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SUMMARY

Tests were conducted on the DOE/NASA Mod-0 horizontal-axis wind turbine to compare and evaluate the performance and the power regulation characteristics of two aileron-controlled rotors and a pitchable tip-controlled rotor. Each of these two-bladed rotors was approximately 39 m in diameter. Test conditions included wind speeds up to 16 m/sec and power output levels up to 140 kW. The two aileron-controlled rotor configurations used 20-percent- and 38-percent-chord ailerons that spanned the outer 30 percent of each blade. The tip-controlled rotor had a pitchable blade-tip length equal to 30 percent of the blade length.

The rotors were evaluated on the ability of the control surfaces to regulate power. This ability was determined by measuring the change in power caused by an incremental change in the deflection angle of the control surface. The test results show that the change in power per degree of deflection angle for the 38-percent-chord ailerons was twice the corresponding value for the 20-percent-chord ailerons. The data for the tip-controlled rotor indicate that the change in power per degree of deflection angle was four times the corresponding value for the 20-percent-chord ailerons.

The effectiveness of the control surfaces in regulating power was determined by measuring the power variation about a given power setpoint. Test results indicate that the root mean square power deviation about a setpoint was highest for the 20-percent-chord aileron, and lowest for the 38-percent-chord aileron. The data for the tip-controlled rotor fell between the two aileron-controlled rotors.

INTRODUCTION

The two power regulation systems presently used on large horizontal-axis wind turbines (HAWT) are full-span pitch control and partial-span pitch control. In an effort to reduce the complexity, cost, and weight associated with these control systems, a third system using aileron control was studied. As a result of detailed analyses (ref. 1), aileron control for wind turbines appears to be feasible.

In analyzing rotor aerodynamic control systems, the factors considered were simplicity, structural efficiency, weight, and control effectiveness. Partial-span tip control offers a simple, straightforward approach, but requires a heavy and critical spindle/pitch bearing system. Aileron control offers a simple, straightforward device that would require a small actuator package and a simple hinging mechanism. The structural benefits of aileron control include a full-span, continuous-spar blade structure at a reduced weight, because the design requires no pitch bearings or large pitch actuators. Preliminary analysis indicated that both partial-span tip control and aileron control would be effective in regulating power and providing overspeed control. Additionally, aileron controls do not require complex actuator sequencing instructions.

Developing aerodynamic controls for use on wind turbines required field testing of the concept. This testing was conducted to determine the effectiveness of power regulation in terms of the change in rotor power and power quality for a given change in control surface deflection.

This report presents the results of tests performed on the DOE/NASA Mod-0 wind turbine to determine rotor performance, effectiveness of power regulation, and power quality of two aileron-controlled rotor configurations and a partial-span tip-controlled rotor. Aileron control tests evaluated a 20-percent-chord aileron control surface and a 38-percent-chord aileron control surface. For comparison, tests were also conducted on a tip-controlled rotor, in which the outer 30 percent of each blade was pitchable. Each of the three two-bladed rotors was approximately 39 m in diameter. Test data were obtained at wind speeds up to 16 m/sec and at power levels up to 140 kW.

Specific results for the aileron-controlled rotors and the tip-controlled rotor were determined from curves of rotor power as a function of wind speed for various control-surface deflection angles; effectiveness, or aerodynamic power gain; the ability to regulate power at 0-, 25-, and 50-kW power levels; and the quality of that power. The measured aerodynamic power gain for the tip-controlled rotor was then compared to that measured for the aileron-controlled rotors.

TEST PROCEDURE

Turbine and Rotor Configurations

The tests were conducted on the Mod-0 wind turbine, which is shown schematically in figure 1. The rotor/nacelle was mounted atop a tubular tower with the rotor axis 38 m above the ground. The three rotors were coned 3° downwind and teetered with $\pm 6°$ of allowable motion dampened by rubber stops.

The first rotor utilized 20-percent-chord ailerons for control, and had a diameter of 39 m. Its planform is shown in figure 2. Each blade consisted of a fixed inboard section and an outboard section incorporating the aileron control. The inboard section, constructed of a laminated wood/epoxy composite, had a NACA 23024 airfoil with zero twist and zero pitch angle relative to the plane of rotation. The outboard section, which spanned the outer 37 percent of the blade, also utilized a NACA 23024 airfoil with zero twist and zero pitch angle relative to the plane of rotation. The outboard section was constructed of fiberglass over a foam core on a steel spar, and provided the entire blade with a smooth, rigid surface. The aileron, contained in the outboard section, extended over 30 percent of the blade span. It was hinged to the low-pressure surface at the 80-percent-chord position. The aileron surfaces could deflect from +10° to -60°, with a negative deflection denoting rotation of the aileron trailing edge toward the low-pressure side of the airfoil.

The second rotor, which utilized 38-percent-chord ailerons for control, also had a diameter of 39 m. Its planform is shown in figure 3. This rotor blade, like that for the 20-percent-chord aileron-controlled rotor, consisted of two major sections. The inboard section was identical to that of the previously described rotor. The outboard section, which spanned the outer 37 percent of the blade, and the aileron were both constructed from aluminum alloy sheet by using standard aircraft fabrication methods. The portion from spanwise stations 12.2 to 13.1 was a transition section between the inboard wooden blade, with its NACA 23024 airfoil section, and the outboard section, with its NACA 64-624 airfoil. This transition section also provided a linear change in twist angle, from zero twist at station 12.2 to 3° of twist at station 13.1. The thickness-to-chord ratio and twist then varied linearly to 15 percent and 1°, respectively, at station 19.2. The aileron surface, contained in the outboard section, extended over 32 percent of the blade span and was hinged at the low-pressure surface at the 62-percent-chord position. The aileron control surfaces could be deflected from 0° to -90°. A leading-edge trip strip spanned the entire length of the outboard section to cause early boundary-layer transition from laminar to turbulent flow.

The third rotor, utilizing a pitchable tip section for control, also had a diameter of 39 m. The planform and dimensions of this rotor are shown in figure 4. The blades were composed of an inboard section and a pitchable tip section. The inboard portion of the blade was 70 percent of the blade span, had a NACA 23024 airfoil, and was constructed of doped fabric over ribs mounted on a steel spar. The tip section spanned the outer 30 percent of the blade, had a NACA 23024 airfoil, and was constructed of fiberglass cloth over foam on a tubular steel spindle. Both the inboard and tip sections had zero twist. The inboard section was set to a zero pitch angle during these tests.

Operating Conditions

The tests on the Mod-0 wind turbine were conducted with the rotor downwind of the tower, at a rotor speed of 20 rpm. The nacelle yaw angle (fig. 1) was set to 0°. Test results reported in this paper document performance, power regulation, and power quality operating parameters. Performance data were obtained for a specific control-surface deflection angle by fixing the deflection angle and allowing the wind turbine power to vary with wind speed, the power limited only by blade stall (stall-limited mode). Power regulation and power quality data were obtained by setting the alternator power limit to one of the required levels and controlling aileron deflection, or blade-tip pitch, so as not to exceed that power limit.

Data Collection and Reduction

Wind speed and direction data were taken from anemometers at the rotor hub height mounted on an array of five towers, each located 59.4 m (1.5 rotor diameters) from the wind turbine and spaced 45° apart. For a given test run, the tower most nearly upwind of the wind turbine was selected as the reference wind station.

Alternator power, rotor speed, control-surface deflection angle, wind speed, and yaw angle data were collected at a rate of 10 samples per second. Mean and cyclic values were recorded on digital tape on a once-per-rotor-revolution basis for each sensor. Mean values were calculated as one-half the sum of the minimum and maximum values of samples during one rotor revolution, and cyclic values were calculated as one-half the difference of the minimum and maximum values during one rotor revolution.

The objective of rotor performance analysis is to determine rotor power as a function of wind speed. In this study results are based on averages of mean power and wind speed values over 2.5-min intervals. This was done for two reasons. First, average power over a given time period is more representative of the energy captured in varying winds than of instantaneous power. Second, the use of time averages minimizes the effects of distance between the wind speed measuring station and the wind turbine.

A simplified drive train model was developed from measured drive train losses to define the relation between rotor power and alternator power. This empirical relation, described in the following equation, was used to convert measured alternator power to rotor power, as required for the comparison of aerodynamic performance in this study:

$$P = 1.168P_a + 7.1 \tag{1}$$

in which

P rotor power, kW
P_a alternator power, kW

Atmospheric pressure and temperature were taken for each test run, and the power was corrected to sea-level standard conditions. Since test runs were normally 4 hr or less in length, atmospheric conditions changed very little during a run. Therefore, a single calculation of air density would suffice for a particular set of data. Rotor power was corrected to sea-level standard conditions in accordance with the following equation:

$$P' = 0.05785 \frac{PT}{p} \tag{2}$$

where

P' rotor power at sea-level standard conditions, kW
T air temperature during test run, °R
p barometric pressure during test run, in. Hg

The effect of yaw angle variations on power output was accounted for by adjusting the rotor power to a zero yaw angle by using the following equation:

$$P'' = \frac{P'}{\cos^3 \Psi} \tag{3}$$

in which

P" rotor power at zero yaw angle, kW
Ψ yaw angle, deg

Combining equations (1) to (3) and deleting the prime notations yield

$$P = \frac{0.06757(P_a + 6.1)T}{p \cos^3 \Psi} \tag{4}$$

Thus, equation (4) was used to convert measured alternator power to rotor power for sea-level standard conditions at a yaw angle of 0°. The power regulation analysis was performed directly on mean and cyclic values of measured alternator power and wind speed for each rotor revolution.

For both rotor performance and power regulation, the final data reduction consisted of a bins analysis, performed in the following manner. The wind speed range during a test run was divided into intervals or bins, each about 0.5 m/sec in size. Power data were then sorted into the wind speed bins. The population in each bin was analyzed statistically to determine the median wind speed, the median power, and the 16th and 84th percentile powers (approximately ± one standard deviation). Median values of rotor power and wind speed were considered to best represent the performance of the rotor. The 16th and 84th percentile powers were used as a measure of power regulation and power quality.

RESULTS AND DISCUSSION

Performance Curves

Performance curves for the rotors with 20-percent- and 38-percent-chord ailerons were constructed to show rotor power as a function of both wind speed and aileron deflection angle. Performance curves for the 20-percent-chord aileron-controlled rotor are shown in figure 5 for aileron deflection angles of 0°, -15°, -30°, -45°, and -60°. In this figure, the data points represent median values from a bins analysis performed on the 2.5-min averages of wind speed and rotor power, sorted on aileron deflection. For this rotor with an NACA 23024 airfoil tip section and 0° aileron deflection, the performance curve indicates a maximum power of 128 kW at a wind speed of 15 m/sec. Deflecting the aileron in the negative direction always resulted in a decrease in rotor power.

The measured performance curves for the 38-percent-chord aileron-controlled rotor for aileron deflection angles of 0°, -15°, and -30° are shown in figure 6. Again, the points represent median values from a bins analysis performed on 2.5-min averages of wind speed and rotor power, sorted on aileron deflection. For this rotor with a NACA 64-624 airfoil tip and 0° aileron deflection, maximum power was 122 kW at a wind speed of 14.5 m/sec. A comparison of the 0° deflection curves in figures 5 and 6 shows significantly lower power produced by the rotor with the 38-percent aileron. This is not caused by the aileron, however, but by the nonoptimum twist distribution in the

64-series airfoil tip. Because this study is concerned with changes in power rather than absolute power output, nonoptimum performance is not significant. Again, deflecting the aileron in the negative direction always resulted in a decrease in rotor power.

Performance curves for the tip-controlled rotor as a function of tip pitch angle are shown in figure 7. The figure shows rotor power for tip pitch angles of 0°, -7°, -10°, -15°, and -20°. The points represent median values from a bins analysis of 2.5-min averages of wind speed and rotor power, sorted on tip pitch angle. The data indicate that the optimum blade-tip pitch angle is less than 0° at wind speeds greater than 9 m/sec. A tip pitch angle of -7° produces about 25 percent more power than a tip pitch angle of 0° at a wind speed of 12 m/sec. This characteristic is different from that of the aileron-controlled rotor, where a negative deflection of the control surface reduces power under all conditions. Once again, the optimum pitch angle for power output is not significant in this study.

Aerodynamic Power Gain

A parameter denoted as aerodynamic power gain (APG) was developed to quantify the effectiveness of various rotor aerodynamic control configurations. The APG is a measure of the change in rotor power attributed to a unit change in the control surface deflection for a constant wind speed. In general, the higher the APG, the more sensitive and effective is the control system. To compare the APG for various rotors, the rotor power at zero deflection was used to normalize the values. The APG, defined as the percent change in power per unit change in control surface deflection, can be expressed as follows:

$$APG = \frac{\Delta P/\Delta\delta}{P_o} \times 100 \qquad (5)$$

in which

ΔP change in rotor power, kW
$\Delta\delta$ change in deflection of control surface, deg
P_o rotor power at $\delta = 0°$, kW

The terms used to calculate the APG value are illustrated in figure 8. For a given wind velocity and corresponding tip-speed ratio, a second order curve fit was made for power as a function of deflection angle for three consecutive deflection angles. The slope of the curve fit (the change in power per unit change in deflection angle) was then obtained at specific deflection angles. The slope was then normalized by dividing by P_o, the power generated at zero deflection of the control surface, and multipled by 100 for conversion into a percentage. This defined the APG for a specific combination of wind speed (or tip-speed ratio) and initial deflection angle. As shown in figure 8, the maximum power produced at any given velocity occurred near $\delta = 0°$, depending on the magnitude of the wind velocity as well as the type of control surface used.

Experimental data for the 20-percent- and 38-percent-chord aileron-controlled rotors and a 30-percent-span pitchable tip-controlled rotor at various initial deflection angles over a wide wind speed range were analyzed to provide data for the APG plots for each of the three control surfaces. The APG values for the 20-percent-chord aileron-controlled rotor were derived from figure 5, and are plotted in figure 9 for initial aileron deflection angles of 0°, -15°, -30°, -45°, and -60°. The highest APG achieved was about 1.6 percent per degree for an initial aileron deflection of 0° and a tip-speed ratio of 4. For this configuration the APG values rose sharply, peaked out, and then dropped gradually with increasing tip-speed ratio. In the lower tip-speed ratio range, the aileron was more effective at deflection angles between 0° and -15°.

The APG values for the 38-percent-chord aileron-controlled rotor, derived by using figure 6, are plotted in figure 10. For this control configuration the maximum APG values occur at tip-speed ratios between 4 and 6, and the APG values increase as the initial control surface deflection angle increases.

The APG values for a pitchable tip-controlled rotor, derived by using the data from figure 7, are plotted in figure 11. The APG of the tip-controlled rotor is characterized by a 6-percent negative value at an initial deflection angle of 0°, and a negative APG for an initial deflection angle of -7° at the higher wind speeds (lower tip-speed ratios). This indicates that at the higher wind speeds the tip deflection angle for maximum power varies from 0° to somewhere near -7° as wind speed increases above 9 m/sec. The data would indicate that the control system for a rotor of this type should be programmed to set the tip angle to its optimum value to obtain maximum power at all wind speeds below rated wind speed. Aside from this characteristic, the APG of the tip-controlled rotor is quite well behaved.

In evaluating and comparing the APG of the various aerodynamic control system configurations, the APG values and trends should both be considered. An initial deflection of -15° of the various control surfaces was used to make the comparison. The APG value as a function of tip-speed ratio for these control configurations is shown in figure 12. From this figure, the APG values for a 20-percent-chord aileron-controlled rotor peaked at 1.0 percent per degree at a tip-speed ratio of 4.5. The APG value for a 38-percent-chord aileron-controlled rotor peaked at 2.0 percent per degree at a tip-speed of 4.8. The APG values for a tip-controlled rotor peaked at 3.8 percent per degree at a tip-speed ratio near 4. Comparing these values, the APG of the 38-percent-chord aileron-controlled rotor was twice that of the 20-percent-chord aileron-controlled rotor, and the APG of the pitchable tip-controlled rotor was four times that of the 20-percent-chord aileron-controlled rotor. These proportions for the aileron-controlled rotors appear to be valid throughout the range of tip-speed ratios evaluated. These APG ratios can be correlated with respect to the control-surface area ratios: the 38-percent-chord aileron has twice the area of the 20-percent-chord aileron and is two times more effective. The pitchable tip has five times the area of the 20-percent-chord aileron and is four times more effective at its peak APG.

The other area of comparison was APG trends. From figures 9, 10, and 11, APG values for a given initial deflection angle tend to peak at fairly low tip-speed ratios. However, as shown in figure 12, the APG for the tip-controlled rotor drops sharply on either side of its peak value, while the APG values for the aileron-controlled rotors are much more uniform. This indicates that control algorithms for the ailerons might be simpler than those for tip control. Another trend is that, for the 20-percent-chord aileron-controlled rotor, the APG values decrease with larger negative initial deflection angles, whereas, for the 38-percent-chord aileron-controlled rotor and pitchable tip-controlled rotor, the values increase with the larger initial deflection angles.

Power Regulation

The aileron-controlled rotors and the tip-controlled rotor were evaluated on the basis of their ability to control to a power setpoint. The evaluation was made by using alternator power data recorded for power setpoints of 0, 25, and 50 kW for each of the three rotor configurations.

Deflection angles of both aileron and tip control surfaces were commanded by an analog controller which used both integral and proportional gain functions. The values of the controller gains were different for different rotor configurations. Gains were adjusted until reasonable power regulation was achieved that required only minimal activity of the control surface actuators. No attempt was made in this preliminary study to optimize the gain settings.

The ability of the 20-percent-chord aileron-controlled rotor to regulate power is shown in figures 13 and 14. Strip chart recordings made during the 50-kW power regulation tests are shown in figure 13. Included in the figure are traces of alternator power, wind speed, and aileron deflection. This chart shows a typical aileron control system response to wind fluctuations and the resulting effect on alternator power. Figure 14 shows alternator power as a function of wind speed during the power regulation tests and quantifies the variability in power output. Each circle on the plot represents the median value of alternator power data in a wind speed bin. Note that power control is only effective within certain wind speed ranges which are typically 4 to 5 m/sec in size. At the lower end of the range the wind speed is too low for the wind turbine to produce the setpoint power. At the high end of the wind speed range, the aileron has reached its deflection limit (-60° in this case) and can no longer prevent power from increasing with increasing wind speed. Within the range of effective aileron control, power variability is shown by the 16th and 84th percentile values of the alternator power data in each bin. The range size of these percentile intervals indicates the accuracy with which the control system was able to maintain the power at the setpoint; the narrower the interval, the more accurate was the regulation of the power.

The ability of the 38-percent-chord aileron-controlled rotor to regulate power is shown in figures 15 and 16. Figure 15 shows strip chart traces of alternator power, wind speed, and aileron deflection taken during the 50-kW power regulation tests. Figure 16 quantifies the results of the power regulation tests on the rotor with the 38-percent-chord ailerons. The major difference between figure 14 for the 20-percent-chord ailerons and figure 16 is in the sizes of the wind speed intervals over which the control surfaces are effective. The 38-percent-chord ailerons are effective over a much wider wind speed range than the 20-percent-chord ailerons: 20 m/sec compared with 4 to 5 m/sec. The data for both aileron-controlled rotor configurations show a tendency for the interval between the 16 and 84 percentile power values to increase with increasing wind speeds.

Figure 17 shows a strip chart recording from power regulation tests of the tip-controlled rotor. A plot of power as a function of wind speed is shown in figure 18. The power regulation behavior for the tip-controlled rotor is similar to that of the 38-percent-chord ailerons in that both control surfaces are effective over a wide wind speed range.

Good correlation was found between the variability of power during the power regulation tests and the wind turbulence during the test period. The variability of power was quantified by the standard deviation from the power setpoint, or root mean square (RMS) deviation, which was calculated from data that were sorted to eliminate data points with wind speeds beyond the effectiveness of the control surface. Cyclic wind speed, the maximum variation from the mean wind speed during one rotor revolution, was used to quantify wind turbulence.

Figure 19 is a plot showing the RMS power deviation from the power setpoint as a function of average cyclic wind speed for the three rotor configurations. Each data point represents one power regulation test period, lasting 1 to 2 hr, at one power setpoint. Comparison of the data from the two aileron-controlled rotor configurations shows that, for a typical cyclic wind speed, the RMS power deviation was 1.4 kW higher for the 20-percent-chord aileron-controlled rotor than for the 38-percent-chord aileron-controlled rotor. Data from the tip-controlled rotor tended to fall between the two aileron configurations. No correlation was found between the value of the power setpoint and the RMS power deviation.

The major difference in power regulation for the two aileron-controlled rotor configurations was the wind speed range for which the control surfaces were effective. The wider range of control provided by the 38-percent-chord aileron was due to the larger control surface and the larger maximum deflection angle (-90° for the 38-percent-chord aileron). Within the wind speed ranges where the control surfaces were effective, both configurations provided acceptable power regulation. Figure 19 indicates that the 38-percent-chord aileron was slightly more effective overall in regulating power to a setpoint. It is probable that the power regulation for both configurations could be improved with appropriate changes of the control parameters, although this may result in an undesirable increase in control activity.

CONCLUSIONS

Rotor performance and power control data were measured on the Mod-0 wind turbine for three types of control surfaces: (1) 20-percent-chord ailerons, (2) 38-percent-chord ailerons, and (3) 30-percent-span pitchable tips. The rotor performance, in terms of rotor power as a function of wind speed, was determined for various control-surface deflection angles. A parameter denoted as aerodynamic power gain (APG) was developed to compare the effectiveness of the three configurations in controlling power. The APG value is a measure of the change in power per unit change in control-surface deflection angle.

Comparing the APG values for the various configurations shows the 38 percent-chord aileron to be twice as effective as the 20-percent-chord aileron. APG values for the tip-controlled rotor show it to be four times as effective as the 20-percent-chord aileron. The APG values for a given initial deflection angle tend to peak at a fairly low tip-speed ratio, and are more uniform for aileron control than for tip control.

Both the 20-percent- and 38-percent-chord ailerons provided acceptable power regulation within the wind speed ranges for which the control surfaces were effective. The 38-percent-chord aileron was slightly more effective in regulating power to a setpoint because of its larger area. It was also effective over a wider range of wind speeds as indicated by the APG value being twice that of the 20-percent-chord aileron. The power regulation data for the tip-controlled rotor fell between the data for the two aileron-controlled rotors.

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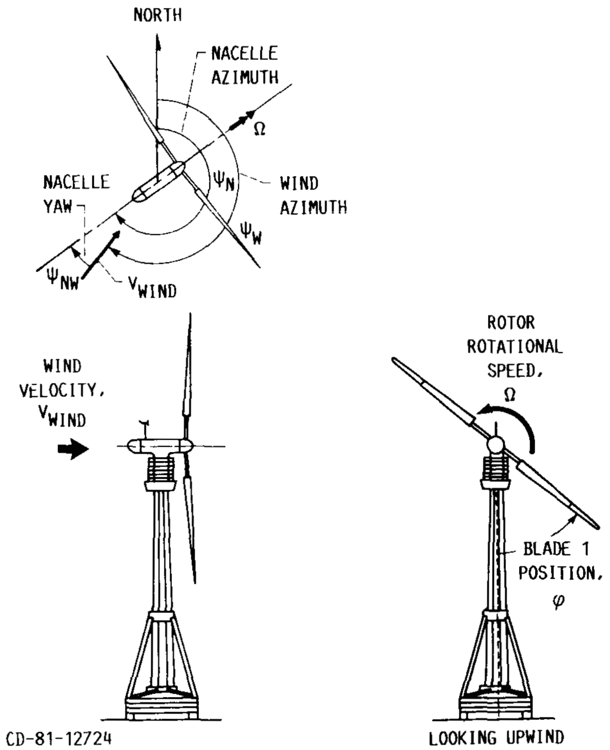
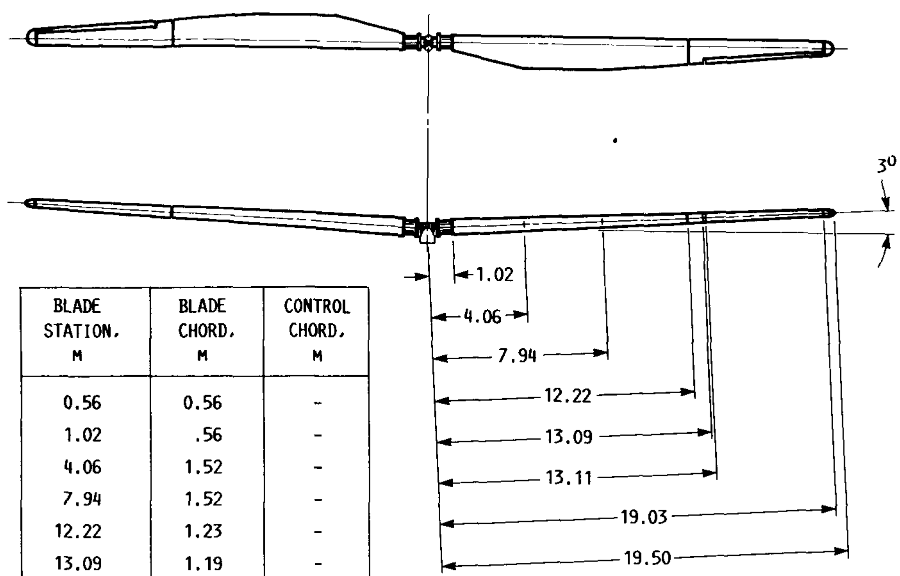
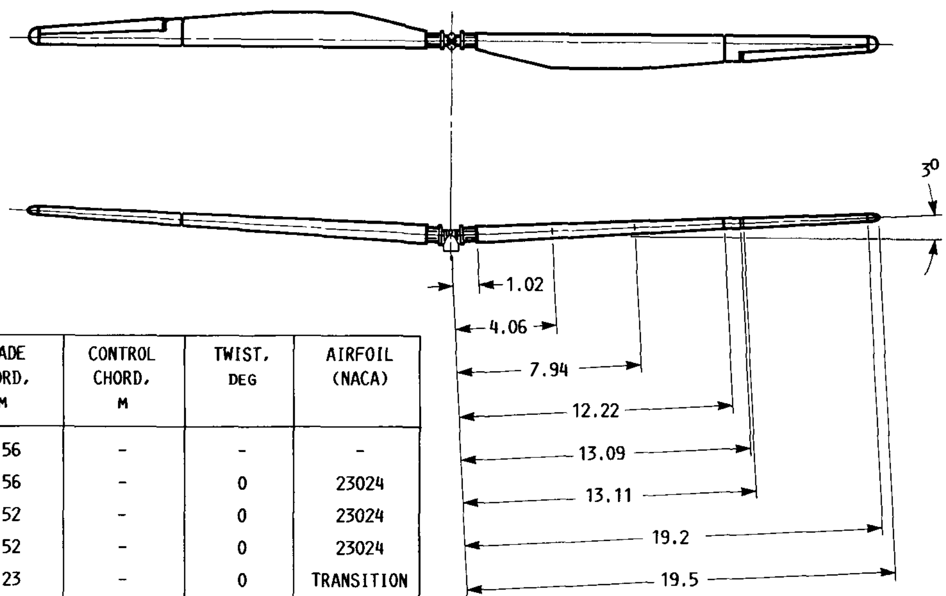


FIGURE 1. - MOD-0 WIND TURBINE. YAW ANGLE IS DENOTED BY ψ.



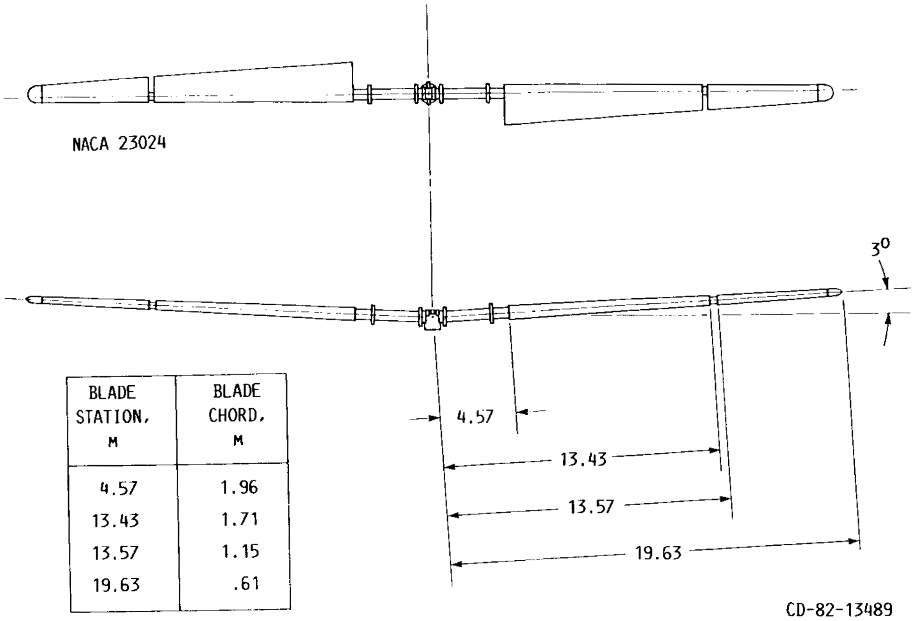
BLADE STATION, M	BLADE CHORD, M	CONTROL CHORD, M
0.56	0.56	-
1.02	.56	-
4.06	1.52	-
7.94	1.52	-
12.22	1.23	-
13.09	1.19	-
13.11	1.20	0.25
19.03	.67	.14
19.50	0	-

FIGURE 2. - PLANFORM OF 20-PERCENT-CHORD AILERON-CONTROLLED ROTOR.



BLADE STATION, M	BLADE CHORD, M	CONTROL CHORD, M	TWIST, DEG	AIRFOIL (NACA)
0.56	0.56	-	-	-
1.02	.56	-	0	23024
4.06	1.52	-	0	23024
7.94	1.52	-	0	23024
12.22	1.23	-	0	TRANSITION
13.09	1.15	-	3	64624
13.11	1.15	0.44	3	64624
19.2	.66	.25	1	64615
19.5	0	-	-	-

FIGURE 3. - PLANFORM OF 38-PERCENT-CHORD AILERON-CONTROLLED ROTOR.



BLADE STATION, M	BLADE CHORD, M
4.57	1.96
13.43	1.71
13.57	1.15
19.63	.61

FIGURE 4. - PLANFORM OF PITCHABLE TIP-CONTROLLED ROTOR.

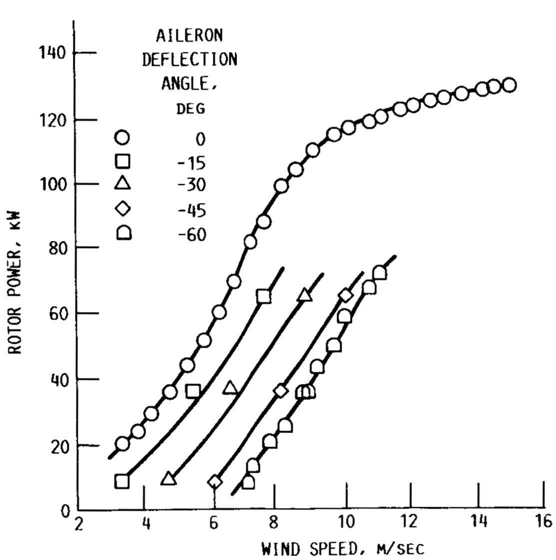


FIGURE 5. - ROTOR POWER AS FUNCTION OF WIND SPEED FOR 20-PERCENT-CHORD AILERON-CONTROLLED ROTOR.

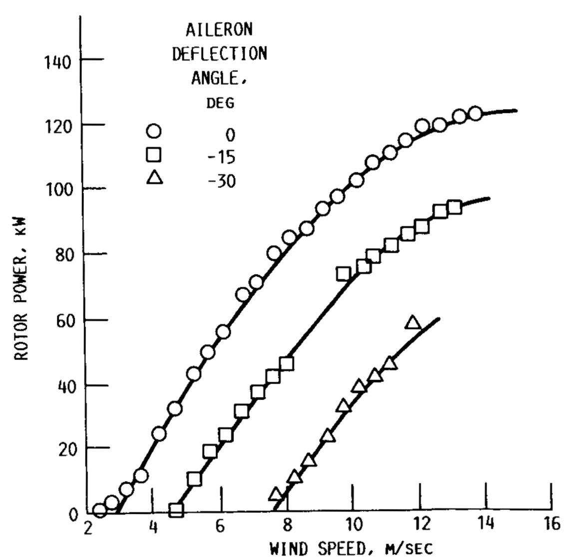


FIGURE 6. - ROTOR POWER AS FUNCTION OF WIND SPEED FOR 38-PERCENT-CHORD AILERON-CONTROLLED ROTOR.

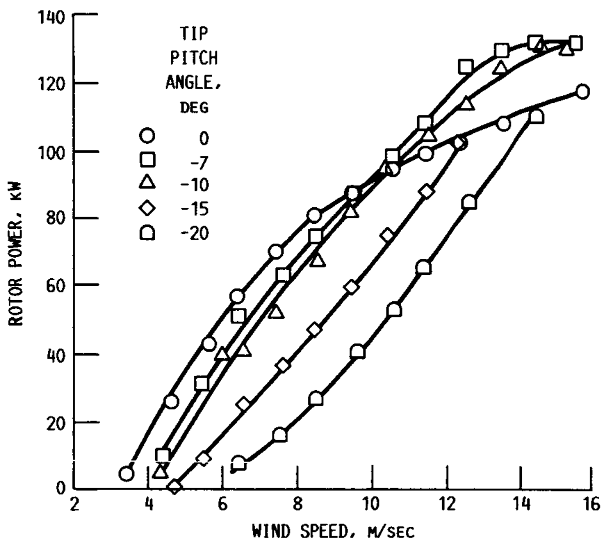


FIGURE 7. - ROTOR POWER AS FUNCTION OF WIND SPEED FOR PITCHABLE TIP-CONTROLLED ROTOR.

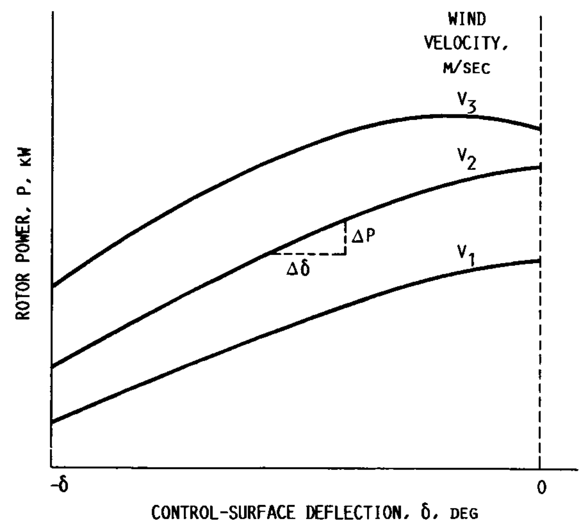


FIGURE 8. - REPRESENTATION OF TERMS USED TO CALCULATE AERODYNAMIC POWER GAIN DEFINED AS $(\Delta P/\Delta\delta)/P_0 \times 100$, PERCENT/DEG, IN WHICH P_0 IS POWER AT $\delta = 0^\circ$.

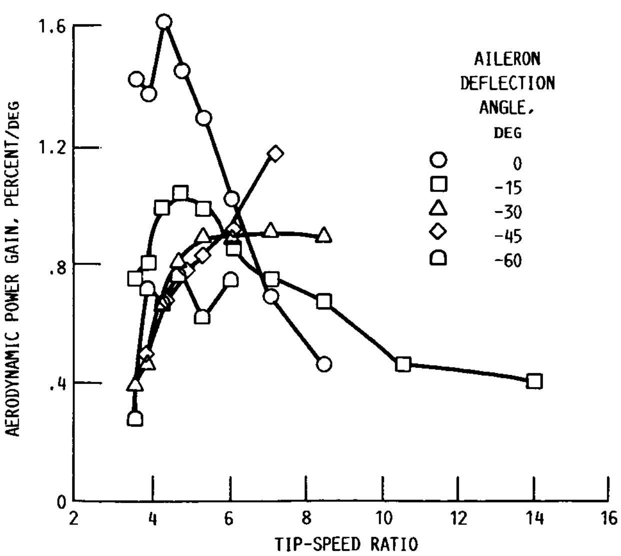


FIGURE 9. - AERODYNAMIC POWER GAIN FOR 20-PERCENT-CHORD AILERON-CONTROLLED ROTOR.

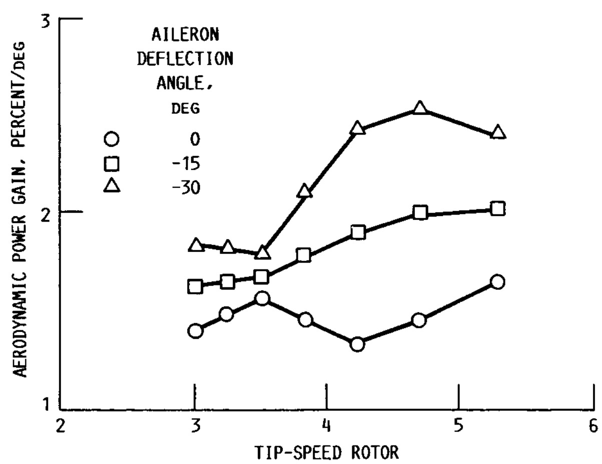


FIGURE 10. - AERODYNAMIC POWER GAIN FOR 38-PERCENT-CHORD AILERON-CONTROLLED ROTOR.

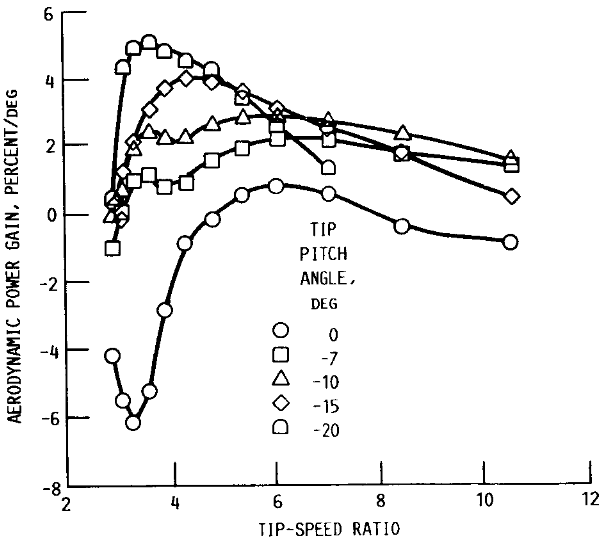


FIGURE 11. - AERODYNAMIC POWER GAIN FOR PITCHABLE TIP-CONTROLLED ROTOR.

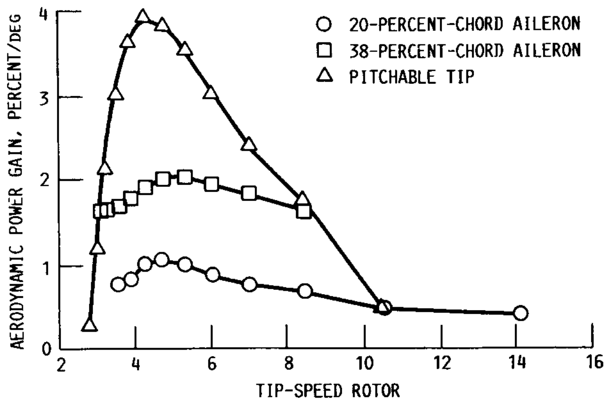


FIGURE 12. - COMPARISON OF AERODYNAMIC POWER GAIN FOR VARIOUS ROTOR CONTROL CONFIGURATIONS AT INITIAL SURFACE DEFLECTIONS OF -15°.

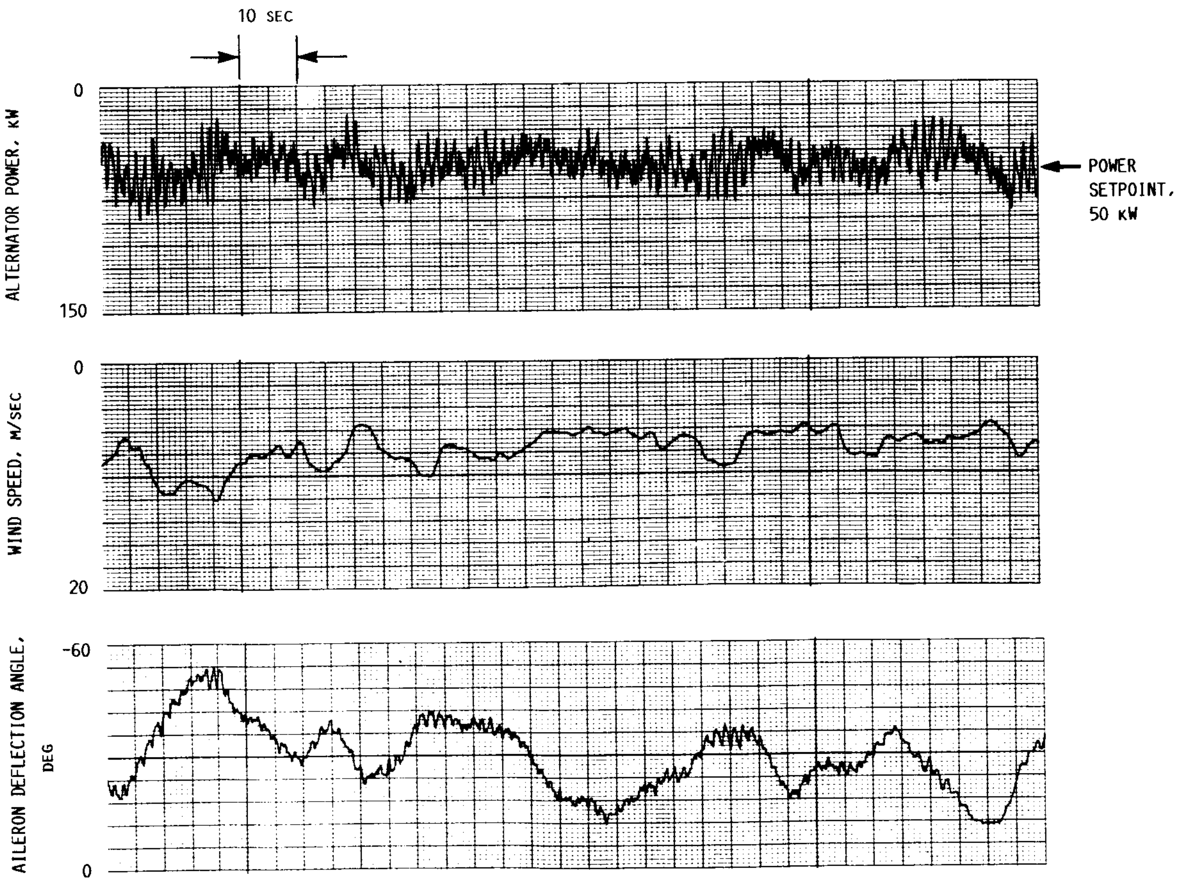


FIGURE 13. - STRIP CHART RECORDING OF POWER REGULATION FOR 20-PERCENT-CHORD AILERON-CONTROLLED ROTOR.

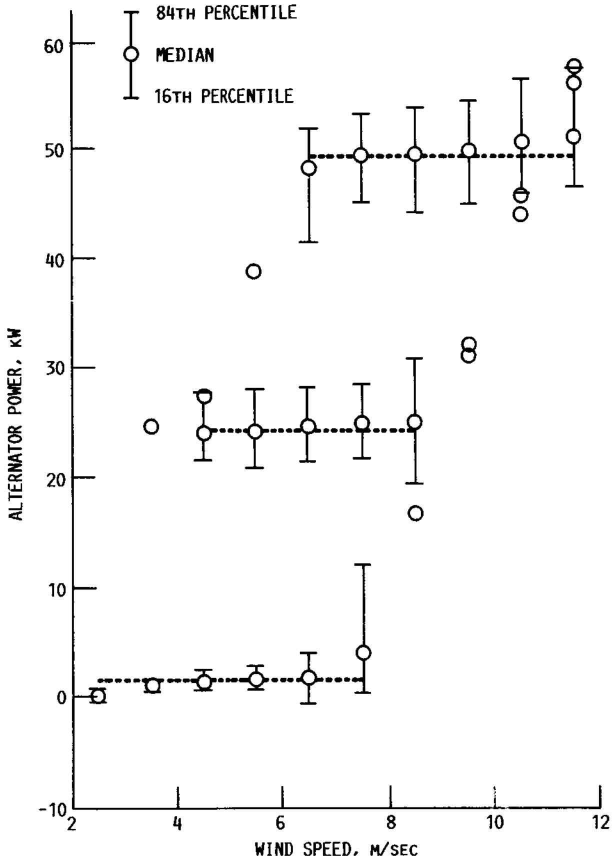


FIGURE 14. - POWR REGULATION FOR 20-PERCENT-CHORD AILERON-CONTROLLED ROTOR.

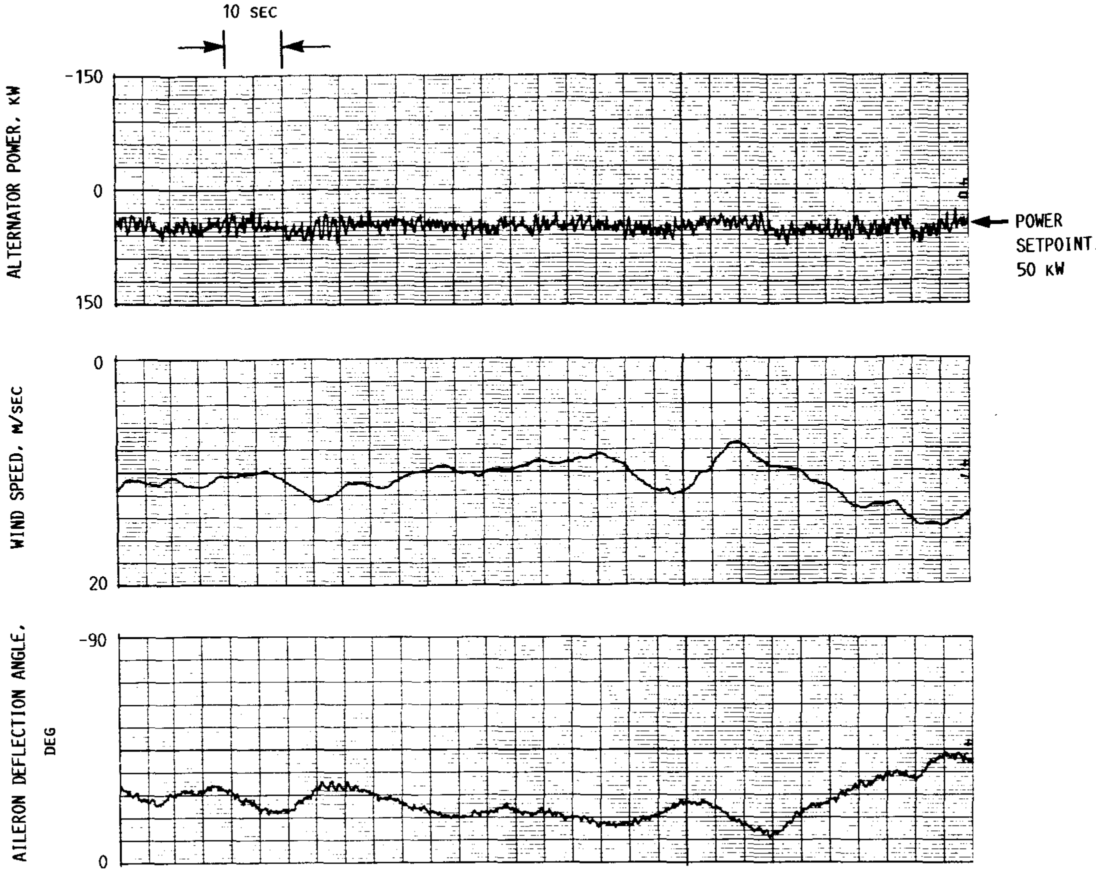


FIGURE 15. - STRIP CHART RECORDING OF POWER REGULATION FOR 38-PERCENT-CHORD AILERON-CONTROLLED ROTOR.

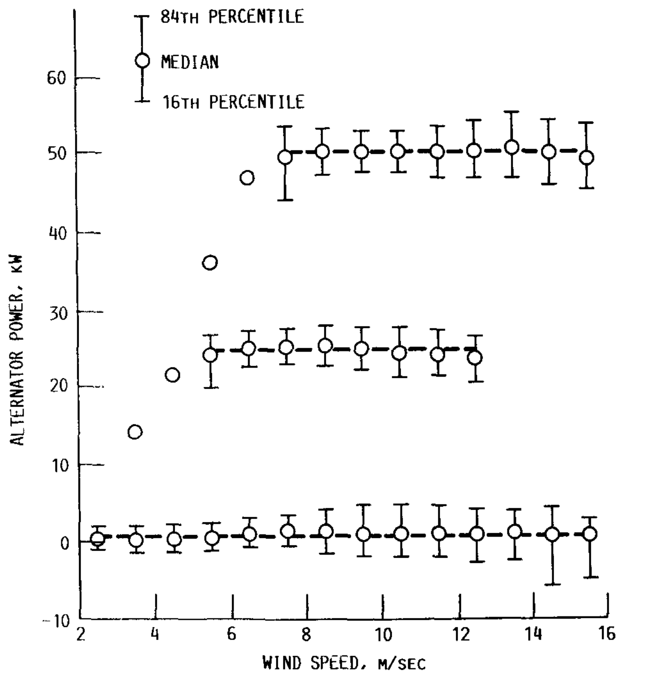


FIGURE 16. - POWER REGULATION FOR 38-PERCENT-CHORD AILERON-CONTROLLED ROTOR.

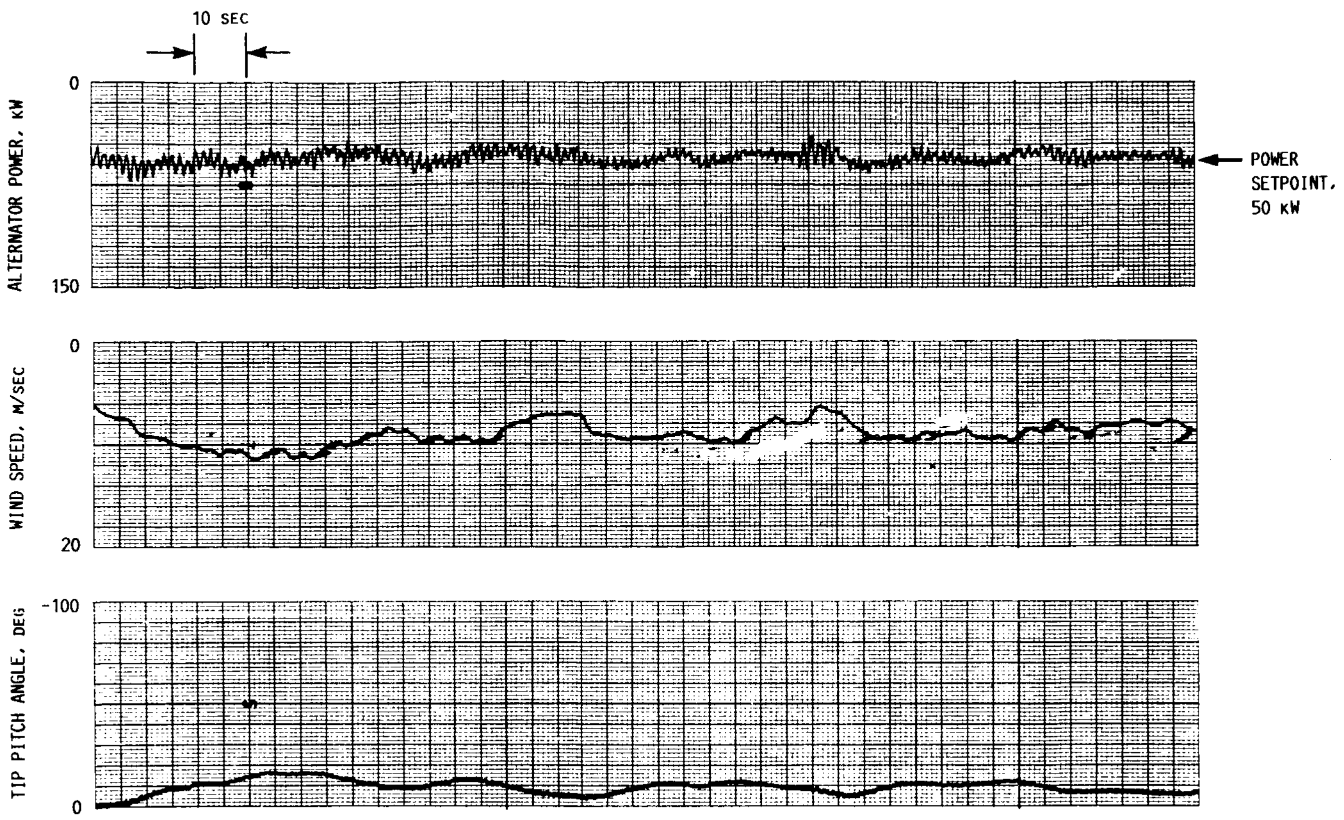


FIGURE 17. - STRIP CHART RECORDING OF POWER REGULATION FOR PITCHABLE TIP-CONTROLLED ROTOR.

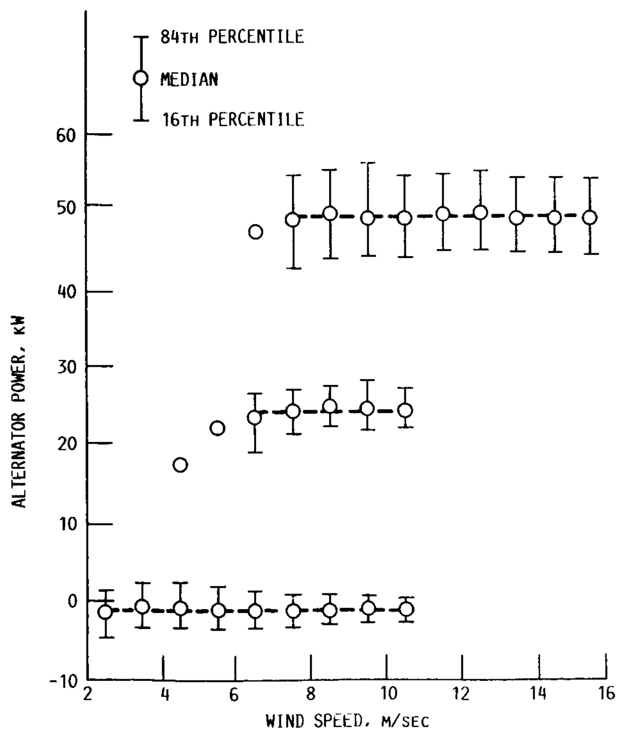


FIGURE 18. - POWER REGULATION FOR PITCHABLE TIP-CONTROLLED ROTOR AT 20 RPM.

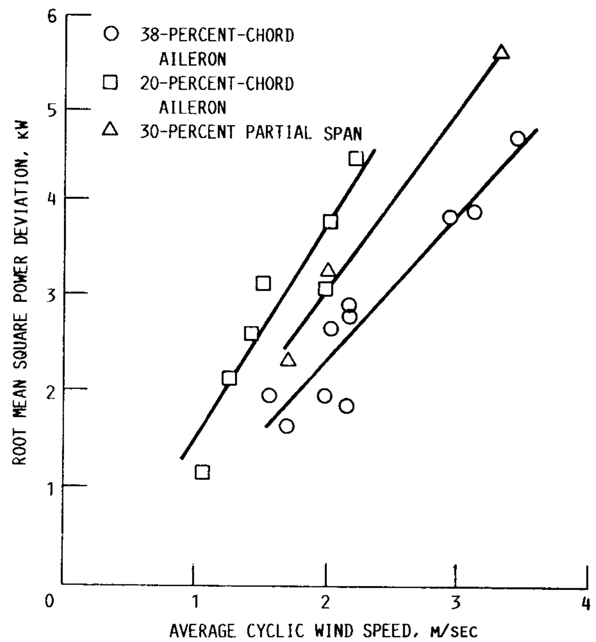


FIGURE 19. - EFFECT OF CYCLIC WIND SPEED ON ROOT MEAN SQUARE (RMS) POWER DEVIATION FROM SETPOINT.

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16. Abstract

Tests were conducted on the DOE/NASA Mod-O horizontal-axis wind turbine to compare and evaluate the performance and the power regulation characteristics of two aileron-controlled rotors and a pitchable tip-controlled rotor. The two aileron-controlled rotor configurations used 20-percent- and 38-percent-chord ailerons, while the tip-controlled rotor had a pitchable blade tip. The ability of the control surfaces to regulate power was determined by measuring the change in power caused by an incremental change in the deflection angle of the control surface. The data shows that the change in power per degree of deflection angle for the tip-controlled rotor was four times the corresponding value for the 20-percent-chord ailerons. The root mean square power deviation about a power setpoint was highest for the 20-percent-chord aileron, and lowest for the 38-percent-chord aileron.

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