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ABSTRACT

Tests were conducted on the Mod-0 100 kW Wind Turbine to determine the performance of a tip-controlled rotor having an NACA 64_3-618 airfoil over the moveable outboard 30% of the blade, while operating at nominal rotor speeds of 21 and 31 rpm. Tests were conducted at two rotor speeds to assess the performance improvement which could be realized with 2-speed operation. Test data are compared with analytical predictions and concluding remarks are presented. The results indicate a clear performance improvement for the 2-speed operation.

INTRODUCTION

This report describes the aerodynamic performance of a 100 kW horizontal axis wind turbine with a tip-controlled rotor using an NACA 64_3-618 series laminar airfoil on the outboard 30% of the rotor blade. Quantitative data on this airfoil is felt to be of interest because high performance airfoils have been largely ignored for use on large horizontal axis wind turbines in the United States. Early rotor designs have relied on airfoils which had convex surfaces, with airfoil selection dictated by a desire to simplify construction and to make use of the potential of wound fiberglass techniques in constructing the blades. As a result, the NACA 230 and NACA 44 series airfoils have been used almost exclusively. There is also a concern about the loss of performance on laminar airfoils as the airfoil surface loses its aerodynamic cleanliness over time. These tests of the NACA 64_3-618 airfoil are a first step in assessing its overall potential for use on large horizontal axis wind turbines.

The performance data were taken on the Mod-0 100 kW experimental wind turbine located at Sandusky, Ohio. The wind turbine and pertinent test equipment are described below. In performing the tests, a system of wind measuring stations was used which provides wind data at approximately 1.5 rotor diameters upwind of the wind turbine. This system is new to the test facility and is described in some detail. The test procedure is described along with the data reduction and analysis. Test data are compared with analytic predictions and, finally, conclusions taken from the results are discussed.

TEST CONFIGURATION

Tests were conducted on the NASA Mod-0 100 kW Experimental Wind Turbine. The wind turbine had a teetered, downwind, two-bladed rotor. The machine was designed for operation at various rotor speeds and these tests were conducted at nominal rotor speeds of 21 and 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 from the horizon to provide adequate blade-to-tower clearance. The rotor hub, mounted on the elevated end of the nacelle, is 31.8 m above ground level. A cutaway view of the nacelle is shown in Figure 2. Parts of the configuration and test support equipment which are particularly important to these tests are described below.

Rotor & Drive Train

The rotor was unconed, had two blades and was capable of ±6 deg of teeter motion. The rotor blades were 19.18 m long with controllable tips over the outboard 30% of the span. The inboard section of the blade was untwisted, tapered and had an NACA 23024 series airfoil. The outboard 30% of the blade was also untwisted and used an NACA 64_3-618 series airfoil. The blades were mounted to have a zero deg pitch angle with respect to the rotor plane, and the tips were pitchable from +10 deg to -65 deg (-90 deg is feathered) to provide aerodynamic control. In the tests, the pitch control system was set to limit power to 90 kW at a rotor speed of 21 rpm and 100 kW at a rotor speed of 31 rpm. Detailed rotor and blade characteristics are presented in Table I and the blade planform is shown in Figure 3.

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 belt drive. A 2-speed high-slip induction generator, set in the low speed mode (1200 rpm) for a rotor speed of 21 rpm and set in the high speed mode (1800 rpm) for a rotor speed of 31 rpm, was used in the tests. Drive train and generator characteristics are summarized in Table II.

Data taken during the test indicate the following relationships between the rotor power and generator power output.

At 21 rpm

$$P_1 = 1.20\,P_3 + 3.5 \qquad (1)$$

and at 31 rpm

$$P_1 = 1.16\,P_3 + 6.0 \qquad (2)$$

where

P_1 = Rotor Power (kW)

P_3 = Alternator Output Power (kW)

These equations were derived from a Bins Analysis of rotor torque, alternator power and rotor speed.

Yaw Control

The yaw drive assembly, shown in Figure 2, consists of a single hydraulic motor/clutch/gear system connected to a pinion gear. This in turn moves a ring gear which is attached to the nacelle. The yaw drive motor is controlled by a yaw controller. The yaw controller compares the nacelle yaw angle reading taken from the nacelle-mounted wind vane, 3.4 m above the nacelle and 4.6 m upwind of the rotor, with a desired yaw angle (normally a yaw angle of zero deg is desired). 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 desired yaw angle. The yaw brake was used to prevent nacelle yawing motions which cause oscillatory yaw loads in the yaw drive. While the control logic described above is generally acceptable in turbulent winds, it has been found to produce unacceptable yaw errors in steady winds typical of overnight operation. Occasionally this system was also found to allow large yaw angles when taking performance data and corrections were required to account for yaw misalignment.

Meteorological Instrumentation

Meterological data was taken from instruments mounted at rotor hub height on an array of five measuring station towers 59.4 m (1.56 rotor diameters) from the wind turbine and spaced 45 deg apart. This array is termed the "Performance Array". An additional meteorological tower with measuring stations at four heights is located 200 m southwest of the wind turbine. The wind measuring system is shown in Figures 4 and 5. 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. The anemometers and wind vanes are common at all locations and have the characteristics shown in Table III.

TEST DATA

The performance of the tip-controlled rotor with the NACA 64_3-618 tips was determined based on 18 hours of operation conducted over a period of several weeks. The test data was multiplexed, recorded on FM tape and digitized. The details of how the data was processed to obtain the performance data is discussed below.

Data Reduction and Processing

Since this analysis concerns itself only with power as a function of wind speed, the results presented are based on the average of a given parameter over a period of time. This decision was made for the following reasons. First, the average performance over a time period is more representative of the information desired; which is energy capture in varying winds. Second, the use of a time average minimizes the effects of distance between the measuring station and the wind turbine. Third, the use of time averaged data facilitated the of use correction factors which could be applied on a point by point basis, such as yaw angle corrections.

The data system currently in use at the Mod-0 test facility is set up to record data on FM tape and to digitize this data for off-line processing. The digitized data is highly compressed and contains only the maximum and the minimum value seen over a single revolution of the rotor. To obtain a time average, the values taken over the required number of rotor revolutions are averaged. The data reduction program allows for variations in the rotor speed in determining the proper number of rotor revolutions for a preselected averaging time.

In determining rotor performance for this report the following parameters were averaged over five minute intervals: wind speed, wind direction, wind turbine nacelle azimuth, blade pitch angle and alternator power. From this data, wind speed, yaw angle and power output was determined.

Corrections to the Test Data

Corrections were made to the test data for density and yaw angle. Pressure and temperature were taken for each test run, and the data for each day were corrected to sea level standard conditions. Normally, test runs were four hours or less and atmospheric conditions changed very little during the test; therefore, a single correction would suffice for a particular set of data with regard to air density. Yaw angles varied widely during a test run, however, ranging from zero to as high as 25 deg on isolated occasions. To account for this, a correction was made for yaw angle for each five minute interval of data.

In making the corrections for density or yaw angle, measured alternator power was first converted to rotor power using the relationships of equation 1 or 2. Corrections were then made to rotor power as indicated below and these corrected values were then converted back to alternator power. This procedure avoids applying corrections to a fixed drive train loss.

For density

$$P_1' = \rho_0 P_1 \rho \qquad (3)$$

For Yaw Angle

$$P_1' = P_1/\cos^3\Psi \qquad (4)$$

where

P_1 rotor power

ρ_0 air density at sea level, standard conditions

ρ air density during test

Ψ rotor yaw angle

(') corrected parameter

RESULTS AND DISCUSSION

The aerodynamic performance of the Mod-0 Wind Turbine, having a teetered, tip-controlled rotor with an NACA 64_3-618 airfoil tip section and an NACA 230 series airfoil inboard section, was measured at rotor speeds of 21 and 31 rpm. For these tests, power output was limited to 90 kW for 21 rpm and 100 kW for 31 rpm. These limiting power values were set in the power controller of the tip pitching mechanism and are referred to as rated power level for these tests.

Tests were conducted over a broad range of wind speeds and approximately 12 hours of data at 31 rpm and 6 hours at 21 rpm were taken. The data is presented in two forms, first as alternator power corrected for density and yaw angle, and second as rotor power which is derived from a curve fit of the corrected alternator power test data. The alternator power is presented to indicate the actual power output while the rotor power is of interest to the analyst in making performance comparisons between the two rotor speeds. The data is presented and discussed in the text below.

Measured Data

Test data were taken as described above and 5 minute averages of alternator power, wind speed and yaw angle were obtained. The power data were corrected to standard sea level atmospheric conditions and for yaw angle. Alternator power versus wind speed data for rotor speeds of 21 and 31 rpm are shown in Figures 6 and 7. Also shown in the figures are lines describing a curve fit for the measured data. These lines were determined by use of the least squares method. Data near and above rated power, which were affected by the power controller, were eliminated from the sample prior to performing the curve fit. These data were identified by noting the blade pitch angle, i.e. data points having a blade pitch other than zero were eliminated from the curve fit sample. This was done to eliminate the effect of power control on the curve at wind speeds below the rated power level. The dashed line indicates rated power.

At 21 rpm most data were measured in wind above 5.5 m/s. However, very little operating time was spent at wind speeds above 9 m/s because of teeter instability associated with operation in the higher wind speeds at the 21 rpm rotor speed (5).

2-Speed Operation

To compare the performance of the rotor at two rotor speeds, the curves derived from the test data in Figures 6 and 7 were converted to rotor power using equations 1 and 2. These curves are shown in Figure 8 and define the rotor power versus wind speed for 21 and 31 rpm. This was done to remove the effect of the drive train and to provide information which would be of more value to the analyst. The curves intersect at a wind speed of 6.3 m/s and at a power level of 57 kW. Below this point the rotor produces more power at a rotor speed of 21 rpm for a given wind speed and above this point the rotor produces more power at 31 rpm. This intersection or crossover point is theoretically the optimum point at which a speed change should be made for 2-speed operation of this rotor. At wind speeds below 6.3 m/s the rotor operates more efficiently at 21 rpm and at wind speeds above 6.3 m/s the rotor operates more efficiently at 31 rpm.

Comparison with Analytic Predictions

A comparison of the measured data was made with analytical predictions derived from the PROP computer program (6) and airfoil data as described in Reference (7). The analytic model accounted for thickness ratio, and included semi-empirical refinements using aspect ratio. With the blade planform shown in Figure 3, the gap between the inboard blade section and tip section of approximately .15 meters was considered to have a large effect on rotor performance. A method to account for this gap is presented in Reference (8). The method adjusts the blade aspect ratio and on the blade planform and the width of the gap. The inclusion of this factor in the model reduced the predicted energy capture of the rotor by 8%.

Figures 9 and 10 show the comparisons of measured alternator power, corrected density and yaw, with predicted power based on the analysis, for rotor speeds of 21 and 31 rpm. Differences near rated power can be attributed to biasing of the measured data by the power controller. The predictions were 3% higher than the measured data for the 21 rpm case and 7% higher for the 31 rpm case; based on an energy comparison for the tests. Points near rated power were excluded in calculating these differnces. No provision was made for the drag associated with the tip pitch mechanism which is exposed in the gap between the fixed and moveable portions of the blade. This loss increases with the square of the rotor speed and is a possible source of the difference in the agreement between the analysis and the test results for the two rotor speeds.

CONCLUDING REMARKS

Testing was conducted on an unconed, teetered, two-bladed rotor having an NACA 64_3-618 airfoil over the outboard 30% of the blade. The tests were conducted at 21 and 31 rpm and performance data were measured. In addition to measured performance, predicted performance was obtained using the PROP computer program. As a result of the tests and analyses, the following concluding remarks were made.

- Performance of a rotor having an NACA 64_3-618 airfoil tip section was measured at rotor speeds of 21 and 31 rpm.
- Measurements show the increase in energy capture which can be realized with 2-speed operation of the rotor.
- Analytical predictions correlated reasonably well with experimental data, being 3% high at 21 rpm and 7% high at 31 rpm.

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(8) Hoerner, S. F.: Fluid-Dynamic Drag. S. F. Hoerner, 1965.

TABLE I

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 sect.), 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)

TABLE II

DRIVE TRAIN AND GENERATOR CHARACTERISTICS

	Nominal Rotor Speed	
	21 RPM	31 RPM
Rotor Speed @ 0 Power	20.6	30.8
@ 100 kW	22.1	31.2
Slip @ 100 kW	8.5%	4.0%
Efficiency P_3/P_1 @ 100 kW	.81	.82

TABLE III

METEOROLOGICAL SENSOR SPECIFICATIONS

Performance	Wind Speed	Wind Direction
Accuracy	±0.07 m/s or ±1.0%	±2.^{o}
Threshold	0.22 m/s	0.22 m/s
Distance Constant	1.5 m of air max	1.1 m of air max
Operating Range	0-56 m/s	0^o - 540^o
Damping Ratio	--	0.4 at 10^o initial angle of attack

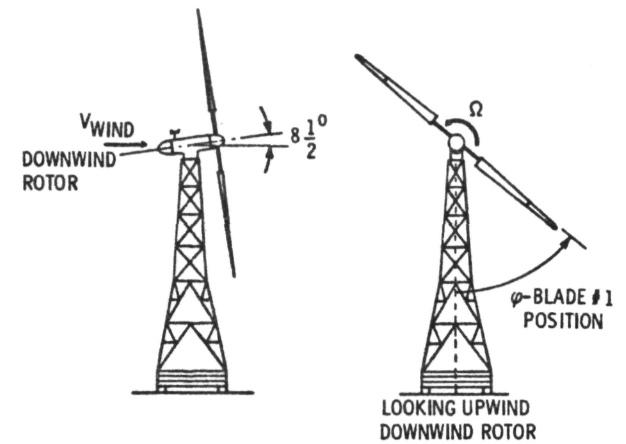


Figure 1. - NASA Mod-0 100 kW wind turbine.

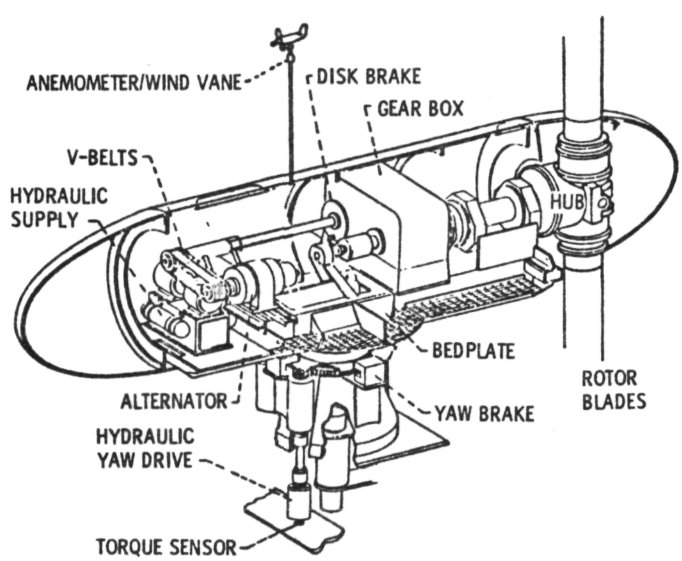
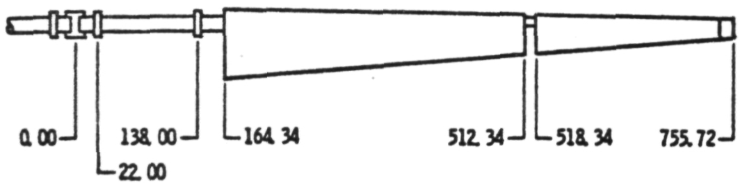


Figure 2. - Nacelle interior of the NASA Mod-0 wind turbine.



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.

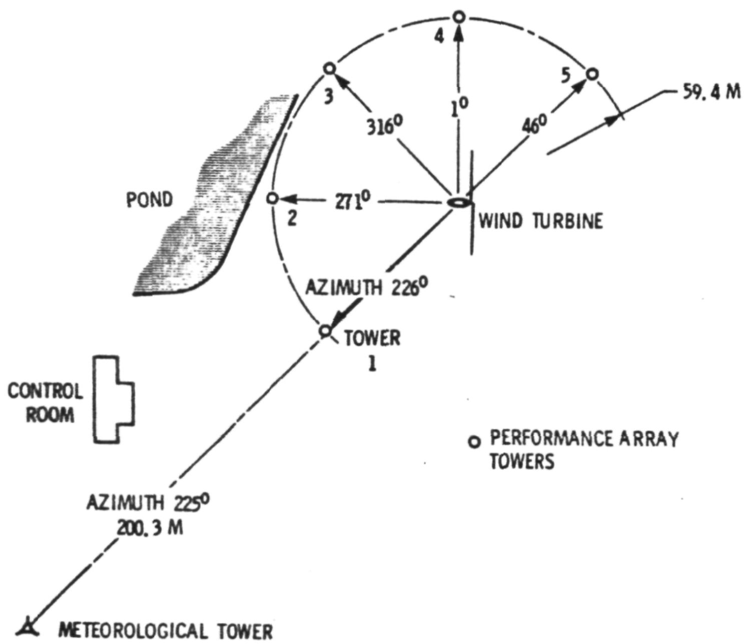


Figure 4. - Mod-0 wind turbine site layout showing location of wind monitoring stations relative to the wind turbine.

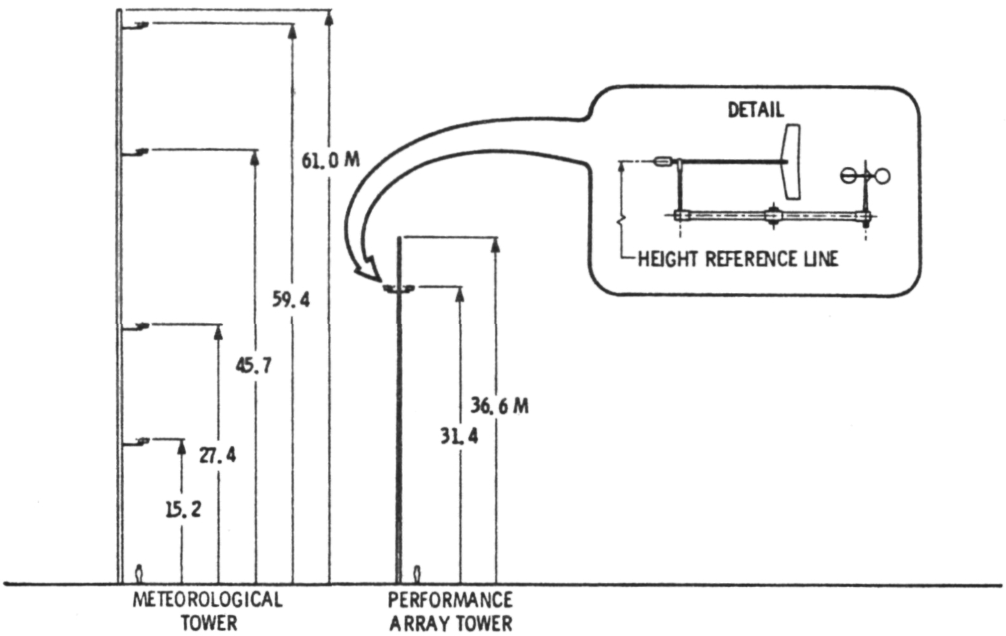


Figure 5. - Mod-0 wind monitoring stations.

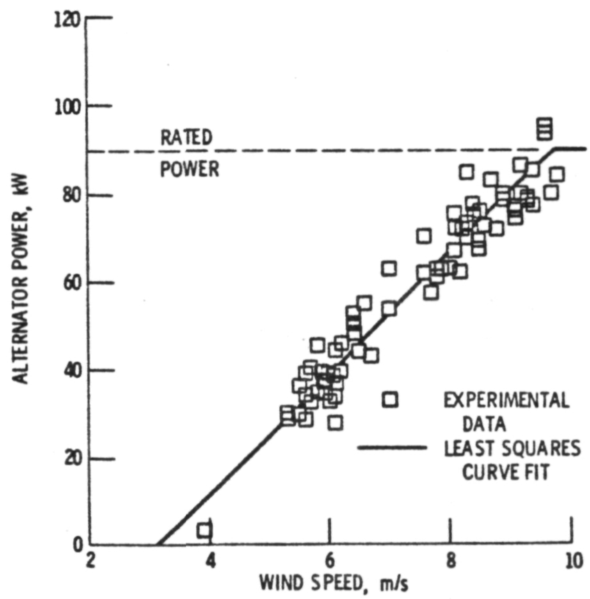


Figure 6. - Alternator power versus windspeed at a rotor speed of 21 rpm

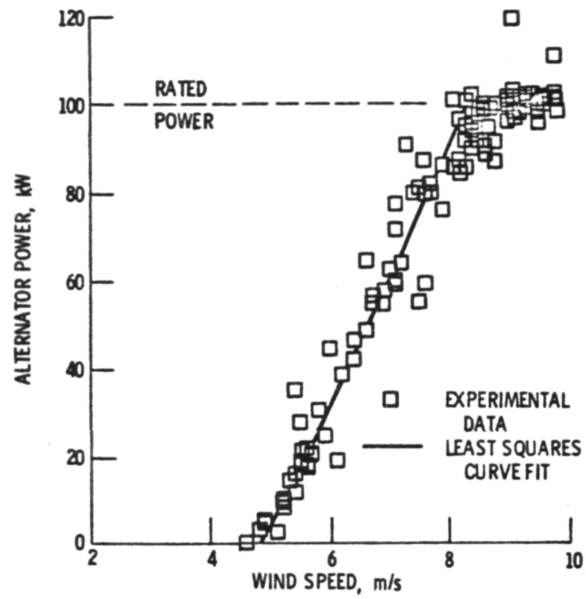


Figure 7. - Alternator power versus windspeed at a rotor speed of 31 rpm.

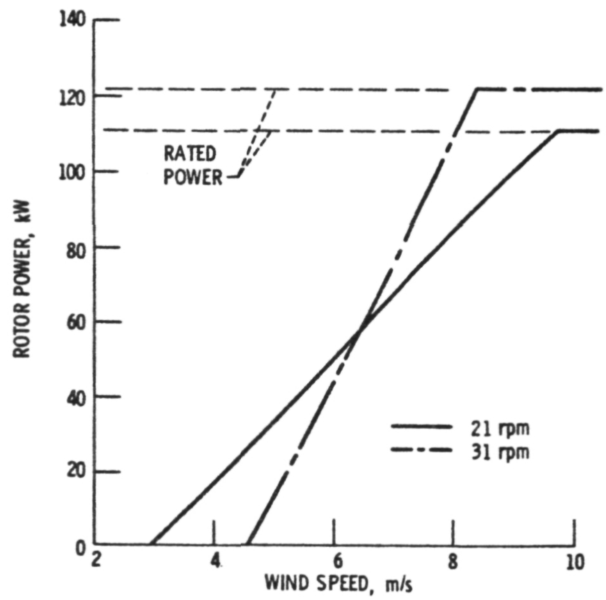


Figure 8. - Rotor power versus windspeed at rotor speeds of 21 and 31 rpm.

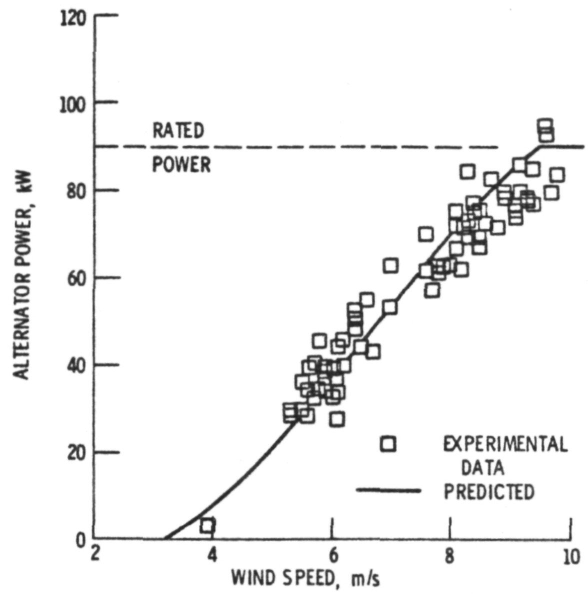


Figure 9. - Comparison of predicted alternator power to measured data, for a rotor speed of 21 rpm.

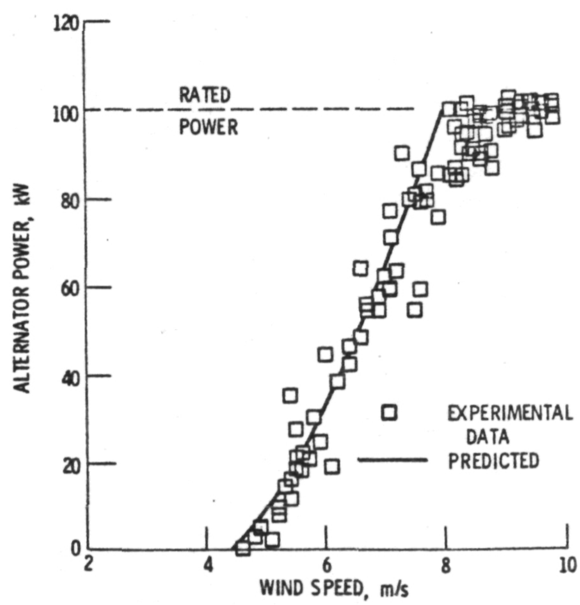


Figure 10. - Comparison of predicted alternator power to measured data, for a rotor speed of 31 rpm.

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16. Abstract

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