NREL/TP-257-4594 • UC Category: 261 • DE92001215

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A Division of Midwest Research Institute
Operated for the U.S. Department of Energy
under Contract No. DE-AC02-83CH10093

February 1992

# Measured and Predicted Rotor Performance for the SERI Advanced Wind Turbine Blades

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## ABSTRACT

Measured and predicted rotor performance for the SERI advanced wind turbine blades were compared to assess the accuracy of predictions and to identify the sources of error affecting both predictions and measurements. An awareness of these sources of error contributes to improved prediction and measurement methods that will ultimately benefit future rotor design efforts. Propeller/vane anemometers were found to underestimate the wind speed in turbulent environments such as the San Gorgonio Pass wind farm area. Using sonic or cup anemometers, good agreement was achieved between predicted and measured power output for wind speeds up to 8 m/sec. At higher wind speeds an optimistic predicted power output and the occurrence of peak power at wind speeds lower than measurements resulted from the omission of turbulence and yaw error. In addition, accurate two-dimensional (2-D) airfoil data prior to stall and a post stall airfoil data synthesization method that reflects three-dimensional (3-D) effects were found to be essential for accurate performance prediction.

## INTRODUCTION

The SERI thin and thick airfoil blades (1) were developed to provide aerodynamic improvements over original equipment blades currently operating on more than 7000 stall-regulated horizontal-axis wind turbines (HAWTs) in the California wind farms. These improvements are:

- Restrained peak power for greater drive-train life
- Minimal peak power sensitivity to surface roughness
- Greater annual energy output
- Higher power-to-thrust ratio for lower wind farm array losses.

The 7.9-meter thin airfoil blades were designed for stall-regulated HAWTs having a generator rating of 65 to 85 kW. The 9.7-meter thick airfoil blades were designed for stall-regulated wind turbines having a generator rating of 110 to 150 kW. Both the thin and thick airfoil blades have undergone comprehensive atmospheric testing on Micon 65 and Micon 108 wind turbines, respectively, at the SeaWest San Gorgonio wind farm in Palm Springs, California throughout the 1989, 1990, and 1991 wind seasons (Figure 1). The thin airfoil blades have also been evaluated on the Bonus 65 and Nordtank 65 and show annual energy improvements of 20 to 30%. The larger thick airfoil blades have also been evaluated on the Bonus 120 and Nordtank 150, and annual energy improvements are expected to be in the 15 to 20% range. Planform drawings of these blades are shown in Figure 2.

A key objective of the SERI advanced blades test program was to compare the measured performance curves of these blades to predicted performance obtained using the PROPPC blade-element/momentum code (2). Results from this comparison measured the degree to which the advanced blades met their clean blade predicted performance objectives and provided the basis for refinements to blade airfoil design criteria. Identifying key discrepancies between the predicted and measured performance provided better insight into modelling the aerodynamic characteristics of the rotor and will lead to more accurate performance prediction. The largest contributor to the performance discrepancy was determined to be a previously unknown wind speed measurement error resulting from the use of propeller/vane anemometers in a dense wind farm environment with high turbulence. In addition, by neglecting turbulence and yawed flow effects, predicted peak rotor power occurred at a lower wind speed than that measured.

Figure 1. SEAWEST-SAN GORGONIO WIND FARM, PALM SPRINGS, CALIFORNIA

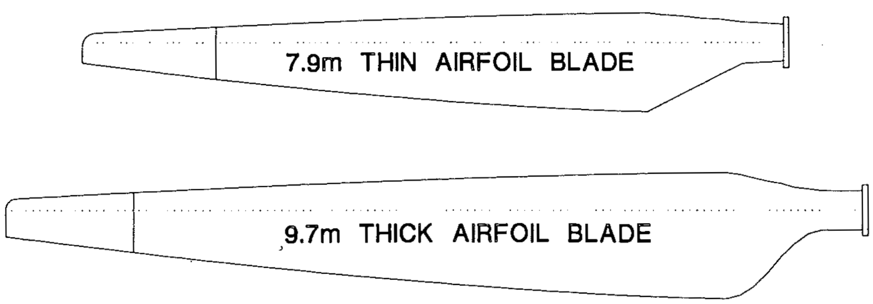


Figure 2. SERI ADVANCED WIND TURBINE BLADES

## MEASURED PERFORMANCE

Measured generator power for the thin airfoil blades, acquired during the 1989 and 1990 wind seasons, is shown in terms of kilowatts and power coefficient versus wind speed in Figure 3. Peak generator power was measured to be 67 kW at 14 m/sec. The corresponding peak generator power coefficient was calculated to be 0.57 at 6 m/sec. The abnormally high generator power coefficient puts the rotor power coefficient above the Betz limit of 0.593. The source of this error could not be adequately explained until the 1991 wind season when a similar, much larger error, was observed while testing the thick airfoil blades. Figure 4 shows the initial generator power curve measured for the thick airfoil blades. Peak generator power was measured to be 104 kW at 14 m/sec. Showing no respect for the Betz limit, the peak generator power coefficient was calculated at an unrealistic value of 0.75 at 7.5 m/sec. Calibration checks of the power transducers used for measuring the generator output for the thin and thick airfoil blades showed the transducers to be accurate.

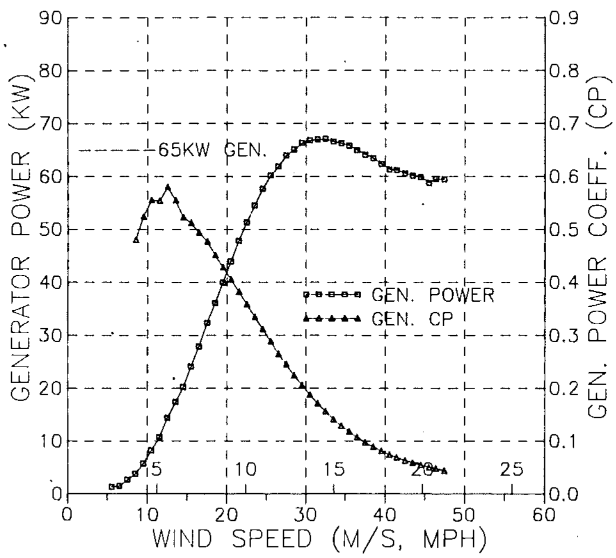


Figure 3. MICON 65/13 THIN AIRFOIL BLADE PERFORMANCE (WINDSPEED ERROR)

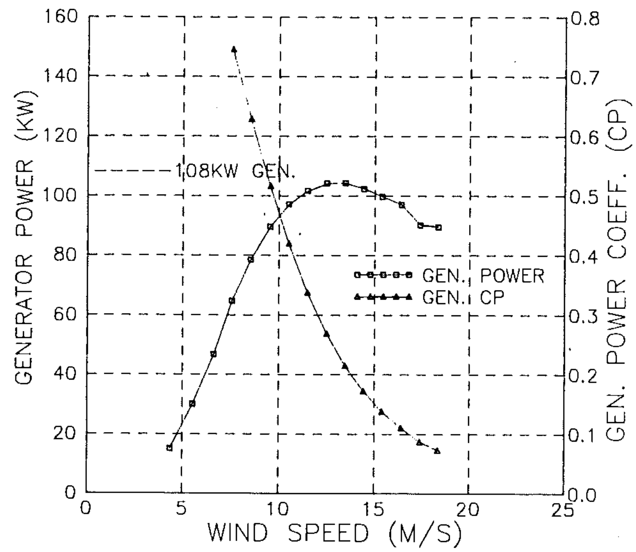


Figure 4. MICON 108 THICK AIRFOIL BLADE PERFORMANCE (WINDSPEED ERROR)

Figure 5. R.M. YOUNG PROPVANE

Figure 6. STRATAVANE PROPVANE

Further investigation uncovered a disturbing anemometer accuracy problem. During the thin airfoil blade tests wind measurements from the hub-height R. M. Young anemometer (vane damping ratio = 0.34) at the test site shown in Figure 5 recorded a regular periodic wind direction change of 30 degrees a second in the turbulent San Gorgonio Pass environment. These rapid wind direction changes did not agree with the adjacent, more accurate sonic anemometer. Rapid yawing motions of the propeller/vane anemometer frequently occurred when the sonic anemometer measured high vertical flow velocities. Wind speed measurements with the R. M. Young anemometers were often 0.7 to 0.9 m/sec (1.5 to 2 mph) lower than the sonic anemometer under turbulent but stable atmospheric conditions.

The wind speed measurement problem was worse for the lightly damped (vane damping ratio = 0.20) Stratavane anemometer used initially at the thick airfoil test site, as shown in Figure 6. The lower damping ratio is designed to provide better anemometer survivability under demanding applications, but results in greater dynamic instability. To provide more accurate wind speed measurements for the thick airfoil test, the Stratavane anemometer was replaced by a Teledyne Geotech cup anemometer to measure wind speed and a separate vane to measure wind direction. Using the cup anemometer the measured wind speed increased 1.3 to 1.8 m/sec (3 to 4 mph) for a given generator power output relative to the Stratavane propeller/vane anemometer. The higher wind speed measurements now result in realistic performance curves for the thick airfoil blade test.

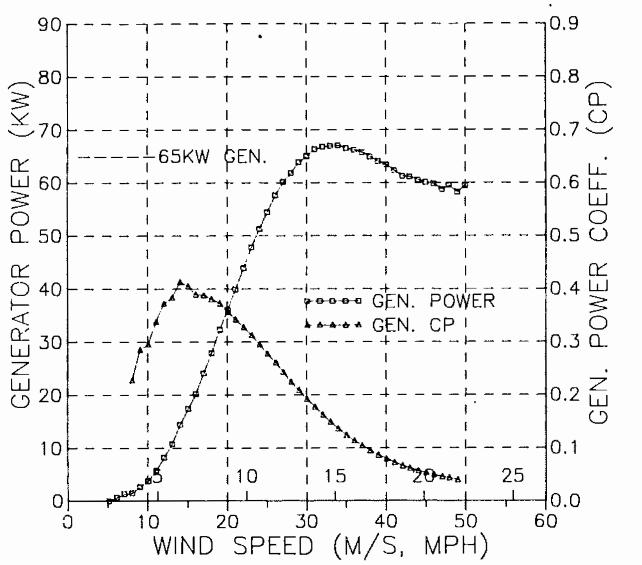


Figure 7. MICON 65/13 THIN AIRFOIL BLADE (CORRECTED PERFORMANCE)

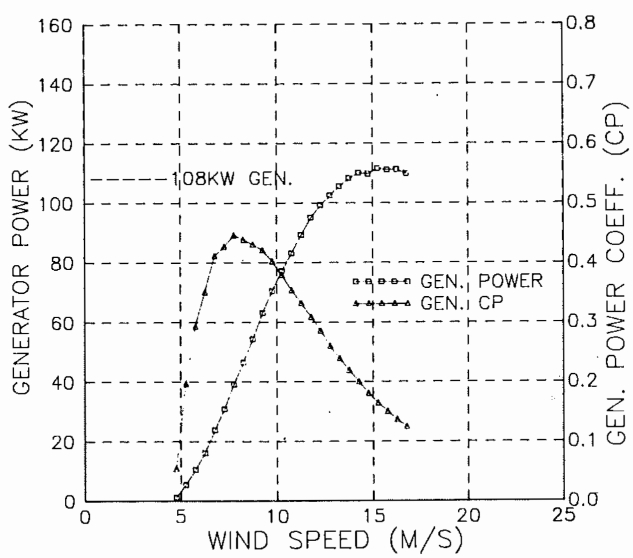


Figure 8. MICON 108 THICK AIRFOIL BLADE (CORRECTED PERFORMANCE)

To correct the thin airfoil blade power curve for the wind speed measurement error, the measured R. M. Young propvane wind speed data was corrected based on corresponding sonic anemometer horizontal wind speed measurements. The measured power was then replotted against the corrected wind speed data (Figure 7). The overall power curve shifts to the right by a wind speed increment of 0.7 m/sec (1.5 mph). The correction does not change the magnitude of the measured peak power, but does shift peak power to a slightly higher wind speed of 14.7 m/sec. The corrected generator power coefficient drops to a realistic 0.41 and also occurs at a slightly higher wind speed of 7 m/sec. A similar, but larger, correction occurs for the thick airfoil blades when the measured power is plotted versus the measured cup anemometer wind speed (Figure 8). The overall corrected power curve shifts to the right by a wind speed increment of 1.3 to 1.8 m/sec (3 to 4 mph). Peak power now occurs at a wind speed of 15.5 m/sec. (Note: The higher peak power of 116 kW results from a blade pitch change from -2.6° to -1.9°.) The corrected generator power coefficient now registers a realistic 0.44 at a higher wind speed of 7.5 m/sec.

The low wind speed measurements of the propeller/vane anemometer relative to the sonic and cup anemometers may be the result of several factors. In the highly turbulent San Gorgonio Pass environment the propeller/vane anemometers become more dynamically unstable as the damping ratio is reduced. The result of this instability is a yaw error relative to the horizontal wind vector. The yaw error by itself may be insufficient to account for the large wind speed error. Another potential factor to cause low wind speed measurements is the rotor wake swirl generated by upwind turbines. A potential bias error toward lower wind speeds is possible because the wind turbines in the park rotated in the direction opposite the propeller anemometer. With such a high concentration of wind turbines in a given area, the potential for a more global wind park swirl exists. The wind speed error was found to be greatest at night when the turbulent wind park atmospheric conditions were stable with low vertical convection. During the day the error is minimal when the wind park atmospheric conditions are generally unstable with substantial vertical convection. If the wind turbines rotated in the same direction as the anemometer, one might expect a bias error toward higher wind speeds. Further studies are needed to quantify those factors contributing to the large wind speed error associated with the propeller/vane anemometers in a wind park environment.

## PREDICTED ROTOR PERFORMANCE

Performance predictions were obtained using the PROPPC blade-element/momentum code. The assumptions used in the code differ from the actual wind turbine operating environment in several respects. The code neglects turbulence, whereas actual performance measurements were acquired in a highly turbulent environment. The code assumes the flow is always parallel to the rotor shaft axis, whereas, the control algorithm for the Micon 65 and Micon 108 HAWTS orient the machine toward the prevailing wind, but no yaw error correction is made until the machine is more than ±20 degrees off the wind axis. For the sake of simplicity, no dynamic stall model is included in this version of the code. Due to these simplifications, discrepancies can be expected to exist between the predicted power curve with uniform inflow and the measured power curve with highly turbulent inflow.

In addition to the above factors, airfoil data inputs are also a common source of error in predicted performance. Airfoil data inputs of lift coefficient ($C_l$) and drag coefficient ($C_d$) prior to peak power are typically required from an airfoil catalog of 2-D wind tunnel data. An alternate source of this data is to calculate it from an airfoil design code such as the Eppler code (3). However, this approach tends to result in steeper lift curve slopes prior to stall than actual wind tunnel data; this results in the peak power prediction occurring at slightly lower wind speeds.

Determining peak power and its associated wind speed is also dependent on an accurate simulation of the $C_{lmax}$ distribution, which accounts for Reynolds number effects from blade root to tip. In addition, delayed stall effects resulting from both the 2-D airfoil characteristics and the 3-D blade geometry effects need to be included for accurate peak power prediction. An airfoil with a low $C_{lmax}$ tends toward a soft stall that lingers for several degrees. Experimental studies by Butterfield (4), Madsen (5), and Wood (6) have shown the blade root airfoils experience 3-D induced, abnormally high $C_{lmax}$ and delayed stall, the degree of which may be dependent on the amount of blade taper and twist.

Post peak power is affected most by the exponentially increasing drag between the angle of attack range of 15 to 30 degrees. The drag in this range is largely independent of airfoil type, Reynolds number, and blade aspect ratio effects. However, above 30 degrees blade aspect ratio effects are important for using flat plate theory to determine lift and drag coefficients. This angle of attack region is important for non-twisted blades which experience high angles of attack toward the blade root.

The guidelines outlined for airfoil data inputs were used to establish the $C_l$ and $C_d$ curves for the ten stations comprising the thin-airfoil blade on the Micon 65. The airfoil data for four of these stations (r/R = 0.35, 0.55, 0.75, 0.95) are shown in Figure 9. Prior to stall, the Eppler code was used to generate the $C_l$ and $C_d$ data. Wind tunnel tests (7) of the S805 airfoil indicate the presence of a few degrees of 2-D stall delay that is simulated in the airfoil data inputs. Post stall $C_l$ data were calculated using the Viterna (8) post stall method while post stall $C_d$ values were obtained from non-rotating 3-D wind tunnel tests (9).

The comparison of predicted and measured performance for the thin airfoil blades is shown in Figure 10 for a three-quarter radius blade pitch angle of 4.2 degrees. A generator/transmission efficiency curve (10) was used to derive the rotor power curve from the measured power curve. A comparison of the predicted rotor power curve (plus symbols) to the measured rotor power curve for the same blade pitch angle shows some notable differences. Up to a wind speed of 8 m/sec, the agreement between prediction and measurements is surprisingly good. For higher wind speeds predicted results are more optimistic than

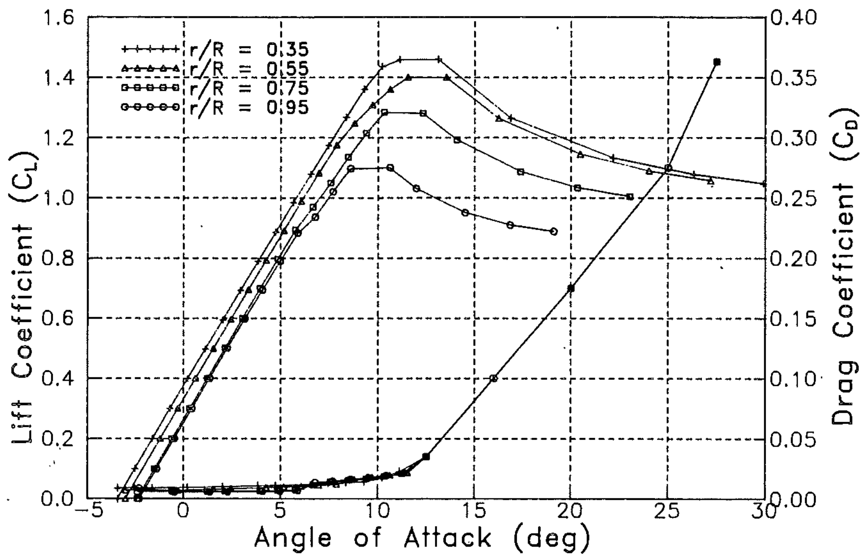


Figure 9. THIN AIRFOIL FAMILY PERFORMANCE CHARACTERISTICS (S806A TIP AIRFOIL, S805A MIDSPAN AIRFOIL, S807 ROOT AIRFOIL)

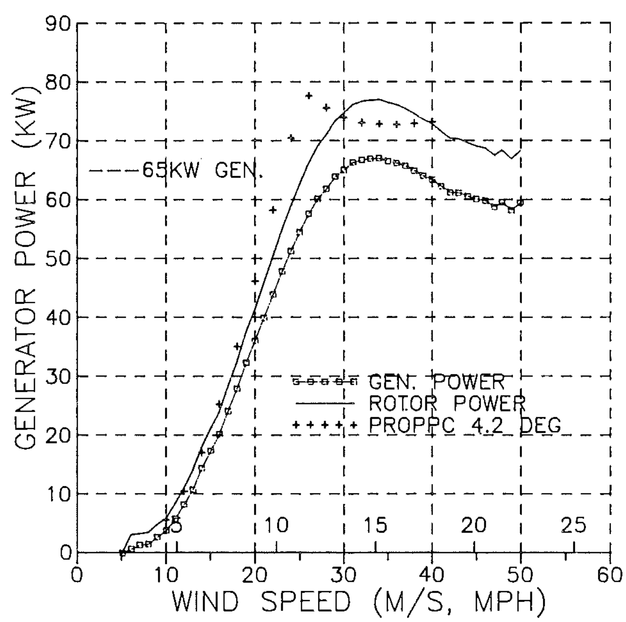


Figure 10. COMPARISON OF PREDICTED AND MEASURED ROTOR POWER FOR THE MICON 65/13 THIN AIRFOIL BLADES

measured results. Predicted and measured peak power both occur at about the same level of 77 to 78 kW. However, the predicted value occurs at about 12 m/sec versus 15 m/sec for the measured power. The discrepancy in the power curves at higher wind speeds is largely attributed to turbulence and the inability of the turbine to accurately track the high winds. Hibbs reported (11) on how these factors affect the steady state power curve. Both turbulence and yaw error were reported to shift peak power to higher wind speeds. This shift was further enhanced from the resulting dynamic stall effects. As mentioned previously, the excessively steep lift curve slopes at high angles of attack, as derived from the Eppler code, add somewhat to this discrepancy through the premature occurrence of predicted peak power.

## CONCLUSIONS

The following conclusions can be drawn from the comparison of measured and predicted performance for the SERI advanced wind turbine blades. Measured performance was affected most by the accuracy of the wind speed measurements. Propeller/vane anemometers were found to underestimate the wind speed in a wind farm having a high concentration of wind turbines and high turbulence. Sonic or cup anemometers with a wind direction vane provided more accurate wind speed measurements in this environment.

Predicted performance was strongly influenced by the accuracy of airfoil data inputs and the rotor inflow model. Peak power prediction accuracy is important for the design of wind turbine components. Peak power is dependent on an accurate spanwise $C_{lmax}$ distribution along the blade that reflects both 2-D and 3-D flow effects and the accurate simulation of stall delay. Predicted peak power, which neglects the effects of turbulence and yaw error, occurs at a lower wind speed than measured peak power under unsteady wind conditions. Post peak power is dependent on accurate values of $C_d$ for angles of attack between 15 to 30 degrees. Values of $C_d$ from 3-D finite aspect-ratio (non-rotating wing) wind tunnel tests provided reasonable predictions of post peak power for the advanced wind turbine blades.

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