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Darrieus Wind Turbine Airfoil Configurations

A Subcontract Report

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FOREWORD

This document summarizes the work performed between Feb. 27, 1981 and July 31, 1981 under SERI Subcontract No. AE-1-1045-1, "Darrieus Wind Turbine Airfoil Configurations". The SERI subcontract administrator was Lori A. Miranda, and the technical monitor was Richard L. Mitchell. The objective of the study was to determine the effect of blade airfoil section on the aerodynamic efficiency and annual energy output of Darrieus wind turbines. At least one airfoil family, the NACA 6-series, can provide a significantly greater annual energy output than the NACA 4-digit airfoils normally chosen for Darrieus turbines.

Richard L. Mitchell
Technical Monitor

SUMMARY

The purpose of this study was to determine what aerodynamic performance improvement, if any, could be achieved by judiciously choosing the airfoil sections for Darrieus wind turbine blades. Analysis was limited to machines using two blades of infinite aspect ratio, having rotor solidities from seven to twenty-one percent, and operating at maximum Reynolds numbers of approximately three million. Ten different airfoils, having thickness to chord ratios of twelve, fifteen and eighteen percent, were investigated. Performance calculations indicated that the NACA 6-series airfoils yield peak power coefficients at least as great as the NACA four-digit airfoils which have historically been chosen for Darrieus turbines. Furthermore, the power coefficient-tip speed ratio curves were broader and flatter for the 6-series airfoils. Sample calculations for an NACA 63_2-015 airfoil showed an annual energy output increase of 17% to 27%, depending upon rotor solidity, compared to an NACA 0015 airfoil. An attempt was made to account for the flow curvature effects associated with Darrieus turbines by transforming the NACA 63_2-015 airfoil to an appropriate shape.

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SYMBOLS AND NOMENCLATURE

c	blade chord
C_D	aeodynamic drag coefficient
C_L	aerodynamic lift coefficient
C_P	power coefficient; the ratio of the energy captured by a wind turbine to the energy available in the projected frontal area
R	blade radius
Re	Reynolds number; based on blade rotational speed and blade chord
t	blade thickness
TSR	tip speed ratio; ratio of blade rotational speed to wind speed
α	airfoil angle of attack
σ	rotor solidity; ratio of the total blade planform area to rotor projected frontal area
AEO	annual energy output
NACA	National Advisory Committee for Aeronautics; airfoil designation
WSU	Wichita State University; airfoil designation

SECTION 1.0

ASSESSMENT OF CANDIDATE AIRFOILS

1.1 BACKGROUND INFORMATION

Of the various methods for improving the energy capture of Darrieus wind turbines, perhaps the most subtle and the most effective method is the judicious choice of the blade cross section. Airfoil aerodynamics influence the peak power coefficient, the tip speed ratio at which it occurs, the general shape of the C_p-TSR curve and a variety of other features which significantly impact the cost of energy [1]. Unfortunately, the present state of knowledge regarding airfoil optimization is not very well developed. Analytical and experimental studies have focused mainly on the symmetrical NACA 00XX airfoil family with the NACA 0015 being the airfoil section chosen most often. Some results [2] have been obtained for 15% elliptical airfoils at low Reynolds numbers, but these experimental data also reflect virtual camber and boundary layer centrifugal effects [3] making interpretation extremely difficult.

The purpose of the present study was to investigate a variety of airfoil shapes, other than the NACA 00XX series, in order to identify the performance improvement which might result from their use. Analysis was confined to machines having two blades of infinite aspect ratio, blade thicknesses of 12% to 18%, rotor solidities of 7% to 21% and maximum blade Reynolds numbers of two to three million. This range of parameters was chosen to reflect the configurations which, at the present time, seem to be commercially viable.

1.2 AERODYNAMIC DATA BASE

There are a great number of airfoil families and thicknesses which might be suitable for Darrieus turbines. Since it is impossible to analyze all of them, the choices must be narrowed in some way.

Symmetrical airfoils have been chosen traditionally because energy capture is approximately symmetrical about the turbine's cross-wind axis. While it is possible to increase the energy capture on either the upwind or downwind side by using cambered airfoils, the energy capture on the opposite side is greatly diminished. The existence of a velocity defect between the upwind and downwind parts of the blade orbit complicates matters further. This situation suggests that slightly cambered airfoils might be used to enhance the energy capture on the upwind side where the available energy is greatest. In any case, the performance prediction methods presently available are not sufficiently accurate to reflect the true performance. Therefore, cambered airfoils were not considered in the present study.

Given that the analysis was to be confined to symmetrical airfoils, it became important to consider what aerodynamic characteristics generally improve blade efficiency. Desirable features include low drag and the greatest possible lift curve slope. Large values of C_{Lmax} per se are not usually helpful because they occur at high angles of attack and because high C_{Lmax} is accompanied by high drag coefficients. For Darrieus turbines high angles of attack occur at low tip speed ratios, or conversely, at high wind speeds. Improvements of C_p at these low TRS's are not very helpful because there are very few hours per year when wind speeds reach these high levels. Therefore, selection of candidate airfoils was not strongly influenced by C_{Lmax}.

The lift curve slope $dC_L/d\alpha$ of most airfoils is fairly close to the theoretical value of 2π per radian, and the variation between competing airfoils is really not that great. One must conclude then, that the measure of merit for the various airfoils is low drag.

A variety of references [4, 5, 6] were consulted in an attempt to identify airfoils having the desired characteristics. As is frequently the case, data were not available at an appropriate Re for some of the airfoils. But several promising candidates were chosen for subsequent performance analysis. Since the NACA 00XX family has been a popular choice for Darrieus turbines, it was retained in the present analysis. Two "low drag" airfoils were also included, the NACA 63_b-0XX and the NACA 64_b-0XX. The difference between the two is the chordwise location of the minimum pressure (maximum thickness) point; 30% and 40% of chord, respectively. The WSU 0015 airfoil [7] was also included in the analysis for direct comparison to the NACA 0015. Thicknesses of 12%, 15%, and 18% were investigated for the NACA 00XX, NACA 63_b-0XX, and NACA 64_b-0XX airfoils.

Aerodynamic data were available in the form of C_L and C_D versus α for various Re. Operation of Darrieus turbines is such that Re varies cyclically due to the cyclic variation of the blade relative inflow velocity. For curved bladed machines, Re also varies along the blade span. Strictly speaking, aerodynamic data must be provided over the entire range of operating Re. Performance calculations are then made on the basis of the local Re and α. Unfortunately, aerodynamic data were not available for the entire Re range and the performance calculations were made on the basis of a single constant Re. It is likely, therefore, that the predicted C_p's are slightly optimistic, although the relative comparison between airfoils should still be valid. Table 1-1 shows the Re of the aerodynamic data for the various airfoils.

Table 1-1. AIRFOILS INVESTIGATED

Airfoil Designation	Thickness-%	Reynolds Number	Reference
NACA 0012	12	3.0×10^6	4
NACA 0015	15	2.7×10^6	5
NACA 0018	18	3.0×10^6	4
NACA 63_1-012	12	3.0×10^6	4
NACA 63_2-015	15	3.0×10^6	4
NACA 63_3-018	18	3.0×10^6	4
NACA 64_1-012	12	3.0×10^6	4
NACA 64_2-015	15	3.0×10^6	4
NACA 64_3-018	18	3.0×10^6	4
WSU 0015	15	2.2×10^6	7

1.3 CALCULATION METHODS

Performance of the candidate airfoils was compared on the basis of C_P-TSR plots. Power coefficients were calculated using a blade element-momentum theory method developed by Strickland and described fully in Ref. 8. A program listing and definition of input parameters was supplied by Dr. Paul Klimas of Sandia Laboratories. Aerodynamic data were input as C_L and C_D versus α for a single Re. A parabolic rotor shape was used and the C_p distribution was assumed to be symmetrical about the cross-wind plane of symmetry.

It was originally intended that the computer program would be modified to account for virtual camber effects [3]. Instead, it was decided to use two-dimensional rectilinear flow aerodynamic data, assuming that an actual airfoil geometry which would demonstrate those aerodynamic characteristics could later be contrived. This would be accomplished by using the inverse virtual camber transformation [9].

1.4 POWER COEFFICIENT COMPARISON

Results of the performance analysis are presented as C_P-TSR curves in Fig. 1-1 through Fig. 1-5. It should be noted that, in general, C_P predictions at low TRS's of four or less are usually slightly optimistic. At these low TSR the blade angles of attack exceed the range of available aerodynamic input data. In this case the interpolated C_D values are unrealistically low.

Figure 1-1 shows that the performance of the NACA 0012 airfoil is better in virtually every respect than that of the thicker sections. This is so because the drag is lower for this section. However, the NACA 0015 is the airfoil usually chosen because its structural strength is much greater due to its larger cross sectional moment of inertia. Figure 1-2 shows the C_P-TSR performance of the NACA 63_2-015 and the NACA 63_3-018 airfoils to be virtually identical to each other and slightly superior to the NACA 63_1-012. Continuing the previous agrument, the NACA 63_3-018 would probably be a better choice than the NACA 63_2-015 because of the greatly increased strength associated with its greater thickness. Figure 1-3 shows the NACA 64_b-0XX airfoils having the same thickness trends as the NACA 63_b-0XX airfoils, but comparing the two series to each other shows that the 63 series has slightly better performance than the 64 series. When the various airfoil series are compared to each other, it is clear that the WSU 0015 is not a serious contender and that the NACA 63_2-015 has better performance than the other airfoils investigated. Figure 1-5 is included to show the relative comparison of the NACA 0015 and the NACA 63_2-015 airfoils.

Choice of the optimum solidity is not as obvious as it might appear from a simple inspection of the C_P-TSR results. The 21% solidity gives the greatest peak C_P values, but these occur at low TSR (high wind speeds) where a large amount of power is not available because of the low frequency of occurrence. The 7% solidity blades have greater C_P's than the higher solidity blades at higher TSR's, where the frequency of occurrence is high. From the view point of blade aerodynamic efficiency, therefore, choice of the optimum solidity must consider the annual energy output.

1.5 ANNUAL ENERGY OUTPUT

Inspection of the C_P-TSR curves reveals obvious differences, but quantifying the relative performance of competing airfoils requires as assessment of annual energy output. These calculations were made for the NACA 0015 and NACA 63_2-015 airfoils. The assumed turbine configuration was approximately that of the Sandia 17-meter machine [10]. The assumed annual wind speed distribution and the velocity-height profile conformed to the methods presented by Justus [11]. The average annual wind speed was assumed to be 6 meters per second at a height of 10 meters.

Figure 1-6 shows the increase in AEO of the NASA 63_2-015 blade compared to the NACA 0015 blade. The calculated improvement was 17% for a 7% solidity rotor and 20% for a 14% solidity rotor. This result clearly shows that judicious choice of airfoil section has a noticeable impact on rotor performance as measured by AEO and that the NACA 63_2-015 airfoil is a better choice than the NACA 0015. Figure 1-6 also shows that the 21% solidity rotor produces the greatest energy capture for the 63_2-015 airfoil. For the NACA 0015 airfoil, maximum energy capture occurs at a solidity of approximately 17%.

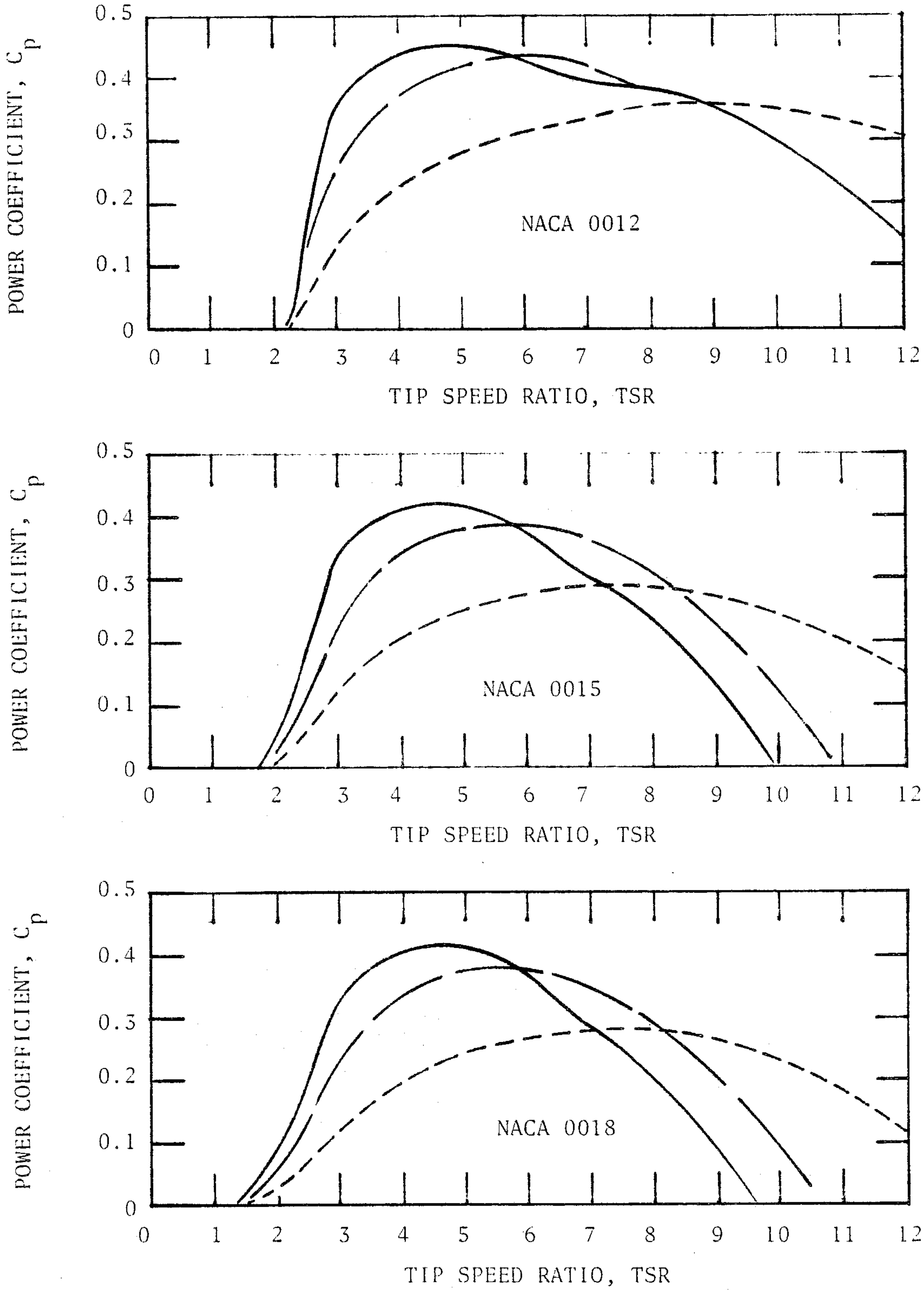


Figure 1-1. C_p-TSR PERFORMANCE OF NACA 00XX AIRFOILS

[--- σ = 0.07, — — σ = 0.14, —— σ = 0.21]

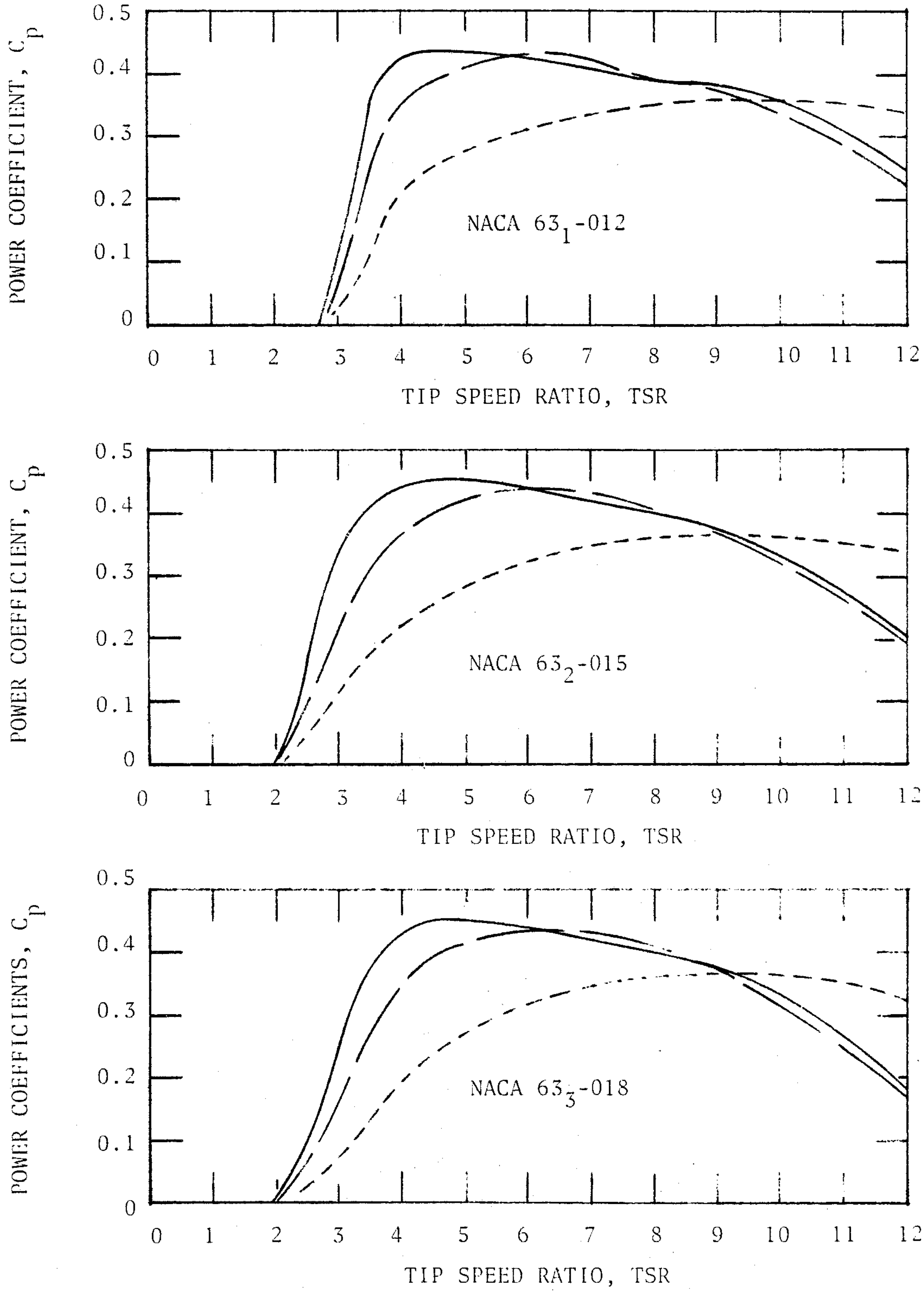


Figure 1-2. C_p-TSR PERFORMANCE OF NACA 63_b-0XX AIRFOILS

[--- σ = 0.07, — — σ = 0.14, —— σ = 0.21]

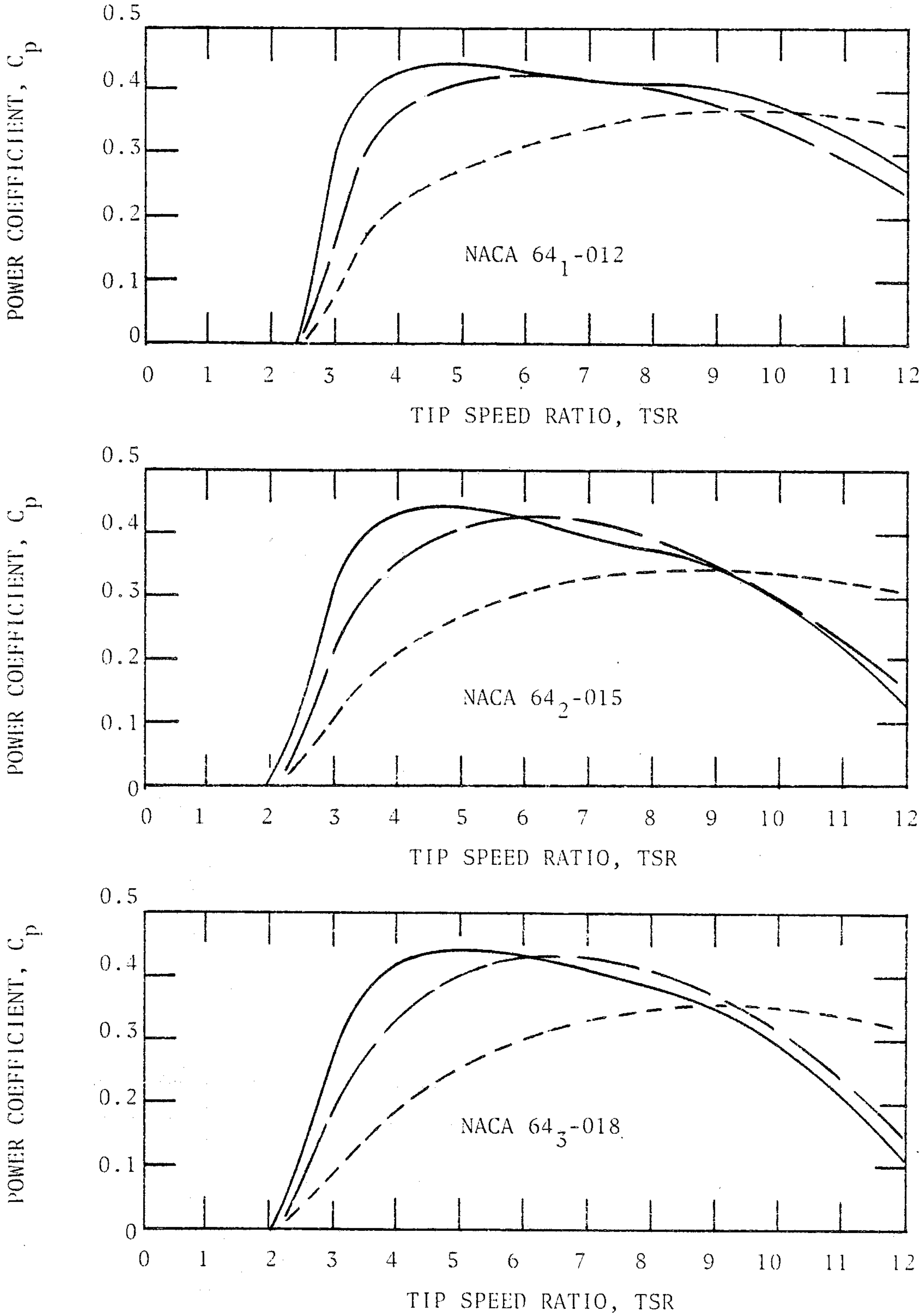


Figure 1-3. C_p-TSR PERFORMANCE OF NACA 64_b-0XX AIRFOILS

[--- σ = 0.07, — — σ = 0.14, —— σ = 0.21]

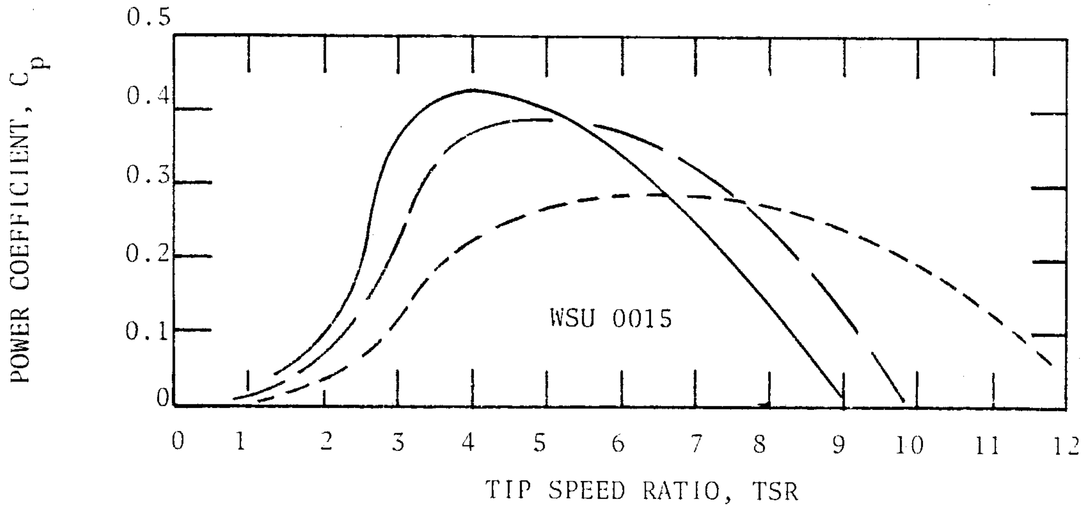


Figure 1-4. C_p-TSR PERFORMANCE OF WSU 0015 AIRFOIL

[--- σ = 0.07, — — σ = 0.14, —— σ = 0.21]

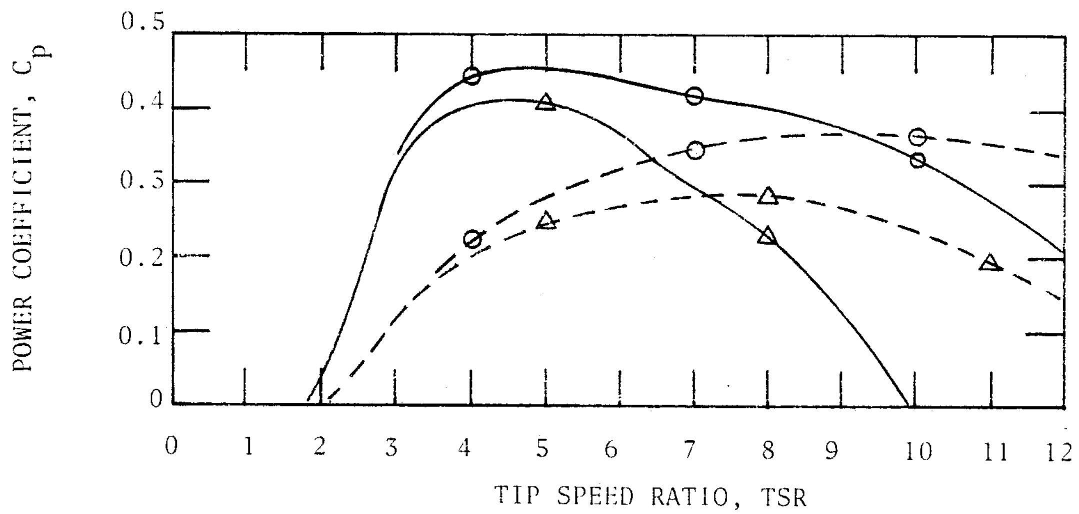


Figure 1-5. COMPARISON OF C_p-TSR PERFORMANCE FOR THE NACA 0015 and NACA 63_2-015 AIRFOILS

[--- σ = 0.07, —— σ = 0.21, ○ NACA 63_2-015, △ NACA 0015]

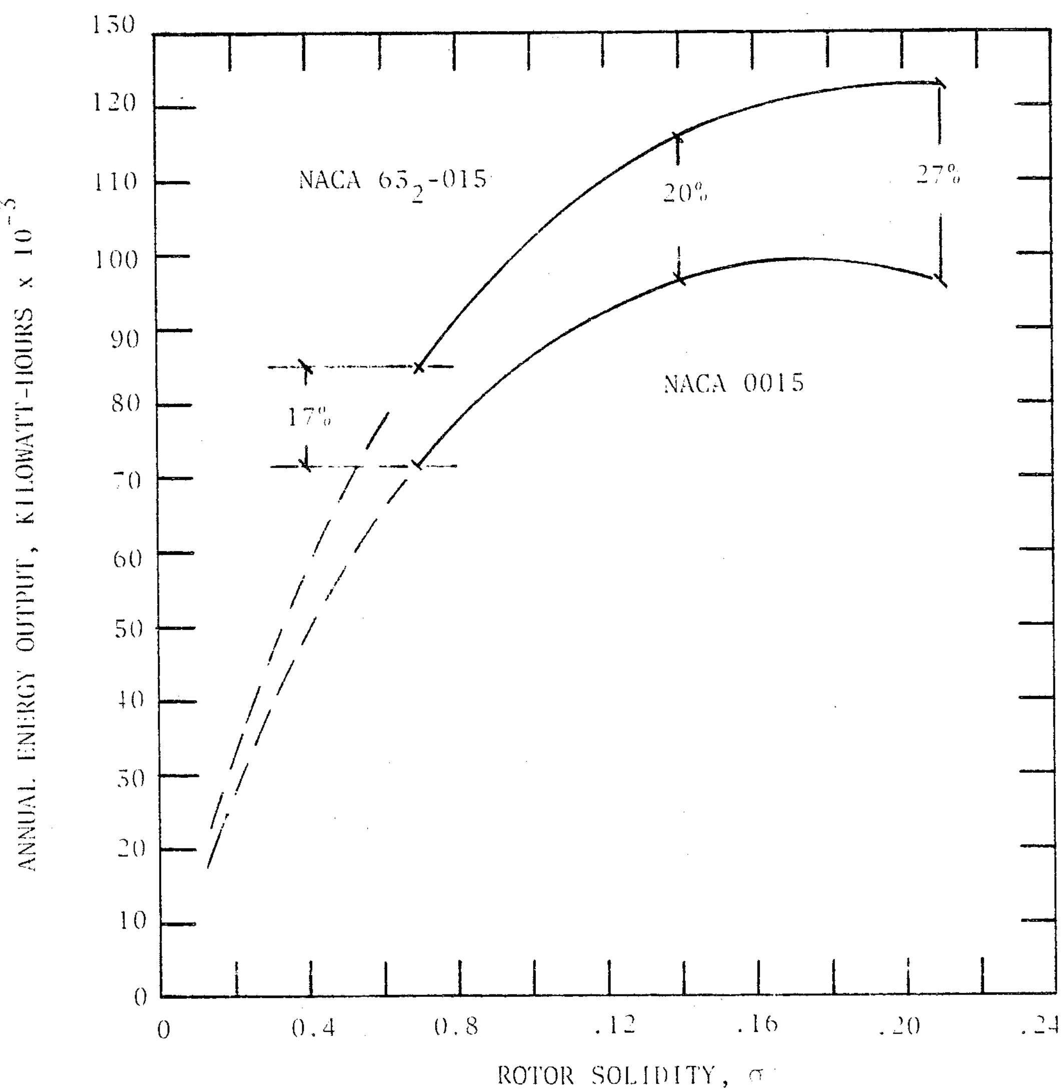


Figure 1-6. ANNUAL ENERGY OUTPUT FOR ROTORS USING NACA 0015 and NACA 65_2-015 AIRFOILS

[Average Annual Wind Speed of 6 mps at 10 m height, Rotor Swept Area of 187 m^2]

SECTION 2.0

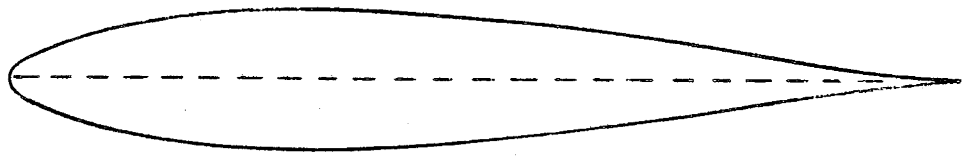
AIRFOIL DESIGN

The performance analysis was based on the aerodynamic characteristics of airfoils in rectilinear flow. It has been demonstrated [2, 3] both analytically and experimentally that Darrieus turbine blades in curvilinear flow experience an apparent camber and incidence which cannot be attributed to the actual geometry of the airfoil. The orbital path of the blade and the associated flow field are responsible for these virtual camber effects. Boundary layer centrifugal effects [3] also come into play. The question which then arises is what actual geometric shape must be used to achieve the assumed aerodynamic properties.

Using the methods presented in Ref. 9, an attempt was made to modify the shape of the NACA 63_2-015 airfoil in the appropriate fashion. The required shape and angle of incidence are dependent on the blade chord to rotor radius ratio and the chordwise location of the mounting point of the blade to the support arm. If boundary layer centrifugal effects are considered, the blade shape is also influenced by the Re at which the blade is operating and by the trailing edge radius of the airfoil. At the present time, there are no techniques available which allow the designer to modify airfoil geometry to account for boundary layer centrifugal effects. Fortunately, these effects become less pronounced at the higher Re, so that in the present case, neglecting them should not significantly alter the aerodynamics of the transformed airfoil.

Figure 2-1 compares the shapes of the original NACA 63_2-015 airfoil and the transformed airfoil assuming a $c/R = 0.07$. The required angle of incidence depends on the blade mounting point. If the mounting point is at mid chord, the angle of incidence is zero. With the mounting point at the quarter chord, the required angle of incidence is - 1.0 degrees nose out. Table 2-1 gives the airfoil coordinates for the original [4] and transformed airfoils.

ORIGINAL NACA 63_2-015 SYMMETRICAL AIRFOIL



TRANSFORMED NACA 63_2-015 CAMBERED AIRFOIL

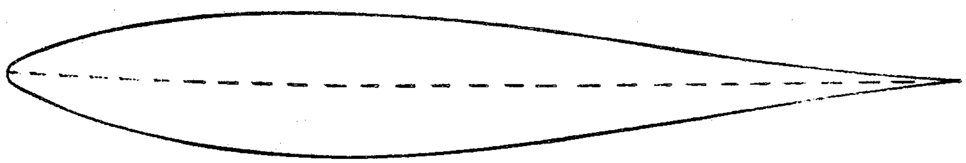


Figure 2-1. INVERSE VIRTUAL CAMBER TRANSFORMED GEOMETRY FOR THE NACA 63_2-015 AIRFOIL WITH $c/R = 0.07$

[Note: Axis of Rotation is toward top of page]

Table 2-1. AIRFOIL COORDINATES FOR TRANSFORMED NACA 63_2-015
Mounting Point: x/c = 0.50; y/c = 0.00; c/R = 0.07

Original Airfoil x/c	Original Airfoil y/c	Transformed Airfoil x/c	Transformed Airfoil y/c
0.000	0.000	0.000	0.000
0.100	0.000	0.100	-0.003
0.200	0.000	0.200	-0.006
0.300	0.000	0.300	-0.007
0.400	0.000	0.400	-0.008
0.500	0.000	0.500	-0.009
0.600	0.000	0.600	-0.008
0.700	0.000	0.700	-0.007
0.800	0.000	0.800	-0.006
0.900	0.000	0.900	-0.003
1.000	0.000	1.000	-0.000

MEAN LINE DATA ABOVE
****
AIRFOIL DATA BELOW

Original Airfoil Upper Surface x/c	Original Airfoil Upper Surface y/c	Transformed Airfoil Upper Surface x/c	Transformed Airfoil Upper Surface y/c
0.000	0.000	0.000	0.000
0.005	0.012	0.005	0.012
0.008	0.015	0.008	0.014
0.013	0.019	0.013	0.018
0.025	0.026	0.025	0.025
0.050	0.036	0.051	0.035
0.075	0.044	0.076	0.042
0.100	0.051	0.101	0.047
0.150	0.060	0.151	0.056
0.200	0.067	0.201	0.061
0.250	0.072	0.251	0.065
0.300	0.074	0.301	0.067
0.350	0.075	0.351	0.067
0.400	0.074	0.401	0.066
0.450	0.071	0.451	0.062
0.500	0.067	0.501	0.058
0.550	0.061	0.551	0.053
0.600	0.055	0.601	0.046
0.650	0.047	0.651	0.039
0.700	0.039	0.701	0.032
0.750	0.031	0.751	0.025
0.800	0.023	0.800	0.018
0.850	0.015	0.850	0.011
0.900	0.009	0.900	0.005
0.950	0.003	0.950	0.001
1.000	0.000	1.000	-0.000

Table 2-1. (continued)

AIRFOIL DATA BELOW

Original Airfoil Lower Surface x/c	Original Airfoil Lower Surface y/c	Transformed Airfoil Lower Surface x/c	Transformed Airfoil Lower Surface y/c
0.000	0.000	0.000	0.000
0.005	0.012	0.005	0.012
0.005	-0.012	0.005	-0.012
0.008	-0.015	0.007	-0.015
0.013	-0.019	0.012	-0.019
0.025	-0.026	0.025	-0.027
0.050	-0.036	0.049	-0.038
0.075	-0.044	0.074	-0.046
0.100	-0.051	0.099	-0.054
0.150	-0.060	0.149	-0.065
0.200	-0.067	0.199	-0.072
0.250	-0.072	0.249	-0.078
0.300	-0.074	0.299	-0.081
0.350	-0.075	0.349	-0.083
0.400	-0.074	0.399	-0.082
0.450	-0.071	0.449	-0.080
0.500	-0.067	0.499	-0.075
0.550	-0.061	0.549	-0.070
0.600	-0.055	0.599	-0.063
0.650	-0.047	0.649	-0.055
0.700	-0.039	0.699	-0.047
0.750	-0.031	0.749	-0.038
0.800	-0.023	0.800	-0.029
0.850	-0.015	0.850	-0.020
0.900	-0.009	0.900	-0.012
0.950	-0.003	0.950	-0.005
1.000	0.000	1.000	-0.000

SECTION 3.0

CONCLUSIONS

The objective of the present study was to determine what performance improvement, if any, could be achieved by judicious choice of airfoil section. The "optimum" section has not been identified, but it has been shown that improvements in C_p-TSR characteristics and AEO are possible. The NACA 00XX airfoils achieve peak C_p's of 0.42 to 0.45, the higher C_p's being associated with the smaller thicknesses. The NACA 63_b-0XX airfoils achieve peak C_p's of 0.44 to 0.46, the higher C_p's being associated with the larger thicknesses. This feature is structurally advantageous. More importantly, however, the NACA 63_b-0XX airfoils have broader, flatter C_p-TSR curves. For example, an NACA 63_2-015 rotor of 14% solidity has a $C_p = 0.26$ at TSR = 11.0, whereas the NACA 0015 rotor has a $C_p = 0$ at the same TSR. This results in a significant increase of 20% in annual enegy output. It may be concluded, therefore, that the NACA 63_2-015 and NACA 63_3-018 airfoils are much better choices than the NACA 0015 airfoil which is frequently used. Furthermore, it is quite likely that even better airfoils could be identified in a more thorough analysis of options.

It should be noted that the foregoing conclusions are based on performance calculations at Reynolds numbers of approximately 3×10^6. These conclusions cannot be generalized to other Re because the airfoil drag, and hence the rotor aerodynamic efficiency, is strongly influenced by Re. In fact, it is almost certain that airfoil selection will be strongly influenced by the proposed Re operating range of the turbine.

SECTION 4.0

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

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17. Document Analysis

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