ADVANCED AIRFOILS FOR HAWTS

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ABSTRACT

A joint research effort involving SERI and Airfoils Incorporated is devoted to performance enhancement of horizontal axis wind turbines through the development of special purpose airfoils. The objective of this effort is to develop airfoil families, for different rotor sizes, that enhance annual energy output at low-to-medium wind speeds and provide more consistent operating characteristics at high wind speeds. Performance enhancement is achieved through the use of laminar flow, while more consistent rotor operating characteristics at high wind speeds are achieved by tailoring the airfoils such that the C_{Lmax} is independent of roughness effects. Using the Eppler airfoil design code, the first of these airfoil families has been designed for a fixed pitch class of machines having a 10 to 20 m rotor and constant rpm. Based on analytical predictions, the three airfoil family, which consists of a root, outboard, and tip airfoil, shows an annual energy increase of 8% to 10% relative to the NACA 23XXX series airfoils at a mean annual wind speed of 12 mph. Currently, a similar, second airfoil family having greater thickness is being designed for machines having a 20 to 30 m rotor. Both two-dimensional wind-tunnel tests and industry cooperative atmospheric tests are being planned and conducted to verify the performance characteristics of these two airfoil families.

INTRODUCTION

In the effort to reduce the cost of energy, various means of enhancing the aerodynamic performance of horizontal axis wind turbines have been proposed and tested. Performance augmentation devices attached to the blades such as dynamic inducers and detached, stationary augmentors such as concentrators and diffusers have shown substantial power output gains. However, when compared to conventional rotors of increased size for comparable power output, their relative cost and reliability are questionable. At the Wind Energy Research Center (WERC), performance enhancement is being pursued through the development of special purpose airfoils, in which performance gains and increased machine reliability are believed possible without impacting machine cost.

Airfoils currently used on horizontal axis wind turbines vary from cambered plates, to well-known airfoils of the NACA 44XX and 23XXX series, to recently designed, special purpose general aviation airfoils such as the LS(1)-0417 Mod. Early airfoil design, during the 1930s, used an empirical design approach to develop the NACA 44XX and 23XXX series airfoils. Over the years, airfoil design theory has progressed to where new airfoils can be designed analytically as was done for the LS(1)-0417 Mod. airfoil [1], which is currently used on such wind machines as the Carter 250 and EST 80/200. Validated analytical design codes such as the Eppler code [2] allow airfoils to be tailored for specific applications.

Although wind turbines have predominately used airfoils designed for aircraft, they have recently been recognized to have a unique design requirement not shared by the aircraft industry. Aircraft designers generally strive for airfoils having both high L/D and C_{Lmax}. For wind turbines it is also desirable to use airfoils having high L/D ratios. However, particularly for fixed pitch horizontal axis machines operating at wind sites having annual average wind speeds of 10 to 14 mph, high C_{Lmax} is desired only on the inboard portion of the blade. Over the outboard portion of the blade, C_{Lmax} should be restrained to help limit peak power and cyclic loads at high wind speeds. This requirement for high L/D and limited C_{Lmax} is somewhat incompatible but achievable using current airfoil design techniques. A recent design effort to meet these needs is reported in Ref. 3. Here a series of airfoils differing in thickness were designed specifically for horizontal axis wind turbines.

At the Wind Energy Research Center, a parallel design effort has been under way to satisfy the unique airfoil design requirements for horizontal axis wind turbines. Airfoils Incorporated, under contract to SERI, has been involved in the design of two special purpose airfoil families for wind turbines of 10 to 30 m in diameter. The first of these airfoil families was designed for high L/D with C_{Lmax} restrained over the outer portion of the blade. This family was designed for rotors 10 to 20 m in diameter that can utilize thin airfoil sections on the outboard portion of the blade. The second family,

currently being designed, is similar to the first but is being optimized for greater airfoil thickness and Reynolds number. This latter design effort is for rotors 20 to 30 m in diameter that require thick airfoil sections over the outboard portion of the blade. Thick airfoils and high L/D are somewhat incompatible and present a greater design challenge than the thin airfoil family. Both the thin and thick special purpose airfoil families will be tested two-dimensionally and through cooperative atmospheric tests with industry to verify their predicted performance characteristics.

AIRFOIL DESIGN

For horizontal axis wind turbines, performance enhancement can be achieved with airfoils designed to be more machine specific in terms of Reynolds number, rotor solidity, annual average wind speed, and machine operational mode. For low solidity rotors, better performance is achieved when L/D_{max} occurs at medium-to-high values of C_L, while for high solidity rotors lower values of C_L are desired for L/D_{max}. In a similar manner, the higher the annual average wind speed for which the rotor is being designed the more desirable it is to shift L/D_{max} to higher values of C_L. Machine operational modes such as fixed blade pitch versus variable blade pitch and constant rpm versus variable rpm also influence the airfoil design. For fixed pitch machine operation, manufacturers have expressed the need for airfoils having a predictable C_{Lmax} insensitive to airfoil roughness effects. This quality provides for more consistent peak power output and helps eliminate unexpected operating characteristics that may be detrimental to rotor life. For variable pitch machines, this requirement can be relaxed since the blades can be feathered to avoid stall during high winds. In the case of variable rpm machines, the influence of Reynolds number may be a concern over the machines' operational range.

The question arises as to the C_L range over which high L/D is to occur for maximum energy output. To answer this question, a C_L versus C_D airfoil polar was modified to simulate three hypothetical cases, as shown in Figure 1. For these cases, a laminar flow bucket was assumed to exist between the C_L values of 0.0 and 0.4, 0.4 and 0.8, and 0.8 and 1.2, respectively. Using a low solidity, 10-m-diameter, two-bladed twisted rotor, performance was calculated for the three cases. The resulting power coefficient versus tip speed ratio curves are shown in Figure 2. For case 1, the laminar flow bucket at low C_L resulted in some performance improvement at high tip speed ratios (low wind speeds) but contributes little to increased annual energy output. For case 2, a substantial increase in performance is achieved at medium to high tip speed ratios; whereas case 3 resulted in substantial performance improvement at low tip speed ratios (high wind speed). Based on this comparison, a laminar bucket over the C_L range of 0.4 to 0.8 showed the greatest potential for enhancing annual energy output. A design point within the bucket (C_L = 0.7) was chosen as the valve for which L/D was to be maximized. In addition to the bucket placement, it was also discovered that C_{Lmax} on the outboard portion of the blade had to be restrained to help reduce excessive power output at high wind speeds. This restraint also helps hold down the airfoil moment coefficient, which can contribute to high control loads or elastic twist during stall.

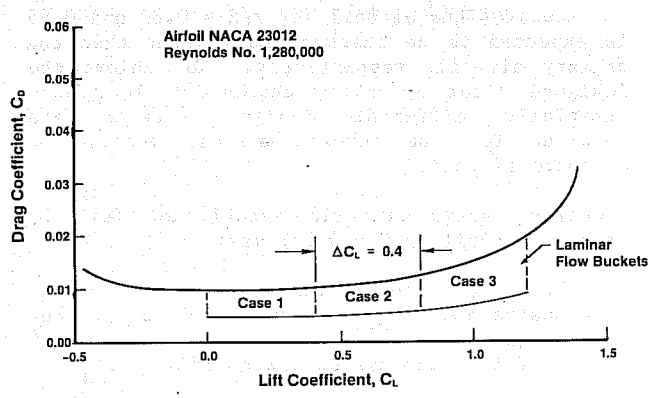

Figure 1. Laminar Flow Bucket Location Simulation

Acknowledging the general airfoil design dependency on rotor solidity, annual average wind speed, and machine operational mode, the first family of special purpose airfoils was directed toward a class of wind turbines having the following properties:

- o Fixed pitch, 10 to 20 m rotor diameter
- o Low solidity rotor with twist and taper
- o Annual average wind speed of 5 to 7 m/s.

The airfoil family consists of three airfoils. The primary airfoil is designed for a radial station of r/R = 0.75, while secondary airfoils are designed for r/R = 0.30 and 0.95. The

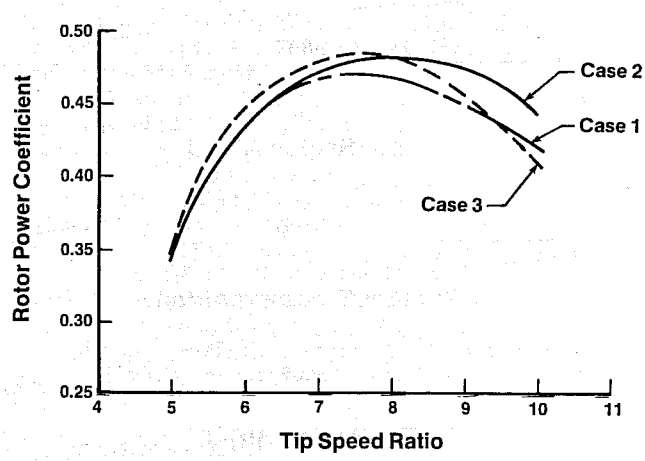

Figure 2. Effect of Laminar Flow Bucket on Rotor Performance

thickness of the airfoil for r/R = 0.30 and 0.95 is expected to be thicker and thinner than the primary airfoil, respectively. To achieve the designed rotor operating characteristics, substantially different design criteria are required for the inboard airfoil versus the outboard airfoil.

Specific design criteria established for the primary airfoil (r/R = 0.75) are:

- o High L/D through laminar flow
- o Restrained C_{Lmax} insensitive to surface roughness
- o Airfoil thickness of 12% to 15%.

Following the design completion and two-dimensional wind tunnel testing of the first airfoil family, the design of a second family of special purpose airfoils was undertaken and is currently in progress. This family is similar to the first family but differs in two respects. The second family is being designed for rotors having a 20 to 30 m diameter due to the predominance of this size in the windfarm business. To accommodate the greater structural needs of larger machines and the use of hollow wood blades, the airfoil thickness of the primary airfoil is increased to 21% at the expense of some loss in L/D. Airfoils having a thickness much over 15% incur some performance penalty.

THIN AIRFOIL FAMILY

Figure 3 shows the thin family of special purpose airfoils. The family consists of a primary airfoil designed for the 75% radial position. Secondary airfoils, designed to complement the primary airfoil, are located inboard and outboard at radial stations of 30% and 95%.

Geometrically, the primary airfoil is characterized by a rather sharp leading edge with little forward camber (i.e., no leading edge droop).

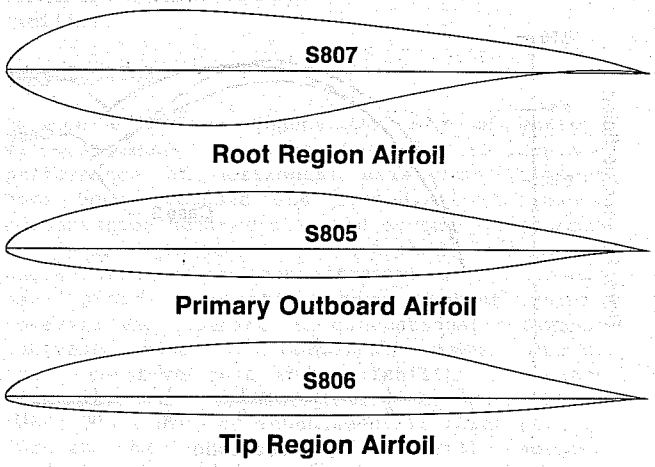

Figure 3. Thin Airfoil Family

Table 1. Design Parameters - Thin Airfoil Family

Airfoil	r/R	Reynolds No.	t/c	$C_{L\,max}$	$C_{D\,min}$	C_{Mo}
S807	0.30	0.4×10^6	0.180	1.4	0.012	-0.11
S805	0.75	1.0×10^6	0.135	1.2	0.006	-0.05
S806	0.95	1.3×10^6	0.115	1.3	0.005	-0.05

Leading edge droop, characteristic of the NACA 23XXX series airfoil family, increases the C_{Lmax} and its sensitivity to roughness effects--a quality undesirable for wind turbines. The primary airfoil achieves low minimum drag with a moderate amount of laminar flow on the upper surface and extensive laminar flow on the lower surface. To restrain the C_{Lmax} and the airfoil's pitching moment, the trailing edge camber is held to a minimum.

The inboard and outboard secondary airfoils are optimized for their respective radial positions. The outboard airfoil is thinner than the primary airfoil to provide a lower C_{Dmin} and is designed for L/D_{max} to occur at a lower value of C_L. The inboard airfoil has greater thickness for structural purposes and substantial aft camber for high C_{Lmax}. Although C_{Lmax} needs to be restrained outboard to help limit peak power at high wind speeds, any restraint on C_{Lmax} inboard at low wind speeds will neutralize the performance gained from the high L/D airfoils outboard. Consequently, the inboard portion of the blade should have a high C_{Lmax} that drops off in a continuous manner to a low C_{Lmax} toward the tip.

A summary of key parameters associated with the thin airfoil family is given in Table 1. The family results in a linear thickness reduction from 18% at the root to 11.5% at the tip. For both outboard airfoils (S805, S806), the C_{Lmax} is restrained to less than 1.3 without adversely affecting L/D_{max}. The inboard airfoil (S807) was designed for high C_{Lmax}. A value of 1.4 is very respectable considering the airfoil's low design Reynolds number and high thickness, both of which work against C_{Lmax}. For the two out-board airfoils, the laminar flow results in a low minimum drag coefficient. For the thick inboard section, which possesses little laminar flow, the minimum drag coefficient of 0.012 is about twice that of the outboard sections. Similarly, the aft camber of the inboard section results in a moment coefficient twice that of the outboard sections.

A comparison of the primary airfoil's measured performance characteristics relative to several other commonly used HAWT airfoils is shown in Table 2. The S805 is seen to have the lowest C_{Lmax} and C_{Dmin} and a moderate moment coefficient. At the design C_L of 0.7, chosen to yield a high annual energy for wind sites having mean annual wind speed in the 10 to 14 mph range, the S805 exhibits the highest L/D for the design Reynolds numbers of 1,000,000. Further improve-

Table 2. Comparison of S805 with Other HAWT Airfoils

Airfoil	t/c	$C_{L\,max}$	$C_{D\,min}$	C_{Mo}	L/D @ $C_L = 0.7$
S805	0.135	1.2*	0.007	-0.05	90
NACA 4415	0.150	1.4	0.009	-0.08	85
NACA 23012	0.120	1.3	0.009	-0.01	70
LS (1)-0413MOD	0.130	1.5*	0.008	-0.10	86

*Insensitive to roughness

ment in L/D relative to the other airfoils was achieved at a Reynolds number of 2,000,000. Both the S805 and LS(1)-0413 MOD have a C_{Lmax} designed to be insensitive to roughness effects, which will help maintain peak power as the airfoil accumulates bugs or leading edge erosion. However, once the airfoil does accumulate bugs, the laminar flow will largely disappear and power outputs will be reduced for low-to-medium wind speeds. The net result is that the contaminated laminar flow airfoil is no worse than the turbulent flow airfoil and significantly outperforms it at low-to-medium wind speeds under clean conditions.

Using the special purpose airfoil family and the PROPSH performance prediction code, calculations were performed for the Carter 25 to determine the performance gain relative to the NACA 23XXX series airfoils currently used on this machine. For each of the two airfoil data sets the performance was calculated at their respective optimum blade-pitch angle. Figure 4 shows the relative performance difference in terms of power coefficient versus tip speed ratio. Peak power coefficient was increased from 0.467 to 0.492, which corresponds to a 5% improvement. At lower wind speeds, the improvement increases to 10% and 25% for tip speed ratios of 10 and 12, respectively. At high wind speeds or low tip speed ratios, in order to stay within the generator's upper torque limit, the objective was to minimize any increase in performance by restraining C_{Lmax}. Figure 5 shows the corresponding rotor power curve versus wind speed. A relatively constant gain in rotor power is

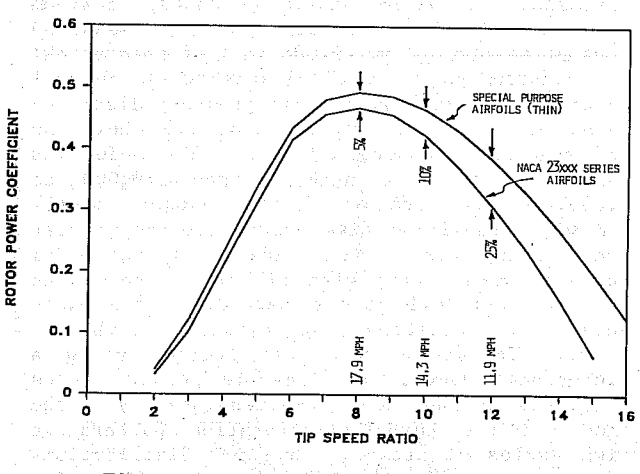

Figure 4. Calculated Nondimensional Rotor Performance

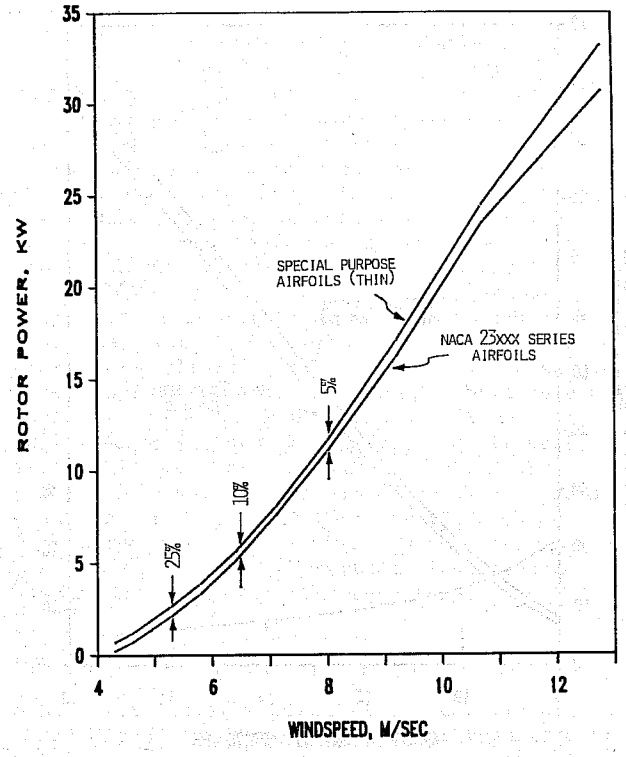

Figure 5. Calculated Dimensional Rotor Performance

observed throughout the wind speed range. Once substantial blade stall is present, at wind speeds over 12 m/s, the accuracy of the calculations becomes tenuous due to the difficulty of properly representing the post stall airfoil characteristics.

The Systems Engineering and Analysis Computer Code (SEACC) described in Ref. 4 was used to determine the machine's improvement in annual energy output as a function of annual average wind speed. The most recent version of the code uses PROPSH to calculate rotor performance. The rotor power is then converted to generator power based on the measured generator/transmission efficiency as determined from dynamometer tests. A Weibull wind distribution is applied to the generator output curve to determine annual energy yield as a function of annual average wind speed. The results of these calculations are shown in Figure 6 for annual power output above wind speeds of 8 mph. At 10 mph the percent improvement with the special purpose airfoil family is 12% to 14%, whereas at 12 and 14 mph the improvements are in the range of 8% to 10% and 6% to 7%, respectively. Assuming the special purpose airfoils cost the same to fabricate as conventional airfoils, this improvement in annual energy translates directly into a corresponding reduction in the cost of energy.

THICK AIRFOIL FAMILY

The thick airfoil family was motivated by the need to accommodate the structural requirements

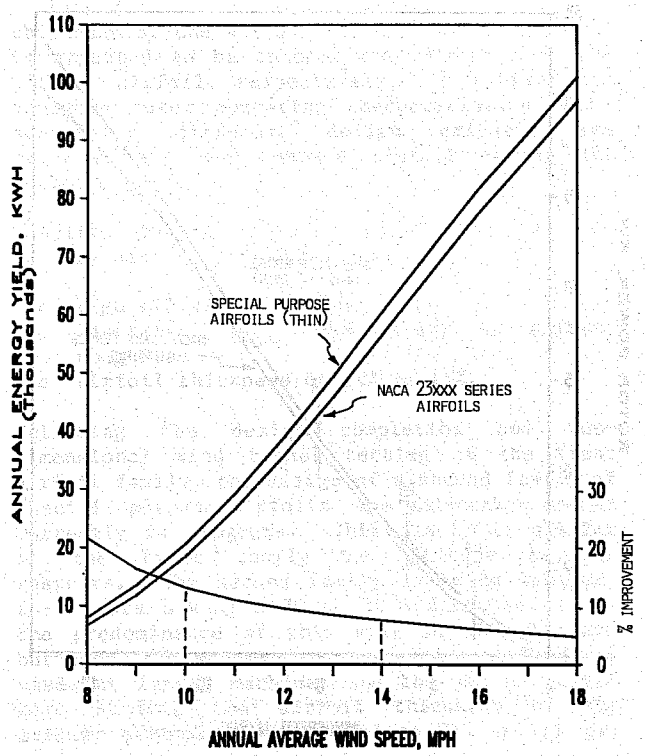

Figure 6. Calculated Annual Energy Yield

of hollow wood blades and the relatively higher cyclic structural loads of large machines. The design criteria for this family are based on those established for the thin airfoil family. The thick airfoil family is being optimized for a primary airfoil thickness of 21% at a Reynolds number of 2,000,000 as shown in Table 3. Inboard and outboard airfoil sections will have thicknesses of 30% and 18%, respectively. Values of C_{Lmax} and C_{Dmin} are not listed since the design effort is still in progress and it is not clear how far these parameters can be pushed for thick airfoils. However, in an effort to maximize the L/D ratio, the C_{Lmax} of the two outboard sections will be held to a minimum and that of the inboard section will be maximized. In addition, all three airfoil sections will strive for low C_{Dmin}.

AIRFOIL TESTING

Testing for the thin and thick special purpose airfoil families consists of two phases. The first phase is a two-dimensional wind tunnel test of the primary airfoil of each family to verify its predicted performance characteristics. If good agreement is achieved the airfoil family will then enter the second test phase, which is an atmospheric test on a manufacturer's machine through a cooperative agreement. Only the two-dimensional wind tunnel test of the thin primary airfoil has been completed. Prior to reviewing these results, a brief discussion is appropriate on the unique requirements of laminar flow airfoil wind tunnel testing.

Table 3. Design Parameters - Thick Airfoil Family

Airfoil	r/R	Reynolds No.	t/c	$C_{L\,max}$	$C_{D\,min}$	C_{Mo}
S811	0.30	1.2×10^6	0.300	max.	min.	none
S809	0.75	2.0×10^6	0.210	min.	min.	min.
S810	0.95	1.9×10^6	0.180	min.	min.	min.

Laminar flow airfoils cannot be accurately tested in a conventional wind tunnel because of their sensitivity to the small-scale turbulence generated by the wind tunnel itself. Flow separation on a laminar flow airfoil has unique characteristics not present with turbulent flow airfoils. At Reynolds numbers less than 1,000,000, laminar separation bubbles are almost always present. These bubbles are relatively unaffected by large-scale atmospheric turbulence. However, intense small-scale (order of cm) wind tunnel turbulence will suppress a laminar separation bubble that would ordinarily be present if the airfoil were operating in the free atmosphere. Bubble suppression leads to optimistic measurements of drag and maximum lift coefficient. At high Reynolds numbers the opposite drag bias error can occur when the small-scale turbulence produces premature boundary layer transition. This case leads to pessimistic measurements of drag and lift coefficient. Consequently, for both low and high Reynolds numbers, a first order error can be present in the data that cannot be corrected. The way to eliminate this error is to test laminar flow airfoils only in well-documented low-turbulence wind tunnels. Low turbulence is considered to exist when flow fluctuations do not exceed 0.05% of the mean flow velocity. The NASA Langley Low-Turbulence Pressure Tunnel (LTPT) and the Delft University Low Speed Laboratory tunnel in the Netherlands are known to meet this criterion.

The wind-tunnel test of the S805 was conducted in the Delft University of Technology Low Speed Laboratory with the assistance of L.M.M. Boermans. A 500-mm (19.7-in.) chord, aluminum model of the S805 airfoil having a measured contour within 0.2 mm (0.008 in.) of theoretical was constructed by DFVLR, Braunschweig, Federal Republic of Germany. Airfoil pressure distributions were acquired by means of 113 chordwise and spanwise pressure orifices. The model was tested at Reynolds numbers from 500,000 to 2,000,000 with transition free (model smooth) and with transition fixed (grit roughness) near the leading edge. For several runs, the model surfaces were coated with oil to determine the location, as well as the nature, of the boundary-layer transition from laminar to turbulent flow. Transition was also located using a microphone mounted on a movable probe. Tufts were used to check the two-dimensionality of the flow and the turbulent-separation pattern at high angles of attack. Pressure distributions and wake profiles were measured for all conditions.

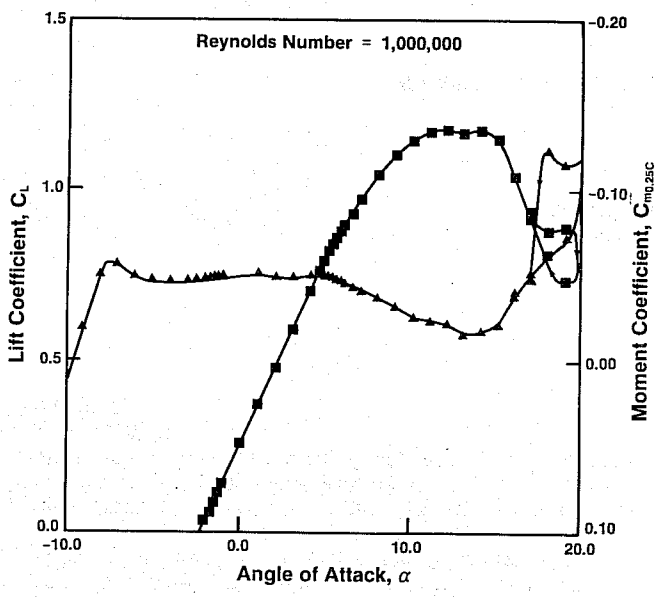

Figure 7. S805 Measured Lift and Moment Coefficient

The preliminary results shown in Figures 7 and 8 are in agreement with the design objectives for the airfoil. The restrained design C_{Lmax} of 1.2 was achieved and found to be unaffected by roughness. The airfoils stall characteristics are seen to be very soft. The pitching moment coefficient was no more negative than the design constraint of -0.05. The low-drag range extended from a lift coefficient of about 0 to 0.9. A maximum section L/D ratio of over 100 was achieved for the design Reynolds number of 1,000,000. The maximum L/D ratio was further increased to 113 using turbulators to alleviate the laminar separation bubbles.

Because the high performance of this airfoil depends primarily on the achievement of extensive laminar flow, it is imperative that the airfoil be manufactured properly on the wind-turbine blade. Four factors must be controlled. First, the shape, particularly the nose, must be accurately reproduced. Second, the surface must be smooth. Polishing or waxing is not necessary. A surface comparable to one sanded with No. 400 sandpaper is adequate. Third, the surface must be fair or wave-free. This can be determined using the "straight-edge test" where a straight edge is rocked chordwise on the surface. If the straight edge moves smoothly, the surface is fair enough for laminar flow. If the straight edge hangs up or moves in jumps, a significant wave exists at each of the hang ups, which will probably cause premature transition. Finally, the surface must be stable under operational loads. Thus, fabric-covered surfaces would be inappropriate for this airfoil. Other factors that affect airfoil performance must also be considered. Thick abrasion strips, for example, are almost certain to cause premature transition if their trailing edges are not faired into the airfoil shape. Also, the manufacturing lines on extruded blades should be checked using the straight-edge test.

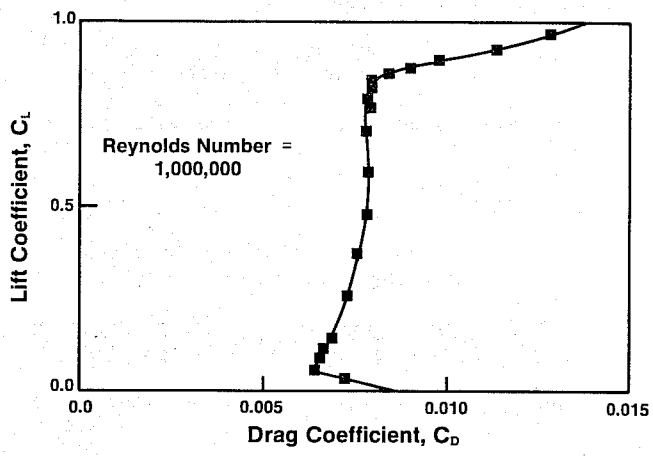

Figure 8. S805 Measured Drag Coefficient

CONCLUSIONS

HAWTs, particularly fixed pitch stall regulated machines, have some unique airfoil requirements not shared by the general aviation industry. Over the outboard portion of the blade, an airfoil's C_{Lmax} needs to be restrained and insensitive to leading edge roughness. These qualities help limit peak power and provide a more consistent peak power output. The net result is reduced structural loads and more reliable machine operating characteristics.

Two airfoil families possessing the above qualities are being developed using the Eppler airfoil design code. The first (thin airfoil family) was designed for a 10 to 20 m diameter rotor system. The predicted performance characteristics of the primary airfoil of this family were verified through two-dimensional wind tunnel testing. Based on predicted and measured results for the thin airfoil family, an 8% to 10% improvement in annual energy output is anticipated for an annual average wind speed of 12 mph. The second (thick airfoil family) is currently being designed for a 20 to 30 m diameter rotor system. Upon completion of this design, the primary airfoil will also undergo a two-dimensional wind tunnel test to verify its predicted performance characteristics. Future plans for both airfoil families call for atmospheric testing on a manufacturer's machine through a cooperative agreement.

NOMENCLATURE

c	chord
C_d	drag coefficient
C_L	lift coefficient
C_m	pitching moment coefficient at quarter chord
C_{mo}	pitching moment coefficient at zero lift

D	drag
L	lift
r	local rotor radius
R	total rotor radius
t	airfoil thickness
max	maximum
min	minimum

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