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U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
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ABSTRACT

Tests were conducted on the Mod-0 100 kW Experimental Wind Turbine to determine the effects of yaw on rotor power, blade loads and teeter response. The wind turbine was operated for extended periods at yaw angles up to 49 deg to define average or mean response to yaw. As a result of the tests it was determined that the effect of yaw on rotor power can be approximated by the cube of the velocity normal to the rotor disc as long as the yaw angle is less than 30 deg. Blade bending loads were relatively unaffected by yaw, but teeter angle increased with wind speed as the magnitude of the yaw angle exceeded 30 deg indicating a potential for teeter stop impacts at large yaw angles. No other adverse effects due to yaw were noted during the tests.

INTRODUCTION

The development of the technology required for a successful fixed-pitch rotor for a large horizontal axis wind turbine is an objective of the Research and Technology Program at the NASA-Lewis Research Center. Such a rotor would greatly simplify the wind turbine and result in a considerable reduction in the cost of energy. One method proposed for controlling such a rotor is yawing the rotor into and out of the wind either to maintain power level as wind speed varies or to unload the rotor for either shutdown or in case of loss of load. The purpose of this paper is to present test results which show the effect of yaw on rotor power, blade loads and teeter angle. This information is directly applicable to intermediate sized rotors and can be used as a check on the validity of theoretical calculations, which may be extended to predict the behavior of larger rotors.

The results presented were obtained on the DOE/NASA Mod-0 100kW Experimental Wind Turbine located near Sandusky, Ohio. The test is one of a series of tests planned to demonstrate various concepts which are essential to the technology required for the development for a fixed pitch rotor.

TEST CONFIGURATION AND EQUIPMENT DESCRIPTION

Tests were conducted on the NASA Mod-0 100 kW Experimental Wind Turbine. The wind turbine was configured with a teetered, down wind, two bladed rotor which operated at a nominal rotor speed of 31 RPM. The main elements of the wind turbine are described in Reference 1.

The Mod-0 wind turbine is shown in Figure 1. A truss tower supports the nacelle, whose longitudinal axis is tilted 8-1/2 deg to the horizon to provide adequate blade/tower clearances. The rotor hub, mounted on the elevated end of the nacelle, is 31.8 meters above ground level. A cutaway view of the nacelle is shown in Figure 2. Parts of the configuration and support equipment which are particularly important to these tests are described below.

Rotor & Drive Train

The rotor assembly consisted of a two bladed teetered rotor with $\pm$ 6 deg of teeter motion and 0 deg of coning, and two blades. The rotor blades were 19.18 meters long with controllable tips over the outboard 30% of span. They were untwisted, tapered and had a NACA 23024 series airfoil over the inboard section and a NACA 64_3-618 series airfoil over the outboard 30% of the blade. The blades were mounted so to have a 0^o pitch angle with respect to the rotor plane, and the tips were pitchable from $+10^o$ to -65^o (-90^o is feathered) to provide aerodynamic control. In the tests, the pitch control system was set to maintain a rated power of 100 kW. Detailed rotor and blade characteristics are presented in Table 1 and the blade planform is shown in Figure 3.

TABLE 1

CHARACTERISTICS OF THE STEEL SPAR, TIP CONTROLLED BLADES

Rotor dia., m (ft.)	38.39 (126.0)
Root cutout, % span	23
Tip control, % span	30
Blade pitch, inb'd sec., deg	Zero
Airfoil (inb'd sect.)	NACA 23024
(outb'd 30%)	NACA 64_3-618
Taper	Linear
Twist, deg	Zero
Solidity	0.033
Precone, deg	Zero
Max. teeter motion, deg	± 6
Blade mass, kg (lb.)	1815 (4000)

The drive train/generator assembly consisted of a low speed shaft connecting the rotor to the gear box, and a high speed shaft connecting the gear box to the generator. A two-speed high-slip induction generator set in the high speed mode was utilized in the tests. Rotor speed varied linearly from 30.8 rpm at a zero power level to 32.1 rpm at 100 kW. Measured drive train/generator efficiency was .91 and generator slip was 4% at 100 kW.

Yaw Control

The yaw drive assembly, shown in Figure 2, consists of a single hydraulic motor/clutch/gear reducer system connected to a pinion gear. This in turn moves the nacelle through a ring gear. The yaw drive assembly is actuated by a yaw controller. The yaw controller compares the nacelle yaw angle reading, from the nacelle-mounted wind vane 3.4 meters above the nacelle and 4.6 meters upwind of the rotor, with a desired yaw angle or controller set point. The controller has an allowable yaw angle error band of ± 20 deg, which, when exceeded for 10 seconds, actuates the system and yaws the nacelle until the yaw angle error is reduced to within a band of ± 15 deg of the set point. The yaw brake was used to dampen nacelle yawing motions and to prevent oscillatory yaw loads from being transmitted to the yaw drive.

For active yaw, the yaw control system was operated with the clutch engaged and the yaw brake pressurized. For free yaw, the yaw drive was disengaged from the ring gear by the clutch and the yaw brake was released, allowing the nacelle to move freely about the yaw axis.

Meteorological Data

Meterological data was taken from instruments mounted at rotor hub height on an array of five measuring station towers 59.4 meters (1.56 rotor diameters) from the wind turbine and spaced 45 deg apart. For a given test run, the tower most nearly upwind of the wind turbine was selected as the reference wind station. Both wind speed and direction were measured at this point and these values were used to determine wind speed and yaw angle. Yaw angle was also measured on the nacelle mounted wind vane and this data is shown in certain instances, and noted, in the report.

SIGN CONVENTION AND DESCRIPTION OF TERMS

Tests were run with the wind turbine in the downwind rotor configuraton and with the nacelle maintained at various yaw angles. Data were taken to define power, loads and teeter response characteristics at the various yaw angles. Data collection and initial data reduction was accomplished by the system described in Reference 2. Further data analyses was accomplished by the "method of bins" described in Reference 3. Explanations and definitions of the terms used in describing the test results are given below.

Rotor and Alternator Power

In determining wind turbine performance, two items were evaluated: alternator power and rotor power. Alternator power was measured directly and rotor power was obtained by processing alternator power thru a drive train loss model:

$$P_2 = 1.004 + 1.0953\, P_1 \quad (1)$$

where,

P_1 = Alternator Output (kW)

P_2 = Rotor Power (kW)

This model was based on a bins analysis of experimental data which defined rotor torque and speed for each alternator power level. Thus, the model reflects the mechanical and electrical losses for the entire drive train/generator systems.

Yaw Angle

The orientation of the rotor with respect to the wind, or yaw angle, is the angular difference between the azimuth of the nacelle longitudinal axis and the wind aximuth as shown in Figure 4. Nacelle and wind azimuths, Ψ_N and Ψ_W, are measured in degrees from north. Yaw angle, Ψ_{NW}, is measured relative to the wind. A positive yaw angle results if the nacelle azimuth is larger than the wind azimuth and is shown in Figure 4 and by the equation below.

$$\Psi_{NW} = \Psi_N - \Psi_W$$

During these tests, two separate yaw angle measurements were utilized, each distinct because of the instrumentation that measured the wind azimuth. The yaw angle used for presentation of most of the data is referred to as the "reference yaw angle" because the wind azimuth was measured at the upwind reference measurement station, which is unaffected by the wind turbine. The yaw angle used by the yaw controller is referred to as the yaw angle measured on the nacelle because it uses the wind azimuth of a wind vane/anemometer mounted on the nacelle. The reason a distinction is made between the reference yaw angle and yaw angle measured on the nacelle is that experimental data indicates there are nacelle/rotor interference factors affecting the yaw angle measurements taken on the nacelle. The effect of these interference factors can be seen in Table 2, where the yaw angle measurements from the nacelle readings are compared with reference yaw angle measurements.

TABLE 2

YAW ANGLE RELATIONSHIPS

YAW CONTROLLER SET POINT DEG	YAW ANGLE FROM NACELLE WINDVANE DEG	YAW ANGLE FROM UPWIND REFERENCE STA. DEG
0	-8	-8
-30	-40	-29
FREE YAW	-53	-40
-60	-60	-49

The tests were run by setting the yaw controller to maintain the wind turbine at a predetermined yaw angle. For the free yaw case, the wind turbine was operated with the yaw drive disengaged. In the series of tests conducted for this report, the wind turbine was operated in the negative yaw angle regime, specifically at yaw angle controller set points of 0, -30, -60 deg and free yaw. Negative yaw angles were chosen because prior testing (1) indicated that negative yaw angles produced lower teeter angles than did positive yaw angles. This teeter motion characteristic is the result of the direction of rotation of the rotor; because; at negative yaw angles the in-plane component of the wind opposes the effect of wind shear and tower interference. Thus, the velocity on the top blade is reduced and on the bottom blade it is increased. This reduces the teeter angle and changes the phase angle.

The analyses of the data indicated median reference yaw angles of -8, 29, -40 and -49 deg for the nominal yaw control settings of 0, -30, free yaw and -60 deg respectively.

Teeter Response

The elements essential in describing the motion of a teetered rotor are shown in Figure 5 and described below. When a rotor is turning in a uniform flow without teetering, the blade tips define a circular track in a plane which is perpendicular to the axis of rotation. This plane is called the rotor reference plane. Teeter motion is described by two quantities, maximum teeter angle, β_{max}, and phase angle, ξ. Positive teeter angle is defined as that teeter angle which causes blade #1 to move upwind of the rotor reference plane and, of course, maximum teeter angle is the largest positive teeter angle during a given rotor revolution. The point of maximum teeter angle is located by a phase angle, ξ, which describes the angular position of β_{max} relative to the lowest point of the rotor disc. In steady wind conditions, the rotor teeters at a frequency approximately equal to the rotor speed or, once per revolution. This produces a tilt in the plane described by the blade tip path relative to the rotor refernece plane. Teeter amplitude, β_{max}, defines the angle the rotor plane makes with rotor reference plane while the phase angle, ξ, defines the orientation of the tilted plane relative to the rotor zero position.

Blade Bending

Bending moments were measured on the rotor blades at Station 35, which is near the blade root. Flatwise bending moments which produce compression in the blade high pressure side are positive i.e. negative flatwise bending is produced on the blade when an unconed rotor is extracting power from the wind. Chordwise or edgewise bending is considered to be negative when tension is produced in the blade trailing edge, i.e. negative chordwise bending is produced when the rotor is extracting power from the wind.

Rotor Position

Rotor position, ϕ, describes the angular position of blade #1 in rotor plane. It is measured in degrees from zero to 360 with zero starting at the lower vertical axis. The rotor direction of rotation is indicated in Figure 1 and by the vector, $\overline{\Omega}$, in Figure 4.

RESULTS AND DISCUSSION

The test data were analyzed using bins averaging techniques and are presented as a function of wind speed for the four yaw angles. The effects of yaw on power output, blade bending loads, and teeter response are discussed below. Aside from the effects described on these operational characteristics, no other adverse effects were noted that could be associated with operation at yaw angles to -49 deg.

Power Output

The power produced by the wind turbine at various yaw angles is presented in Figure 6 which shows alternator power versus wind speed for the four yaw angles: -8, -29, -40 and -49 deg. The rated power level during the test was set at 100 kW, and power output was measured for wind speeds from below cut-in to well above rated wind speed. The effect of yaw angle on power at a given wind speed is quite evident in the data presented. As indicated previously, the data was obtained by setting the yaw control to align the wind turbine at angles of 0, -30, and -60 deg and a "free yaw" condition. The yaw angles indicated on the figures are median reference yaw angles corresponding to the yaw control settings. The alternator power data was converted to rotor power as described once per revolution. This produces a tilt in the plane described by the blade tip path relative to the rotor refernece plane. Teeter amplitude, β_{max}, defines the angle the rotor plane makes with rotor reference plane while the phase angle, ξ, defines the orientation of the tilted plane relative to the rotor zero position.

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In obtaining the analytical predictions, a third order curve fit of the rotor power data for a yaw angle of -8 deg. was made of the form:

$$\text{Rotor Power} = BV^3 + D \tag{2}$$

Corresponding to the relationship

$$\text{Rotor Power} = \frac{1}{2}\rho A C_p V^3 + D \tag{3}$$

where:
- A = Area of Rotor Disc
- B = Constant
- C_p = Coefficient of Power
- D = Drive Train Loss (assumed constant)
- V = Wind Velocity
- ρ = Air Density

In the analytic predictions, wind velocity, V, was modified to reflect the velocity normal to the rotor disc for a rotor operating at a yaw angle,

Ψ_{NW}, or,

$$V = V \cos \Psi_{NW}.$$

Applying this relationship to the equation derived for rotor power produced the curves for the various yaw angles. These curves are compared with the test data in the figure and indicate good agreement for yaw angles of -29 and -40 deg at power levels below 50 kW but very poor agreement for a yaw angle of -49 deg. The agreement between measured data and analytical predictions also deteriorates as the power level increases with the test data indicating less power than would be predicted by the $\cos^3 \Psi_{NW}$ relationship.

The test data indicates only fair agreement using the $\cos^3 \Psi_{NW}$ correction to account for yaw effects on rotor power. The correction is probably adequate for most applications at yaw angles of 30 deg or less but for predictions at larger yaw angles a more sophisticated approach is required.

Blade Bending Loads

Flatwise and chordwise bending moments measured at blade station 35 are shown in Figures 8 and 9. All bending moments are median values obtained from a bins analysis of the test data and are shown as a function of wind speed for each of the four yaw angles, -8, -29, -40 or free yaw, and -49 deg. Mean and cyclic values of the bending moments are shown. The sign convention used for blade bending loads defines flatwise bending to be positive when the load produces compression on the high pressure side of the airfoil and chordwise bending to be positive when the load produces compression in the trailing edge of the blade. With this sign convention, mean flatwise and chordwise bending are negative at the blade root when the rotor is operating at rated wind speed.

Flatwise Bending

Figure 8 shows mean flatwise bending for each of the yaw angles -8, -29, -40 and -49 deg. The data for -8 deg is typical of flatwise bending data and shows the magnitude of the bending load increasing as wind speed increases from cut-in to rated wind speed as the drag on the rotor is increased. At wind speeds above rated, however, the blades are feathered to maintain rated power and the magnitude of the bending moment is decreased.

When the rotor is operated at a yaw angle, rated wind speed increases as the magnitude of the yaw angle increases as indicated in the power curves shown in Figure 6. This characteristics is likewise reflected in the flatwise bending moments at various yaw angles shown in Figure 8. As the magnitude of the yaw angle increases the point where the largest negative bending moment occurs is higher in wind speed, and the magnitude of the bending moment decreases again as wind speed increases above the new rated wind speed. This occurs for a yaw angle of -29 deg but for yaw angles of -40 and -49 deg the test was not run at wind speeds high enough above rated wind speed (at these yaw angles) to show that the magnitude of the bending moment would decrease with still higher speeds. It appears likely that this would occur.

The cyclic component of flatwise bending moment is shown in Figure 8b and shows an increasing trend with wind speed which is characteristic of downwind rotors (4). The data indicates very little change in the cyclic bending moment with yaw angle and no recognizable trend.

Chordwise Bending

Chordwise bending moments at blade station 35 are shown in Figure 9. The mean component of chordwise bending near the blade root reflects the torque applied to the rotor and should therefore show an increase in magnitude with wind speed starting near zero at cut-in wind speed and increasing (in magnitude) up to rated wind speed. At this point mean chordwise bending should remain nearly constant as wind speed continues to increase, reflecting a constant torque corresponding to rated power level.

This characteristic is indicated clearly in the mean chordwise bending data shown for the case with a yaw angle of -8 deg. However, the data for the other yaw angles while showing the expected general trend, indicate some variations for which we have no immediate explanation. For example, the magnitude of the change in mean chordwise bending from cut-in to rated wind speed is about 20% larger for yaw angles of -29, -40 and -49 deg than it is for the baseline case of -8 deg. Also, the shape of the curve for the -40 deg, free yaw case is different from that which would be predicted based on the power output for this case. Chordwise bending increases (in magnitude) at a much lower wind speed than does the power. Of the four cases presented, the free yaw case at a -40 deg yaw angle is the only one exhibiting this trend. The other cases use controlled yaw and the trend for these follow closely that which would be expected based on the measured output power versus wind speed relationships.

A detailed analysis of the loads associated with this free yaw condition may explain the measured data for this case. The 20% difference in chordwise bending relative to the -8 deg yaw angle case may be associated with the data reduction techniques used in the bins analysis which may be sensitive to changes in tower interference effects. These are merely suppositions, however, and cannot be verified at this time.

Cyclic chordwise bending loads are shown in Figure 9b and as with the flatwise bending, cyclic chordwise bending shows little or no identifiable trend with yaw angle. Cyclic chordwise bending is dominated by the gravity load and the slight increase with wind speed is characteristic of this load, reflecting increased blade vibratory response.

Teeter Response

Two quantities are important in describing the motion of a teetered rotor: teeter angle and phase angle. Since rotors teeter at a frequency about equal to the rotor speed, teeter angle describes the tilt of the rotor relative to a plane normal to the axis of rotation and phase angle describes the orientation of the tilted plane. These terms are described in more detail in the section devoted to a description of terms. A description of the effect of yaw on these two quantities is essential to an understanding of the response of a teetered rotor to yaw.

Phase Angle

The effect of yaw on the phase angle of a teetered rotor is illustrated in Figure 10. As shown, the phase angle for a yaw angle near zero is near 90 deg. This is due to the response of the teetered rotor to the effects of tower interference and wind shear. As the yaw angle is increased, the phase angle increases only slightly and previous tests (1) have shown that for positive yaw angles higher teeter angles occur as wind speed increases. This is because the increased yaw angle merely increases the tilt in the plane of the rotor, while not affecting the phase angle or orientation of the tilt. As yaw angle becomes negative; however, the phase angle makes a radical change, from near +90 deg to values approaching -90 deg for high yaw angles. This effect takes place because of the tendency of the rotor to align itself with the wind (a -90 deg phase angle results from the rotor tilting to align itself with the wind at negative yaw angles). These relationships are demonstrated in the phase angle relationships shown in Figure 10.

It should be noted that the yaw angles shown in Figure 10 were measured on the wind turbine nacelle rather than at the reference measuring station upwind of the wind turbine which is used elsewhere in this report.

Teeter Angle

Of more immediate concern to designers is the effect of yaw on teeter angle. This is given in Figure 11 which shows teeter angle versus wind speed for the various yaw angles. As indicated in the figure, teeter angle was relatively insensitive to wind speed for yaw angles of -8 and -29 deg; however, as the yaw angle was decreased below -30 deg the teeter angle increases with wind speed. This appears to be a result of the tendency of the rotor to align itself with the wind. This effect is not evident at a yaw angle of -29 deg because at this point the maximum teeter angle occurs at only 20 deg off the vertical. At yaw angles of -40 and -49 deg maximum teeter angles occurred at -45 and -55 deg respectively. Here, increasing wind speed is reflected more readily in increased teeter angle when the teetering occurs with the blades more nearly horizontal.

Even though the mean teeter angle showed a marked increase for yaw angles of -40 and -49 deg, no instances of teeter stop impact were recorded during the tests. It appears likely, however, that additional operation at the higher yaw angles would result in instances of teeter stop impacts.

CONCLUSION

As a result of the tests performed and an analysis of the data, the following conclusions were drawn:

- o As expected, yaw has a significant effect upon the power developed by the rotor. This effect can be approximated for yaw angles less than 30^{o} by defining rotor power as a function of the wind velocity normal to the rotor plane cubed or: rotor power = $f[(V\cos\Psi_{NW})^3]$. For larger yaw angles and higher rotor powers, experimental data values were less than the predicted values using the "cosine cubed" theory. Therefore, more sophisticated methods are necessary to describe the effects on rotor power in these regimes.

- Mean blade bending loads at the root of the blade were relatively unaffected by yaw. Bending loads as a function of wind speed were changed to correspond with the power versus wind speed relationship at a given yaw angle. The cycle component of blade bending moment was unchanged by yaw angle.

- Teeter angle increased with wind speed when the magnitude of the yaw angle exceeded 30 deg indicating a potential for teeter stop impacts.

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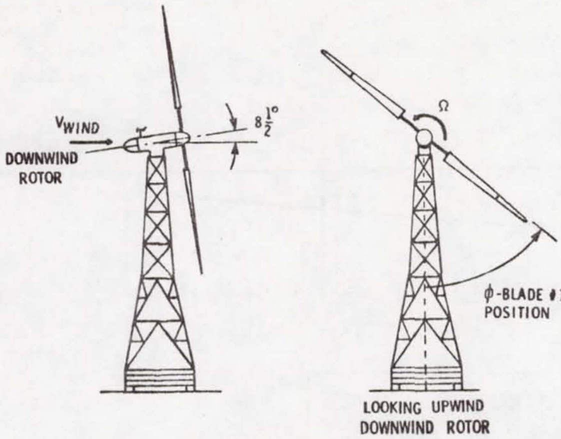


Figure 1. - NASA Mod-0 100 kW wind turbine.

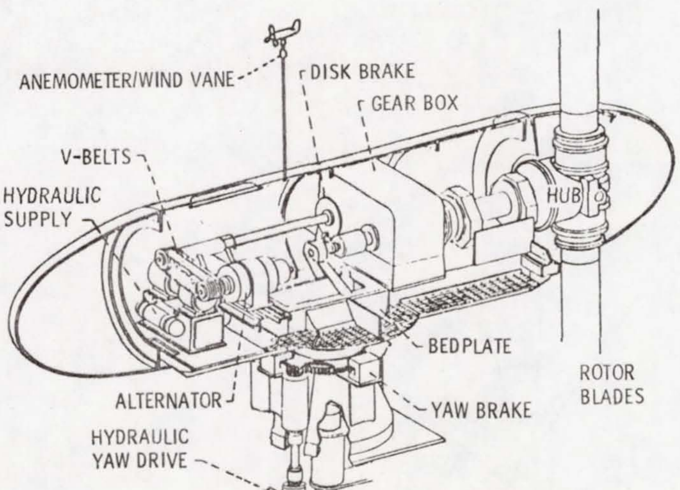
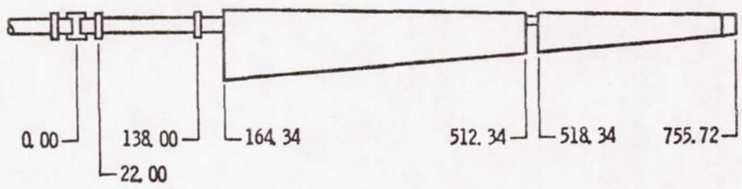


Figure 2. - NASA Mod-0 wind turbine with teetered hub - nacelle interior.



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	.672

Figure 3. - Blade planform - steel spar blade with tip control.

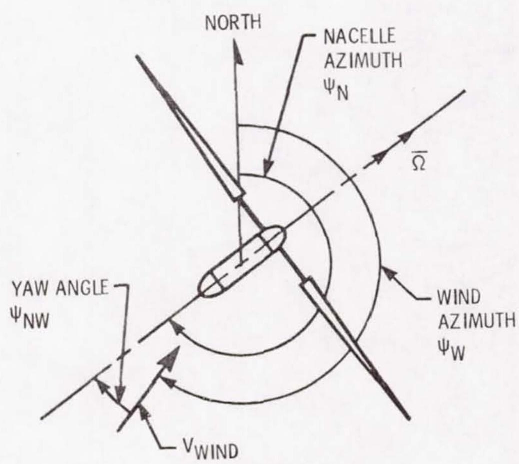


Figure 4. - Yaw angle sign conventions.

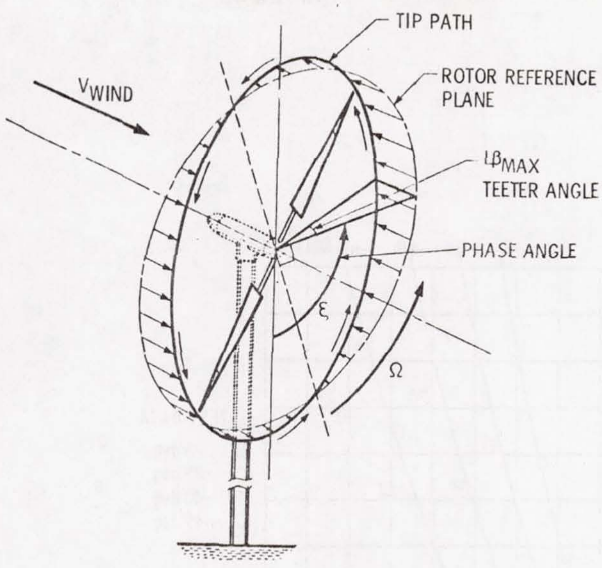


Figure 5. - Teetered rotor coordinates showing maximum teeter angle, β_{max}, and phase angle, ξ.

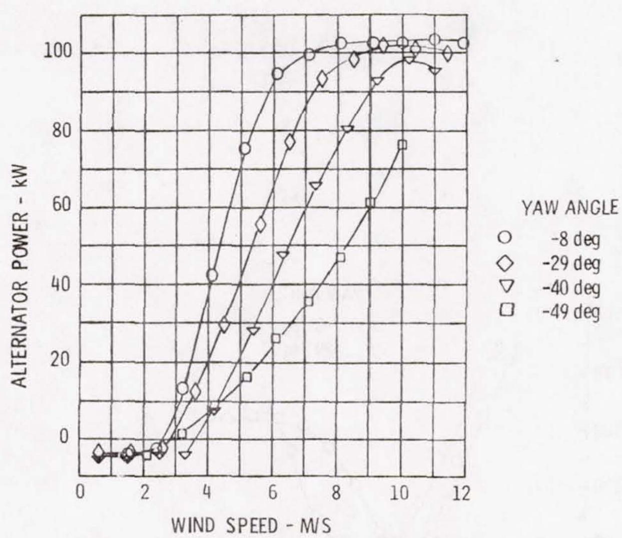


Figure 6. - Alternator power output vs. reference wind speed for various reference yaw angles.

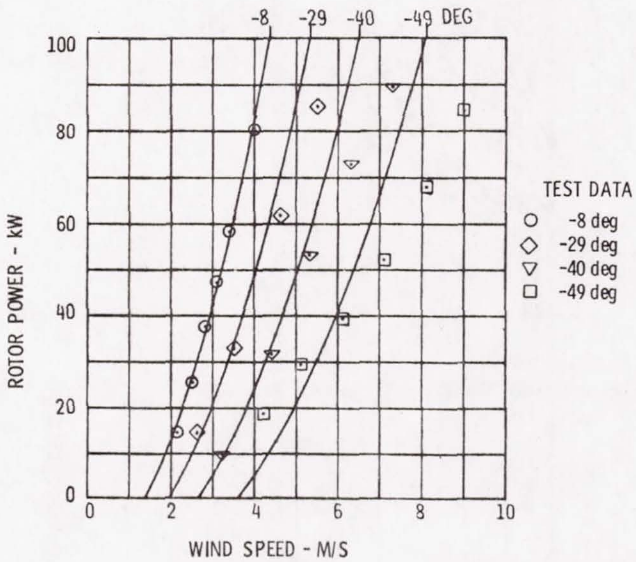
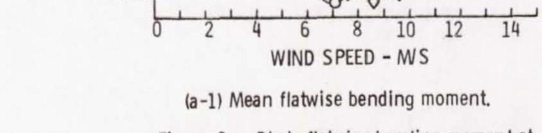
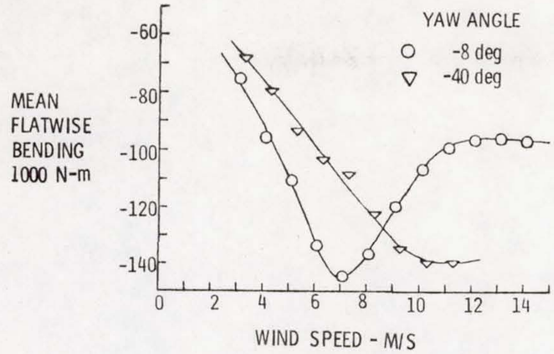


Figure 7. - Rotor power vs. reference wind speed - comparison of experimental data with analytic predictions for various reference yaw angles.



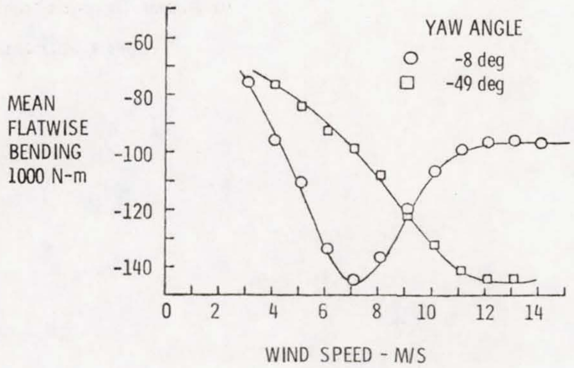
(a-1) Mean flatwise bending moment.

Figure 8. - Blade flatwise bending moment at station 35 vs. reference wind speed for various reference yaw angles.



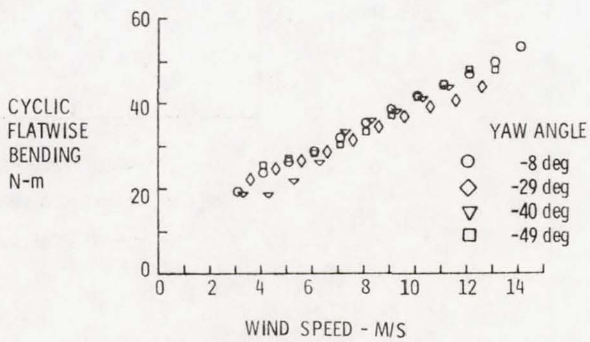
(a-2) Mean flatwise bending moment.

Figure 8. - Continued.



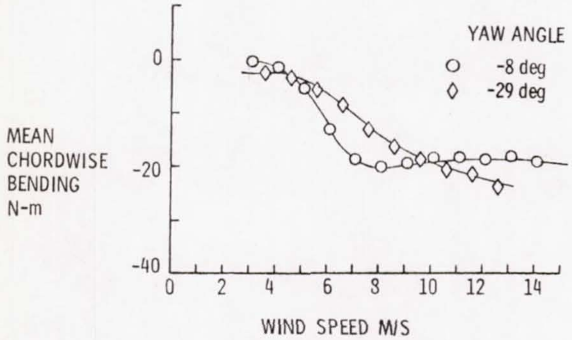
(a-3) Mean flatwise bending moment.

Figure 8. - Continued.



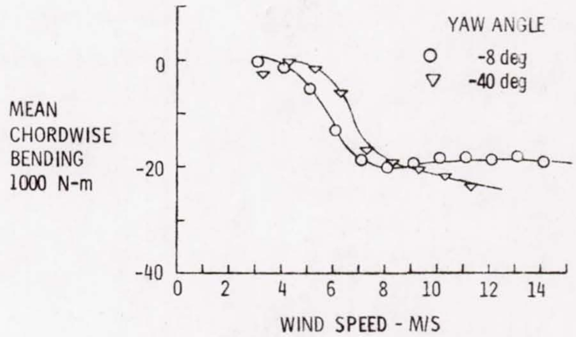
(b) Cyclic flatwise bending moment.

Figure 8. - Concluded.



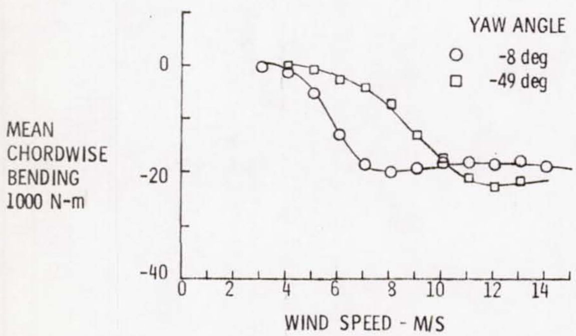
(a-1) Mean chordwise bending moment.

Figure 9. - Chordwise bending moment at station 35 vs. reference wind speed for various reference yaw angles.



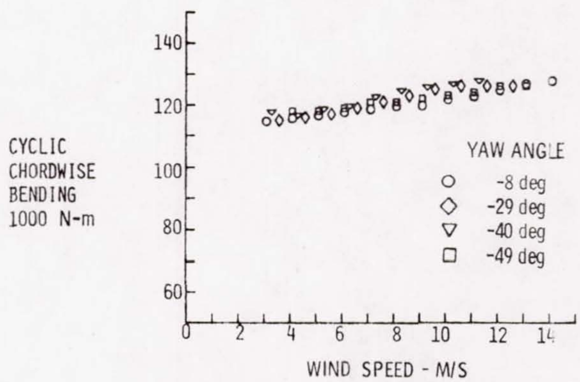
(a-2) Mean chordwise bending moment.

Figure 9. - Continued.



(a-3) Mean chordwise bending moment.

Figure 9. - Continued.



(b) Cyclic chordwise bending moment.

Figure 9. - Concluded.

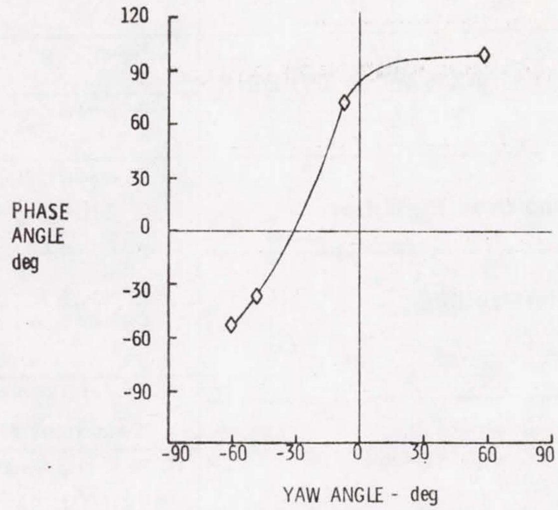


Figure 10. - Rotor phase angle vs. yaw angle (as measured from the nacelle mounted wind vane).

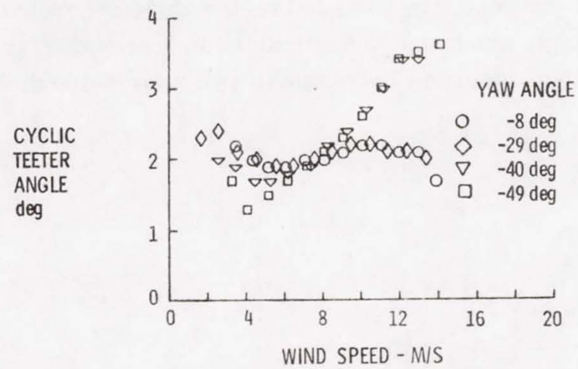


Figure 11. - Cyclic teeter angle vs. reference wind speed for various reference yaw angles.

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15. Supplementary Notes

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16. Abstract

Tests were conducted on the Mod-0 100 kW Experimental Wind Turbine to determine the effects of yaw on rotor power, blade loads and teeter response. The wind turbine was operated for extended periods at yaw angles up to 49 deg to define average or mean response to yaw. As a result of the tests it was determined that the effect of yaw on rotor power can be approximated by the cube of the velocity normal to the rotor disc as long as the yaw angle is less than 30 deg. Blade bending loads were relatively unaffected by yaw, but teeter angle increased with wind speed as the magnitude of the yaw angle exceeded 30 deg indicating a potential for teeter stop impacts at large yaw angles. No other adverse effects due to yaw were noted during the tests.

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