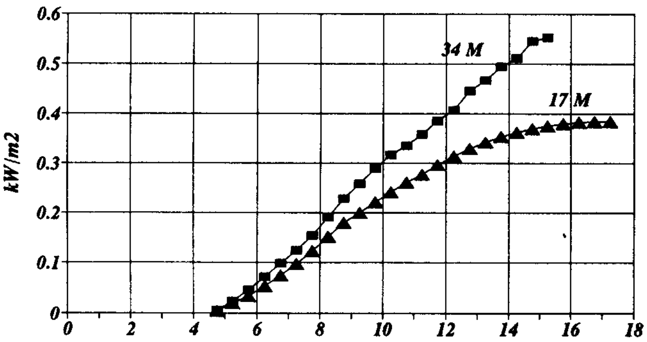

Figure 8–A comparison of the power output per unit area of a 17-m vertical-axis wind turbine and the 34-m research machine.

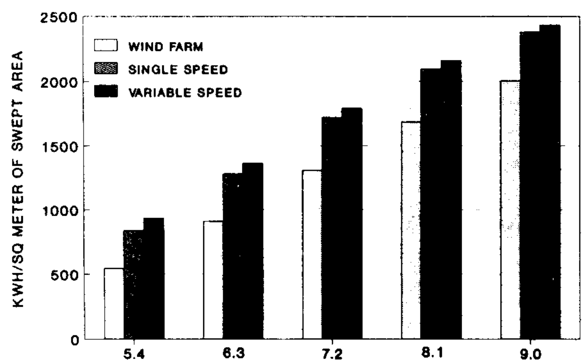

Figure 9–Annual energy capture protection for several average windspeeds for an existing 19-m wind turbine and the 34-m research machine operating at a fixed speed and variable speed.

annual windspeed average of 6.3 m/s, the new wind turbine would be expected to produce 41% more energy if operated as a single speed machine and 50% more if operated as a variable speed machine. The improvement in performance decreases as average windspeed increases; however, much of the United States has average windspeeds less than 7 m/s. This new wind turbine demonstrates that significant improvements in energy production may be expected with this improved technology.

Structural Performance

Data from the more than 70 strain gauges were used to determine gravity stresses, centrifugal stresses, and modal frequencies for comparison to predicted values. Immediately after the rotor blades were installed, blade gravity stresses were measured. The patterns of stress distribution for the measured and predicted were very similar. Stress predictions were made by using a finite element model, NASTRAN (Ashwill, 1989).

A modal analysis was performed on the completely assembled turbine by measuring the frequency response functions due to both the wind and a snap release. These measurements were used to determine the mode shapes, their frequencies of vibration, and modal damping values. The results of the modal tests are presented in Table 1 along with predictions from the finite element model. The first three flatwise modes (both antisymmetric and symmetric), the first tower in-plane and out-of-plane modes, and the second propeller mode were all predicted to within 2% of measured. The close agreement between predicted and measured frequencies for the first eleven modes is an indication that the finite element model does a good job in predicting the modes of the wind turbine.

The rotating modal frequencies are shown in figure 10. The normal operating range of 28 to 40 rpm was selected to reduce the number of modes that would be crossing the natural frequencies modes of 2P and 3P. The first blade edgewise mode crosses the three per revolution line at about 32 rpm causing significant vibrations. This mode is avoided by programing the controller to rapidly accelerate

TABLE 1. Stationary modal frequencies – brakes engaged

Mode Number	Mode Shape	Snap Release	Wind Excitation	Predicted
1	1FA - First flatwise antisymmertic	1.04	1.06	1.05
2	1FS - First flatwise symmetric	1.04	1.06	1.05
3	1Pr - First propeller rotor twist	1.35	1.52	1.56
4	1BE - First blade edgewise	1.81	1.81	1.72
5	2FA - Second flatwise antisymmetric	2.06	2.06	2.07
6	2FS - Second flatwise symmetric	2.16	2.16	2.14
7	1TI - First tower in-plane	2.49	2.50	2.46
8	1TO - First tower out-of-plane	2.60	2.61	2.58
9	3FA - Third flatwise antisymmetric	3.45	3.50	3.49
10	3FS - Third flatwise symmetric	3.45	3.50	3.51
11	2Pr - Second propeller rotor twist	3.59	3.59	3.52

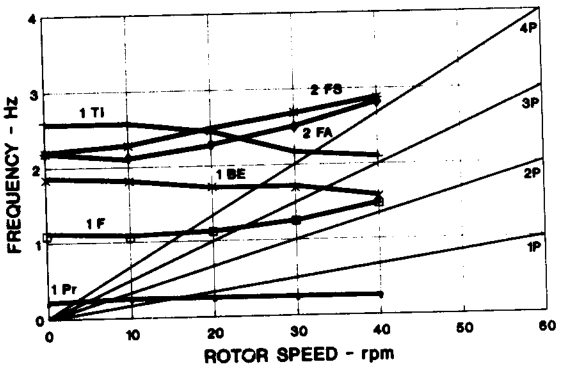

Figure 10–The rotating modal frequencies for the 34-m wind turbine. (1PR - 1st Propeller; 1F - 1st Flatwise; 1BE - 1st Blade edgewise; 2FA 2nd Flatwise antisymmetric; 2FS - 2nd Flatewise symmetric; 1TI 1st Tower in-plane).

or deaccelerate through the rpms associated with this mode. The upper limit of 40 rpm was chosen to avoid the point where the first tower in-plane mode crosses the 3P line. This crossing point can be adjusted by changing the tension in the cable tie-downs; however, cable tension changes with temperature. The first tower in-plane mode was excited at 38 rpm in cold temperatures when the cable tension was significantly higher than anticipated. Work is continuing to remove excitation of all these modes within the normal operating range.

Figure 11 shows a comparison of the measured flatwise centrifugal bending stresses at 28 rpm to those determined analytically. The stresses along the blade from top to bottom are shown along the horizontal axis. The agreement between the measured and predicted stresses is excellent. The increase of centrifugal stresses with higher rpm continues to offset the bending stresses due to gravity until the mean stresses are minimized at 37.5 rpm (the troposkien rpm).

Conclusions

After slightly more than one year of testing, the performance is encouraging because power output is significantly higher than for previous machines. When expressed as power per square meter of rotor area, this new wind turbine is producing about 40% more than the previous unit tested at Bushland, TX. The previous Bushland unit was similar to the designs currently installed in the California wind farms. Using data from the wind farm machines and a Rayleigh windspeed distribution, an annual energy production was calculated for several annual average windspeeds. At an average windspeed of 6.3 m/s, this new wind turbine was predicted to produce 41% more energy than the wind farm models. This demonstrates the improvement that was achieved with the newly designed airfoils. Incorporating the variable speed could add an additional 9% to the energy production; thus, this new vertical-axis wind turbine should produce 50% more energy than the designs currently in use. The energy production advantage of the newer design is reduced when turbines are located at a site with a higher annual average windspeed than 7 m/s.

All structural performance measurements have agreed quite well with the values predicted by the finite element model used. Both the analytical gravity and centrifugal stresses compare quite well to the measured values. Similarly, the measured modal frequencies compared quite well with the analytically predicted values. Two mode crossings occur within the operating range of the turbine and the controller has been programmed to exclude those rpms from the operating positions.

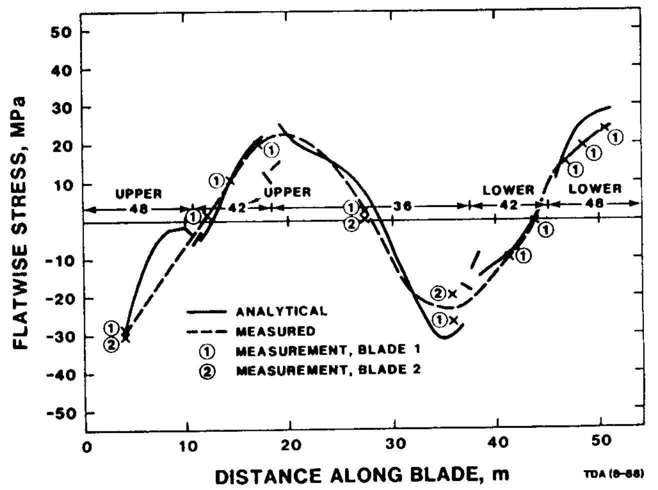

Figure 11–A comparison of the measured and predicted centrifugal stress distribution at 28 rpm.

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