N83 19234

STALL INDUCED INSTABILITY OF A TEETERED ROTOR

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ABSTRACT

Recent tests on the 38m Mod-0 horizontal axis experimental wind turbine have yielded quantitative information on stall induced instability of a teetered rotor. Tests were conducted on rotor blades with NACA 230 series and NACA 64_3-618 airfoils at low rotor speeds to produce high angles of attack at relatively low wind speeds and power levels. The behavior of the rotor shows good agreement with predicted rotor response based on blade angle of attack calculations and airfoil section properties. The untwisted blades with the 64 series airfoil sections had a slower rate of onset of rotor instability when compared with the twisted 230 series blades, but high teeter angles and teeter stop impacts were experienced with both rotors as wind speeds increased to produce high angles of attack on the outboard portion of the blade. The relative importance of blade twist and airfoil section stall characteristics on the rate of onset of rotor unstability with increasing wind speed was not established however. Blade pitch was shown to be effective in eliminating rotor instability at the expense of some loss in rotor performance near rated wind speed.

INTRODUCTION

The latest large horizontal axis wind turbine designs in the U. S. have shown a definite preference for two-bladed, teetered rotors. This design choice is influenced largely by the cost of wind turbine blades and the reduced loads afford by a teetered rotor on a two-bladed machine. Both the 2.5 MW Mod-2 wind turbine, recently installed at Goodnoe Hills, Washington and the 4 MW WTS-4/SVU wind turbine, under construction at Medicine Bow, Wyoming have two-bladed, teetered rotors. In support of these programs, tests have been conducted of the Mod-0 100 kW Experimental wind turbine to provide information on operational characteristics of two-bladed teetered rotors and results were presented in References 1 and 2.

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Concern was expressed early in the design of teetered rotors about the amplitude of teeter motion which affects tower clearance, Coriolis forces in the drive train, and the design of teeter motion stops. Initial tests on the Mod-0 indicated teeter motions in excess of ±6 degrees could be expected in gusty wind conditions [1]. As more operational experience was gained, it became obvious that the large amplitude teeter motions were connected with a reduced rotor stability margin which occurs as the rotor operates near rated wind speed [2], where high local angles of attack occur on the outboard portion of the rotor blade. Subsequent to this discovery, tests were conducted on the Mod-0 wind turbine to more clearly define the effect of stall on a teetered rotor stability. The results of these tests are the subject of this report.

TEST CONFIGURATION

The teetered rotor stall tests were conducted on the Mod-0 100 kW experimental wind turbine shown schematically in Figure 1. The essential features of the machine are described in References 1 and 2. All tests were conducted in the downwind rotor configuration, i.e., with the rotor downwind of the supporting tower. Two rotor configurations were tested, a fixed pitch rotor with highly twisted aluminum blades and a tip-controlled rotor with steel spar blades having no twist. Both rotors were unconed and used the same teetered hub. The blades are described in the rotor section.

Wind speed was measured at hub height on an anemometer 1.56 rotor diameters upwind of the wind turbine tower. (Wind data are currently being taken at the Mod-0 test site on an array of five measuring stations at hub height, at a radial distance of 59.4m (195 ft.) from the tower centerline and spaced at 45 degree intervals covering the directions of the most prevalent winds. The measuring station most nearly upwind during a test is selected as the reference wind speed.) Wind turbine orientation relative to the wind is determined by the anemometer/wind vane mounted on the nacelle.

The tests were conducted at nominal rotor speeds of 20 and 26 rpm; however, actual rotor speeds were somewhat higher due to slip in the drive train, and more precise rotor speed is presented in the text below. The drive train was changed during the test, with the tests of the fixed pitch aluminum blades being conducted with a synchronous generator and a fluid coupling (for slip) in the drive train, and the steel spar blade test being conducted with a high-slip, 2-speed induction generator and with the fluid coupling removed. Other than the slight change in rotor speed, it is felt that the drive train changes had no effect on the test results.

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Rotor

Two rotors were tested for the effect of stall on teetered rotor instability. The first series of tests was run with aluminum blades which employ the NACA 230 series airfoil and are highly twisted. Due to the constraints of the hub geometry, these blades had to be installed such that the chord plane at the 3/4 radius point made an angle of +2.8 degrees with the rotor plane (feathered is -90 deg.) which exacerbated the tendency to stall by creating high angles of attack at lower wind speeds. The second series of tests was conducted with a steel spar, tip-controlled blade with a high performance NACA 64_3-618 airfoil over the movable outboard 30% of the blade. This airfoil has very gentle stall properties, and the effect of this characteristic on stall was of particular interest in the study. The characteristics of the rotors are summarized in Table 1, blade planforms are shown in Figures 2 and 3, and blade thickness and twist distribution for the aluminum blades are presented in Figures 4 and 5.

Table 1 - ROTOR CHARACTERISTICS

Steel Spar, Tip Control Blade		Twisted Aluminum Blade	
Rotor dia., m (ft). .	38.39 (126.0)	Rotor dia., m (ft).	38.5 (126.37)
Root cutout, % span	23	Root Cutout, % Span	5
Tip control, % span	30	Fixed Pitch	--
Blade pitch, inb'd sec., deg.	Zero	Blade Pitch 75% Span, deg. .	2.8
Airfoil (inb'd sect.) .	NACA 23024	Airfoil	NACA 230 series
(outb'd 30%).	NACA 64_3-618	(root to tip)	
Taper.	Linear	Taper	Linear
Twist, deg.	Zero	Twist, deg.	34
Solidity.	0.033	Solidity.	0.030
Precone, deg.	Zero	Precone, deg.	Zero
Max. teeter motion, deg. . . .	±6	Max teeter motion, deg. . . .	±6
Blade mass, kg (lb) . .	1815 (4000)	Blade mass, kg (lb) .	1043 (2300)
Blade Lock number*.	6.56	Blade Lock number*.	11.95

* Blade Lock number, γ, is the ratio of aerodynamic force to inertia force on a rotor blade and is defined as:

$$\gamma = \frac{\rho a_0 c R^4}{I_B}$$

where

ρ = air density

a_0 = slope of airfoil lift curve

c = average blade chord

R = blade radius at tip

I_B = blade mass moment of inertia

TEST RESULTS

Tests were conducted on the wind turbine at low rotor speeds to reduce the wind speed and power at which blade stall was predicted to occur and at two rotor speeds on the fixed pitch rotor to demonstrate any effects which might occur due to increased rotor speed. Results are presented for the tip-controlled rotor in two modes of operation, first with the blade pitch fixed at zero degrees; and second, in the power control mode with the maximum power set at 90 kW.

The test results are presented in terms of power and teeter angle versus wind speed. Data presented were obtained from a Bins analysis [3] of data taken during wind turbine operation. The median values of alternator power output, and the median and maximum values of each bin of the cyclic teeter angle are shown in Figures 6 to 9. It appears from the test results that the median value of teeter angle is indicative of the behavior of the rotor in steady winds while the maximum value of teeter angle is indicative of the stall margin or the behavior of the rotor in unsteady winds. A decrease in stall margin is indicated by an increase in maximum teeter angle. The results are discussed in detail in the Discussion section below.

Tests were conducted at nominal rotor speeds of 20 and 26 rpm; however, due to various levels of slip in the drive train, slight variations in rotor speed occurred from these nominal values. Rotor speeds at zero power level and at a power level of 100 kW along with the slip at 100 kW as a percent of the zero power rotor speed are given in the table below. Drive train slip has been found to vary linearly with power over the normal range of power levels for both the synchronous generator and fluid coupling drive train and for the rigid drive train with the high-slip induction generator. Rotor speeds and values of slip for each test configuration are presented in Table 2 below.

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Table 2 - Rotor Speed and Drive Train Slip for Configurations Tested

Configuration and Nominal Rotor Speed	Rotor Speed - rpm 0 Power	100 kW	Drive Train Slip %
Aluminum Blades - 20 rpm	20.0	21.4	7.2
Aluminum Blades - 26 rpm	26.3	27.5	4.6
Steel Spar Blade 20 rpm Fixed Pitch Mode	19.9	20.8	4.5
Steel Spar Blade 20 rpm Power Control Mode	20.7	22.2	7.2

We feel that the rotor speed changes due to changes in the drive train have no effect on the general conclusions of this work and therefore the nominal values of rotor speed are used in the data presented below.

Results for the twisted aluminum blades with the NACA 230 series airfoil and for the steel spar, tip-controlled blade with the high performance NACA 64_3-618 airfoil are presented below.

Twisted Aluminum Blades

Figure 6 presents power and teeter angle versus wind speed for the 230 series airfoil at 20 rpm. The power curve indicates that rotor stall begins to occur at a wind speed somewhere between 4.5 and 5.5 m/s and that stall is well established by 7 m/s. The plot of teeter angle indicates similar relationships with wind speed, with the median value of teeter angle starting to increase from a base value of 1.25 degrees at about 5 m/s and total stall occurring at 7 m/s. The maximum value of teeter angle indicates a similar trend with unstalled operation indicated below 3.5 or 4 m/s and fully stalled operation occurring above 6 m/s.

Operation of the twisted aluminum blades at 26 rpm, shown in Figure 7, produced results similar to operation at 20 rpm except that the effects of stall are seen at a wind speed about 2 m/s higher. The power versus wind speed curve shows unstalled operation at wind speeds below 6.5 m/s, the onset of stall at about 7.5 m/s and a fully stalled rotor at 8.5 to 9 m/s. The plot of teeter angle versus wind speed would indicate similar conclusions, particularly when only the median values of teeter angle are considered. Using the maximum values of teeter angle as the stall criterion would reduce the wind speeds for stalled and unstalled rotor operation slightly, however.

Tip Controlled Rotor with High Performance Tips

Figures 8 and 9 present output power and teeter angle data for the tip-controlled rotor with the NACA 64_3-618 high performance airfoil on the moveable tip which extends from the 70% span point to the tip. This airfoil was of particular interest in these tests because of its gentle stall characteristics compared to the NACA 230 series airfoil which loses lift abruptly as the stall angle is exceeded. Section lift characteristic for the airfoils tested are shown in Figure 10. The section lift characteristics are derived from Reference 5 and represent values for a "one-half rough" surface [6] on the outboard section of the rotor blade.

The power versus wind speed curve of Figure 8a indicates this gentle stall characteristic but it is demonstrated more vividly in the teeter angle versus wind speed plot, Figure 8b. Although the maximum values of teeter angle indicates behavior similar to that obtained for the rotor with the NACA 230 series airfoil the median values of teeter angle show a much gentler increase of teeter angle with wind speed. To determine the state of the rotor we must rely on the maximum teeter angle rather than the power curve or the median value of teeter angle since maximum values indicate incidence of extreme motion. Using the maximum teeter angle as the criterion, unstalled operation is apparent at wind speeds below 5 m/s, stall onset occurs between 5 and 6 m/s and the rotor is fully stalled, at wind speeds above 6.5 m/s.

Tests of the tip-controlled rotor were run with the maximum power set at 90 kW, referred to as the Power Control mode in Table 2. These results were of interest because they show the effect of power control on rotor teeter stability. As power control becomes effective, the blades are pitched toward feather which reduces the angle of attack. When the blade angle of attack is low enough to unstall the blades, teeter stability is reestablished. These effects are indicated in the results presented in Figure 9. The power versus wind speed plot, Figure 9a, is linear with wind speed and shows no tendency to flatten as wind speed increases, over the wind speed range of the test. The teeter angle plot, however, indicates major differences when compared with the fixed pitch case shown in Figure 8. The median value of teeter angle increases with wind speed until a wind speed of 8 m/s is reached where the teeter angle decreases as power control becomes effective and starts to reduce blade pitch angle to maintain the power set point. The effect of power control is also seen in the maximum value of teeter angle where the data indicates that impact with the teeter stops did not occur at wind speeds in excess of 11 m/s showing the effect of blade pitch angle in reducing the angle of attack on the tip section and reestablishing rotor stability.

A comparison of the teeter angles for fixed pitch operation, Figure 8b, with those of the power control mode of operation, Figure 9b, will show that teeter angles for wind speeds below 8 m/s are higher for the power control mode of operation. No explanation can be given for this difference at this time. Both rotors are operating in the fixed-pitch, full power position at those wind speeds and all other machine parameters with the exception of a small change in rotor speed, were the same. The difference could arise from a difference in the character of the wind for the two tests. Each test was run for a period of approximately 3 hours on different days and turbulence or shear in the wind could affect the results. Regardless of the differences in the details, the general relationships and information obtained are felt to be valid.

DISCUSSION

The test data indicates graphically the effect of blade stall on the stability of teetered rotors. The fact that nearly identical teeter response occurs on the fixed pitch rotor with twisted aluminum blades at 20 and 26 rpm but at 2 m/s higher in wind speed indicates that the rotor instability observed is strongly related to the local angle of attack on the outboard portion of the blade. Figure 11 shows calculated values of angle of attack versus wind speed for 20 and 26 rpm, at 0.7 and 0.9 span for the twisted aluminum blade, obtained from the PROP code [4]. Figure 12 shows similar data for the tip controlled rotor operating at a fixed pitch angle of zero degrees. Figure 11 shows a 2 m/s difference between 20 and 26 rpm for the same local angle of attack. It is also of interest to note that with the highly twisted blades, see Figure 11, the 0.7 and 0.9 blade stations are predicted to have approximately equal angles of attack near the stall point of 14 degrees. This could explain the abrupt nature of the stall indicated by the median teeter angle values in Figures 6b and 7b, as well as the sharp stall characteristics of the NACA 230 series airfoils shown in Figure 10. Indeed, the fact that the twisted blades tested are predicted to stall over the outboard 30% of the blade at the same wind speed may be the most important factor in the behavior of the fixed pitch rotor. Tests are planned with untwisted blades and the NACA 230 series airfoil which may shed more light on the relative importance of twist and airfoil two-dimensional stall characteristics on teetered rotor stability.

The untwisted blades of the tip-controlled rotor, see Figure 12, experience a calculated angle of attack difference of 2 degrees or more from the 0.7 to the 0.9 blade station which could have some effect on the behavior of teeter angles as wind speed increases, as well as the benign stall characteristic of the NACA 64 series airfoil. Unfortunately the configurations tested did not eliminate this variable from the data.

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If the wind speed is obtained for a given rotor condition, i.e., stable or unstable, from Figures 6b, 7b, and 8b, an approximate angle of attack for each condition for the blade tip can be obtained from Figures 11 and 12 which present calculated angles of attack versus wind speed for each rotor. This process has been followed and the results are presented in Table 3 below.

Table 3 - CALCULATED ANGLES OF ATTACK FOR STABLE AND UNSTABLE ROTORS (Average values for Outboard 30% of Blade)

Rotor Configuration	Stable		Unstable	
	Wind Speed m/s	Angle of Attack deg.	Wind Speed m/s	Angle of Attack deg.
230 Series, 20 rpm	4	8.5	6+	13.5
230 Series, 26 rpm	6	9.5	8+	13.5
64 Series, 20 rpm	5	6.5	6.5	9.5

Airfoil section lift properties for the two rotors, derived from Reference 5, are shown in Figure 10. Locating the calculated angles of attack for stalled and unstalled operation on the section lift curves, shows that the calculated angle of attacks and the section lift curves give a good indication of rotor stability for both the NACA 230 series and for the NACA 64_3-618 rotors. In the case of both airfoils, a stable rotor is indicated when the angle of attack is along the linear portion of the section life curve and a stalled rotor is indicated by an angle of attack which is high enough to place the blade on the non-linear portion of the curve. Also, the results indicate that a rather straightforward calculation of blade angle of attack will show where teetered rotor stall can be expected. Operation on the non-linear portion of the lift curve reduces damping which makes the teetered rotor lose stability margin. This makes it subject to high amplitude teeter motions in variable winds.

The results from the teeter angle response tests indicate the need to pitch the blades toward feather as the blade local angle of attack approaches the non-linear portion of the section lift curve. In cases where rotors operate at high blade angles of attack, this action would provide a stall margin and prevent excessive teeter motion. This approach would reduce the performance of the rotor near rated wind speed somewhat, but would reduce the chance of impacting the teeter stops which would improve the reliability and life of the rotor.

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CONCLUSIONS

Tests conducted on the 100 kW Mod-0 experimental wind turbine have demonstrated the causes and effects of stall induced teetered rotor instability. As a result of the experiments performed the conclusions listed below were derived.

- o Rotor stall which produces teetered rotor instability occurs when the angle of attack on the outboard 30% of the rotor blade approaches the non-linear portion of the section lift curve of the airfoil.
- o Tests at two rotor speeds indicated that rotor speed had no influence on stall. The same effects were noted at approximately the same tip speed ratio, i.e., at a higher wind speed for the higher rpm case.
- o Blade angle of attack calculations made with relatively straightforward aerodynamic techniques and airfoil section lift properties appear to explain fully the basic elements of stall induced teetered rotor instability.
- o Blade pitch can be used to provide a stability margin which will prevent or reduce the tendency of rotors to become unstable near rated wind speed. This will result in a slight loss of rotor performance however.
- o The relative importance of blade twist and of airfoil section stall characteristics on the rate of onset of rotor instability with increasing wind speed was not established by these tests. Tests are planned which will provide this information.

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3. Richards, T. R. and Neustadter, H. E.: DOE/NASA Mod-0A Wind Turbine Performance. DOE/NASA 1004-78/13, NASA TM-78916, 1978.
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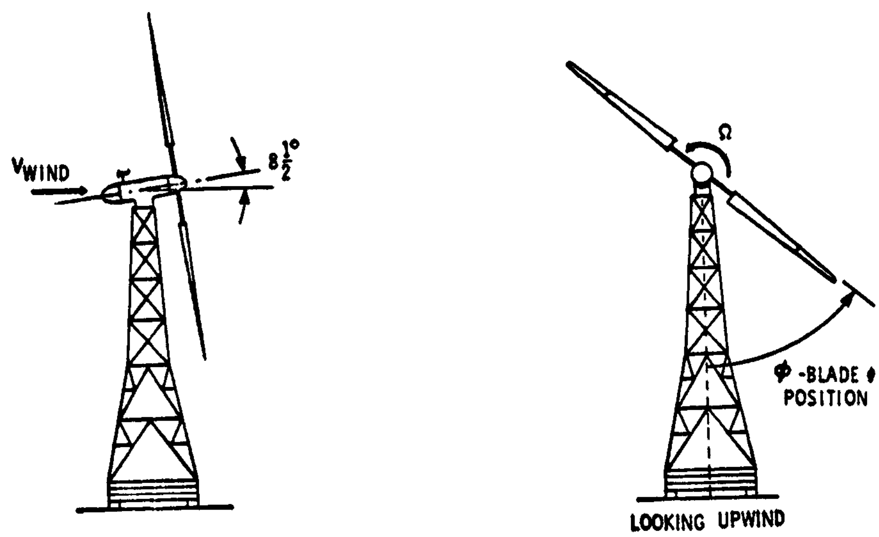
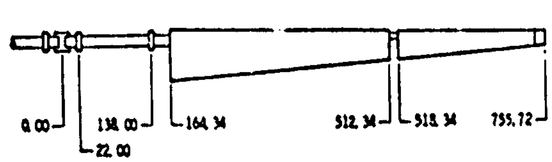
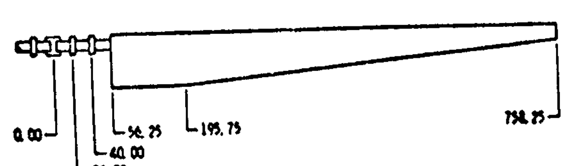


Figure 1. - Mod-0 100 kW Experimental Wind Turbine with Teetered, Tip-Controlled Rotor.



STATION	RADIUS, m	CHORD, m
164.34	4.174	1.964
512.34	13.013	1.171
518.34	13.166	1.154
755.72	19.195	.872

Figure 2. Steel Spar, Tip Control Blade Planform



STATION	RADIUS m	CHORD, m
56.25	1.43	1.473
195.75	4.97	1.473
758.25	19.25	.457

Figure 3. Twisted Aluminum Blade Planform

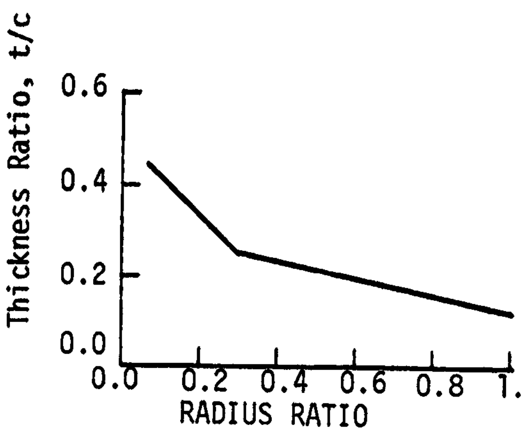


Figure 4. Thickness to Chord Ratio for Twisted Aluminum Blade

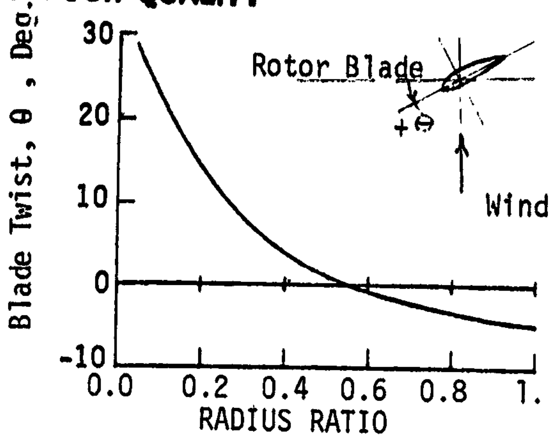
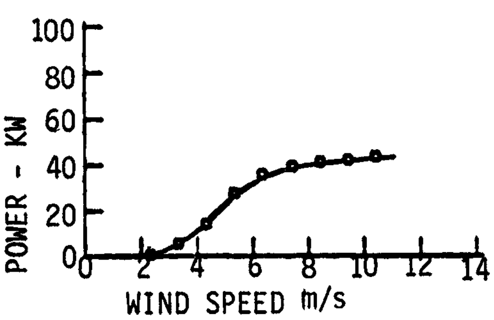
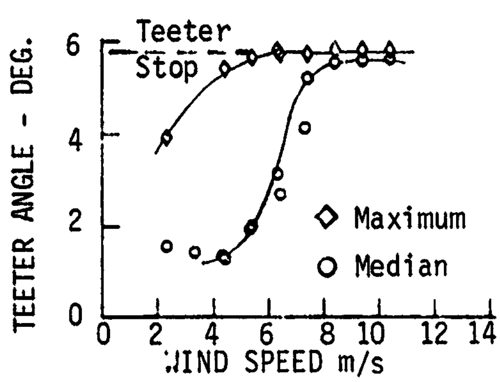


Figure 5. Twist Distribution for Twisted Aluminum Blades

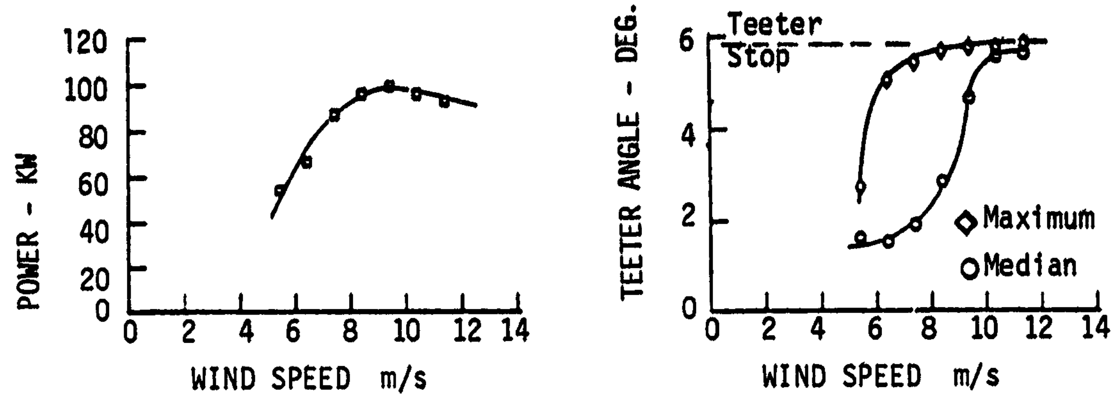


(a) Alternator Power



(b) Cyclic Teeter Angle

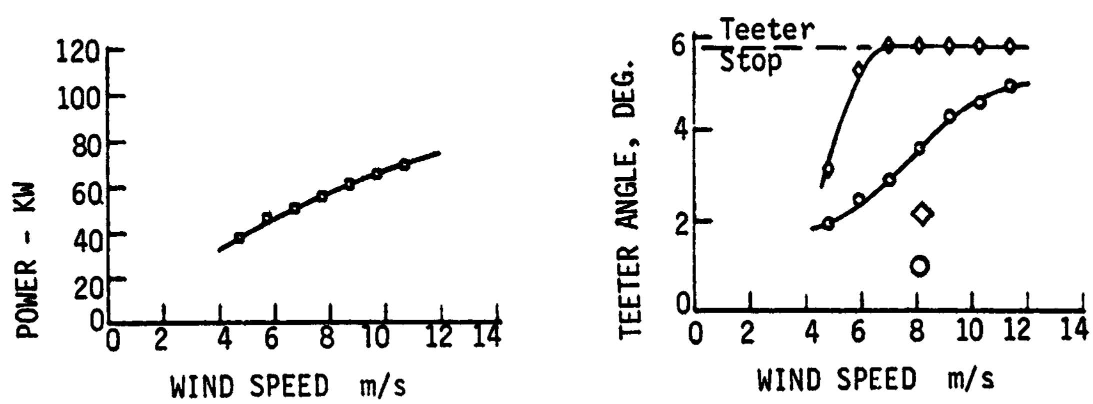
Figure 6. Fixed Pitch Rotor with NACA 230 Series Twisted Aluminum Blades at 20 rpm; (a) Alternator Power Output, and (b) Cyclic Teeter Angle Versus Wind Speed



(a) Alternator Power

(b) Cyclic Teeter Angle

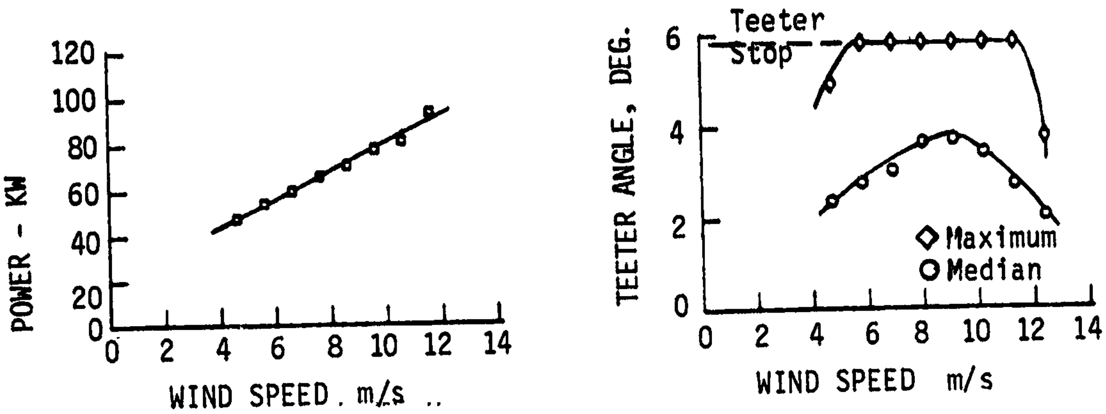
Figure 7. Fixed Pitch Rotor with NACA 230 Series Twisted Aluminum Blades at 26 rpm; (a) Alternator Power Output and (b) Cyclic Teeter Angle versus Wind Speed



(a) Alternator Power

(b) Cyclic Teeter Angle

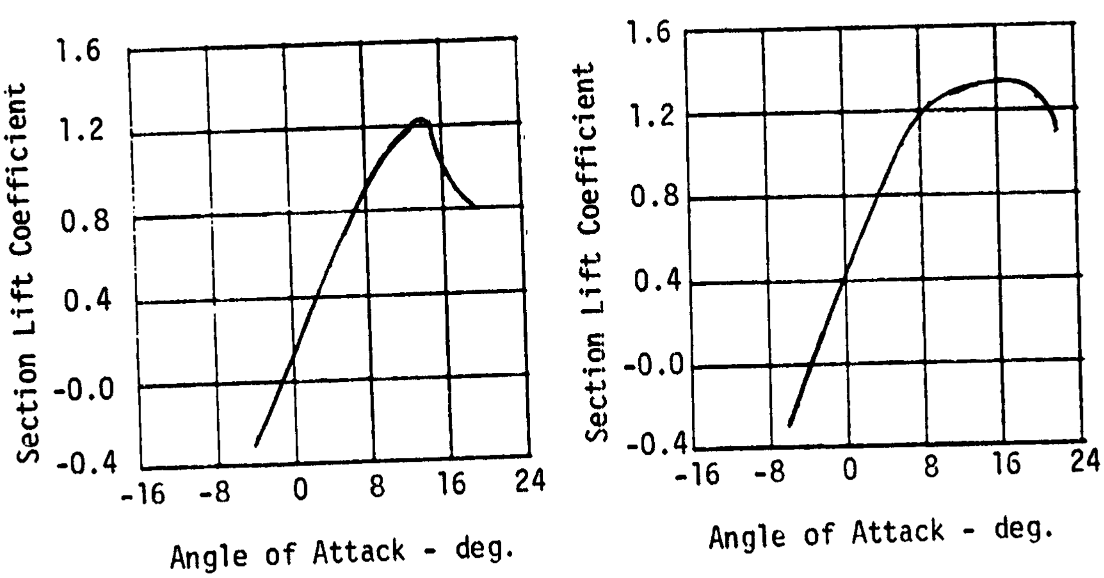
Figure 8. Tip-Controlled Rotor with NACA 64_3-618 Moveable Tip in Fixed Pitch Mode at 20 rpm; (a) Alternator Power Output and (b) Cyclic Teeter Angle Versus Wind Speed



(a) Alternator Power

(b) Cyclic Teeter Angle

Figure 9. Tip-Controlled Rotor with NACA 64_3-618 Moveable Tips in Power Control Mode at 20 rpm; (a) Alternator Power Output and (b) Cyclic Teeter Angle versus Wind Speed



(a) NACA 23018

(b) NACA 64_3-618

Figure 10. Section Lift Characteristics for (a) NACA 23018 and (b) NACA 64_3-618 Airfoils. From Abbott, van Doenhoff, and Stivers [5], ("half rough")

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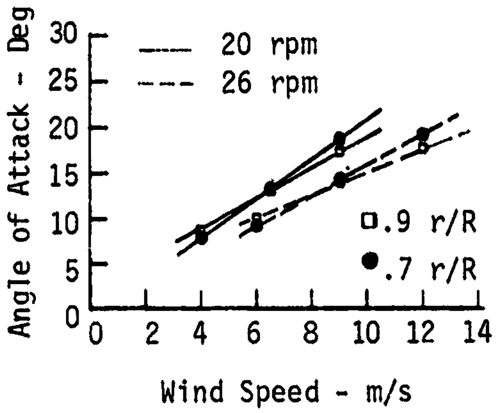

Figure 11. Calculated Blade Angle of Attack Versus Wind Speed for Twisted Aluminum Blade at 0.7 and 0.9 Blade Span for Two Rotor Speeds 20 and 26 rpm

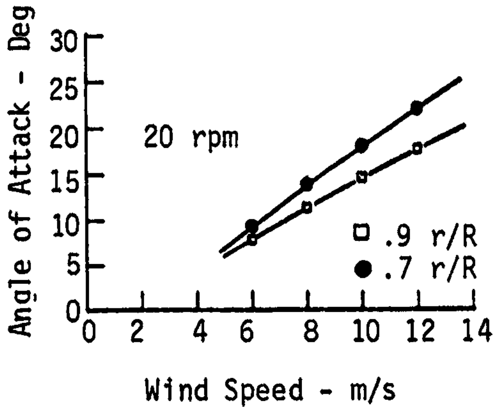

Figure 12. Calculated Blade Angle of Attack Versus Wind Speed for Tip-Controlled Blade, for Blade Pitch Angle of 0 Deg., at 0.7 and 0.9 Blade Span. Rotor Speed 20 rpm