SANDIA REPORT SAND-81-1762 • Unlimited Release • UC-60
Printed October 1981

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

SF2900Q(8-81)

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: $5.00
Microfiche copy: A01

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Distribution
Category UC-60

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Abstract

Current designs of curved-blade Darrieus vertical-axis wind turbines (VAWTs) have blades mounted in such a way that the position vector from the axis of rotation intersects the blade chord perpendicularly between the -25% and -50% chord points. This paper describes the effects on aerodynamic performance of the Sandia National Laboratories' (SNL) 5-m-dia turbine when its symmetrical cross-section blades are mounted such that the axis of rotation-blade chord position vector effects a normal intersection with the blade chord at points between -180% and +77% chord. These variations produce significant changes in cut-in tip-speed ratio, peak efficiency, and peak power.

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Introduction

Present designs of the curved-blade Darrieus vertical-axis wind turbines (VAWTs) generally feature blades of symmetrical cross section mounted such that the position vector from the axis of rotation to any blade spanwise position perpendicularly intersects the blade chord between the -25% and -50% chord points. Figure 1, Drawing S33451, denotes the sign convention used here. For a typical extruded aluminum blade, the intersection is approximately at -40% chord; this is a rough compromise between the stalled and unstalled center-of-pressure locations.

It is possible that this configuration may not provide optimum aerodynamic performance from the cost-of-energy (COE) or reliability points of view. Varying the chordwise mounting point from the -40% value is one way to alter aerodynamic performance, the result of two sources:

1. The local blade airstream incidence angle (angle-of-attack) as a function of circumferential position (relative to the free-stream wind) would change. Blade torque varies strongly with circumferential position caused by flowfield differences in the advancing/retreating and upwind/downwind portions of the blade trajectory.
2. The blade's normal force now is able to contribute (both positively and negatively) to the turbine torque. The current design mounting points are too near the blade section center-of-pressure for the normal forces to provide significant turning torque.

Again, the variation of flowfield with blade circumferential position is an important factor in the aerodynamic output of turbines using noncurrent offset mounting. Different offset mountings have the potential of reducing COE by suitably tailoring the power vs windspeed characteristics of a turbine, and can increase turbine reliability by smoothing the blade torque vs circumferential position signature of the turbine. This paper details a parametric study performed on the Sandia National Laboratories' (SNL) 5-m-dia Darrieus VAWT wherein the axis of rotation-blade chord position vector perpendicularly intersected the blade chord at points between -180% and +77% chord.

Experiment

The 5-m VAWT was fabricated in 1974 as a proof-of-concept machine and has seen recent use as a test bed for examining VAWT blade aerodynamics. Reference 1 describes the turbine and reports the results of performance testing of this height/diameter = 1.02 turbine fitted with straight line-circular arc-straight line planform extruded aluminum blades using the NACA 0015 cross section with a 15.24-cm chord. The position vector from the axis of rotation to the blade chord intersected the chord perpendicularly at the -40% chord point for all of this testing. The present series of performance tests differs from the previous one in that the central tower/blade attachment hardware (Figure 2) allows rapid adjustment of the perpendicular intersection point from between -180% to +77% of chord in roughly 13%-chord increments. These percentages may be translated into effective preset pitch or incidence angles as shown in Figure 1. That the angles shown are flow-incidence angles may be more easily seen if a blade, at some positive percentage orientation, is advanced such that the blade's leading edge intersects the zero percentage position vector; the chord of the advanced blade will make a toe-in (positive) angle relative to the chord of the zero percentage (zero incidence angle) blade. Blades at negative percentage orientations will similarly correspond to negative preset incidences.

Testing was performed at six values of preset pitch angle. These values were -7°, -4°, -2°, -1/2°, +1°, and +3° (see Figure 1 for the equivalent percentage chord equivalents). The rotational speed of the rotor was held constant at 175 rpm, giving a blade Reynolds number based on equatorial radius of 3.5 x 10^5. Wind velocities were measured by anemometers located two turbine diameters away from the turbine axis of rotation and at a height equal to that of the turbine equator. Rotor rotational speed and torque were measured by a Lebow Associates rpm and torque transducer. Performance data were assembled using the method of bins.[2] A data sampling rate of 20/s was used throughout all testing.

Results

Figures 3 through 8 give the power coefficient as a function of tip-speed ratio (C_p vs X) for the six values of preset pitch, β. Rotor power as a function of freestream velocity (P vs V_∞) is depicted in Figures 9 through 14. The tip-speed ratio and power coefficient are defined as:

$$X = R\omega/V_\infty \quad ,$$

$$C_p = Q\omega/(1/2\ \rho_\infty V_\infty^3 A_s) \quad ,$$

where

R = Maximum rotor radius
ω = Rotor rotational speed
Q = Rotor torque
ρ_∞ = Ambient air density
A_s = Rotor swept area

In all testing, Q was corrected for frictional losses and ρ_∞ was adjusted to correspond to a constant ambient air density of 0.0625 lbm/ft^3. The wind velocities were measured by anemometers lying within ±45° from the ambient wind direction. Composites of the data appear in Figures 15 and 16. Each individual data set is comprised of at least 300 000 data points with one exception. The β = -7° set represents 170 000 points. It was apparent early in the testing at this pitch setting that this configuration was not of sufficient interest to warrant additional investigation.

For the preset pitch angles tested, power coefficients ranged from a maximum of 0.36 at β = -2° to a minimum of 0.24 at β = +3°. Tip-speed ratios at maximum power coefficient fell between 5.4 (β = -7°, -2°) and 6.5 (+1°, -1/2°). Maximum and minimum values of shaft power were 2.97 kW and 1.89 kW, respectively. As was the case with C_p, the highest value occurred at β = -2° while the lowest was measured at the +3° incidence. Stall regulation (maximum power) took place between 30 and 32 mph (X = 3 ±0.1) for all settings save +3°. Regulation had not occurred for this geometry over the range of windspeeds at which it was tested. Runaway (zero shaft power) speeds varied with pitch/offset setting. The highest value was 12 mph (X = 7.9) at β = -7°; the lowest was just over 9 mph (X = 10.5) with the pitch at -1/2°.

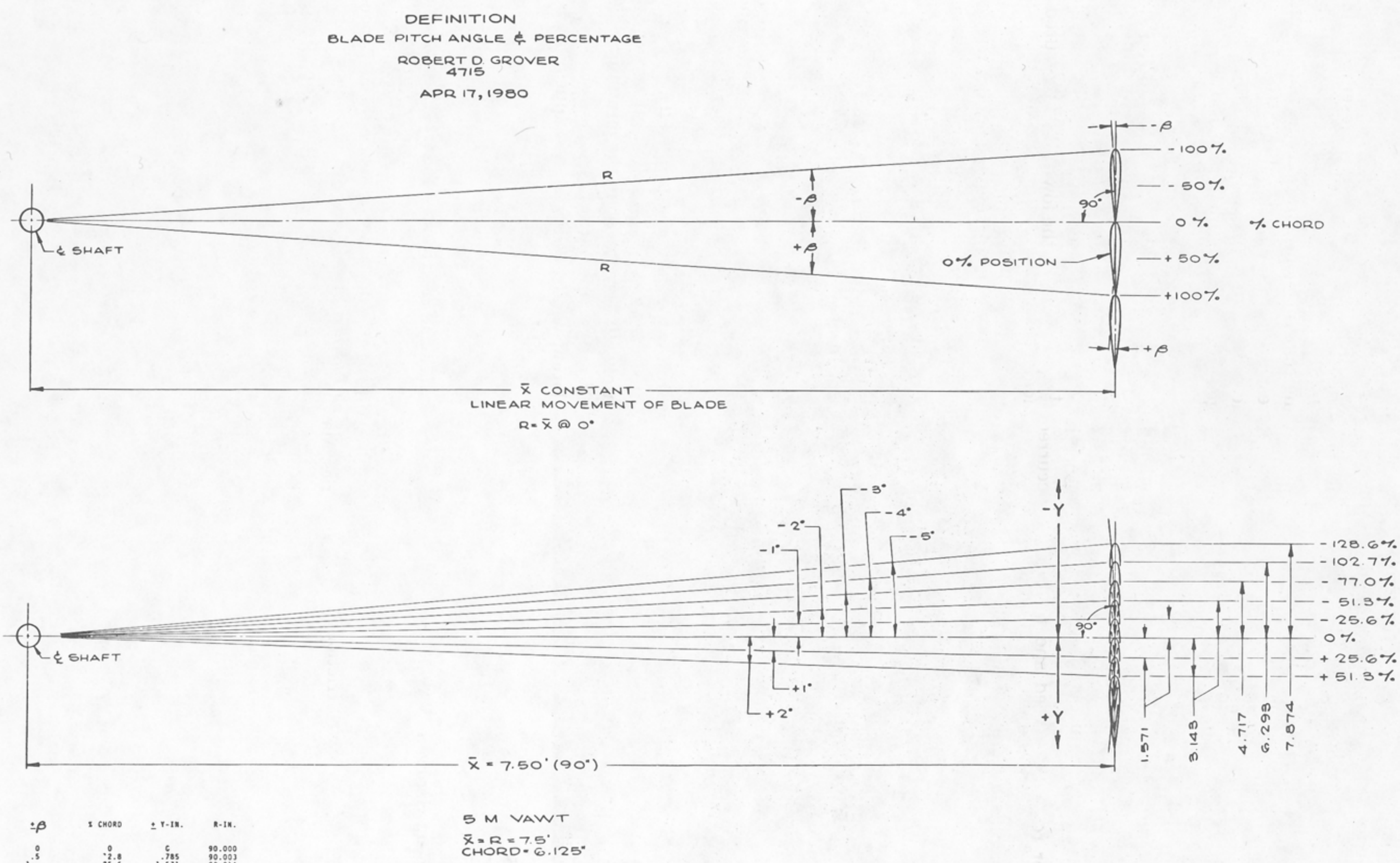
Conclusions

Small variations in blade preset pitch/offset lead to large variations in the aerodynamic performance of a curved-blade Darrieus VAWT as measured by peak efficiency and peak power. Specifically, maximum values of turbine efficiency and output power were approximately 50% greater than the minimum values over the 10° range of preset pitch-angle values tested. Stall regulation windspeeds did not appear to be a strong function of incidence angle.

References

[1] R. E. Sheldahl, P. C. Klimas, and L. V. Feltz, *Aerodynamic Performance of a 5-Metre-Diameter Darrieus Turbine With Extruded Aluminum NACA 0015 Blades*, SAND80-0179 (Albuquerque: Sandia National Laboratories, March 1980).

[2] R. E. Akins, *Performance Evaluation of Wind Energy Conversion Systems Using the Method of Bins - Current Status*, SAND77-1375 (Albuquerque: Sandia Laboratories, March 1978).



±β	% CHORD	± Y-IN.	R-IN.
0	0	0	90.000
.5	12.8	.785	90.003
1	25.6	1.571	90.014
1.5	38.5	2.357	90.031
2	51.3	3.143	90.055
2.5	64.2	3.929	90.086
3	77.0	4.717	90.124
3.5	89.9	5.505	90.168
4	102.7	6.293	90.220
4.5	115.6	7.063	90.278
5	128.6	7.874	90.344
5.5	141.5	8.666	90.416
6	154.4	9.459	90.496
6.5	167.4	10.254	90.582
7	180.4	11.051	90.676

Figure 1. Incremental Blade Locations 5M VAWT

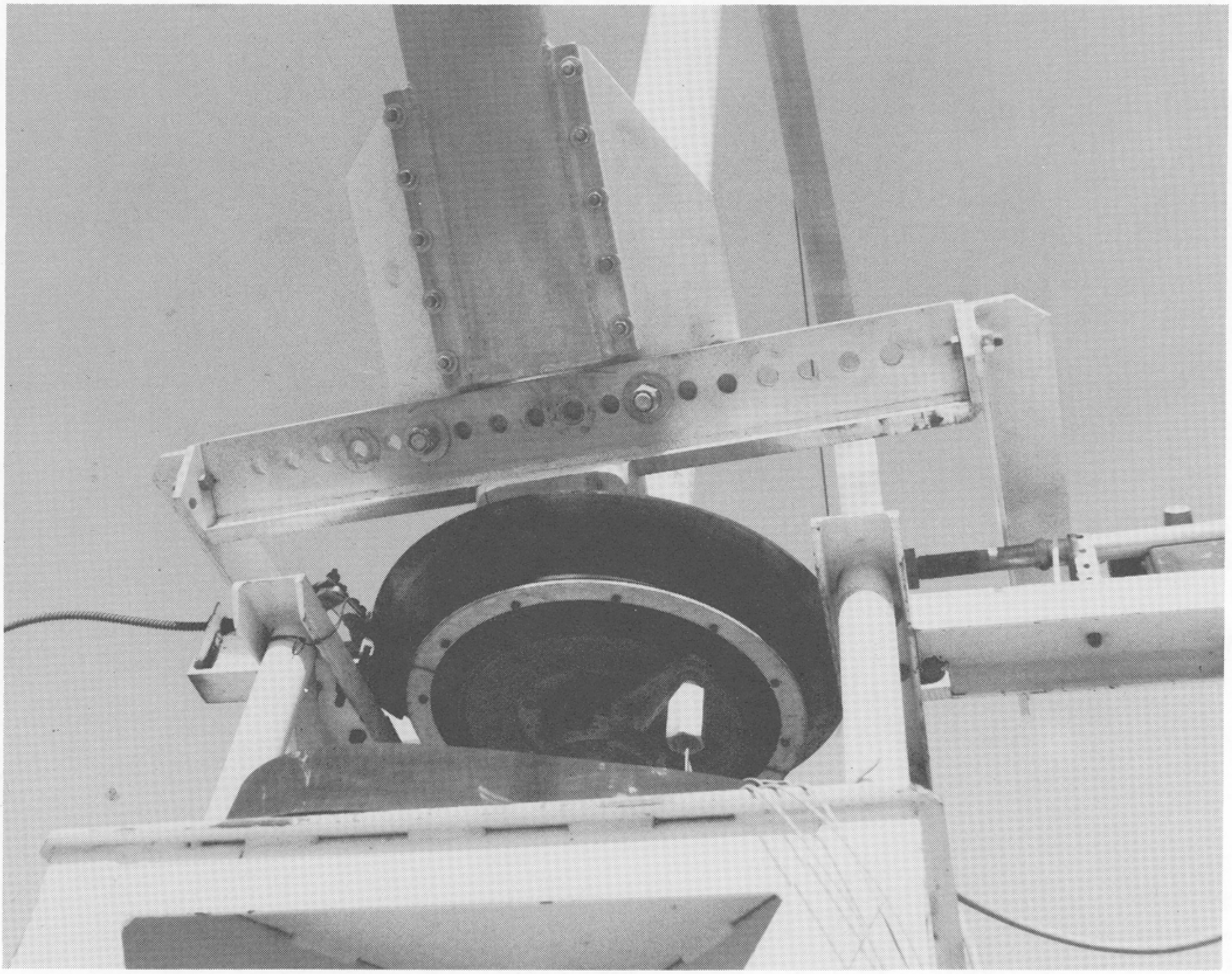


Figure 2. Central Attachment Hardware, VAWT

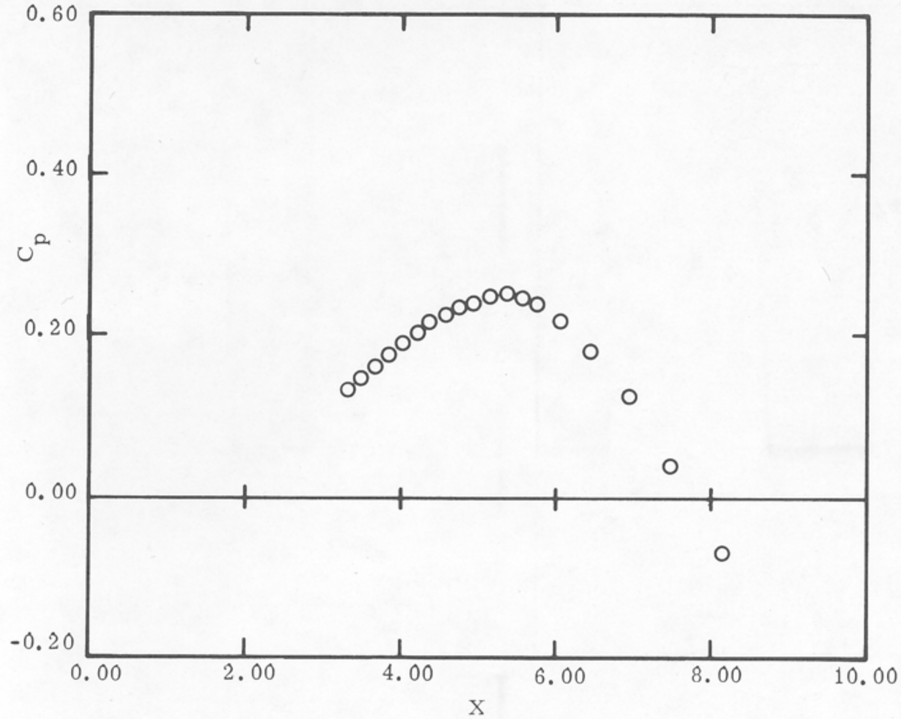


Figure 3. Power Coefficient vs Tip-Speed Ratio; Pitch Angle = -7°

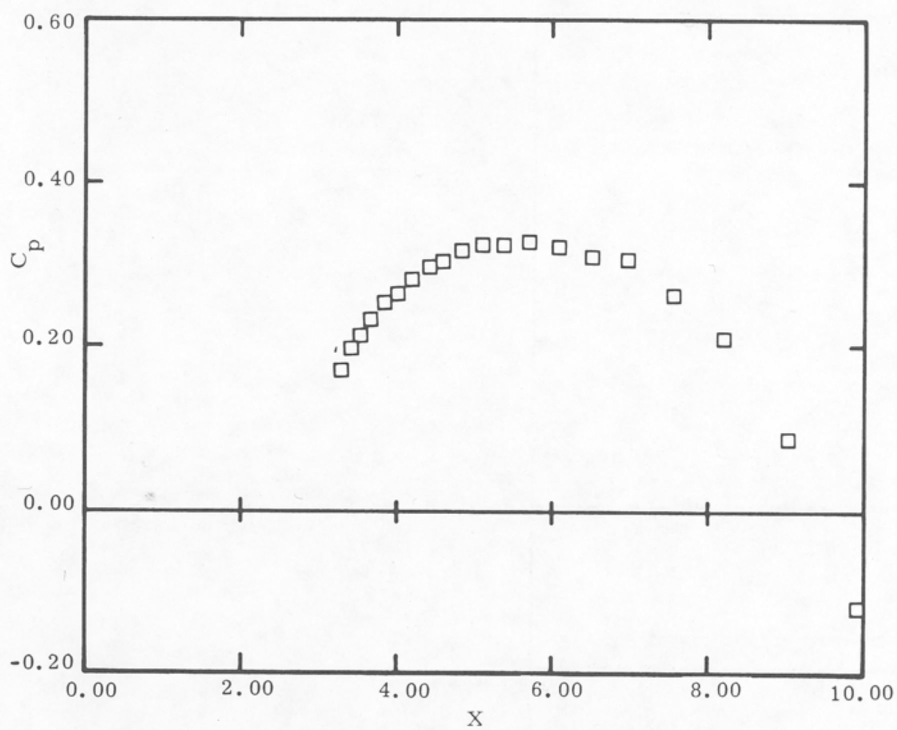


Figure 4. Power Coefficient vs Tip-Speed Ratio; Pitch Angle = -4°

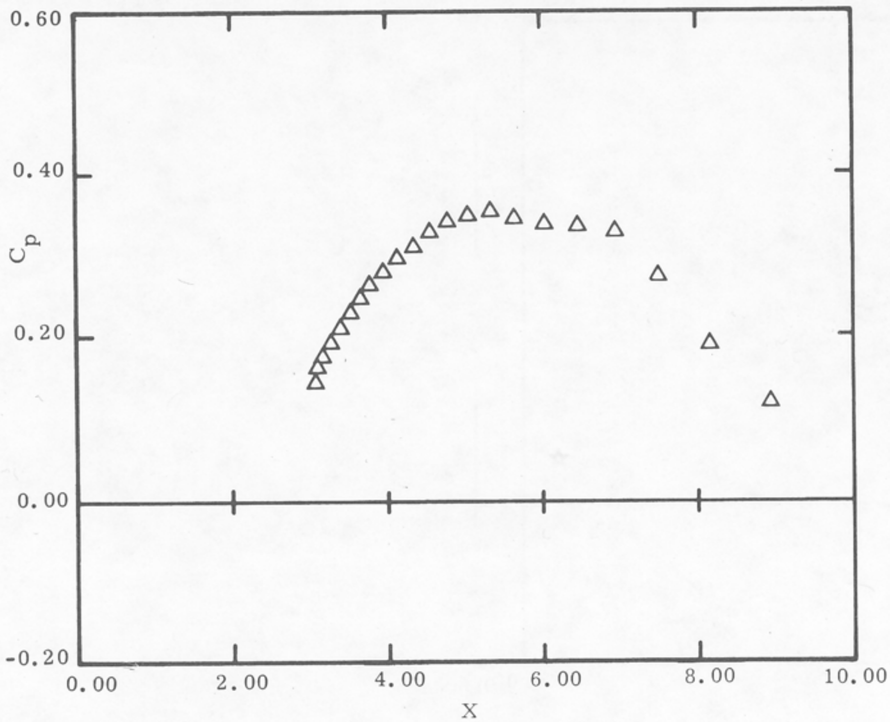


Figure 5. Power Coefficient vs Tip-Speed Ratio; Pitch Angle = -2°

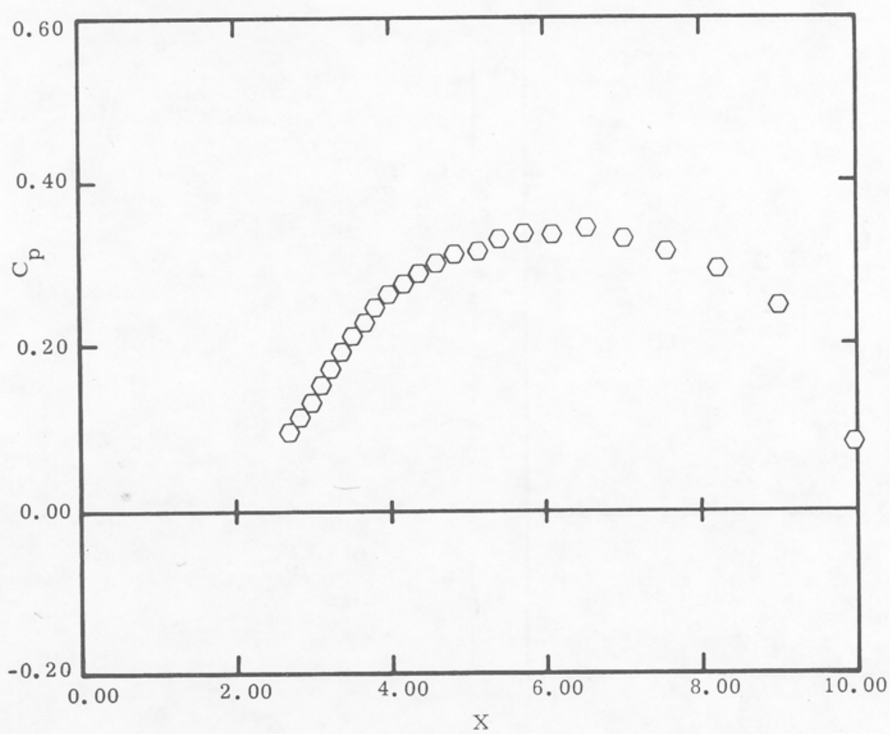


Figure 6. Power Coefficient vs Tip-Speed Ratio; Pitch Angle = -1/2°

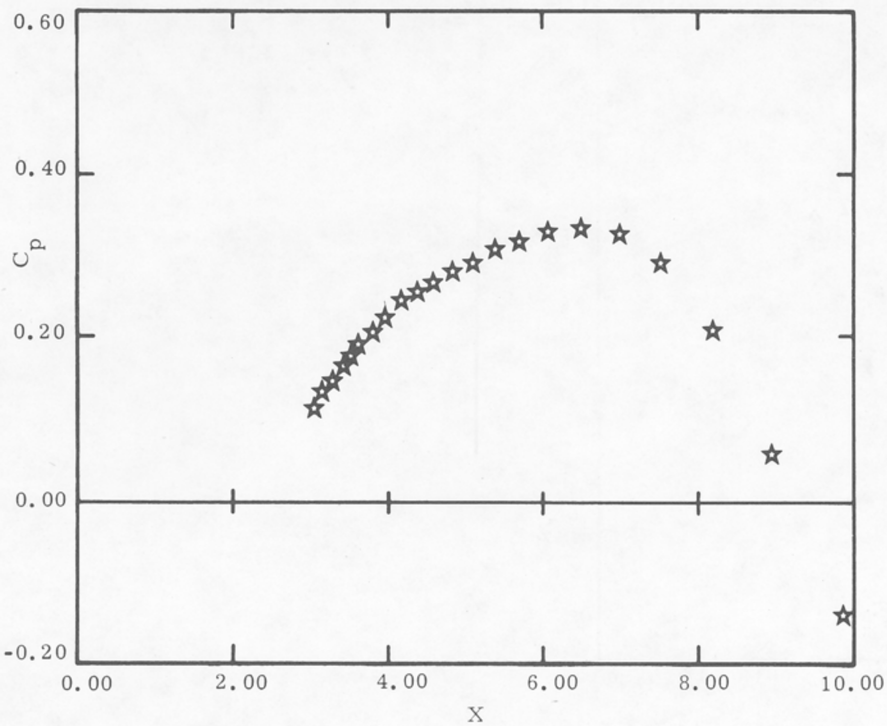


Figure 7. Power Coefficient vs Tip-Speed Ratio; Pitch Angle = +1%

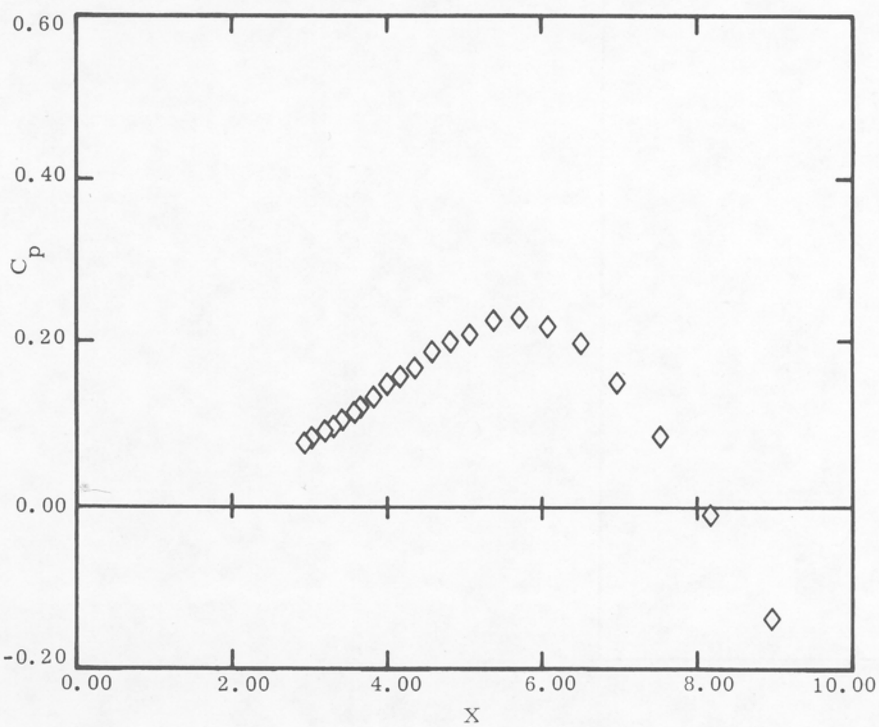


Figure 8. Power Coefficient vs Tip-Speed Ratio; Pitch Angle = +3%

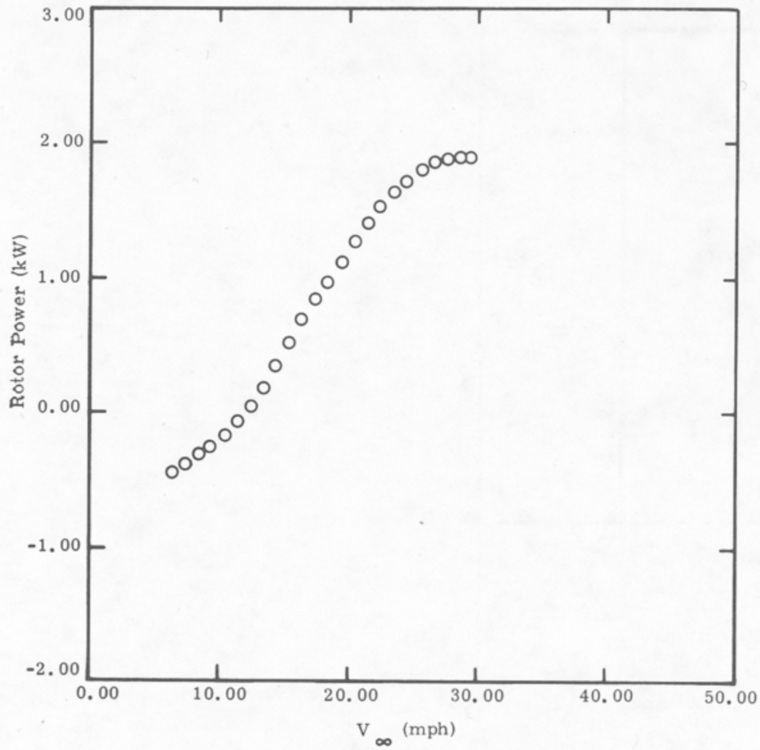


Figure 9. Rotor Power vs Free-Stream Velocity; Pitch Angle = -7°

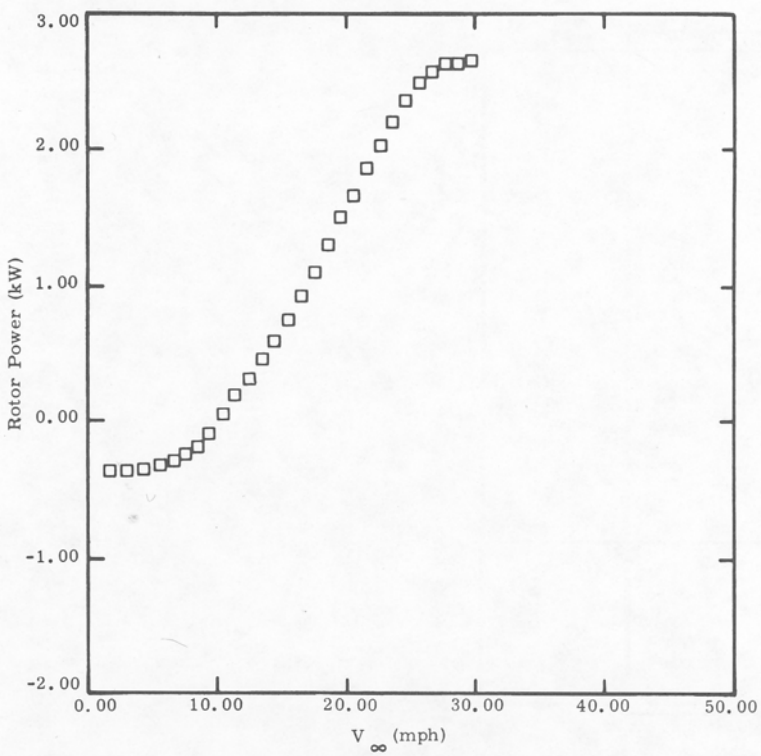


Figure 10. Rotor Power vs Free-Stream Velocity; Pitch Angle = -4°

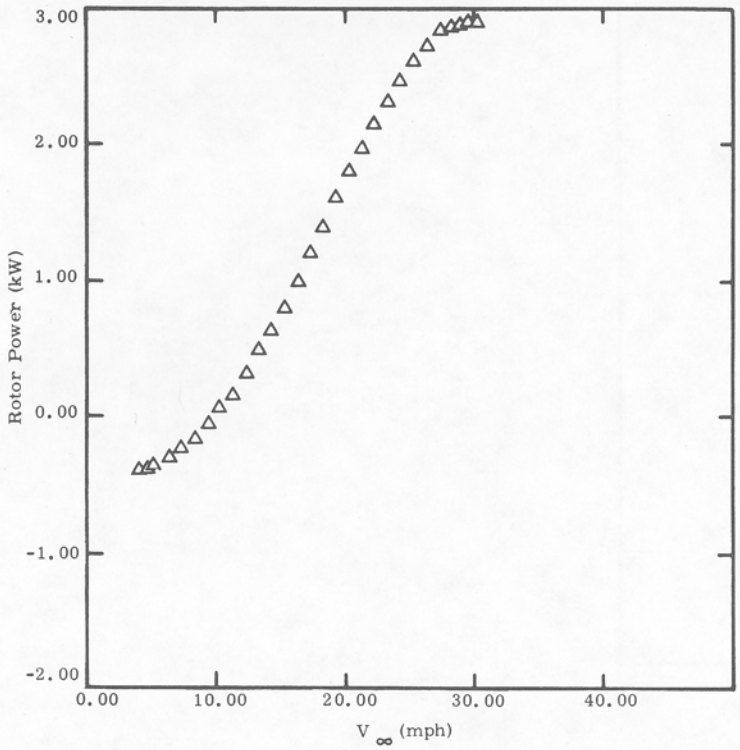


Figure 11. Rotor Power vs Free-Stream Velocity; Pitch Angle = -2°

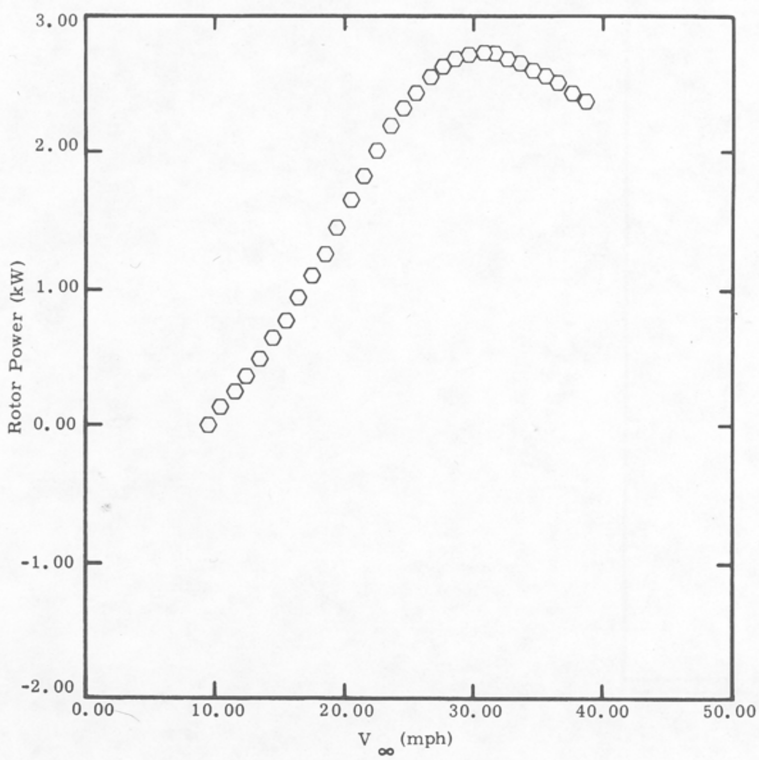


Figure 12. Rotor Power vs Free-Stream Velocity; Pitch Angle = -1/2°

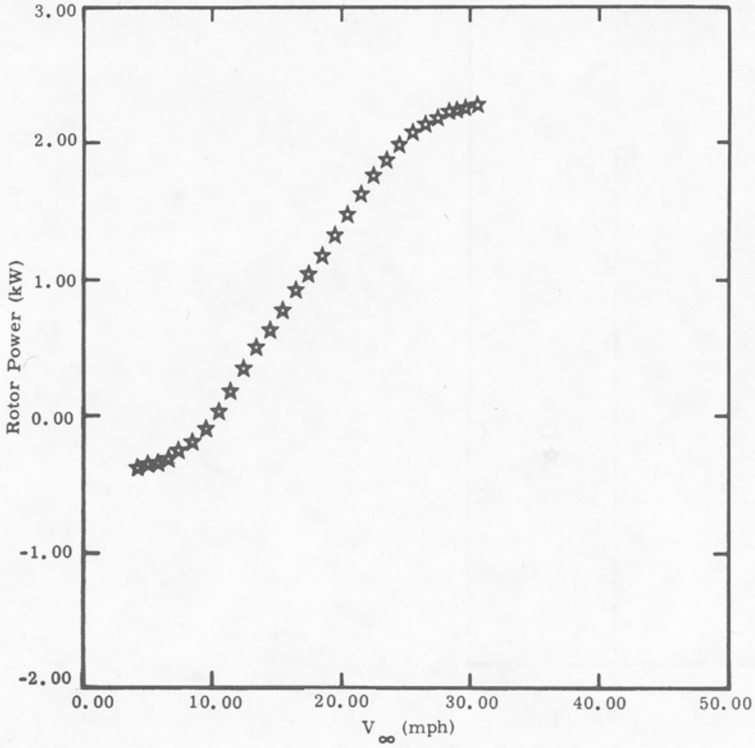


Figure 13. Rotor Power vs Free-Stream Velocity; Pitch Angle = +1%

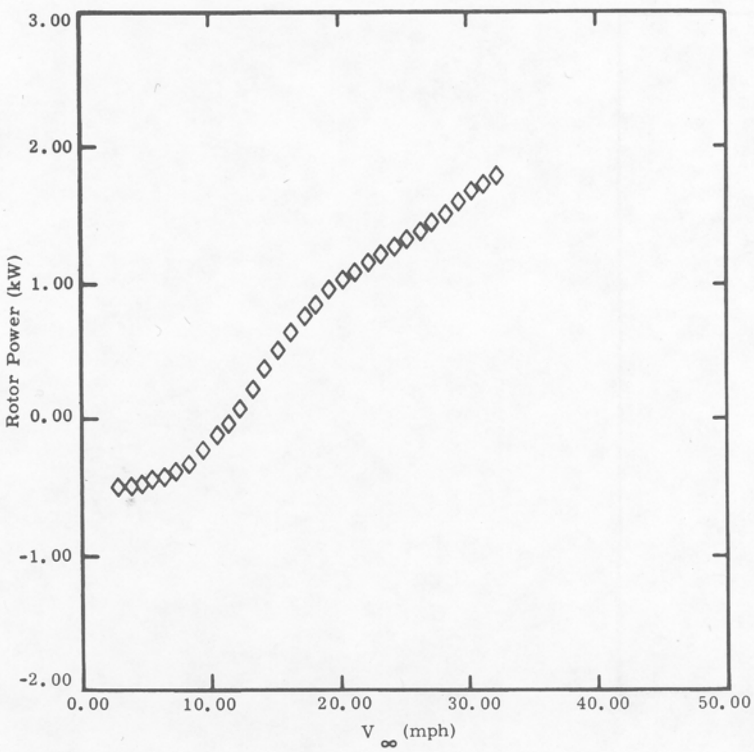


Figure 14. Rotor Power vs Free-Stream Velocity; Pitch Angle = +3°

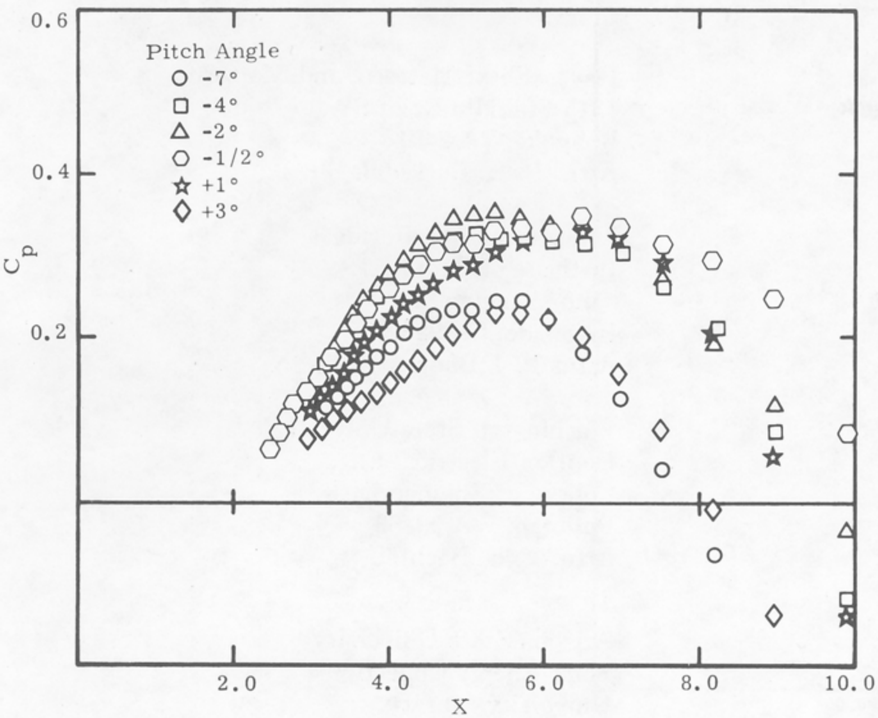


Figure 15. Composite: Power Coefficient vs Tip-Speed Ratio

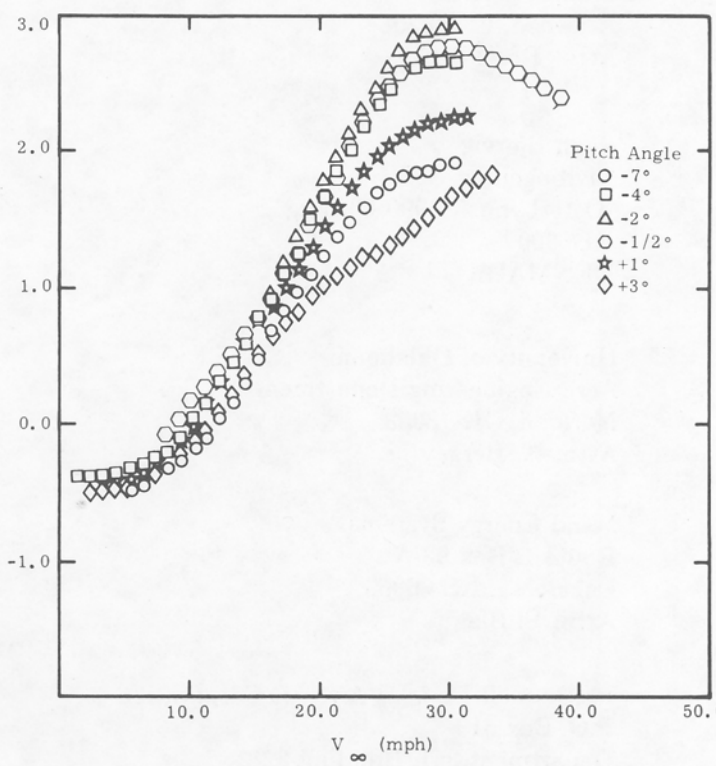


Figure 16. Composite: Rotor Power vs Free-Stream Velocity