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TEETERED, TIP-CONTROLLED ROTOR: PRELIMINARY TEST RESULTS FROM MOD-0 100-kW EXPERIMENTAL WIND TURBINE

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Abstract

A series of tests is currently being conducted using the DOE/NASA 100 kW Experimental Wind Turbine with a two-bladed, teetered rotor with 30% span tip control. Preliminary evaluation test results indicates that the teetered rotor significantly decreases loads on the yaw drive mechanism and reduces blade cyclic flapwise bending moments by 25% at the 20% span location when compared to rigid hub rotor. The teetered hub performed well but did impact the teeter stops on occasion as wind speed and/or direction varied rapidly. The tip-controlled rotor performed satisfactorily with some expected loss of control when compared to the full span pitchable blade. The performance results indicate that a review of techniques used to calculate rotor power is in order.

Introduction

The Mod-0 100 kW Experimental Wind Turbine located near Sandusky, Ohio, has served as the test bed for the U.S. Large Horizontal Axis Wind Energy program since its initial operation in 1975. The machine was designed and fabricated and has been operated by the NASA Lewis Research Center under the direction of the U.S. Department of Energy. Many concepts currently used in large horizontal axis wind turbine designs were initially evaluated on the Mod-0 machine.

The teetered, tip-controlled rotor tests continue this tradition and are designed to obtain operating experience with the same type of rotor which will be used on the Mod-2, 2.5 MW Wind Turbine currently under construction. Tests were conducted on the teetered, tip-controlled rotor to determine startup, shutdown and power control characteristics and aerodynamic performance of the tip-controlled rotor and the response of the teetered rotor under normal operation. The hub was designed with the capability for converting the teetered hub to a rigid hub and tests were run in the rigid hub mode to provide data for comparing rigid and teetered hub blade loads.

Preliminary data presented in this paper describe teetered rotor response, a comparison of blade bending moments and yaw loads for teetered and rigid hub operation and performance of the tip-controlled rotor as it relates to power output.

Test Configuration

The teetered, tip-controlled rotor tests were conducted on the Mod-0 100 kW Experimental Wind Turbine which has been described previously.[1,2] The wind turbine with the exception of the rotor was essentially unchanged and is depicted in Fig. 1. The rotor is downwind of the tower and the nacelle was tilted 8-1/2° to provide tower clearance for the unconed rotor. The rotor speed was 33 rpm with a drive train slip of 5.3% at a 100 kW. Wind speed and nacelle yaw angle are measured on the anemometer/windvane mounted atop the nacelle as shown in Fig. 1.

Tower. The wind turbine is mounted on the Mod-0 open truss tower; however, an adjustable spring base has been added to provide capability for simulating various tower flexibilities.[3] The tower first cantilever bending frequency for this test configuration was measured to be 1.6 to 1.7 Hz or 2.9 to 3.1 times the rotor speed at 33 rpm. Tests are planned with the tower in a more flexible configuration. The flexible tower base adds 3 feet to the nacelle centerline height placing it 103 feet above the ground at the tower centerline. A sketch of the wind turbine mounted on the tower with the flexible base is shown in Fig. 2. This figure also presents parameter definitions and sign conventions pertinent to the paper.

Rotor. The teetered, tip-controlled rotor is depicted in Fig. 3. The rotor is unconed. The blades have a 23% root cutout and a 30% span pitchable tip. The blade section is a NACA 23024 airfoil from root to tip. Speed and power control is achieved by pitching the blade tip about its 25% chord point. The tip is capable of pitch angle changes from +10° to -90° or the full feather position. The tip is driven by a hydraulic actuator and the rotor is stopped by feathering the blade tip at a rate of 2° per second. Rotor and blade characteristics are presented in Table 1.

Table 1 - Rotor Characteristics

Rotor diameter, ft	124.5
Root cutout, % span	23
Tip control, % span	30
Blade pitch, inb'd section, deg.	Zero
Airfoil (root to tip)	NACA 23024
Taper	Linear
Twist, deg	Zero
Solidity	0.033
Precone, deg	Zero
Max. teeter motion, deg.	±6
Rotor speed @ 100 kW, rpm	33
Drive train slip @ 100 kW, percent	5.3
Blade weight, lb	4000
Blade Lock number	6.56
Blade first cantilever bending frequency	
Flapwise - Hz	1.76
Edgewise - Hz	1.90

The teetered hub is depicted in Fig. 3 and was designed to mate with the Mod-0 low speed shaft at the original hub-shaft interface. The hub has the capability of operating as a rigid as well as a teetered hub. The change from teetered to rigid

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hub is accomplished by replacing the rubber faced teeter stops with close fitting steel inserts which lock out the teeter motion. This feature was used to obtain a direct comparison between rigid and teetered hub blade bending moments.

The teetered hub provides capability for approximately ±6° of teeter motion with initial contact with the stop occurring at approximately ±5.8°. The stops were designed to be easily replaceable should they become damaged or worn during the test program and this feature has been used several times to date.

Test Results

The teetered, tip-controlled rotor tests were designed to define the operating characteristics, teeter motion, blade loads, and the performance of the rotor. Operating characteristics such as startup and shutdown, response to gusts, etc., are determined by review of time history data which describe the event and the remainder, including teetered hub response, loads and rotor performance, is described by statistical analysis of a large sample of operational data.[4] Ideally this data sample should be distributed over the operating wind speed range from cut-in wind speed to cut-out wind speed with equal operating times at each wind speed. We presently feel that 4-1/2 to 5 hours of operational data, well distributed over the operational wind speed range, would adequately describe normal wind turbine aerodynamic performance and loads. The results presented in this paper are based on over 5 hours of operational data but the sample is deficient in high wind data; however, results presently available appear to indicate the general trend of the data.

Four aspects of the test results are discussed in this paper: teetered rotor response, comparison of rigid and teetered hub blade bending moments, yaw loads and rotor performance and control.

Teetered rotor response. Teetered rotor response is based on a statistical evaluation of 5 hours of operational data and the results are presented in Fig. 4 in terms of cyclic teeter angle versus average wind speed and cyclic teeter angle versus average nacelle yaw angle. (In these plots and those following, a cyclic value is defined as one half the peak-to-peak amplitude of a variable over a given rotor revolution. Mean value is one half of the sum of the maximum value and the minimum value of a variable over a rotor revolution and average value is the average of all values of the variable over a rotor revolution.) Figure 4 also gives the distribution of the data contained in the sample over the range of the independent variables showing the number of data points at each wind speed or yaw angle. Cyclic teeter angles increase as wind speed increases and as nacelle yaw increases. This trend is more pronounced in the maximum values than with the median or 84 percentile data. Also an impact with the teeter stop was indicated at a wind speed of between 20 and 25 mph and at yaw angles of between 20° and 30°. The data sample did not include adequate data at the higher wind speeds but there appears to be a reduction in teeter angle as wind speed increases above 25 mph. The wind data in the sample is more stable directionally as wind speed increases and this could explain some of this reduction in teeter response at higher wind speeds.

The variation in teeter angle as the nacelle yaw angle increases is to be expected in that positive yaw angles tend to add to the effect of wind shear and tower shadow. Both conditions cause the plane of the rotor to tilt slightly upwind on the side of the ascending blade.

The data was sorted further by nacelle yaw angle and plotted versus average nacelle wind speed. These results are presented in Fig. 5 and show the effect of wind speed on teeter response for various ranges of yaw angle. The figure is arranged to indicate the effect of increasing yaw angle, progressing from negative yaw angles to positive yaw angles. The median value of the cyclic teeter angle increases as the yaw angle becomes more positive and the most positive yaw angles, +15° to +50°, produce teeter response which increases sharply as wind speed increases. Cyclic teeter angles are the smallest in the yaw angle range of −15° to −5° indicating that the optimum off wind operating point may lie in this range, but the data indicate that high teeter angles can be expected on occasion at any yaw angle when the wind speed is above 15 mph. In this five hour data sample, cyclic teeter angles of 5° or more were experienced in each yaw angle range except −15° to −5° (Fig. 5(b)).

A time history of the rotor impacting the teeter stops is shown in Fig. 6. This particular event was chosen over approximately ten other such events which have occurred during the test program because it was one of the most severe impacts recorded and the wind conditions typify the winds associated with high teeter response in that they are highly variable. Just prior to the high teeter response the wind speed increased from seven mph to 25 mph in seven seconds and during the period of low wind speed the wind vane indicated yaw angles of −24°, +32° and −24° in a period of five seconds. Also, during the entire time history of the event, the average yaw angle was between −15° and −20°.

As the teeter angle increased, Coriolis forces become evident as twice per revolution power oscillations on the alternator power trace and these oscillations approach 60 kW peak-to-peak at the time when the rotor is impacting the stops. Also, as the rotor impacts the teeter stops, the yaw shaft torque increases to 200 000 in-lb, the operating limit of the yaw drive indicating that significant yaw forces are transmitted to the wind turbine nacelle by the rotor contact with the teeter stop. For comparison, less than 50 000 in-lb of yaw shaft torque are required to yaw the machine with the yaw drive.

The rotor impact condition is not fully understood at this point. The wind data taken on the nacelle does not indicate a direct cause and effect relationship and present analytical techniques do not describe rotor response to transient phenomenon. The large increase in torque oscillations at the point of teeter stop impact, compared to that experienced just 15 seconds earlier, is probably due to added teeter angle velocity caused by rebound after the rotor hits the teeter stop. Also, average rotor power is less than 100 kW even though the indicated wind speed is well above 20 mph. This could be the result of aerodynamic losses caused by high blade flapping velocities. The power oscillations caused by the Coriolis acceleration are reduced by the fluid coupling which introduces 5.3% of slip in the drive train at 100 kW. These power oscillations would approach ±100 kW for a rigid drive train with ±6° of teeter motion.

A short test was run with the teetered rotor to determine how the rotor tilts with the wind turbine at various yaw angles relative to the wind. For this test the machine yaw controller was shut off and the wind turbine was set at azimuths to produce average yaw angles of -30°, 0° and +30°. With the wind turbine azimuth held constant the rotor position at which the blade tip is at its maximum upwind position was determined. For the downwind rotor this upwind position indicates the point of closest travel to the tower. Approximately 50 rotor revolutions were included at each wind turbine azimuth and winds ranged from 15 to 40 mph during the test. The results are shown in Fig. 7 which indicates the region over the rotor disk where the blade tip achieved its maximum upwind position for each average yaw angle. The median and the region which contains 68% of the data is also indicated. Negative yaw angles are most critical from the viewpoint of tower clearance for this downwind rotor rotating in the direction indicated.

During startup and shutdown the teetered rotor hit the teeter stops at rotor speeds below 15 or 20 rpm. Therefore, teetered hub designs should provide a lock-out device or make other provisions for handling low speed operation.

Rotor loads. Blade bending moments measured in the test are presented in Figs. 8 and 9 showing the flapwise and chordwise moments at blade station 151. (Flapwise bending occurs when the blade moves perpendicular to the plane of the rotor disk and chordwise bending is bending in the plane of the rotor disk.) The bending moments are presented as mean and cyclic moments versus average nacelle wind speed. The bending moments were measured at blade station 151, Fig. 3, and for the lower wind speeds a comparison of rigid and teetered hub bending moments is shown.

The mean value of flapwise bending increases in value as thrust on the rotor increases until rated wind speed is reached, at which point the bending load decreases as the thrust on the rotor is decreased to maintain constant power, as the wind speed continues to increase. The mean chordwise bending moments increase as the power increases to rated value and remains at this level providing constant rotor torque from rated wind speed to cut-out wind speed.

Blade moments for the rigid hub case and the teetered hub case show no appreciable difference in the mean flapwise moments and in the chordwise moments. However, the teetered rotor case shows a decrease of approximately 25% in the cyclic flapwise moment in both the median and the 84th percentile values when compared to the rigid hub moments. This is due to the fact that in the teetered rotor case a portion of the flapwise moments are converted into teeter motion and are resisted by distributed aerodynamic and inertia forces.

Flapwise blade bending moments were also measured at station 541 on the blade moveable tip but the rigid hub and teetered hub blade moments were essentially the same at this outboard station.

Yaw loads. In testing the two configurations, rigid hub and teetered hub, a significant difference was noted in the force required to restrain the machine in yaw. For the rigid hub case, a constant yaw brake pressure of 300 to 600 psi was required to obtain satisfactory operation of the machine whereas for the teetered hub rotor case the wind turbine could be operated satisfactorily without the yaw brake. However, the machine with the teetered hub was usually operated with a yaw brake pressure of 50 psi and, in isolated instances when the teetered hub rotor hit the stops, significant forces were transmitted to the yaw drive as indicated above. If adequate freedom for teeter motion were allowed in the design, the yaw brake would be unnecessary.

Rotor performance and control. Measured power output versus average nacelle wind speed is presented in Fig. 10. The rotor performed well over the operating range of wind speeds and no problems were experienced with startup, control or shutdown of the rotor. However, rotor startup and shutdown were slower than with a full span pitchable blade. Data will be available at a later date defining startup and shutdown characteristics in a more quantitative manner.

The program used to calculate rotor power[5] indicated that the rotor would not maintain rated power output at wind speeds above 29 mph due to the onset of stall on inboard portions of the blade at higher wind speeds. The program uses two dimensional airfoil data which shows the onset of stall at section angles of attack of 15.5°. If this were the case, the entire blade would be stalled at 33 rpm and 40 mph with a zero tip pitch angle. The results of the calculations are shown in Fig. 10 with the power dropping off to zero at 35 mph. The Mod-0 tests did not indicate any tendency to lose power at higher wind speeds and alternator output power remained at 100 kW throughout the operating wind speed range to 40 mph. Blade pitch angles were continuously decreased as the wind speed increased up to 40 mph. Figure 11 shows these results out to a wind speed of 33 mph and later test results indicate that the trend continues to 40 mph. The test results clearly indicate that modifications to the rotor power program are required in the high wind speed region to account for the delayed stall which occurs in the real world.

Conclusions

Preliminary evaluation of the teetered, tip-control rotor tests on the Mod-0 100 kW wind turbine lead us to the following conclusions based on the test results.

1. The teetered rotor reduced cyclic flapwise moments by 25% at 20% of the blade span when compared to rigid hub moments measured at the same location. No change was noted in cyclic flapwise moments at 72% of span.

2. It is estimated that the teetered rotor reduces yaw loads by an order of magnitude when compared with the rigid hub rotor. The yaw brake, required for satisfactory rigid hub operation, is not required with the teetered rotor.

3. Teeter angle amplitudes rarely exceeded ±3° in steady wind conditions; however, when sudden changes in wind speed and/or direction occurred, the teeter angle amplitudes occasionally increased to ±6° and hit the teeter stops transferring high loads to the nacelle and the yaw drive. Provisions must be made for handling these extreme conditions in future designs. Predicting maximum teeter motion is the most critical design problem.

4. A teeter lockout device should be provided for low rpm operation during startup and shutdown conditions.

5. The 30% span tip control rotor performed satisfactorily with some expected loss in control as demonstrated by slower startup and shutdown when compared to a fully pitchable blade.

6. Techniques for calculation of rotor power should be reviewed. Test results indicate that stall predictions from two dimensional airfoil data are inadequate for predicting stall on an operating wind turbine rotor.

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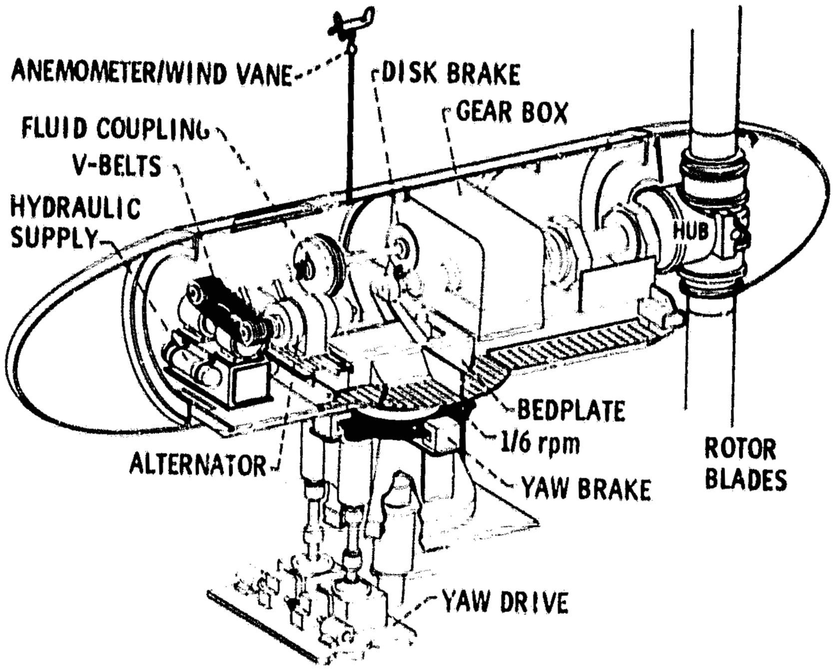


Figure 1. - Mod-O 100 kW wind turbine; Nacelle interior with teetered hub.

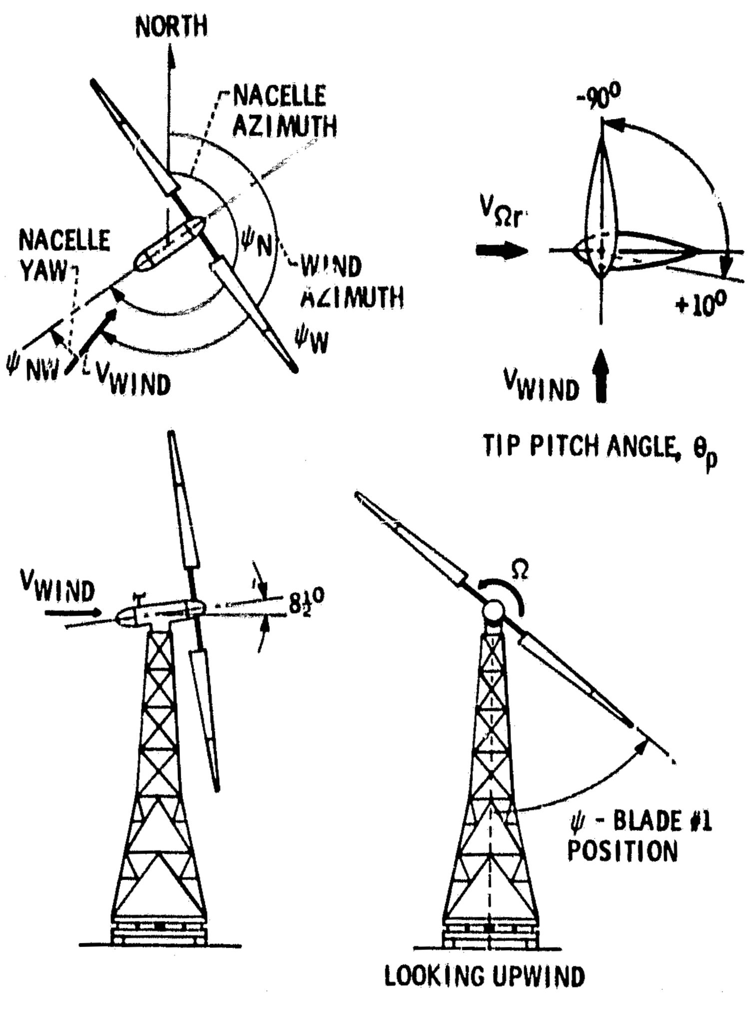


Figure 2. - Mod-O 100 kW of wind turbine with teetered, tip control rotor.

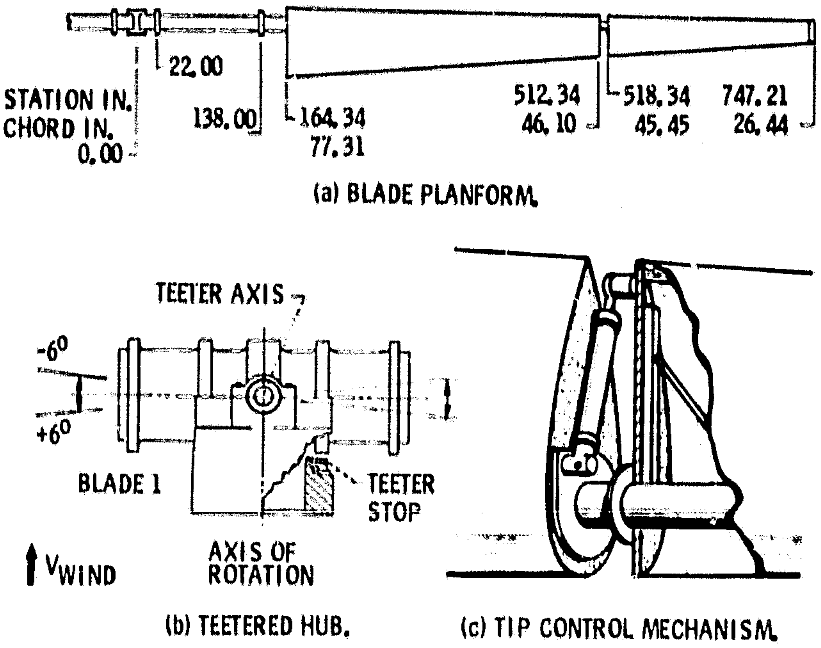
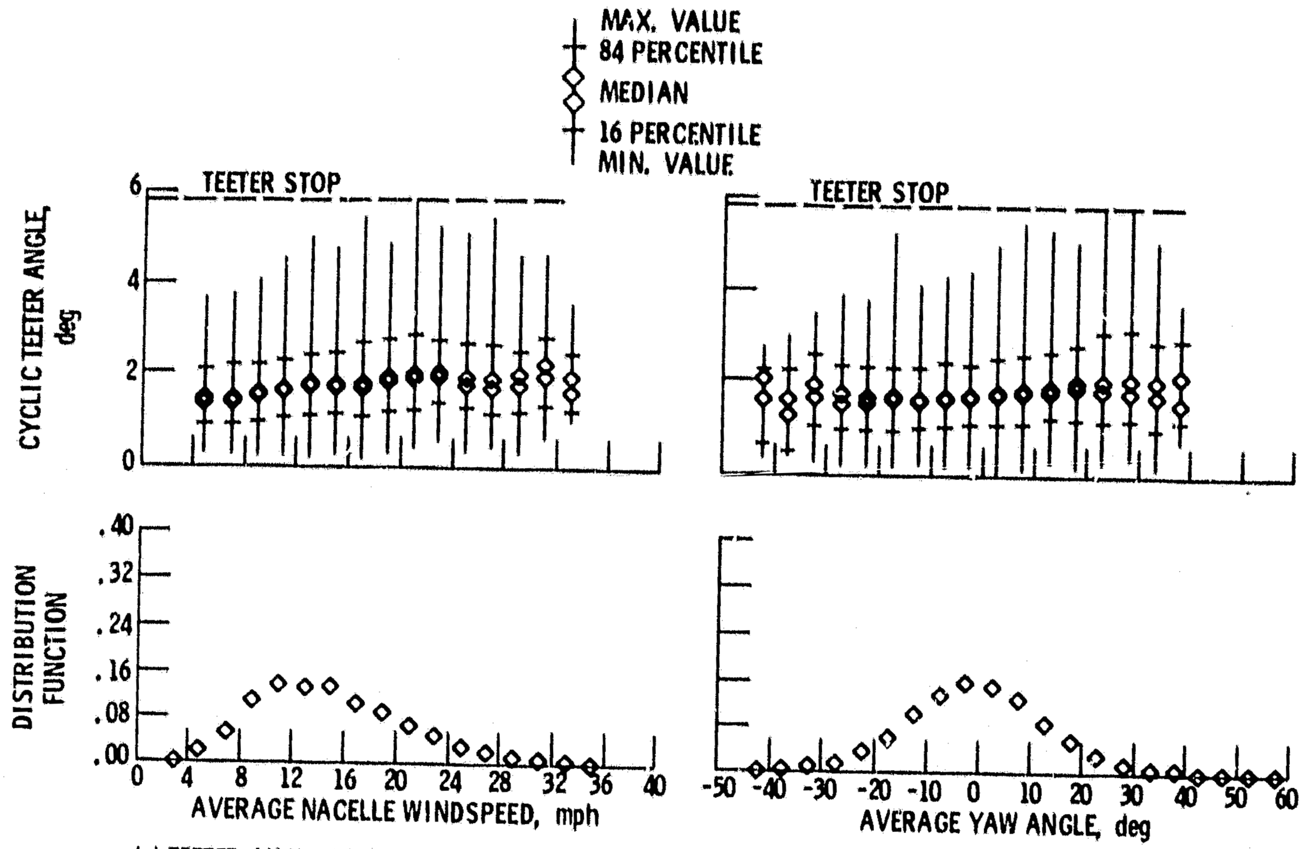


Figure 3. - Mod-0 rotor details.



(a) TEETER ANGLE AS A FUNCTION OF AVERAGE WIND SPEED AND DISTRIBUTION.

(b) TEETER ANGLE AS A FUNCTION OF AVERAGE YAW ANGLE AND DISTRIBUTION.

Figure 4. - Cyclic teeter angle.

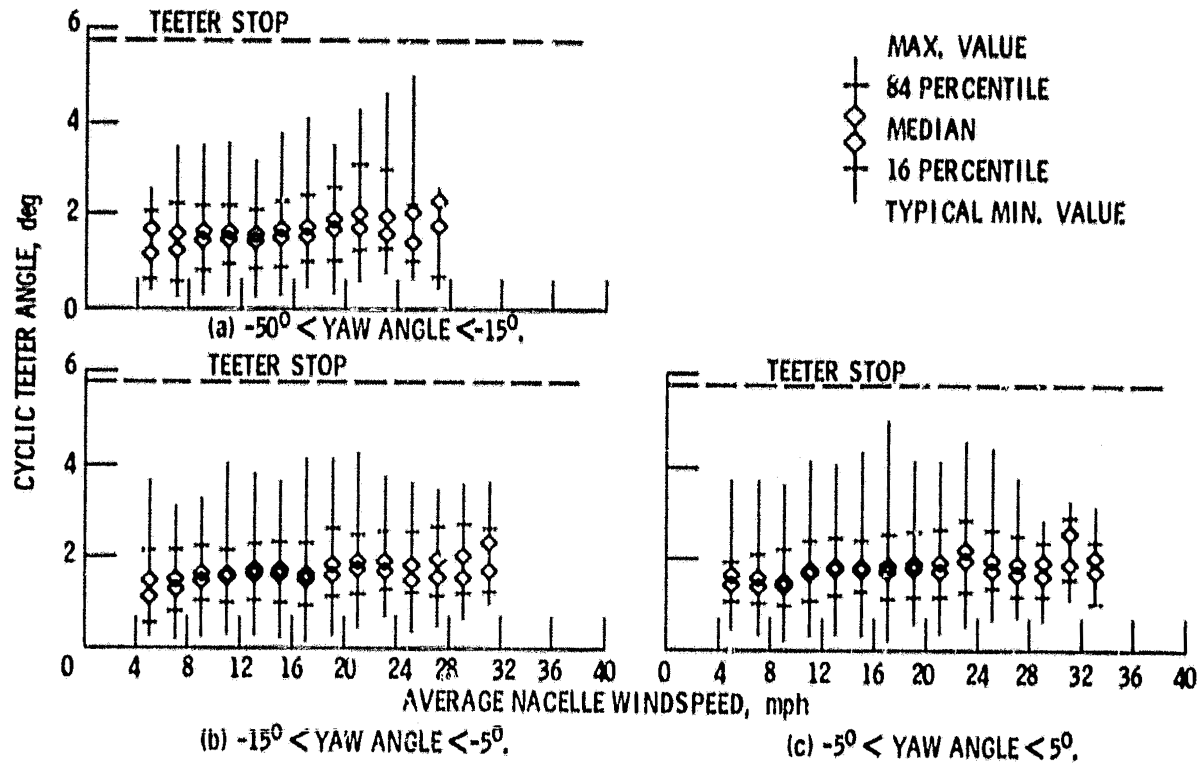


Figure 5. - Cyclic teeter angle versus average nacelle wind speed.

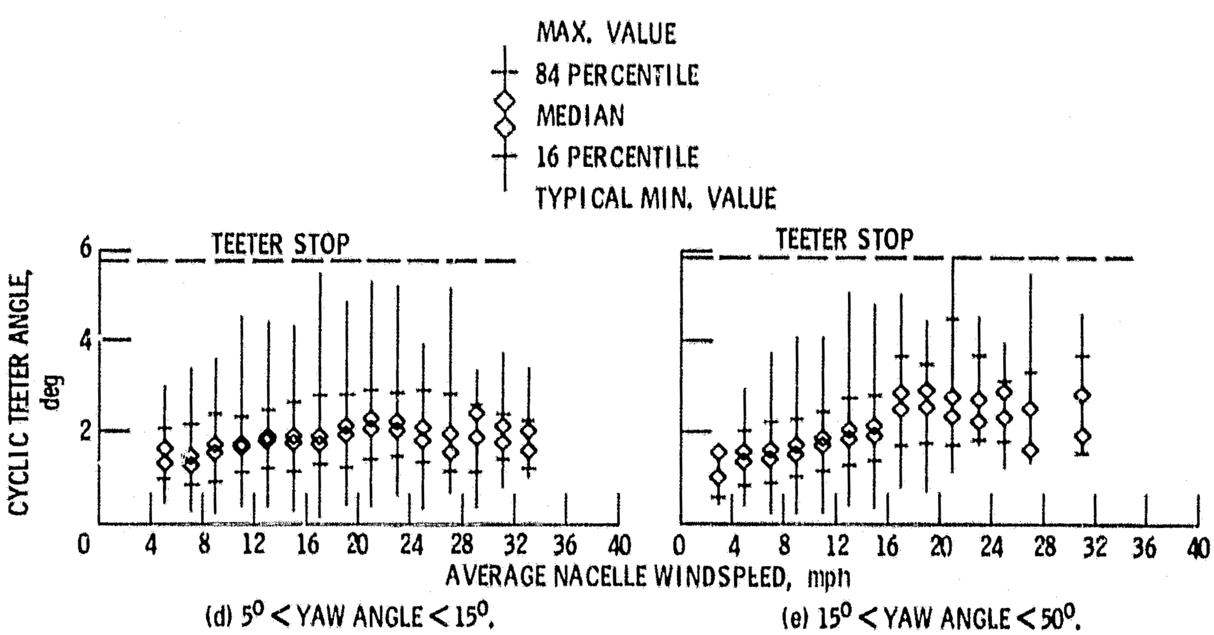


Figure 5. - Concluded.

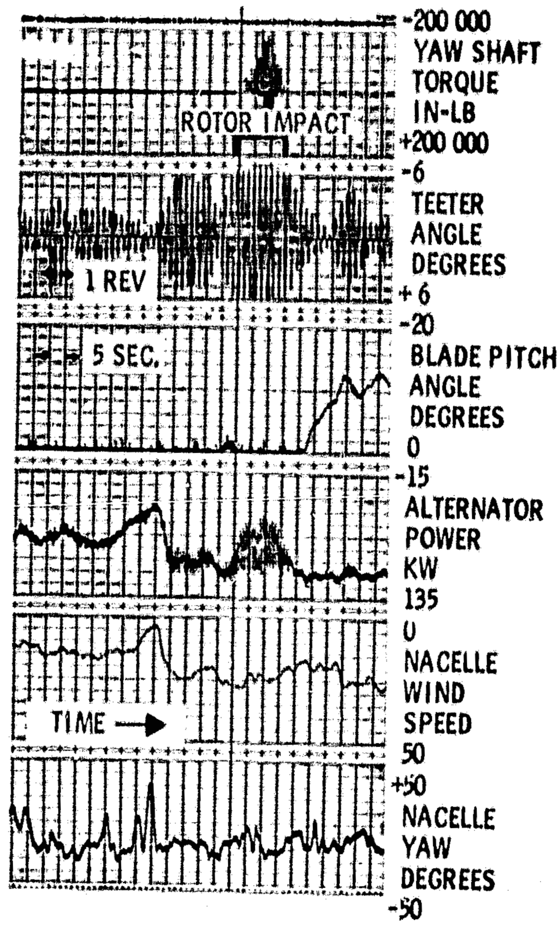


Figure 6. - Rotor impact with teeter stops - time history of various operating parameters.

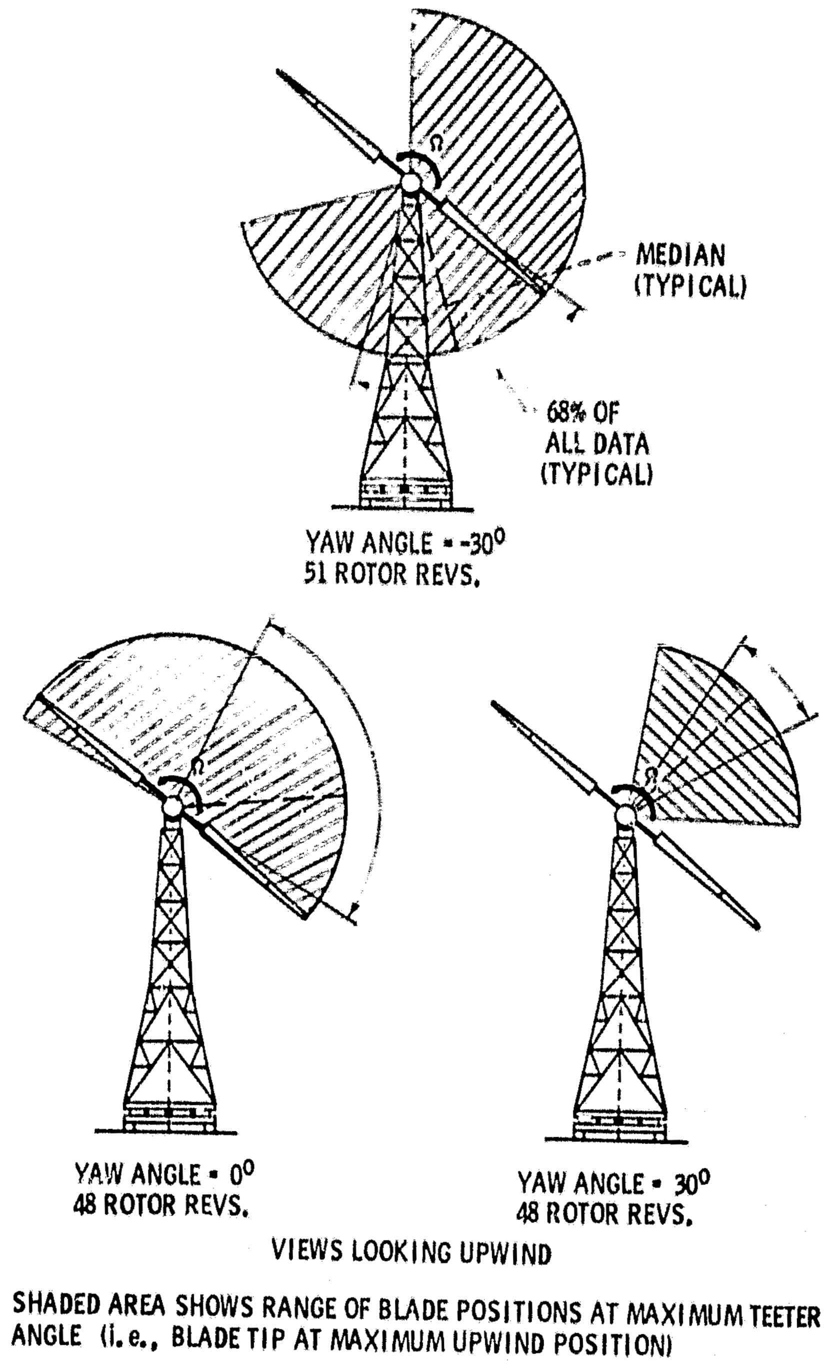


Figure 7. - Range of rotor position at which maximum teeter angle occurred for three average yaw angles.

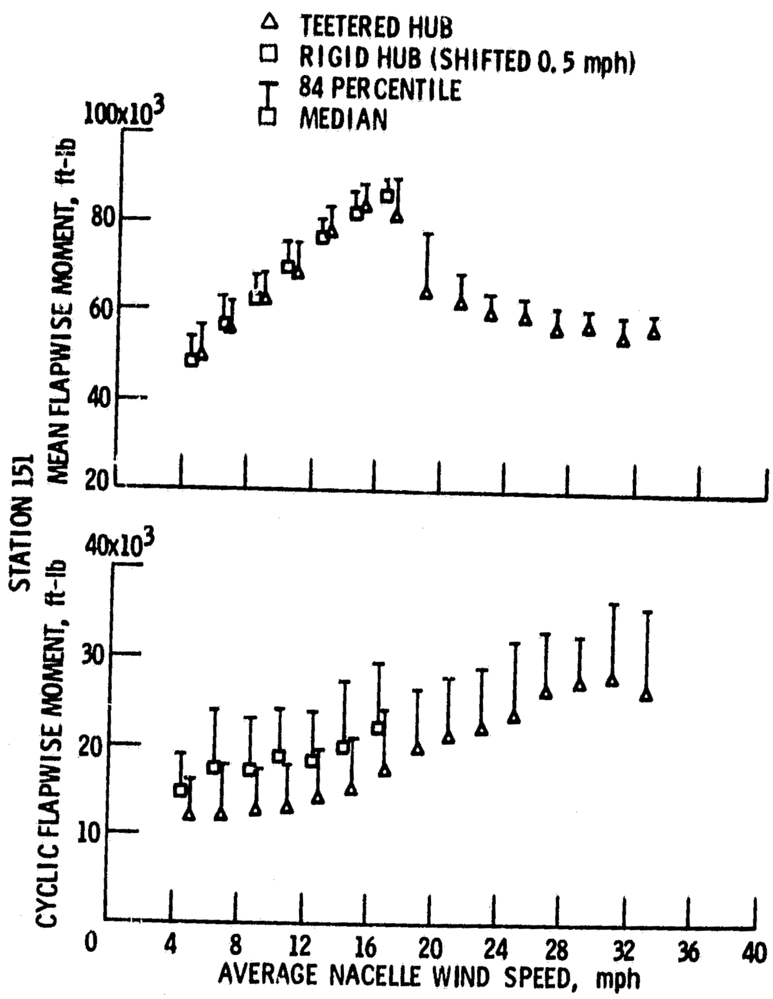


Figure 8. - Comparison of blade flapwise bending moments, teetered and rigid hub at Station 151.

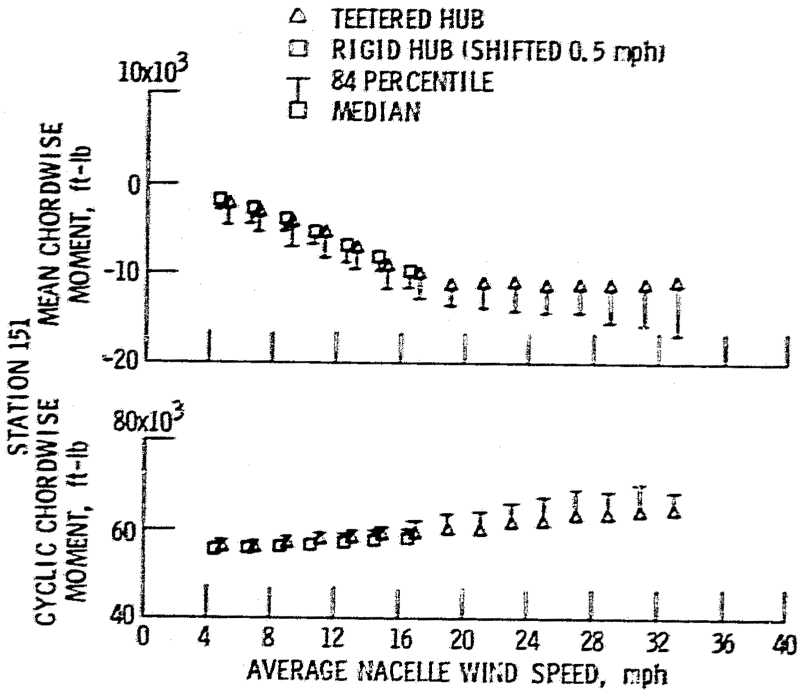


Figure 9. - Comparison of blade chordwise bending moments, teetered and rigid hub at Station 151.

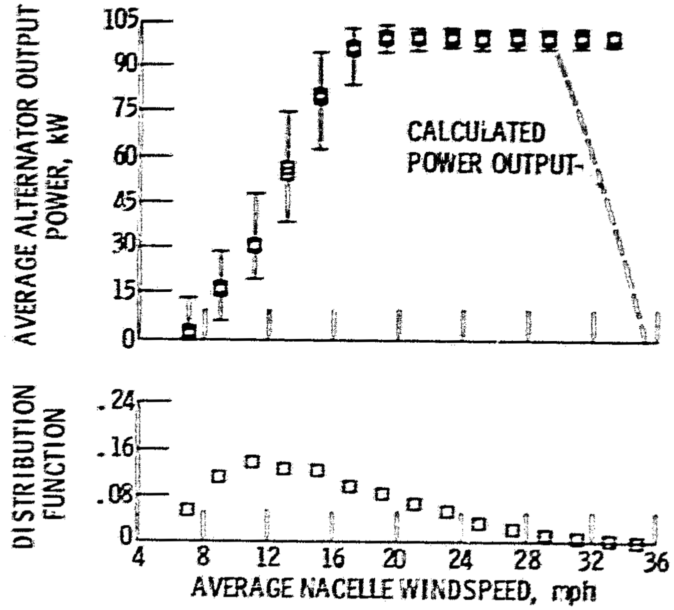


Figure 10. - Performance of tip-controlled rotor.

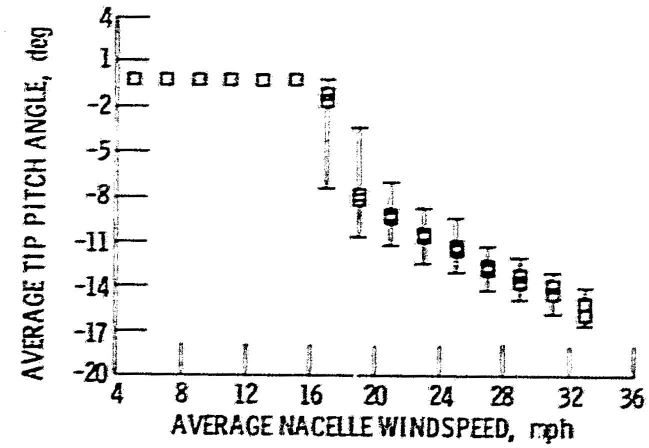


Figure 11. - Blade tip pitch angle versus nacelle wind speed.