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Development and Application of a Multipoint Inverse Design Method for Horizontal Axis Wind Turbines

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ABSTRACT

An inverse method for the aerodynamic design of horizontal axis wind turbines has been developed, and a computer program (PROPID) has been written based on the approach. The new inverse approach is a significant improvement over the traditional approach of repeatedly prescribing the blade geometry and then determining the performance through analysis. Instead, with the current method, the desired rotor performance characteristics and blade aerodynamic characteristics can be directly specified from which the corresponding blade geometry is determined. To illustrate the inverse design method, a new 10.5 m blade for use on the stall-regulated three-bladed Micon 108 and Bonus 120 wind turbine generators has been designed to replace the ageing AeroStar 9.06 m blade currently in widespread use on thousands of machines. The design effort primarily focused on improving the blade performance for the Micon 108 machines since they are more numerous than the Bonus 120's. As compared with the AeroStar 9.06 m blade, the improvement in annual energy of the new blade is 13-25% over the average wind speed range 4.47-8.94 m/s (10-20 mph) for the Micon 108. When dirty (i.e., when the leading edge is contaminated with insect debris), the new blade produces 28-53% more annual energy than the AeroStar blade.

I. INTRODUCTION

In the past, wind turbine design has been performed largely by the direct approach, sometimes called the design-by-analysis approach. In practice, the procedure of repeatedly analyzing candidate geometries that successively approach the desired goals has several advantages that are not unique to the wind turbine design problem. During the design process, some of the requirements and constraints may be changed if sufficient advantages emerge in the resulting performance. Moreover, sometimes the initial design objectives are not physically realizable. Consequently, the requirements and constraints may have to be changed owing to physical limitations that are not known a priori. Thus, it is anticipated that due to the myriad of tradeoffs and physical limitations involved designers will favor for some time design methods that have interactive design capabilities. For example, most (if not all) designers currently use for design a refined blade-element/momentum method[1] – an approach that can be readily implemented on a personal computer and allow for rapid interactive design. The industry standard for design by such an approach is the PROP blade-element/momentum computer program, which is incorporated into the current inverse design method and documented chiefly in References 2-5.

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Despite its simplicity, sole use of the direct approach to design is often time consuming and challenging. The difficulty is that many of the wind turbine rotor characteristics that are required or otherwise desired cannot be specified directly. For instance, the blade chord and twist distributions are often predicated on obtaining under specified conditions some desired aerodynamic characteristics along the blade,[6-8] e.g., uniform inflow and section lift coefficient for best local airfoil lift-to-drag ratio. Also, if the rotor is to be operated in a fixed-pitch/fixed-speed mode (often termed the stall-regulated mode) the rotor geometry is further constrained by a specified peak rotor-power limitation to avoid damage to the wind turbine generator.[1] Clearly, if several different combinations of peak power, blade lift characteristics, inflow characteristics, blade length, rotor rpm, etc. are all considered by the designer during the conceptual design phase, the blade shape optimization process can be especially daunting when performed using a design-by-analysis methodology.

A particularly attractive approach to wind turbine design is to retain the traditional advantages of the direct design approach within the framework of an inverse design methodology. In this case, the designer has the flexibility to specify either independent or dependent parameters (e.g., rotor geometry or aerodynamic performance characteristics). Moreover, the ability to specify desired characteristics from the outset can greatly reduce the level of tedious work during the design process. The development and application of such a design methodology is presented. A computer program (PROPID – available from the authors) has been written based on this approach.

PROPID can be used to directly specify desired aerodynamic characteristics from which the corresponding blade geometry is determined. More generally, any number of desired physically realizable characteristics can be achieved as long as some other variables are left to be determined (e.g., blade chord and twist distributions, pitch and rpm – traditional input variables). The degree to which the inverse capability is used remains the designer's decision. For instance, the geometry can be prescribed over part of the blade, such as the hub region, while over the remaining part desired aerodynamic characteristics can be prescribed.

The method also has multipoint design capabilities. For example, the blade lift coefficient distribution can be prescribed for one condition and the axial induction factor distribution for a different condition. Both of these specifications can be achieved simultaneously. In addition, the designer can simultaneously specify the peak rotor-power constraint, which may correspond to yet another condition. The remainder of this paper discusses the formulation of the problem and its implementation and application.

II. FORMULATION OF THE INVERSE DESIGN PROBLEM

As previously discussed, the blade chord and twist distributions are sometimes predicated on obtaining desired lift coefficient and axial induction factor distributions. For the most part, these desired characteristics are defined based partly on past experience and partly on experience developed during the actual design effort. Several schemes have been devised to achieve a near optimal axial induction factor distribution,[6-8] but to achieve both a desired lift coefficient and axial induction factor distribution the design-by-analysis approach is usually adopted. In an interactive and iterative fashion, these desired aerodynamic characteristics in addition to other design objectives are achieved by careful and tedious adjustment of the blade geometry followed by analysis. Based on feedback from successive analyses and with some experience, the designer changes the geometry in the direction necessary to bring the wind turbine closer to the desired goals.

A systematic approach to this iterative design-by-analysis procedure can be formulated as follows. As a preliminary, Figure 1 shows a convenient parameterization of the blade geometry. The chord c is composed of the sum of a constant level at the blade root and a chord distribution relative to this constant level, that is, $c_0 + \tilde{c}$. Likewise, the blade pitch is the sum of the pitch at 75% radius ($\beta_{75\%}$) and the twist relative to this point (θ), both measured positive in the direction toward feather from the rotor plane.

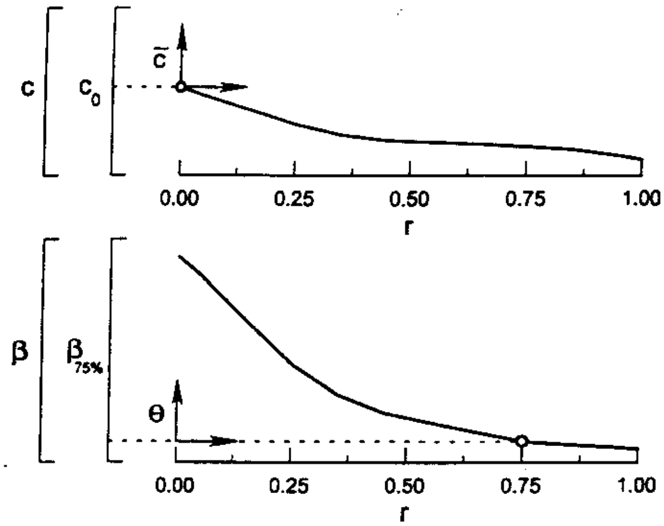

Figure 1. Parameterization of blade chord and twist distributions.

In the current approach, a relatively simple case is considered. A three-bladed, 9.25 m radius rotor operates at a constant speed of 50 rpm with a fixed pitch of 3 deg at 75% radius. The design goals are to achieve a specified peak power of 75 kW and a desired lift coefficient distribution at a condition (wind speed) yet to be determined. Within the framework of the current parameterization, a means of achieving the desired peak power is to adjust the solidity via the blade chord offset c_0 as shown in Figure 2. The dotted curve for the chord distribution corresponds to the dotted power curve,and so on.

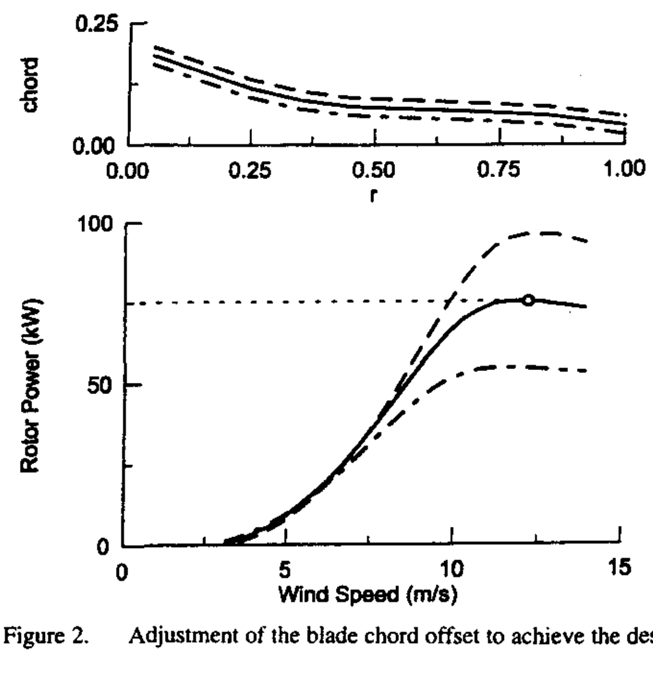

Figure 2. Adjustment of the blade chord offset to achieve the desired peak power.

The desired lift coefficient distribution is shown in Figure 3. As with the blade twist distribution, it is convenient to divide the desired C_ℓ distribution into two components: $C_{\ell,75\%} + \tilde{C}_\ell$. This C_ℓ distribution (Figure 3) corresponds roughly to the maximum L/D condition of the airfoils along the blade span. The speed corresponding to this C_l distribution is defined in part by the peak power level for the following reason. As shown in Figure 2, the peak rotor power is reached at a wind speed near 13.41 m/s (30 mph). At this speed, the rotor blade is stalled inboard and unstalled outboard. Thus, the C_l distribution along the span is close to the airfoil $C_{l,max}$ – above inboard and below outboard. Near the cut-in speed of 4.47 m/s (10 mph), the net C_l distribution is slightly above zero lift. It would therefore be inconsistent to specify that the desired C_l distribution occur at a wind speed near 13.41 m/s (30 mph) or near the cut-in speed. In fact, the speed corresponding to the desired C_l cannot be specified; rather, the speed must be determined since it is predefined somewhat by the cut-in and peak-power speeds.

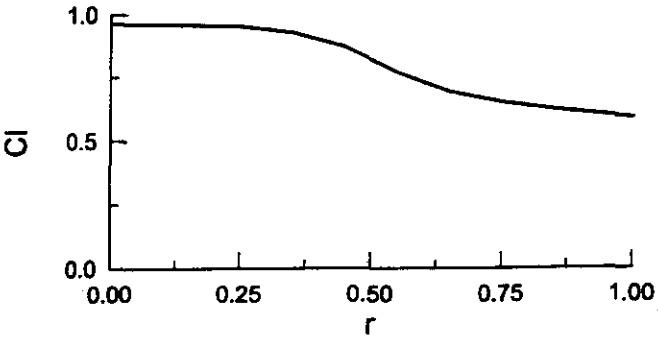

Figure 3. Desired C_l distribution corresponding to a wind speed to be determined.

As shown in Figure 4, the wind speed can be adjusted to find the value that yields the desired value for $C_{l,75\%}$ of 0.65. This wind speed is referred to as the wind speed design point or V_{DP}. At this stage, the twist θ is adjusted to achieve the desired $\tilde{C}_l$ as shown in Figure 5.

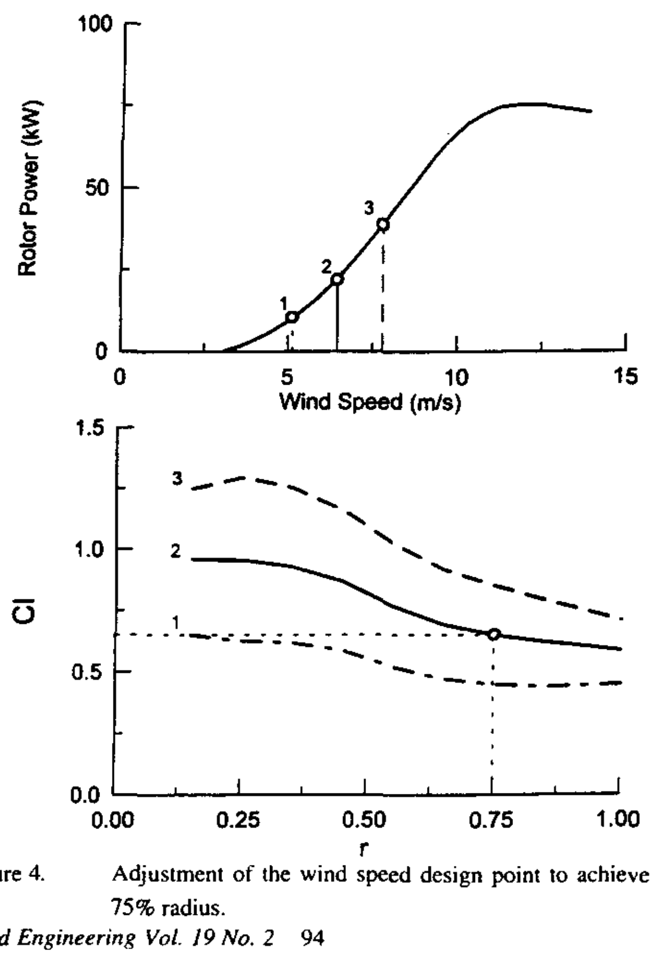

Figure 4. Adjustment of the wind speed design point to achieve the desired C_l at 75% radius.

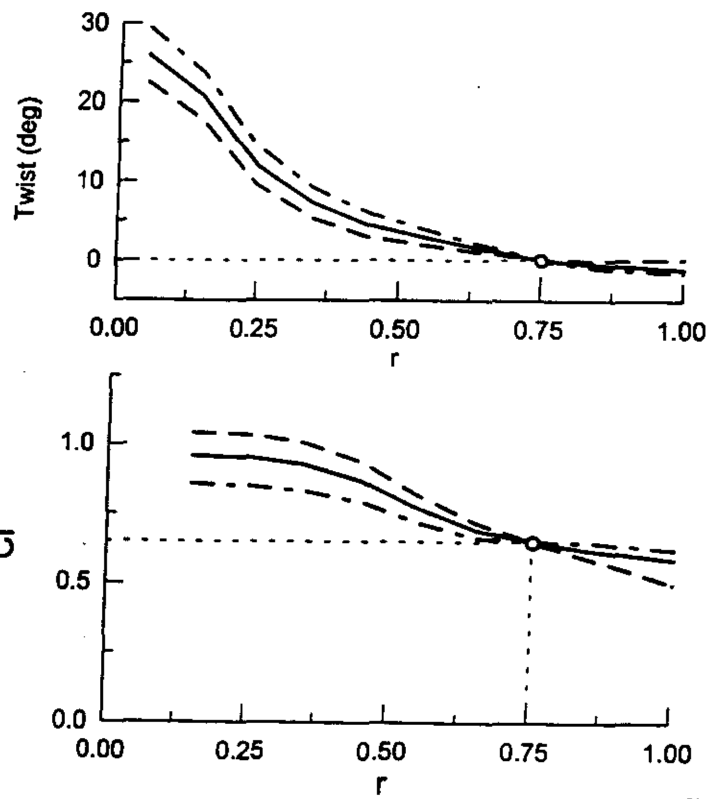

Figure 5. Adjustment of the twist distribution to achieve the desired $\tilde{C}_l$ distribution.

Of course, it should be mentioned that as the twist is adjusted, the peak power will change. (To avoid confusion, these excursions were not presented in the example discussed.) Furthermore, the change in the peak power will require a change in the blade chord offset. In turn, the wind speed design point will change and so on. Clearly, the principal difficulty in using the direct approach to design is that attempting to match all the desired characteristics can be especially challenging and often discouraging.

From this illustrative example, however, emerges the basis of a practical inverse design method. Specifically, in terms of the current example, the blade chord offset (effectively the solidity) can be automatically adjusted through an iteration scheme to achieve the desired peak power, and similarly the wind speed design point can be iterated to achieve the desired lift coefficient at the 75% location. The blade twist can be defined by movable spline supports or collocation points and iterated simultaneously to achieve the desired relative lift coefficient distribution at an equal number of points. In the current approach, multi-dimensional Newton iteration is used to solve the system of nonlinear equations that result from the parameterization as described. The method readily generalizes and easily allows for the specification of parameters like power coefficient, blade thrust loads, axial inflow distribution, etc.

III. WIND TURBINE PERFORMANCE PREDICTION METHOD

The analysis method currently used in the design method is the PROP code, which is based on blade-element/momentum theory. It should be noted, however, that the PROP model currently employed could readily be replaced in PROPID by a more computationally intensive, higher fidelity rotor vortex code if a rapid design cycle time is not critical and if there exist sufficient computer resources. Briefly, the earliest version of PROP was developed nearly two decades ago,[2,7,8,9] and after various improvements[3,4,5] it has become an industry standard. Desirable features of the code are that it allows for rapid analysis, accommodates different airfoil data for each blade element, and includes a 3-D post-stall airfoil performance synthesization model for better peak power prediction at high wind speed.[10,11,12] Although discrepancies between field tests and predictions have been documented and discussed,[13,14] the code has proved to be invaluable as a guide to the design of a series of wind turbine blade designs.

IV. APPLICATION OF THE INVERSE METHOD

Overview

To demonstrate the utility of the inverse method, a new 10.5 m blade (termed the ATV 10.5 m blade) to be jointly developed by Burlington Glass Fiber, Inc. and AtoutVent, S.A. has been designed for use on the Micon 108 and Bonus 120 wind turbines. Currently, the AeroStar 9.06 m blade (originally produced by the now defunct AeroStar Corporation) is widely used on the Micon 108 and Bonus 120 wind turbine machines in California windfarms. The AeroStar blade shown in Figure 6 makes use of the NACA 44XX series airfoils that were originally designed for use on aircraft. Work conducted at the National Renewable Energy Laboratory (NREL), formerly Solar Energy Research Institute (SERI), has shown that these airfoils when used on wind turbine blades produce three undesirable consequences.[13] First, the lift produced by these airfoils is too high, and this requires a relatively short blade radius to control peak power. The reduced blade radius lowers the annual energy production. Moreover, to control peak power the blade must be operated near the stall angle, which increases windfarm array losses and therefore reduces the net annual energy capture. Second, these airfoils are known to be highly sensitive to roughness. Consequently, energy capture is reduced when the leading edge along the blades becomes contaminated (dirty) owing to insect accumulation. Third, the NACA 44XX airfoils were designed for relatively low thickness-to-chord ratios. The relatively thin NACA airfoils are not ideal for use on wind turbine blades for which high thickness ratios are desired.

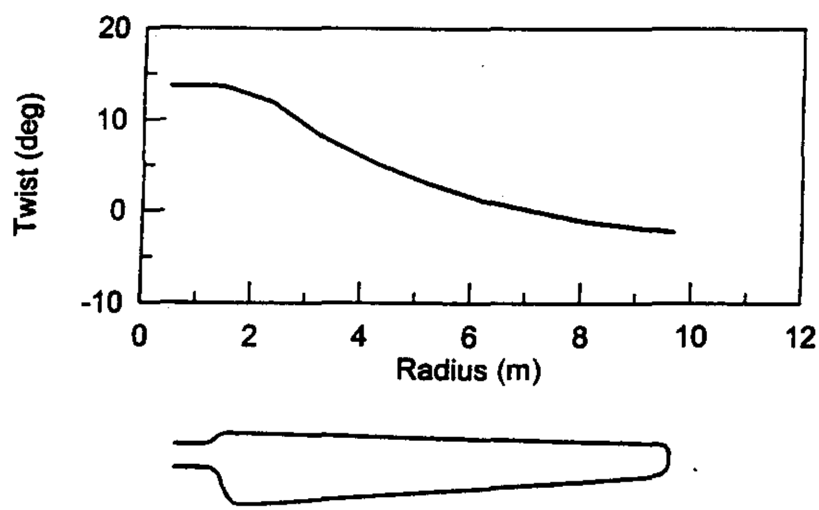

Figure 6. AeroStar 9.06 m blade chord and twist distribution.

NREL airfoils[15-17] were specially tailored for use on horizontal-axis stall-regulated wind turbines. The NREL airfoils – S814 (root), S809 (primary – 75% radius location) and S810 (tip) – were incorporated into the current blade design and offer the following advantages:

Restrained $C_{\ell max}$ tip airfoils for peak power control with optimum blade radius, increased annual energy production and lower windfarm array losses.

- Reduced roughness sensitivity for improved energy capture under dirty blade conditions.
- Increased section thickness (S814-24%, S809-21% and S810-18%) for lower blade weight, lower cost, increased stiffness and improved fatigue resistance.

The unique design requirements of the current blade are shown in Table 1 together with the characteristics of the AeroStar 9.06 m blade for comparison. Shown in Table 2 are the Micon 108 and Bonus 120 wind turbine generator characteristics relevant to the current design effort.

Table 1. Wind Turbine Blade Characteristics/Design Requirements

	ATV 10.5 m	AeroStar 9m
Blade Span (ft)	36.417	31.693
Hub Radius (ft)	1.969	1.969
Rotor Diameter (ft)	76.772	67.323
Blade Number	3	3
Cone Angle (deg)	4	4
Airfoil Series	NREL†	NACA 44XX

†Thick airfoil series S814/809/810

Table 2. Wind Turbine Generator Characteristics

	Micon 108	Bonus 120
Rotor Peak Power (kW)†	130	144
RPM	45	45

†Based on a generator and gearbox efficiency of 90%

Design Approach

Since there are substantially more Micon 108 machines in use than Bonus 120's, the design effort first focused on maximizing blade performance for the Micon 108 machine. Each candidate blade design for the Micon 108 machine was then analyzed on the Bonus 120. For both machines, the overall objective was to maximize the annual energy production as predicted by the NREL SEACC program.[18] Better performance on the Micon 108 machine, however, was desirable since they are more numerous. It should be mentioned that the ATV 10.5 m blade design reflects considerable experience with four other blades that were designed to take advantage of NREL advanced airfoils, namely, the NREL 7.96 m thin airfoil blade,[19] NREL 9.66 m thick airfoil blade,[13] Lynette 12 m blade,[20] and the Atlantic Orient Corp. 7.22 m blade.[21]

As discussed in Section II, the peak power was prescribed as well as the blade lift coefficient distribution along the blade span. Also, in this case the axial induction factor distribution was prescribed. Consistent with the approach presented in Section II, the peak power specification was achieved through iteration on the blade chord offset, that is,

$$c_0 \Rightarrow P_{max} \tag{1}$$

where the notation " $\Rightarrow$" means that the design parameter has a first-order effect on the desired characteristic. The performance of a wind turbine greatly depends on the airfoil characteristics along the blade, specifically, the lift coefficient distribution C_l (whic changes with wind speed). Based on preliminary work, a C_l distribution was determine and found to be near optimum. The specified C_l distribution was achieved through itera tion on the wind speed design point and twist distribution, that is,

$$VDP \Rightarrow C_{l,75\%} \quad (2$$

$$\theta(r) \Rightarrow \tilde{C}_l(r) \quad (3$$

Typically, optimal wind turbine rotors have a nearly constant axial induction facto along the blade. In the current design, a nearly constant axial induction factor distributioı was prescribed through iteration on the relative chord as

$$\bar{c}(r) \Rightarrow \tilde{a}(r) \quad (4$$

Blade Geometry

Based on the previous specifications, PROPID was used to solve the inverse problem o finding the corresponding blade geometry. The final design blade chord and twist distrib utions are shown in Figure 7. (Note: The 11.1 m radius of the rotor is equal to the sum oı the blade length of 10.5 m and the hub radius of 0.6 m) The design process led to an opti mized blade that had a nearly constant taper from 17.5% to 72.5% radius; that is, the blade leading and trailing edges were nearly straight lines. This optimized blade geometry wa slightly modified so that the blade leading and trailing edges were straight from 17.5% tc 72.5% radius. The resulting loss in annual energy production was everywhere less than a quarter of a percent. Thus, in the interest of simplifying the detailed design and manufacturing process, the linear taper was accepted.

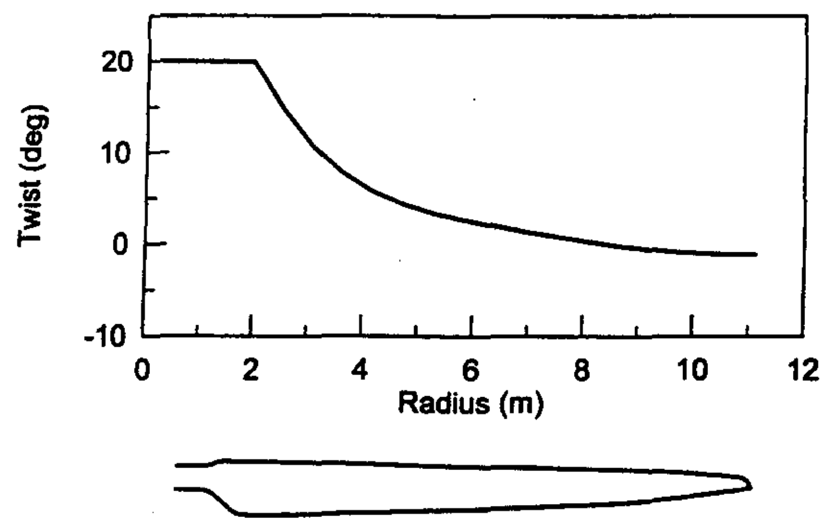

Figure 7. ATV 10.5 m blade chord and twist distribution.

Performance Predictions

In this section, the power curves for the ATV 10.5 m blade are compared with the AeroStar 9.06 m blade for both clean and dirty conditions. The comparison is made for both the Micon 108 and Bonus 120 machines. Table 3 lists additional input data (besides that shown in Tables 1 and 2) required for the analysis.

In the clean state, the airfoil data was obtained from predictions generated by a modification of the Eppler airfoil design and analysis code. The Eppler code[22] is well known for its accuracy in predicting airfoil performance at low speeds. The Dini modification[23] that was used includes a laminar separation bubble to better predict laminar separation bubble effects on airfoil performance. For the dirty condition, the airfoil data itself was not modified. Rather, the clean power curve was empirically scaled based on field test data of the AeroStar 9.06 m blade[24] and the NREL 9.66 m blade.[13] The clean power curves were scaled by the equation

$$P_{dirty} = (1 - \in)P_{clean} \tag{5}$$

where

$$\in = a_0 + a_1 V_{wind} \tag{6}$$

Table 3. PROP Input Data for Performance Analysis†

	ATV 10.5 m	AeroStar 9 m
Micon Optimum blade pitch (deg)	3.00	2.19
Bonus Optimum blade pitch (deg)	4.31	3.50
Shaft Tilt (deg)	0.00	0.00
Hub Cutout (ft)	5.05	5.05
Wind Exponent	0.00	0.00
Air Density (slug/cu. ft)	0.002378	0.002378
Tip Loss Model	Prandtl	
Hub Loss Model	Prandtl	
Brake State Model	Advanced	
Airfoil Stall Model	Viterna	
Wake Swiral	Included	

†(see also Tables 1 and 2)

The values used for a_0 and a_1 are given in Table 4. The loss factor $\in$ is different for each blade because the airfoils are different. The loss factor for the ATV 10.5 m blade is less than for the AeroStar 9.06 m blade since the airfoil family used on the ATV 10.5 m blade is known to be less sensitive to roughness than the family used on the AeroStar 9.06 m.[15,17]

Table 4. Power Loss Coefficients

	ATV 10.5 m	AeroStar 9m
a_0	0.00541	0.00740
a_1	–0.01960	0.00815

For the Micon 108, Figures 8a-b compare the predicted rotor power for the ATV 10.5 m blade and AeroStar 9.06 m blade for clean and dirty conditions. In the dirty condition, the power loss is less for the new blade (as could be deduced from Table 4). As seen over the normal operating wind speed range (0-15 m/s), the peak power is limited to 130 kW as per the design objectives. Based on experience in comparing PROP code predictions with field test data, the increase in power past 15.65 m/s (35 mph) is not expected to occur.

Another advantage of the new blade is that the the generator cut-in speed can be reduced by 0.67 m/s (1.5 mph) from that of the AeroStar blade. Comparisons between the annual energy production for the new blade and the AeroStar blade are shown in Figures 9a-b for clean and dirty conditions. The corresponding percent improvement in annual energy production is shown in Figures 10a-b. When clean (Figure 10a), there is a 35% improvement at an average wind speed of 4.47 m/s (10 mph), 18% at 6.71 m/s (15 mph), and 13% at 8.94 m/s (20 mph). For dirty blade conditions (Figure 10b), the improvement is more substantial: 53% at 4.47 m/s (10 mph), 33% at 6.71 m/s (15 mph) and 28% at 8.94 m/s (20 mph). These results are based on a combined generator and gearbox nominal efficiency of 90% and a standard wind speed distribution curve according to the Weibull distribution model with a shape factor k of 2 (a Rayleigh distribution).

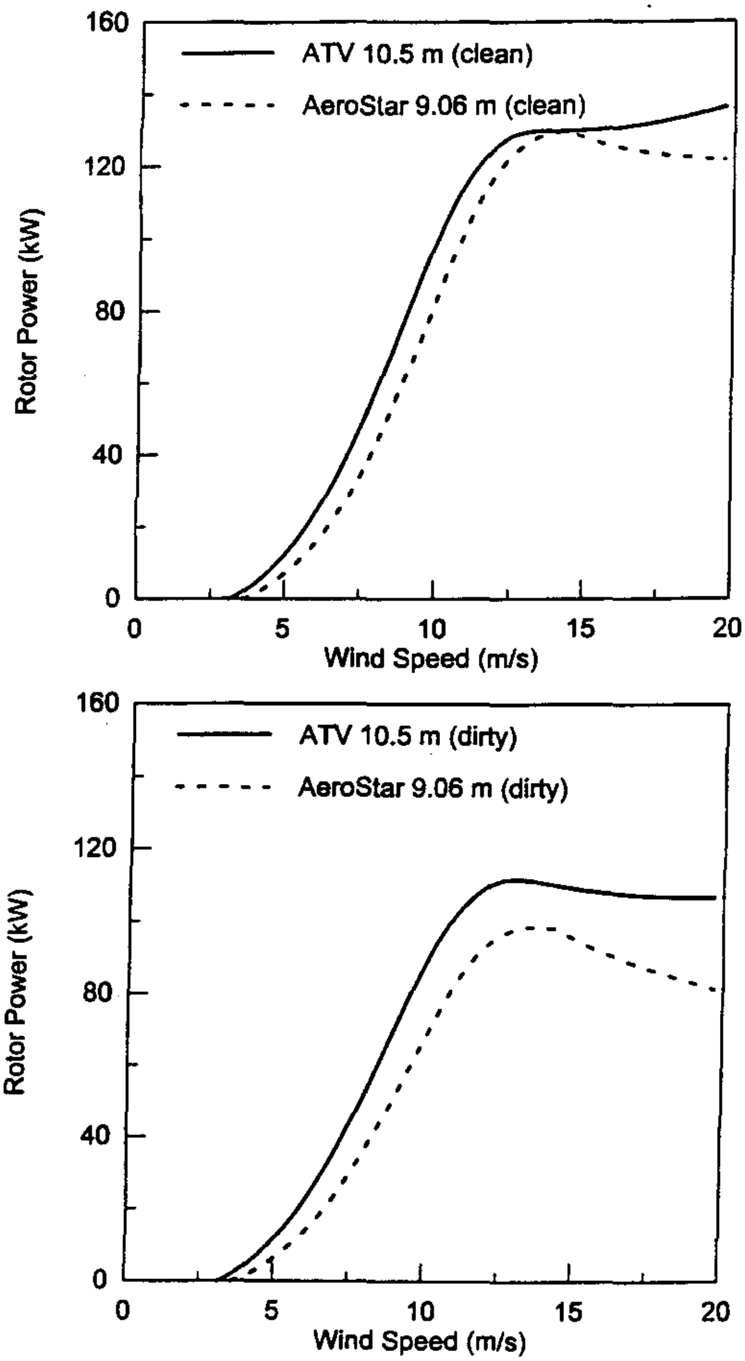

Figure 8. ATV 10.5 m blade (solid) and AeroStar 9.06 m blade (dotted) power curves for clean conditions (a) and dirty conditions (b) on the Micon 108 wind turbine.

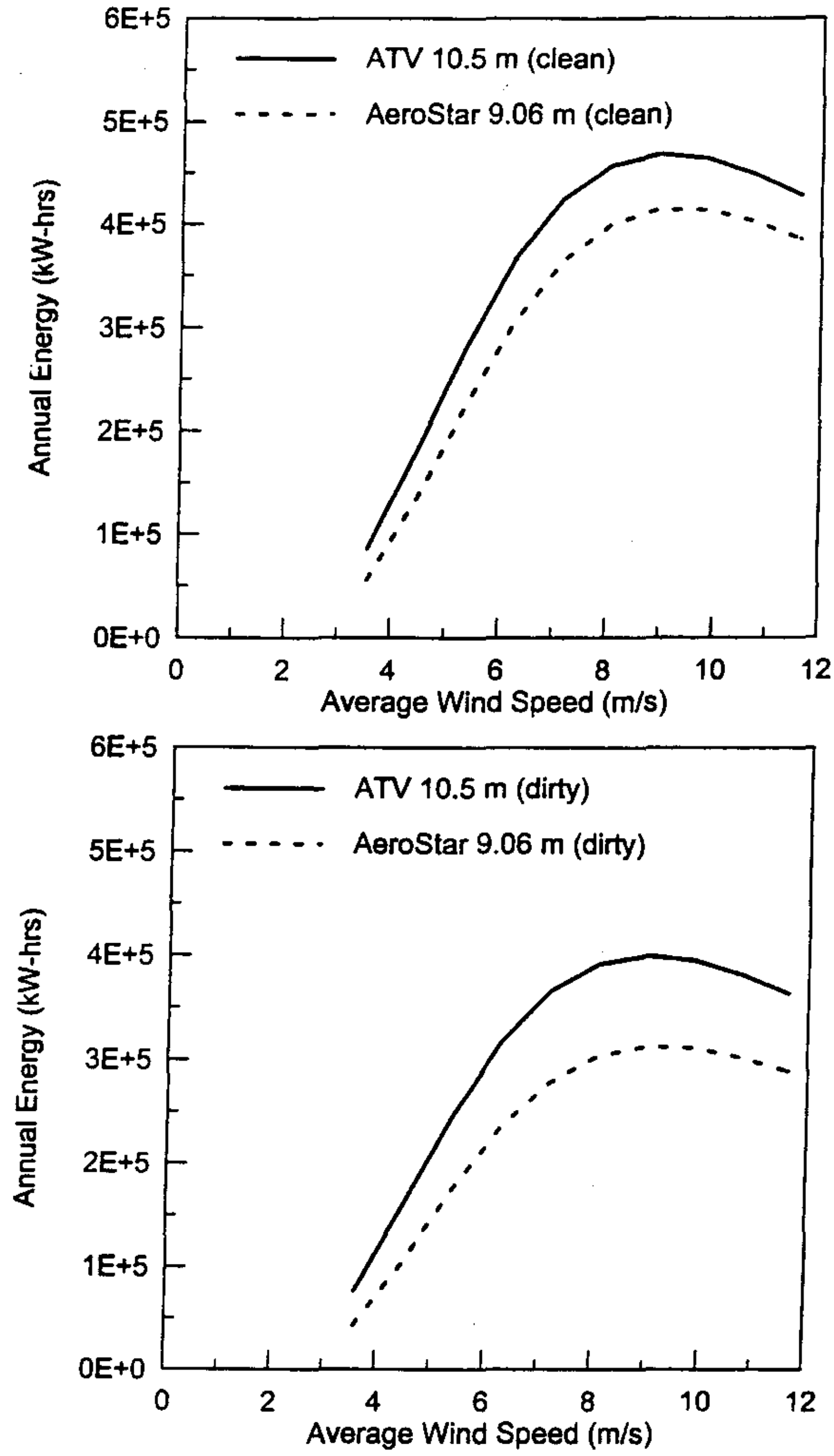

Figure 9. ATV 10.5 m blade (solid) and AeroStar 9.06 m blade (dotted) annual energy production for clean conditions (a) and dirty conditions (b) on the Micon 108 wind turbine.

For the Bonus 120 machine, peak power is restricted to 144 kW. The resulting cut-in speed is similar to that of the AeroStar blade. When clean/dirty, the improvement is

25/41% at 4.47 m/s (10 mph), 14/28% at 6.71 m/s (15 mph) and 10/25% at 8.94 m/s (20 mph).

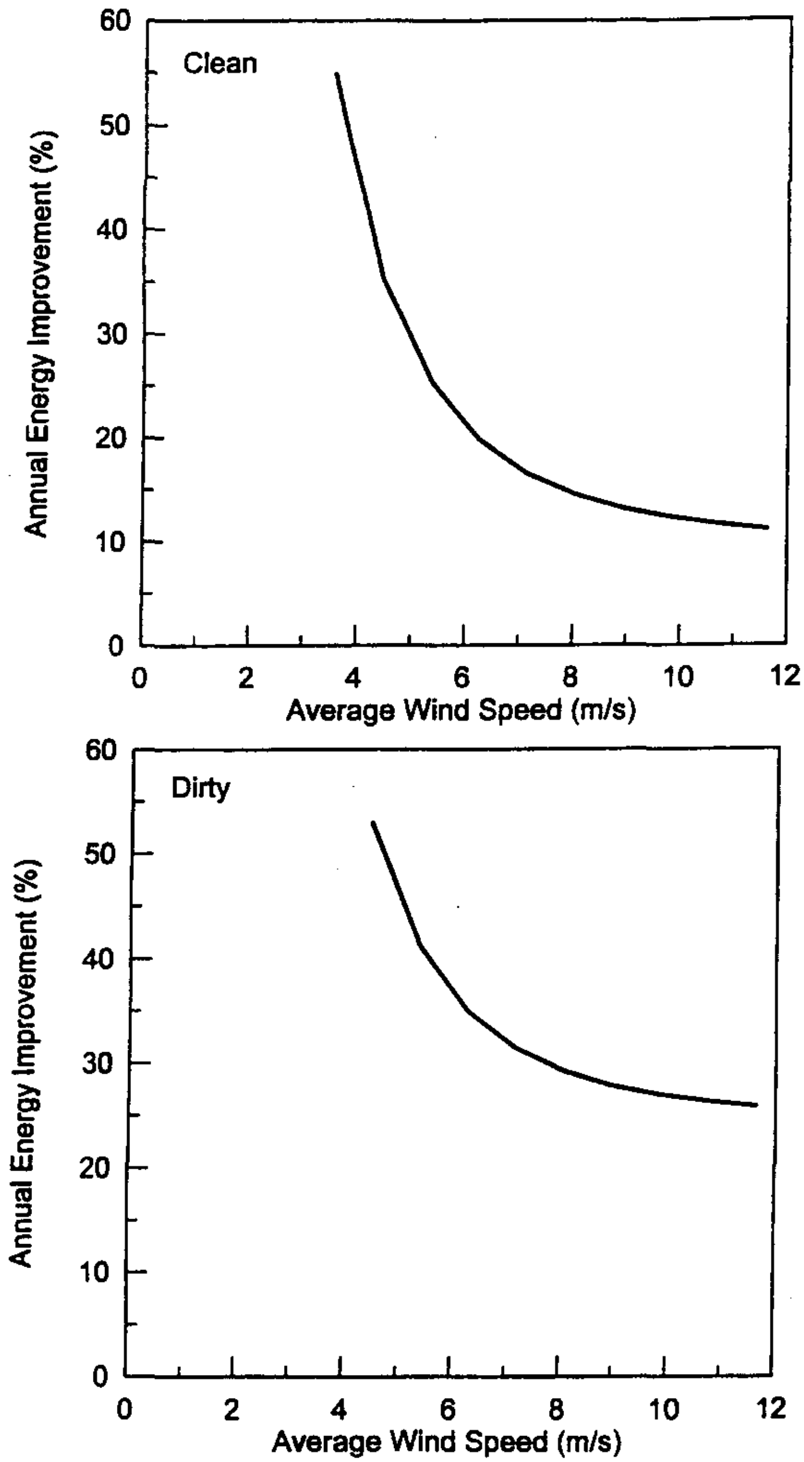

Figure 10. Improvement in annual energy production of the ATV 10.5 m blade (solid) over the AeroStar 9.06 m blade (dotted) for clean conditions (a) and dirty conditions (b) on the Micon 108 wind turbine.

V. CONCLUSIONS

The new inverse approach to wind turbine design implemented in PROPID should prove to be a valuable aid in the design of horizontal axis wind turbines. In particular, the ability to tailor the aerodynamic characteristics along the blade span and simultaneously match several constraints makes it possible for the designer to concentrate on optimizing the blade while interactively exploring the myriad of tradeoffs. For instance, the new inverse method greatly facilitated the design of the ATV 10.5 m blade and in part helped to achieve the rather dramatic improvements in annual energy production over the existing AeroStar 9.06 m blade. Overall, the gains in performance can be attributed to improved aerodynamics, increased swept area and NREL airfoils with reduced sensitivity to roughness.

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