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J. L. Tangler
P. K. C. Tu

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PEAK POWER AND BLADE LOADS ON STALL-REGULATED ROTORS AS INFLUENCED BY DIFFERENT AIRFOIL FAMILIES

J. L. Tangler
P. K. C. Tu

Solar Energy Research Institute
1617 Cole Blvd. Golden, Colo., 80401

ABSTRACT

At the Solar Energy Research Institute (SERI), new airfoils have been developed to help improve the performance and economics of horizontal-axis wind turbines (HAWTS). The objective of this study was to compare the performance characteristics of one of these airfoil families to other commonly used airfoil series for a typical three-bladed, stall-regulated HAWT. The traditional airfoil series chosen for comparison with SERI's new thin airfoil family were the NACA 23XXX, NACA 44XX, and NASA LS (1). The Micon 110 wind turbine was chosen because it is a typical three-bladed, stall-regulated rigid rotor system. The performance characteristics of the different airfoil series were derived analytically using the Eppler airfoil design code in the analysis mode. On a relative basis, this approach to comparing airfoils was considered more accurate than using airfoil performance characteristics based on wind-tunnel test data. After generating the performance characteristics for each airfoil series, the subsequent rotor performance and blade loads were calculated using SERI's PROPSH computer code. Resulting annual energy output, which is dependent on the wind-speed distribution, was calculated using SERI's Systems Engineering and Analysis Computer Code (SEACC). The results of the study show that fixed-wing airfoils generally result in excessive peak power for stall regulated, rigid rotors. By operating the wind turbine at a less desirable blade pitch angle, peak power can be reduced at the expense of higher mean blade loads and lower annual energy output. In contrast, the thin airfoil family was designed to reduce peak power at optimum blade pitch to minimize blade loads and maximize annual energy output.

INTRODUCTION

Several new, "special-purpose" airfoil families, designed specifically for HAWTs, have been developed through a joint venture between SERI and Airfoils Incorporated [1]. This study deals with one of these airfoil families, the "thin airfoil family". Two versions of the thin airfoil family, with only subtle differences, are available; one is for 10-meter rotors (S805A, S806A, S807, and S808) and the other is for 20-meter rotors (S805, S806, S807, and S808). This study involves the latter version, but the results are applicable to both versions.

The performance characteristics of the thin airfoil family have previously been compared to the NACA 23XXX series airfoils on a Carter 25 wind turbine [2]. In that limited comparison, the thin airfoil family was predicted to increase annual energy production by 10% for winds of 12-14 mph. Two-dimensional wind-tunnel data were used to represent the performance characteristics of the NACA 23XXX series airfoils, while data for the thin airfoil family were derived from both two-dimensional wind-tunnel tests and the Eppler airfoil code. The Alternative Energy Institute is currently preparing to verify these predictions through atmospheric testing of the thin airfoil family on a Carter 25. WestWind Industries is conducting a simultaneous atmospheric test of the thin airfoil family on a three-bladed, stall-regulated rotor.

Current industry needs are for further guidance in the use of the thin airfoil family for the developing blade-replacement market. This market consists mainly of blades for stall-regulated machines. The use of conventional fixed-wing airfoils on this type of machine has been a major contributor to their peak-power problem. Excessive peak power on stall-regulated machines has resulted in burned out generators, damaged transmissions, and high blade loads. The easiest and most common means of controlling excessive peak power is to operate the blades at a less-efficient pitch angle. The consequences of this approach are poor aerodynamic efficiency at lower wind speeds and higher thrust loads for all power levels. Other, less-desirable means of treating the peak-power problem are using oversize generators and transmissions or reducing rotor radius and RPM. These solutions lead to poor aerodynamic and electrical efficiency and increase machine cost.

The new SERI special-purpose airfoil families help control peak power by restraining the airfoil's maximum lift coefficient ($C_{l,max}$) in the tip region. As peak power is approached, the stalled blade region progresses from the root toward the outer blade. Peak power is achieved just before the tip region stalls, or as it reaches $C_{l,max}$. This approach of controlling peak power through the airfoil characteristics of the tip region allows the rotor to achieve maximum annual energy output at optimum blade pitch. Further (though not as significant) reductions of peak power are possible through reduced rotor solidity in the tip region.

To demonstrate the operational problems created by using fixed-wing airfoils on stall-regulated HAWTs, the three most popular airfoil series for rotor blades, the NACA 23XXX, NACA 44XX, and NASA LS (1), were compared to the thin airfoil family. This comparison consisted of looking at each airfoil series' effect on peak rotor power, mean thrust loads, and annual energy output. Two options were considered for acquiring the performance characteristics for each airfoil series: (1) wind-tunnel test data, and (2) analytically derived airfoil characteristics using the Eppler airfoil design code in the analysis mode. This latter option was chosen because the relative differences between airfoil series are considered to be more accurate when the airfoil characteristics are calculated analytically. In contrast, when these characteristics are obtained from wind-tunnel test results, significant bias errors can occur because data for the various airfoils typically come from different wind tunnels.

The approach used to compare the NACA 23XXX, NACA 44XX, and LS (1) series airfoils with the thin airfoil family consisted of the following steps. (The Micon 110, with its 20-meter rotor, was chosen as a representative three-bladed, rigid-hub, stall-regulated rotor.)

1. For analysis purposes, the blade was represented by ten segments that decreased in chord and thickness from blade root to tip.
2. For each blade segment, the NASA Langley smoothing/scaling airfoil code [3] was used to determine the airfoil coordinates for different thicknesses of a given airfoil series. Such a code is necessary because airfoil thickness must be scaled about the airfoil camber line rather than the chord line.
3. The resulting airfoil coordinates were then input to the Eppler code to calculate the performance characteristics of lift, drag, and moment coefficients (C_l, C_d, and C_m) along the blade as a function of the respective blade-station thickness and Reynolds number.
4. The airfoil performance characteristics were then used in the PROPSH code [4] to calculate rotor power and thrust loads as a function of wind speed.
5. The Systems Engineering and Analysis Code (SEACC, [5]) was used to account for the wind-speed distribution when calculating annual energy output as a function of the mean annual wind speed.

STALL-REGULATED, RIGID ROTORS

In designing a wind turbine, some means must be provided to limit peak rotor power as the energy in the wind increases with wind speed. Unchecked peak rotor power introduces excessive blade loads that in turn overload the transmission and generator. The consequence is short machine life that leads to lost operating revenues. The most successful means of controlling peak rotor power is to use variable-pitch blades (either full-span or partial-span). Machines such as the Hamilton Standard WTS-4, the DOE MOD-2, and the Westinghouse 600 have used this means of control. The main disadvantage of variable pitch is greater machine cost. Another means of controlling peak rotor power is to reduce the projected rotor disc area as wind speed increases by yawing the rotor out of the wind or by variable blade coning. Examples of machines that control peak power by yawing are the Jacobs 8-10 KVA and Berger Excel; machines such as the Carter 25 and Carter 300 rely on large coning angles to limit peak power.

The most common, although not the most successful, means of controlling peak power is through the progressive stall of the rotor blade, from root to tip, with increasing wind speed. Most foreign machines operating in California wind farms fall in this category of stall-regulated, rigid rotors. This approach largely depends on the airfoil's stall characteristics to effectively control peak power. The high $C_{l,max}$ of aircraft airfoils, which are currently used on wind turbines, produces excessive peak rotor power. In addition, the $C_{l,max}$ of aircraft airfoils, with the exception of the NASA LS (1) series, is sensitive to roughness effects. This sensitivity adversely affects energy yield and blade loads. These performance characteristics of aircraft airfoils are incompatible with the wind turbine's need to extract maximum energy from the wind at low to medium wind speeds while providing a restrained peak power that is largely insensitive to roughness effects at high wind speeds.

The Micon 110

The Micon 110 wind turbine was selected to demonstrate the operational problems encountered when using aircraft airfoils on a stall-regulated HAWT. The general results for this example should be applicable to other rigid-hub, stall-regulated machines such as the Enertech 44 and Bonus 20/120, along with teetered-hub machines such as the ESI 54 and ESI 90. The Micon 110 (Figure 1) has a three-bladed, stall-regulated, upwind rotor with a diameter of 62 feet that operates at 44 rpm. The rotor is mounted on a 72-foot tower with its axis of rotation tilted up 4° for tower clearance. Rotor power is absorbed by an asynchronous, three-phase electric generator rated at 108 kW. The geometric characteristics of the Aerostar 9-meter blades are shown in Figure 2. The blade uses a NACA 4425 airfoil toward the root that tapers nonlinearly to a NACA 4412 at the blade tip. The fiberglass/polyester blade has a movable tip section that is centrifugally activated for overspeed control.

CALCULATED AIRFOIL CHARACTERISTICS

Airfoil performance characteristics were required for the four airfoil series as a function of the airfoil thickness and Reynolds number that characterize the 9-meter Aerostar blade from root to tip. These characteristics were calculated using the Eppler airfoil design code [6] in the analysis mode. Prior to applying the Eppler code, airfoils for each series were established at three thicknesses to approximate that of the blade. To preserve the camber of a given airfoil series, the thickness change must be made

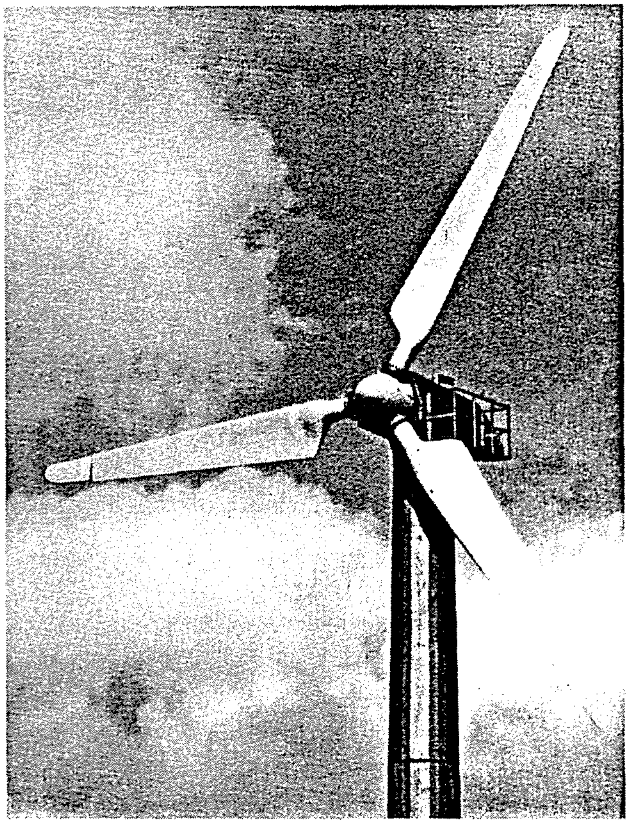

Figure 1. Micon 110 Wind Turbine

about the airfoil camber line rather than the chord line. The NASA Langley smoothing/scaling airfoil code provides the capability to vary the thickness of a given airfoil about its camber line. Four airfoil series, each comprised of three thicknesses, resulted in twelve airfoils for analysis in the Eppler code. Although the blade, characterized by 10 segments for analysis in the PROPSH code, was only approximated by three thicknesses, the proper Reynolds number for each blade segment was used for calculating airfoil performance characteristics. A comparison of the airfoil characteristics, calculated with the Eppler code for the four airfoil series, is shown in Figure 3 for blade stations of 95%, 75%, and 35% radius. At the 95% radial station, the distinguishing difference between the S806 and the other airfoils is its low minimum drag and $C_{l,max}$. The low minimum drag enhances energy output at low to medium wind speeds; the low $C_{l,max}$ helps restrain peak power. At the 75% radial station, the S805 still provides, but to a lesser degree, low minimum drag and $C_{l,max}$. Moving inboard from this station to the S807 at 35% radius shows a continuous increase in $C_{l,max}$. High $C_{l,max}$ toward the root enhances energy output at low to medium wind speeds, as does the low minimum drag toward the blade tip. The S807 provides a high $C_{l,max}$, which is relatively insensitive to roughness effects, toward the root. The NASA LS(1)-421 and NACA 4421 also provide a high $C_{l,max}$, with the latter lacking any roughness insensitivity.

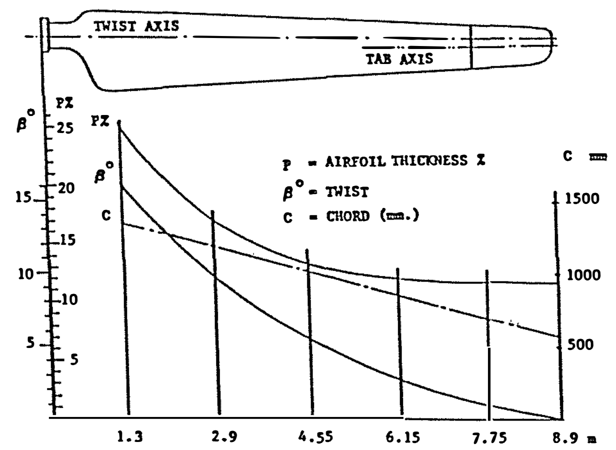

Figure 2. Blade Thickness, Twist, and Chord Distribution for the Aerostar 9-meter Blade

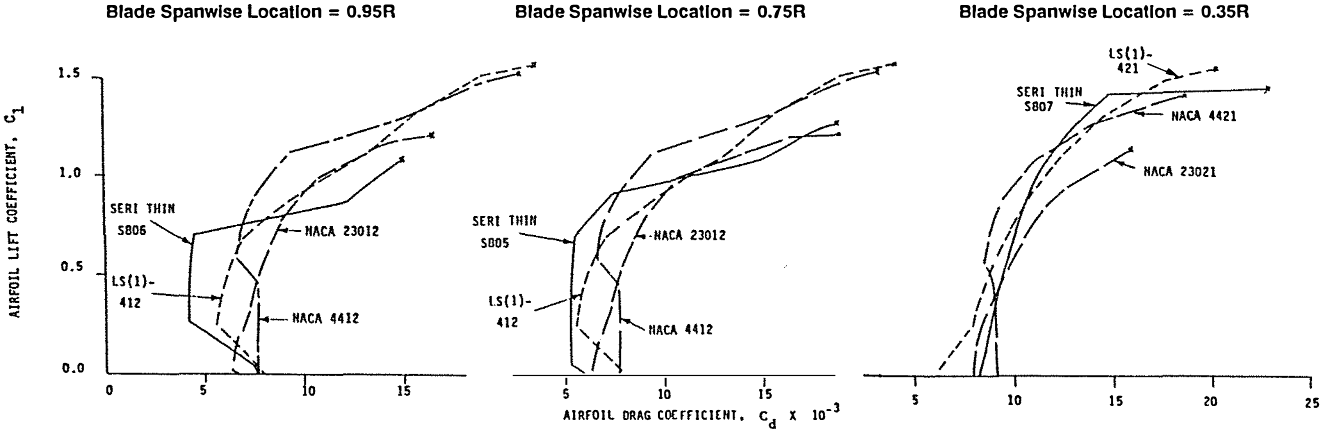

Figure 3. Lift and Drag Polars of the Airfoil Families

The airfoil characteristics shown for the three blade stations were calculated as a function of angle of attack up to stall. Airfoil stall was assumed to occur when the upper airfoil surface trailing edge separation was calculated to be 10% or greater. The $C_{l,max}$ associated with this amount of separation has been found to agree reasonably well with wind-tunnel measured $C_{l,max}$.

ROTOR PERFORMANCE COMPARISON

Rotor performance was calculated using the "PROPSH" computer code. Airfoil performance characteristics, as calculated in the Eppler code; were input at each of the 10 equally spaced blade stations for angles of attack up to 15°. When $C_{l,max}$ for a given airfoil station was reached before an angle of attack of 15°, that value of C_l was retained up to 15°. For angles of attack greater than 15°, the Viterna [7] poststall synthesization method was used to calculate the airfoil characteristics. Although this poststall approach is based on an empirical fit to limited experimental data, it has been shown to provide better peak and postpeak power predictions than did two-dimensional poststall airfoil data and was therefore applied consistently to all four airfoil series for lack of a better method. Using the PROPSH code, both rotor performance and blade element data comparisons were conducted to illustrate the relative merit of the thin airfoil family over the other airfoil series. The SEACC computer code couples the rotor performance curve, as calculated by PROPSH, with a Rayleigh wind-speed distribution for calculating annual energy output as a function of mean annual wind speed. Optimum blade pitch for the various airfoil series is treated in this study as that pitch that provides the greatest annual energy output for a wind site with a mean annual wind speed of 13 mph.

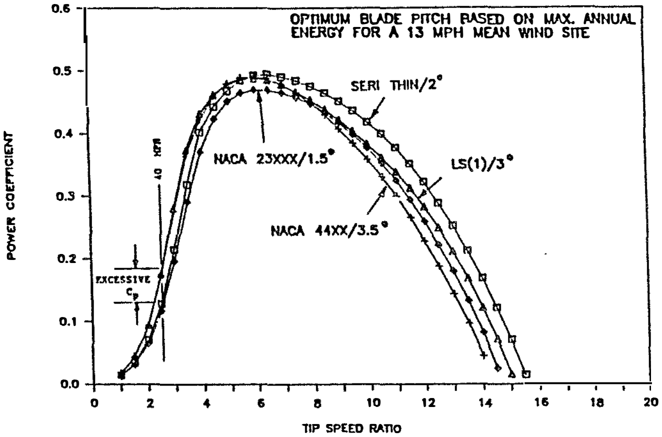

Figure 4. Micon 110 Power Coefficient versus Tip Speed Ratio

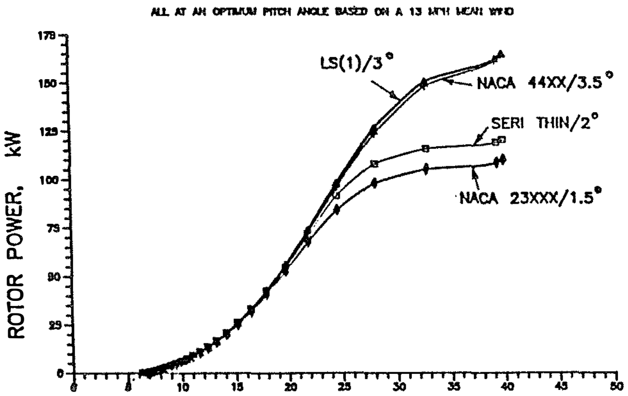

Figure 5. Micon 110 Rotor Power Comparison

The Problem of Peak Power

The most common type of wind turbine used in California wind farms is the three-bladed, fixed-pitch, rigid-hub, stall-regulated HAWT. These machines are largely dependent on the blade's airfoil characteristics in the tip region for regulating peak power. Peak power is proportional to the airfoil's $C_{l,max}$ over this portion of the blade. For reasons specific to the technology, aircraft airfoils were designed to have a high $C_{l,max}$. Unfortunately, when these airfoils are used over the outboard portion of a stall-regulated HAWT blade, the result is excessive peak power. Figures 4 and 5 illustrate how the airfoil characteristics of the four airfoil series affect power. In these two figures, the NACA 44XX, NACA 23XXX, NASA LS (1), and thin airfoil series are all operated at an optimum blade pitch for generating the maximum annual energy at a site with a 13-mph mean annual wind speed. At medium to high tip-speed ratios (low to medium wind speeds), the thin airfoil family has the greatest aerodynamic efficiency and the NACA 23XXX series has the lowest. At low tip-speed ratios (high wind speed), low aerodynamic efficiency is needed for stall regulation of peak power. For the Micon 110, peak power well over 120 kW at 40 mph will eventually result in generator or transmission damage. With a 90% power-train efficiency, 120 kW at the rotor results in a rated generator output of 108 kW. The NACA 44XX series airfoils, currently used on this machine, can generate 160 kW at 40 mph with the blades set at optimum pitch. Similar results are seen for the NASA LS (1) series airfoils. The thin airfoil family restrains peak power to 120 kW at 40 mph for optimum blade pitch. The calculations show both the NACA 44XX and NASA LS (1) series airfoils to generate 30% too much power at optimum blade pitch. The low peak power of the NACA 23XXX is suspect since analytical airfoil codes are known to significantly underpredict this airfoil's $C_{l,max}$. Future use of the NACA 23XXX series on wind turbines is unlikely because of the sensitivity of this airfoil's $C_{l,max}$ to roughness effects and its greater deterioration in performance with increased airfoil thickness. Because of these factors, the NACA 23XXX series is omitted from subsequent comparisons in this paper.

The Solution with Blade Pitch

The common solution for controlling peak power on stall-regulated rotors is to operate the blades several degrees off optimum pitch, toward stall. Figures 6 and 7 illustrate how this approach alters the power curve. In Figure 6, the power coefficient curves for the Micon 110 operating with the NACA 44XX series airfoils are shown for an optimum blade pitch of 3.5° versus a non-optimum blade pitch of -0.7°. The non-optimum pitch angle was chosen to reduce the rotor peak power at 40 mph from 160 kW to 120 kW. The curves show that non-optimum blade pitch operation controls peak power at the expense of low aerodynamic efficiency at low to medium wind speeds. In contrast, the thin airfoil family operating at optimum pitch limits peak rotor power to 120 kW at 40 mph while it provides high aerodynamic efficiency at low to medium wind speeds. These results are illustrated in Figure 7. Because the NACA 44XX airfoil is forced to operate off optimum pitch to control peak power, the thin airfoil family generates 18% more power at 15 mph. Also, the thin airfoil family at optimum pitch can be expected to provide a lower cut-in wind speed.

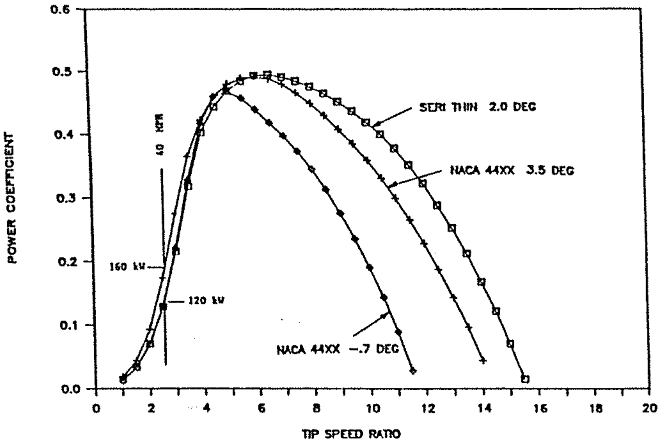

Figure 6. SERI Thin Airfoil versus the NACA 44XX Airfoil, Micon 110 Non-Dimensional Performance

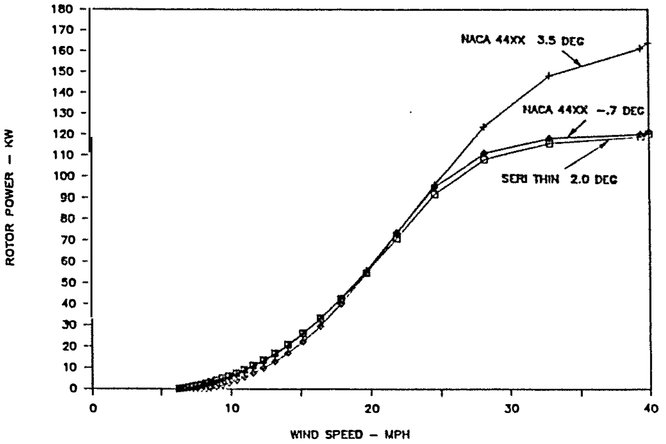

Figure 7. SERI Thin Airfoil versus NACA 44XX Airfoil, Micon 110 Dimensional Performance

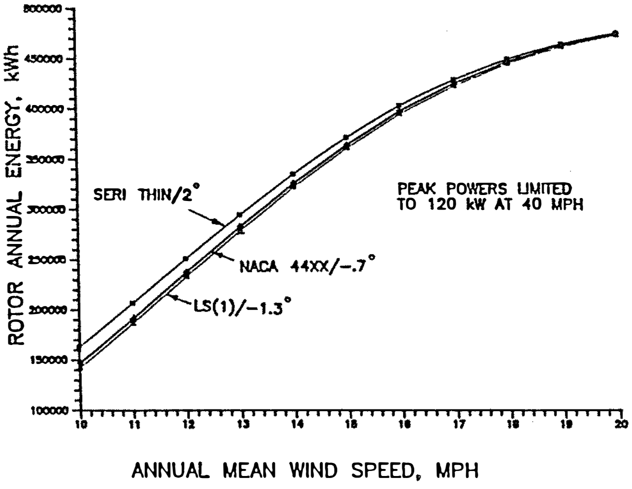

Figure 8. Influence of Airfoil Family on Annual Energy Output

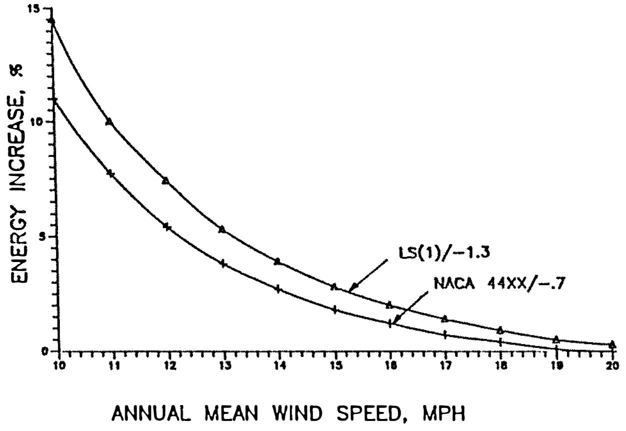

Figure 9. Thin Airfoil Family Energy Improvement

The influence of the various airfoil series on annual energy output as a function of mean annual wind speed is shown in Figure 8. Again, this comparison is with peak rotor power limited to 120 kW at 40 mph. For sites with mean annual wind speeds of up to 20 mph, the thin airfoil family produces higher annual energy output than the other airfoil series. The percentage improvements are shown in Figure 9. For a wind site with a 13-mph mean annual wind speed, the thin airfoil family shows a gain of 4%-5% over the NACA 44XX and NASA LS (1) series airfoils. A larger gain is shown relative to the NASA LS(1) series because it is forced to operate further from optimum blade pitch to restrain peak power due to its higher $C_{l,max}$ in the tip region. The energy gains shown are based on using the Aerostar blade chord and twist distribution. Further improvement in energy output and peak power control can probably be achieved by optimizing these parameters.

The Problem of Blade Loads

Potentially more important than the lost energy associated with non-optimum blade pitch operation are the resulting greater blade loads at a given power output. By limiting peak power through operating at non-optimum blade pitch, a blade-load problem arises. At a given power output, the thin airfoil family has lower blade thrust loads than do the NACA 44XX and NASA LS (1) series airfoils. This difference is shown in Figure 10 for a rotor power of 60 kW. For this case, the resulting thrust load is 20% lower. Figure 11 shows the resulting blade root bending moment as a function of wind speed for the different airfoils. Throughout the wind-speed range, the thin airfoil family at optimum blade pitch has a substantially lower bending moment. At peak rotor power, this reduction is in the range of 15% to 20%.

As shown, the natural consequences of operating a rotor at non-optimum blade pitch for a given power output are higher thrust loads. When non-optimum blade pitch is used to provide early stall for peak power regulation, the airfoil's force vector rotates downwind (Figure 12) to decrease the torque component and increase the thrust component. A larger percentage of the energy being extracted from the wind goes into destructive blade and machine loads rather than useful electrical power. Another undesirable consequence is that this energy ultimately results in a stronger rotor wake for a given electrical output. Rotor wake-induced effects can be up to 50% greater at the rotor disk. In a wind farm, a compounding energy loss can be expected from the first to last row of wind turbines as each row extracts more energy from the wind than is needed to generate the electrical output. Likewise, less available energy in the wind and greater wake-induced turbulence can be expected for each succeeding row relative to a wind farm where all the turbines are operated at optimum blade pitch.

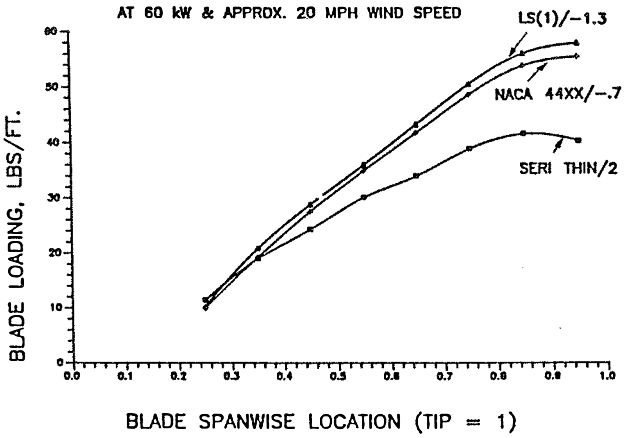

Figure 10. Micon 110 Blade Load Comparison

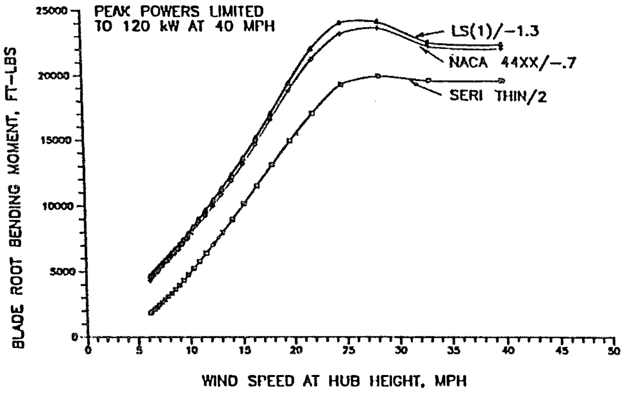

Figure 11. Micon 110 Blade Root Bending Moment

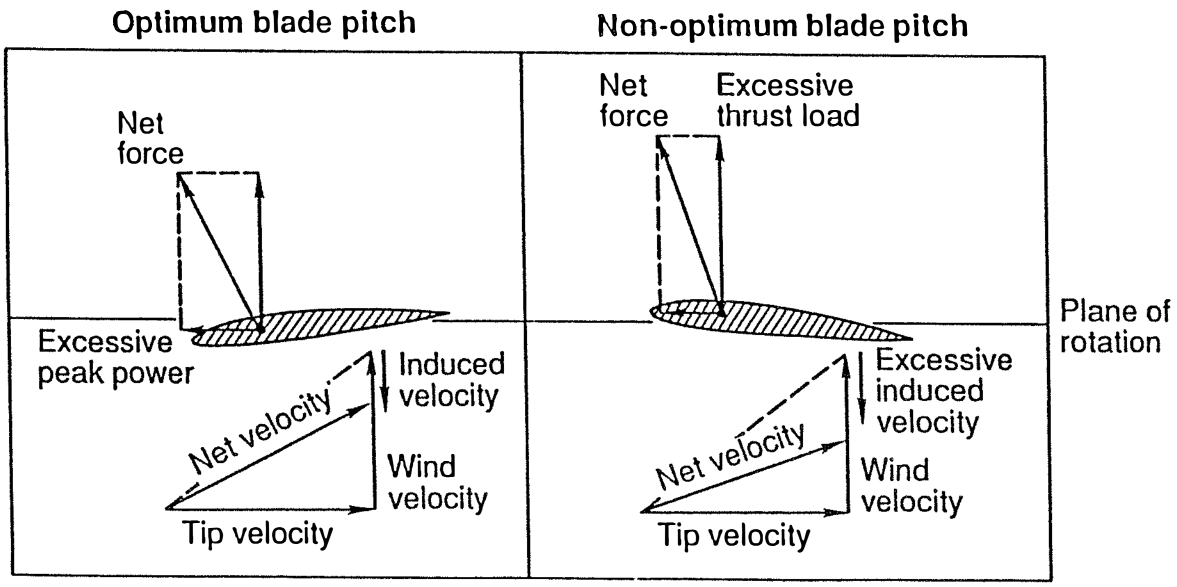

Figure 12. Replacing the Peak-Power Problem with a Blade-Load Problem

CONCLUSIONS

Most HAWTs in the California wind farms have fixed-pitch, stall-regulated, three-bladed rotors. Using conventional aircraft airfoils over the outboard portion of the blade on this type of machine generally results in excessive peak power in high winds. The common means of controlling peak power is to set the blade pitch several degrees from optimum, toward stall. This approach controls peak power at the expense of greater thrust loads and lower aerodynamic efficiency for a given power output. Lower aerodynamic efficiency leads to lost overall electrical output from the machine, while greater thrust loads lead to higher rotor-induced flow, which contributes to energy losses in the wind farm array.

SERI's solution to the problem of excessive peak power is a new class of airfoils for stall-regulated wind turbines. In contrast to current aircraft airfoils, these airfoils possess the following characteristics:

- Restrained $C_{l,max}$ over the outboard portion of the blade to reduce peak power.
- A maximum lift/drag ratio shifted to lower values of lift coefficient toward the blade tip as compared to typical aircraft airfoils.
- The ability to operate at optimum blade pitch for increased annual energy at low to medium wind speeds.
- Ability to provide lower mean blade loads for a given power output.

To complement the tip airfoil characteristics, the root airfoils are designed for the opposite end of the spectrum, with a high $C_{l,max}$ and the maximum lift/drag ratio occurring at a high C_l. In addition, the airfoil family is designed to provide a peak power largely independent of airfoil roughness effects.

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