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Aerodynamic Performance of a 5-Metre-Diameter Darrieus Turbine With Extruded Aluminum NACA-0015 Blades

Robert E. Sheldahl, Paul C. Klimas, Louis V. Feltz

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AERODYNAMIC PERFORMANCE OF A 5-METRE-DIAMETER DARRIEUS TURBINE WITH EXTRUDED ALUMINUM NACA-0015 BLADES

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ABSTRACT

A 5-metre-diameter vertical-axis wind turbine has undergone continued testing since 1976 at the Sandia Laboratories Wind Turbine site. The latest tests of this machine have been with extruded aluminum blades of NACA-0015 airfoil cross section. The results of these tests at several turbine rotational speeds are presented and compared with earlier test results. A performance comparison is made with a vortex/lifting line computational code. The performance of the turbine with the extruded blades met all expectations.

ACKNOWLEDGMENT

The authors are grateful for the support provided by the personnel of the Advanced Energy Projects Division 4715.

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NOMENCLATURE

A_s	Turbine swept area
c	Blade chord
C_{d_o}	Zero wind drag coefficient
C_p	Power coefficient, $\dfrac{Q\omega}{\frac{1}{2}\rho_\infty V_\infty^3 A_s}$
J	Advance ratio, $\dfrac{V_\infty}{R\omega}$
K_p	Power coefficient, $\dfrac{Q\omega}{\frac{1}{2}\rho_\infty A_s (R\omega)^3}$
L	Blade length
N	Number of blades
Q	Turbine aerodynamic torque $(T + Q_f)$
Q_f	Friction tare torque
R	Turbine maximum radius
Re_c	Chord Reynolds number, $\dfrac{\rho_\infty R\omega c}{\mu_\infty}$
T	Turbine shaft torque

NOMENCLATURE (cont)

V_∞ Average freestream velocity

X Turbine tip-speed ratio, $\frac{R\omega}{V_\infty}$

μ_∞ Freestream viscosity

ρ_∞ Freestream density

ω Turbine rotational speed

σ Solidity, $\frac{NcL}{A_s}$

SUMMARY

The Sandia 5-metre vertical-axis wind turbine has undergone continued testing since 1976 in free air at the Sandia Laboratories Wind Turbine site. The turbine was operated at several fixed and nearly constant rotational speeds by an induction motor/generator which can act as either a motor delivering power to the turbine or as a generator delivering power from the turbine to the utility line. The extruded aluminum blades on the turbines are of the straight line/circular arc troposkien approximation with a constant NACA-0015 airfoil cross section from hub-to-hub. The turbine height-to-diameter ratio is 1.02. The solidity of the present system is 0.22 with three blades and 0.15 with two blades. These blades differ from previous blades which had an NACA-0012 airfoil section only on the circular arc portion of the blades. The straight line segments which attached the original blade to the center column were not of airfoil cross section but merely a flat sheet of steel rolled back onto itself with a circular leading edge.

Five different constant-rotational-speed data sets were obtained with the extruded aluminum blades: three sets (125, 137.5 and 150 rpm) with three blades and two sets (162.5 and 175 rpm) with two blades. The performance data were obtained with the aid of a minicomputer using a computer program which utilized statistical methods. The unsteadiness of the winds necessitates the statistical averaging of the data. The "method of bins" computer technique (computer code BINS) used for averaging the data is, at the present time, the only method by which reasonable performance information has been obtained in free air. The results show the performance of the turbine with the extruded aluminum blades to meet all expectations relating to wind tunnel performance and analytical models. The maximum power coefficient, C_p, for the turbine was found to be 0.392 at a rotational speed of 150 rpm with three blades. This is an improvement of 44% over the former three-piece blades also operating with three blades at 150 rpm.

Part of the improvement in the performance is due to the elimination of the nonairfoil straight segments and part is due to the improved performance of the NACA-0015 airfoil over the NACA-0012 airfoil.

AERODYNAMIC PERFORMANCE OF A 5-METRE-DIAMETER DARRIEUS TURBINE WITH EXTRUDED ALUMINUM NACA-0015 BLADES

Introduction

The vertical-axis wind turbine,[1] which was patented in the United States in 1931 by G. J. M. Darrieus, has been receiving continued attention at Sandia Laboratories.[2-14] Sandia Laboratories fabricated its first machine, a 5-metre diameter Darrieus turbine, in 1974. The original turbine design allowed a variable rotational speed mode of operation; however, subsequent studies identified the constant rotational speed/ synchronous power grid application as being very promising for the Darrieus turbine. Since 1976, the Sandia 5-metre turbine has been operating in a synchronous grid mode.

The first performance data for this turbine with its original blades were reported in Ref 2. Each of its original blades consisted of three segments: a circular arc located near the turbine equator with a 19-cm chord NACA-0012 airfoil cross section, and two straight sections that attached the circular arc to the center column. Each straight section was steel sheet formed to a "streamlined" shape with a 10-cm chord. This straight line/circular arc combination was designed to approximate the shape that a perfectly flexible blade would assume under the action of centrifugal forces and has been given the name troposkien[3] (Greek for turning rope). It was determined that the straight sections were detrimental to the turbine performance[2] and that the blades should have the airfoil cross section from hub-to-hub. With that in mind, new one-piece blades were designed and the airfoil cross section was changed to the NACA-0015 cross section to take advantage of the fact that these airfoils exhibit more favorable stall characteristics. This report describes the performance of the turbine using these new blades.

The 5-metre turbine shares the test site with a 17-metre turbine and a 2-metre turbine. Also at the site is the instrumentation building which houses the controls for the three turbines, turbine instrumentation, anemometry instrumentation, and the Hewlett-Packard HP 21 MX minicomputer system. It should be noted that the elevation of the test site is 1658 metres and that the nominal air density is 82% of standard sea level density.

The 5-Metre Vertical-Axis Wind Turbine

The Sandia 5-m turbine, a proof-of-concept machine fabricated in 1974, was designed to be erected in the shortest possible time at reasonable cost. These ground rules were the basis for the construction of its original blades which were later found to perform below expectations.[2] It was decided in 1977 to design and purchase new aluminum blades for this machine with the blades being one-piece extrusions with the NACA-0015 airfoil cross section extending from hub-to-hub. Figure 1 shows the turbine at the test site with the new one-piece blades. It can be seen that overall, the blade design is much "cleaner" than the original design shown in Figure 2. The new blades eliminate the nonaerodynamic straight sections as well as the knuckles at the attachment to the circular arc portion of the blades.

The new blades are one-piece hollow aluminum (Alloy 6061 T6) extrusions conforming to the NACA-0015 airfoil cross section with a chord of 15.24 cm (6 in.). They were bent to the curved blade shape by incremental bending and then stress-relieved. The blades were furnished to Sandia from Aluminum Company of America (ALCOA) without end fixtures for attachment to the rotating tube of the turbine. The end fixtures were attached to the blades with an aircraft structural adhesive as the primary joining method. Representative joint components are shown in Figure 3. The upper item is a short segment of the blade extrusions, and the item at the right is the machined blade end fixture. The tapered plug end of this fixture is inserted into a closely matched cavity in the blade extrusion. This cavity was obtained by spark discharge machining, using an identical plug as the

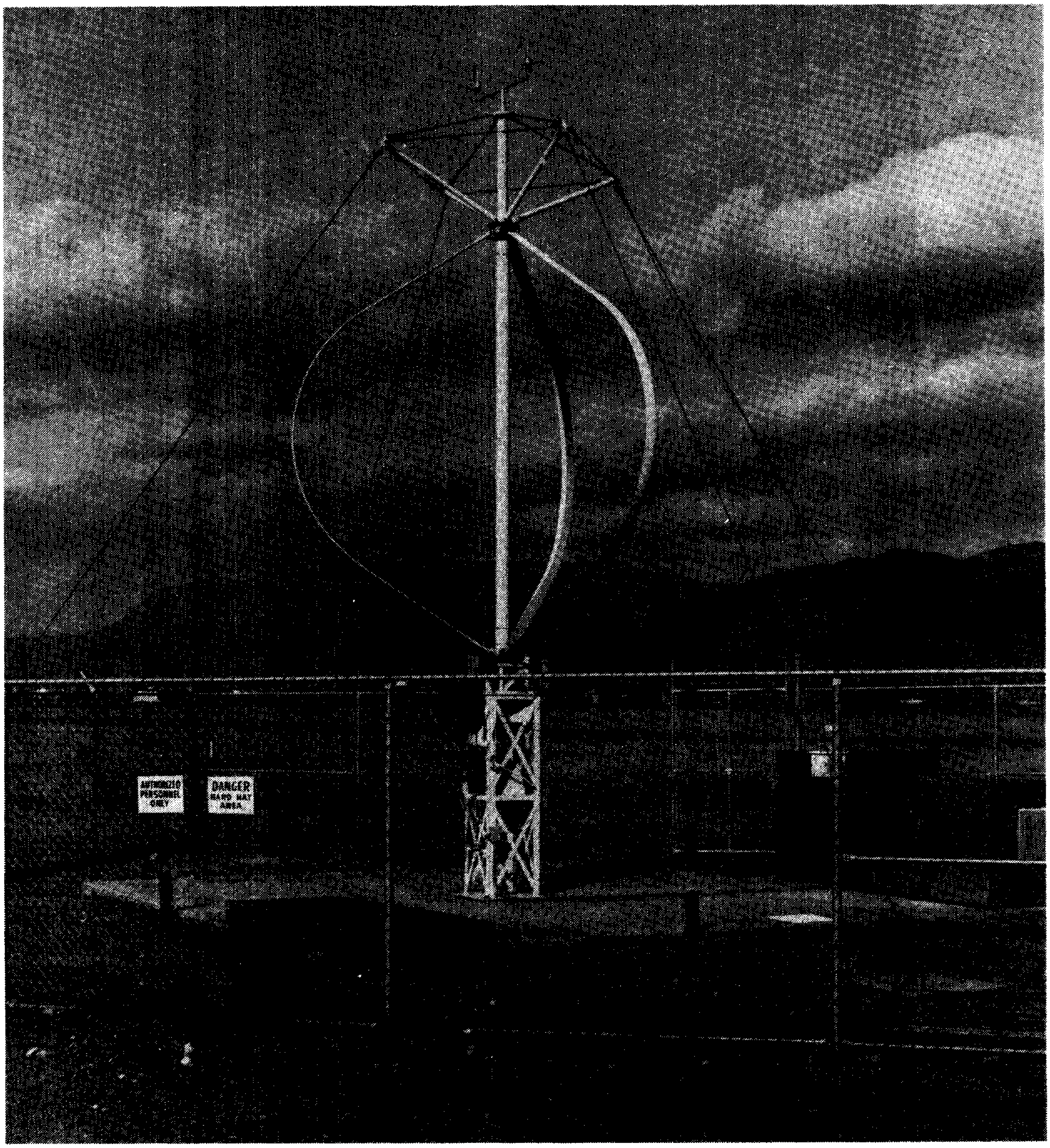

Figure 1. The 5-Metre Vertical-Axis Wind Turbine at Sandia Laboratories Test Site

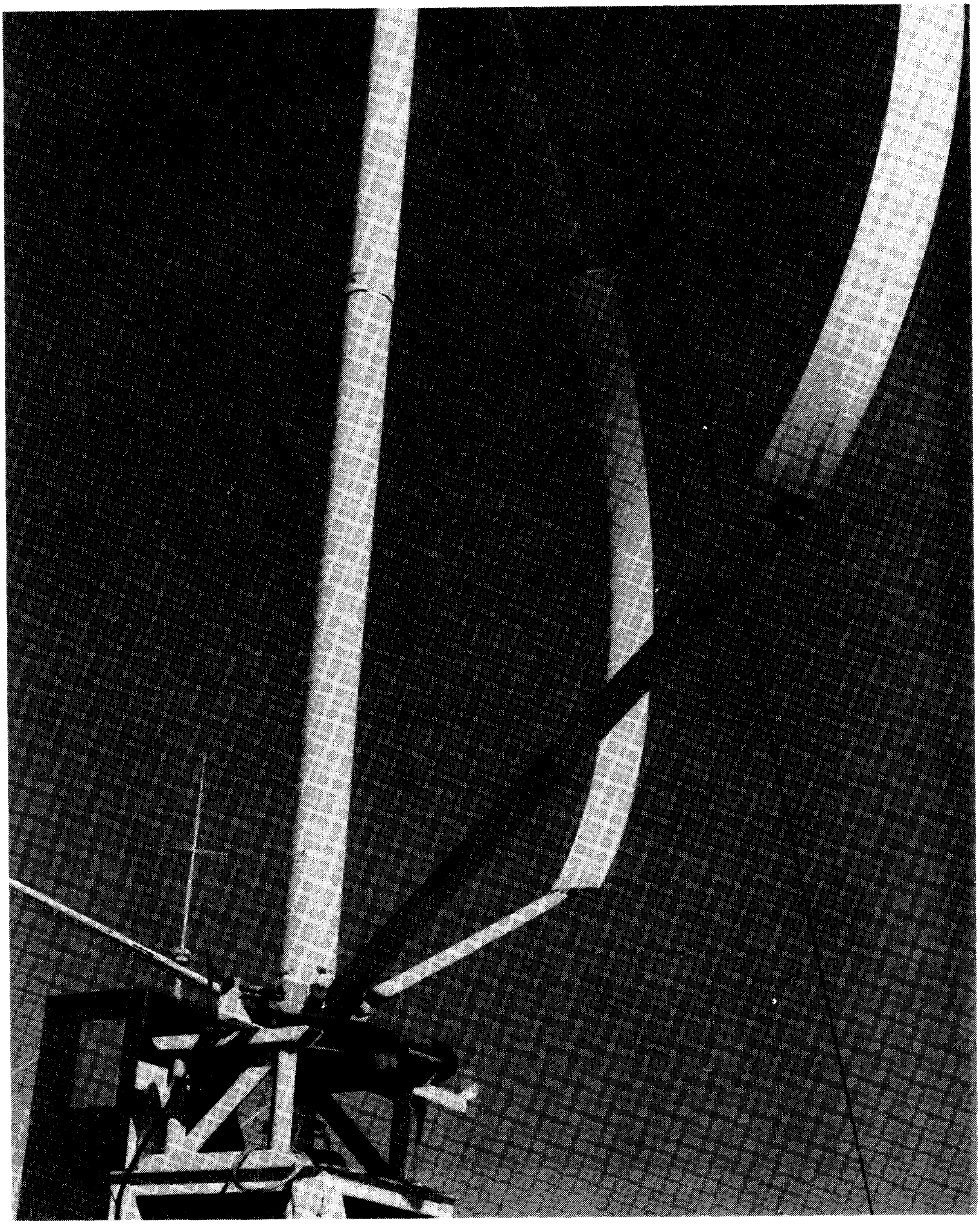

Figure 2. Original Three-Piece Blades on 5-Metre Turbine

machining mandrel. This mandrel is seen in the lower left corner of the figure. After the end fixtures were installed, sheet aluminum cover plates were contoured to the external airfoil surface and added as a double-lap joint strengthener over the joint of the end fixture and blade with the same adhesive. Finally, rivets were placed through the entire sandwich structure of the joint. Destructive static tensile tests were conducted on short, straight blade segments with three candidate joint designs: (1) plug and adhesive (2) plug and adhesive with contoured cover plates, and (3) plug and adhesive with riveted contoured cover plates. The tests indicated the mode of failure and confirmed the predicted strength levels. Each of three samples tested failed only after tensile yielding of the aluminum extrusion had commenced (Figure 4). The blades failed at loads in excess of 2.67×10^5 N (60,000 lb_f). For reasons of maximum safety, design 3 was chosen for the blade end fixtures.

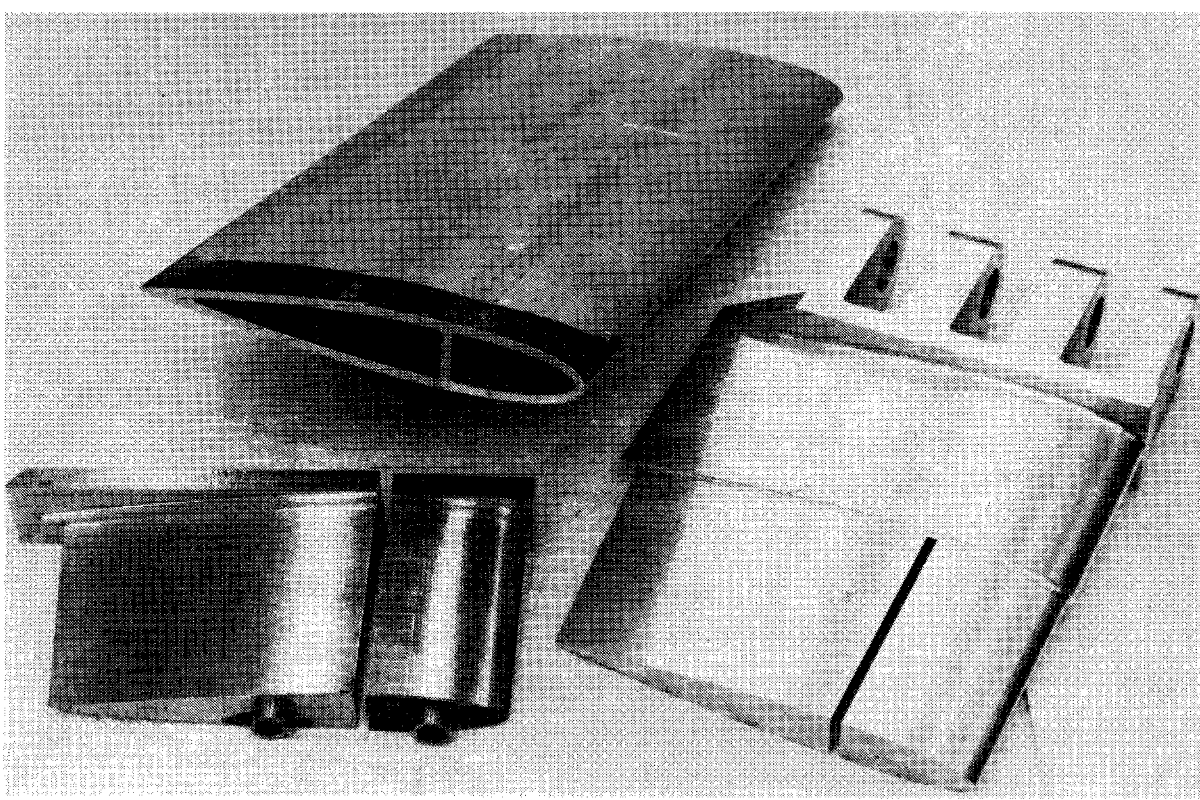

Figure 3. Short Segment of the NACA-0015 Airfoil Extrusion With End Fixture and Mandrel

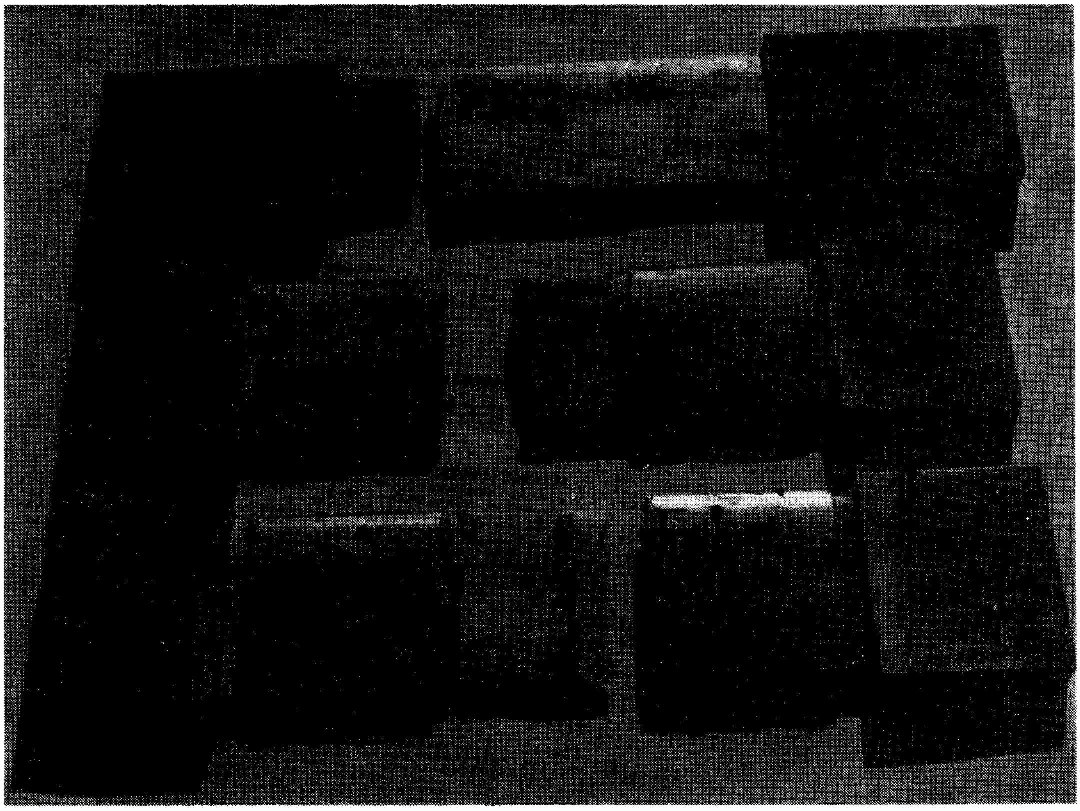

Figure 4. Destructive Static Tensile Samples of Three Candidate Joint Designs

The turbine is designed to operate at a nearly constant rotational speed by connecting the turbine shaft through a two-stage timing belt drive to an induction motor/generator operating at 3600 rpm. By changing pulleys, the turbine speed can be changed in discrete steps. Figure 5 is a schematic of the 5-m system showing the relationship of the induction machine, speed increaser, Lebow* RPM and torque transducer, and the turbine shaft. Nominal rotational speed of the turbine is determined by the synchronous speed of the induction machine and the timing belt sprocket ratios. The induction machine can act as either a motor, delivering power to the turbine from the utility line, or as a generator, delivering power to the utility line from the turbine.

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*Lebow Associates, 1728 Maple Lawn Road, Troy, Michigan 48084

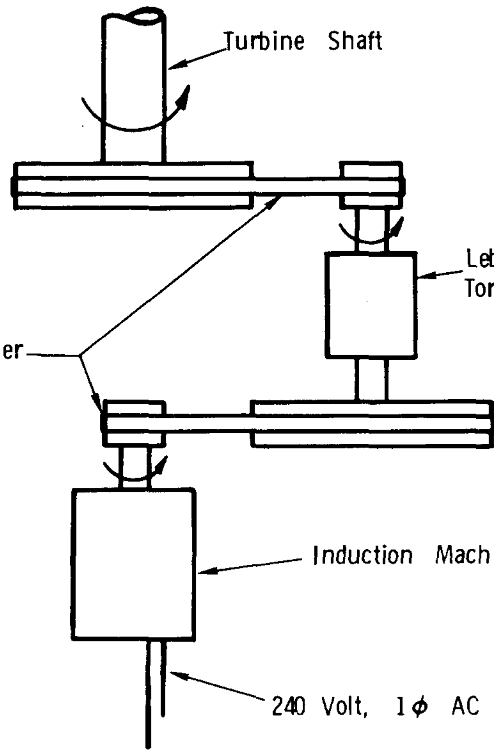

Figure 5. Schematic of 5-Metre Turbine System

Testing and Data Acquisition

The testing of turbines in free-air offers problems not usually encountered in wind tunnel testing. In particular, the atmospheric wind speed seldom remains constant for any appreciable length of time. Consequently, it is difficult to assign an appropriate wind velocity corresponding to a given torque measurement. A record showing typical wind velocity and turbine torque fluctuations is shown in Figure 6. The unsteadiness of the velocity and torque shows some of the problems of obtaining free-air data from a wind turbine. Computer code BINS,[2] which uses the "method of bins" to statistically average the wind speed and torque data, was developed to assist the data acquisition. The wind speed and torque are recorded at sample rates chosen by the operator, generally from 1 to 10 data samples per second. The data are then stored in velocity bin widths of 0.5 mph, i.e., a datum point is taken and the wind velocity is determined which, in turn, locates the velocity bin. The datum point is widths of 0.5 mph, i.e., a datum point is taken and the wind velocity is determined which, in turn, locates the velocity bin. The datum point is counted, and the value of the torque obtained at that wind speed is added to the summed torque in the bin. The data are stored as a function of the velocity bins (120 bins for velocities from 0 to 60 mph). Each bin records the number of data points and the total summed torque. Each data record, consisting of the 120 velocity bins, number of data points, and the summed torque for each bin, also contains information which is constant for each data record. These constants are the rotational speed, number of blades, anemometer identification, wind shear correction factor, temperature, barometric pressure, time of day, and turbine tare torque. The turbine tare torque is the torque lost in the turbine due to bearing friction and belt losses.

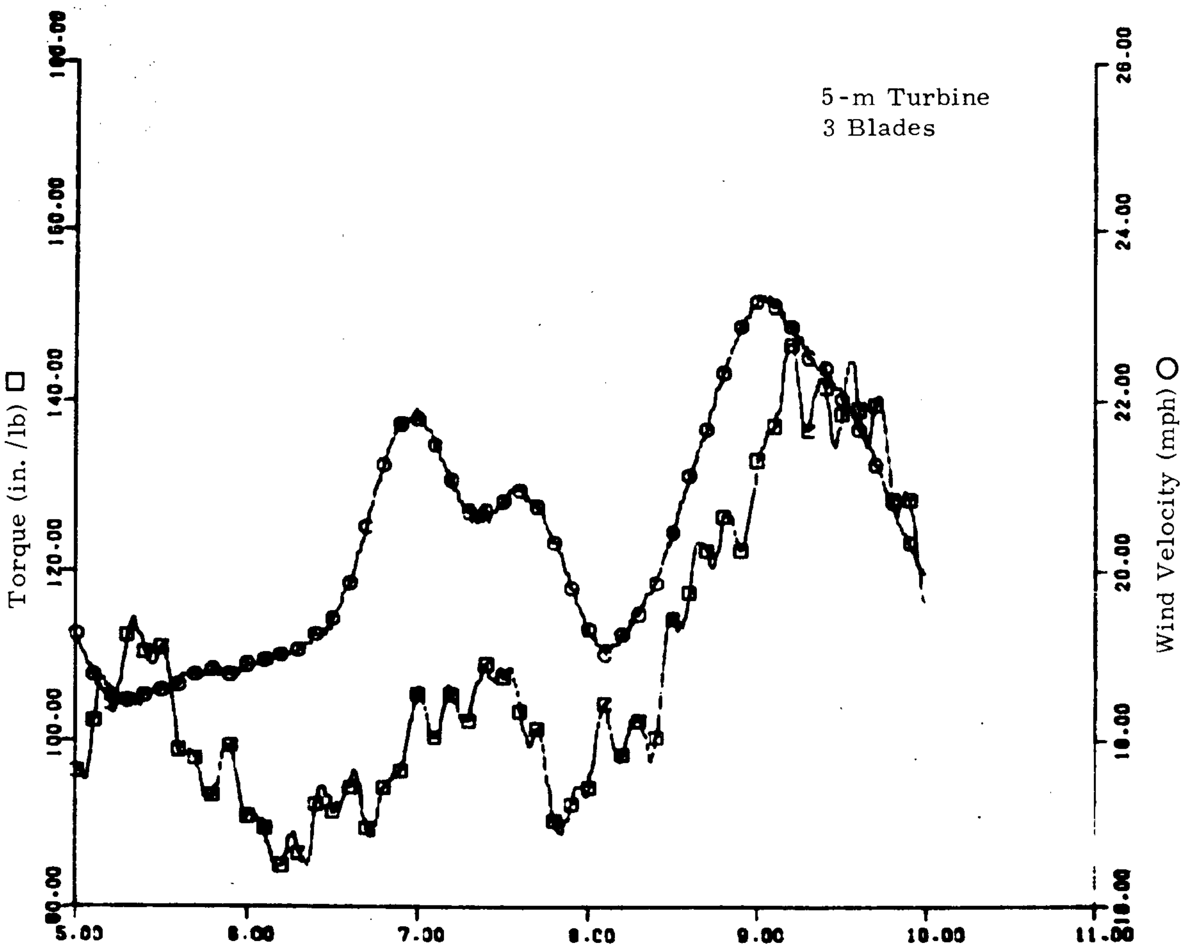

Figure 6. Representative Time Histories of 5-Metre Turbine Torque and Site Wind Velocity

The computer will accept simultaneously wind-velocity data from three separate anemometers; thus, during a single test three data records can be generated, all with the same turbine torque information but with wind velocities corresponding to each separate anemometer. The operator has the option of taking wind-velocity data from any of the available anemometers at the turbine site up to a total of three.

During a test, the required constant information is input to the computer. With the turbine operating, the computer is instructed to take data. If during the test the temperature or barometric pressure changes, the test is terminated and the data record stored. The new information is input to a new data record and testing is resumed. Data are taken when the winds are available, so a test may be a few minutes long or extend past an hour. These tests are performed on a day-to-day basis; the end result is a large amount of data taken for a wide range of wind conditions over many days.

Results and Discussion

The data records for a given rotational speed and anemometer can be combined into a data set, and the performance of the turbine can be computed by the minicomputer in the control building. The data are corrected for the day-to-day variations of the ambient air density, and the results of the summed data records are presented in the form of power coefficient as a function of tip-speed ratio or advance ratio.

The power coefficient, which is a standard measure of turbine performance, is calculated by

$$C_p = \frac{Q\omega}{\frac{1}{2}\rho_\infty V_\infty^3 A_s} \tag{1}$$

where Q is the turbine torque corrected for tare torque losses, is the turbine rotational speed, ρ_∞ is the ambient air density, V_∞ is the far field wind velocity, and A_s is the turbine swept area.[2] The values of this power coefficient are plotted against a tip-speed ratio defined as:

$$X = \frac{R\omega}{V_\infty} . \tag{2}$$

A second power coefficient has been defined[2] as

$$K_p = \frac{Q\omega}{\frac{1}{2}\rho_\infty A_s (R\omega)^3} \tag{3}$$

where the wind velocity of the first power coefficient has been replaced by the blade equatorial velocity. This power coefficient was developed for three reasons: (1) K_p shows that power reaches a maximum at a particular value of the advance ratio (wind speed) when the turbine rotational speed is constant; (2) K_p describes more clearly the power output characteristics of the wind turbine operating in the synchronous mode; and (3) since the calculation of C_p involves a wind velocity cubed, large errors in the calculation can occur due to errors in the wind speed measurement. The values of this second power coefficient are plotted against an advance ratio defined as

$$J = \frac{V_\infty}{R\omega} . \tag{4}$$

which is merely the inverse of the tip-speed ratio.

Each data set consisted of eight or more data records and contained more than one-third million data points. Five data sets were obtained during the course of the test program. Three of the data sets (125, 137.5, and 150 rpm) are for a three-bladed turbine configuration with a turbine solidity, σ, of 0.22. The test plan originally called for testing the three-bladed configuration at rotational speeds above 150 rpm; however, the improved performance (higher torques) could not be accommodated. The attempt with a rotational speed of 162.5 rpm resulted in overspeeding of the induction motor and finally timing belt skip and breakage. The remaining two data sets (162.5 and 175 rpm) were for a two-bladed configuration with a turbine solidity of 0.15. Again, other rotational speeds were planned; however, at lower rotational speeds the two-bladed configuration entered a natural frequency regime which caused excessive vibration of the turbine; at rotational speeds in excess of 175 rpm, the turbine output again exceeded the torque limitation of the induction motor.

The wind velocities presented in all five data sets were obtained from anemometers located two turbine diameters away from the axis of rotation and at the turbine equator height. The usual winds at the turbine site are easterly or westerly, and the anemometers are located to the north and south of the turbine to minimize the influence of the turbine on the anemometers.[2] Data were not taken when the wind was not from the usual wind directions.

The power coefficients, C_p, for the three data sets of the three-bladed configuration are presented in Figure 7 as a function of the tip-speed ratio. It can be seen that with each increase in chord Reynolds number (rotational speed) there is a corresponding increase in maximum power coefficient. At a chord Reynolds number of 2.5×10^5 (125 rpm), the maximum C_p is 0.335; at $Re_c = 2.8 \times 10^5$ (137.5 rpm), $C_{p_{max}}$ is 0.360; at $Re_c = 3.0 \times 10^5$ (150 rpm), $C_{p_{max}}$ is 0.392. Run-away, the high tip-speed ratio at which no power is produced, occurs near the tip-speed ratio of 8 for all three rotational speeds. The power coefficients, K_p, are presented for the three-bladed configuration in Figure 8. This figure shows the inherent self regulation (K_p reaches a maximum value and does not continue to increase with increasing wind velocity) of a Darrieus turbine operating at a constant rotational speed with the maximum power coefficient, $K_{p_{max}}$, occurring between an advance ratio of 0.3 and 0.4. The value of $K_{p_{max}}$ increases with increasing chord Reynolds number as expected.

The power coefficients, C_p, for the two data sets of the two-bladed configuration are presented in Figure 9. The maximum power coefficients are lower than the three-bladed data as expected due to the lower solidity of the turbine with two blades.[4] The K_p data presented in Figure 10 shows a large increase in $K_{p_{max}}$ with increased chord Reynolds number. As mentioned earlier, data at higher rotational speeds could not be obtained since the turbine torque near the maximum power output of the turbine

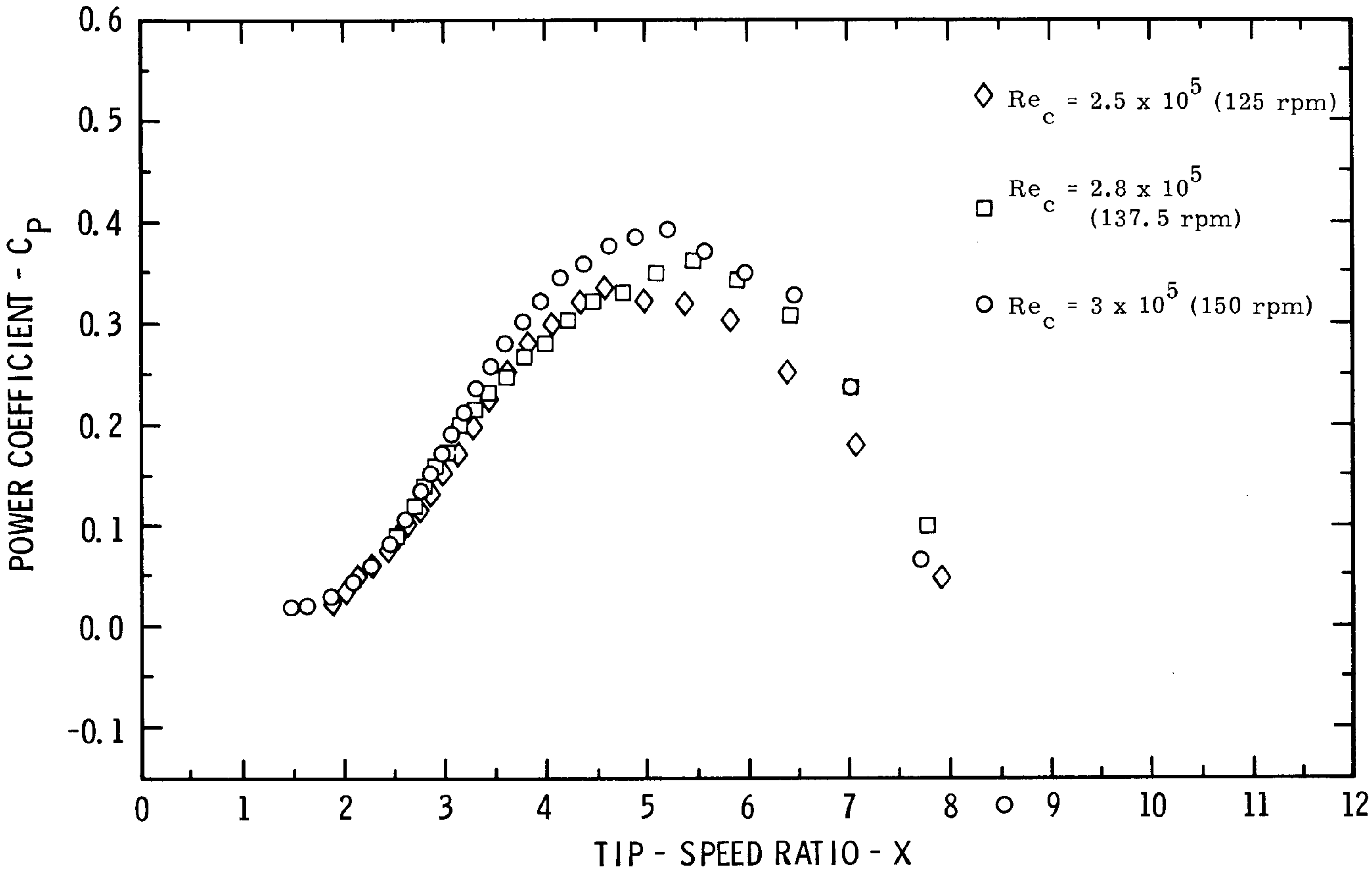

Figure 7. Power Coefficient, C_P, Performance Data for 5-Metre Turbine With Three Extruded NACA-0015 Blades at 125, 137.5, and 150 rpm

planned; however, at lower rotational speeds the two-bladed configuration entered a natural frequency regime which caused excessive vibration of the turbine; at rotational speeds in excess of 175 rpm, the turbine output again exceeded the torque limitation of the induction motor.

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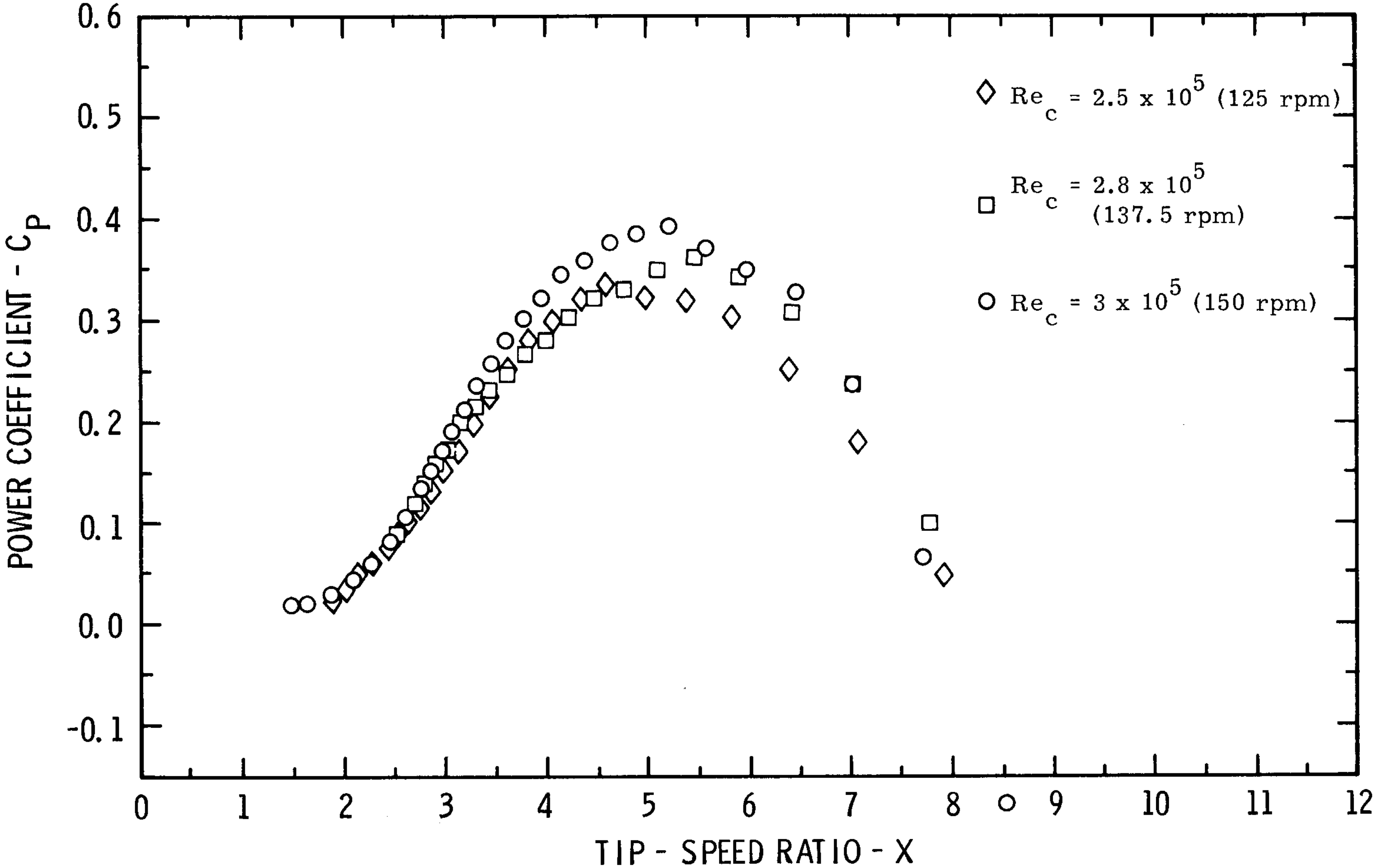

Figure 7. Power Coefficient, C_p, Performance Data for 5-Metre Turbine With Three Extruded NACA-0015 Blades at 125, 137.5, and 150 rpm

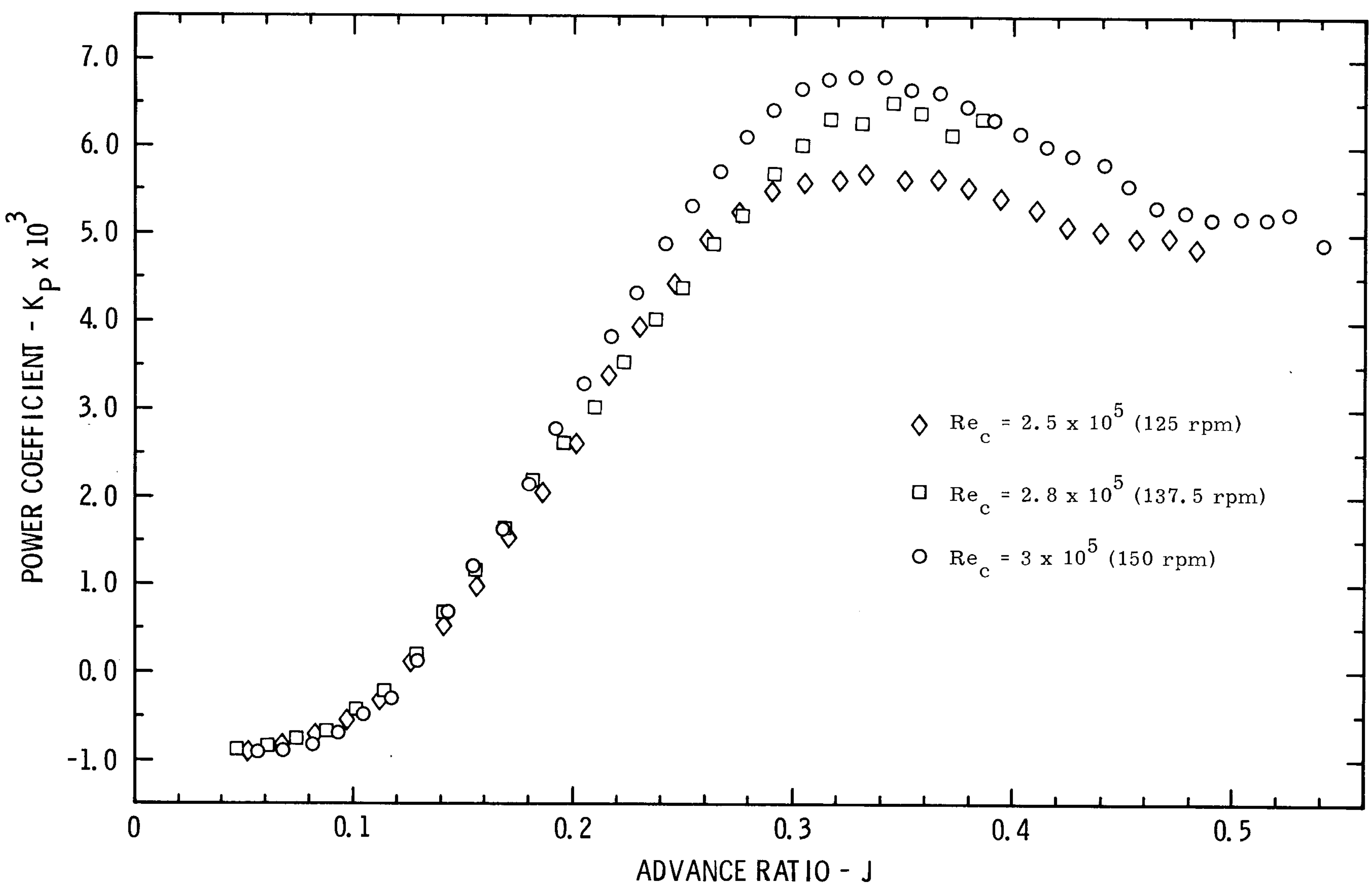

Figure 8. Power Coefficient, K_p, Performance Data for 5-Metre Turbine With Three Extruded NACA-0015 Blades at 125, 137.5, and 150 rpm

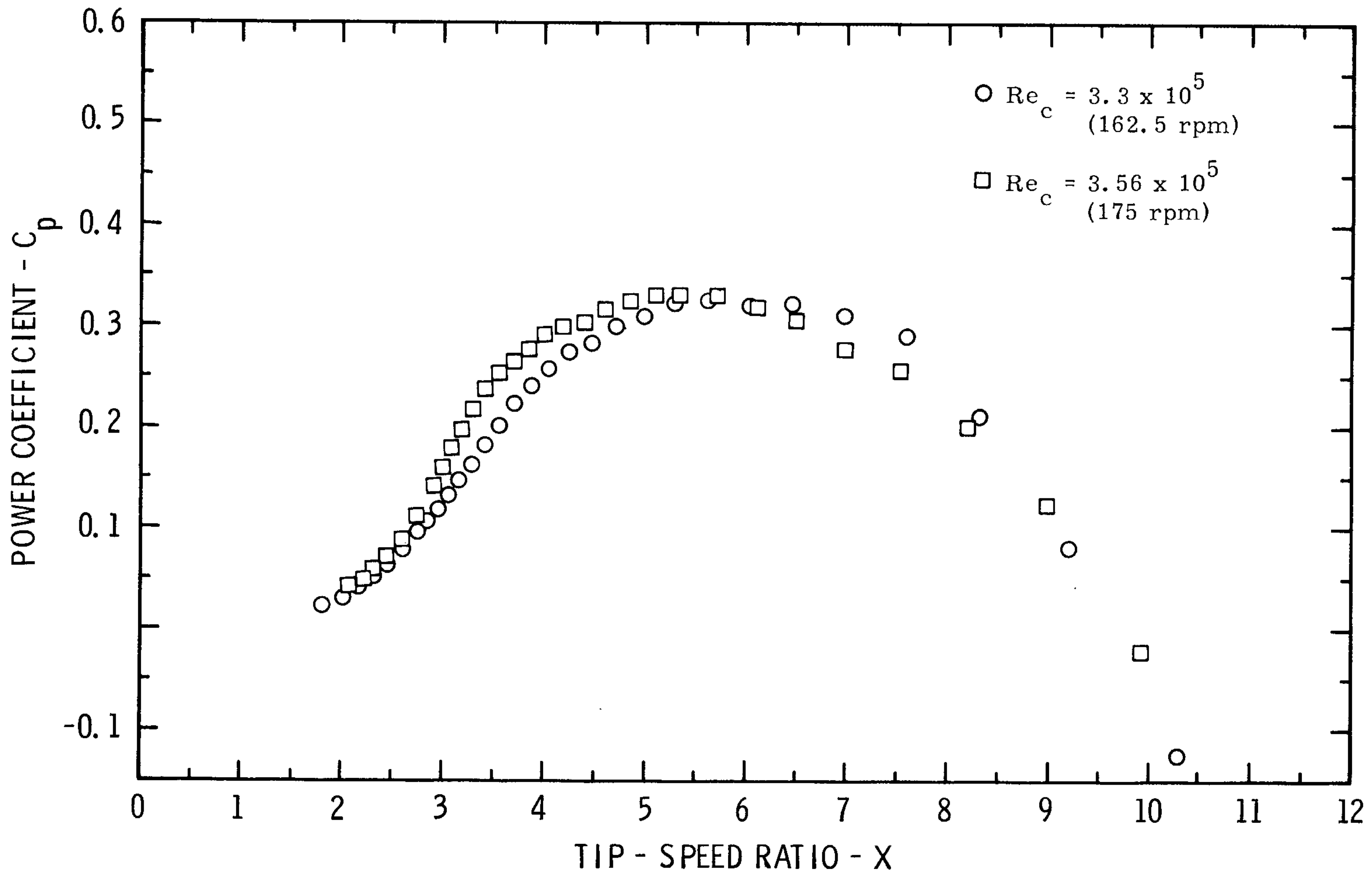

Figure 9. Power Coefficient, C_p, Performance Data of 5-Metre Turbine With Two Extruded NACA-0015 Blades at 162.5 and 175 rpm

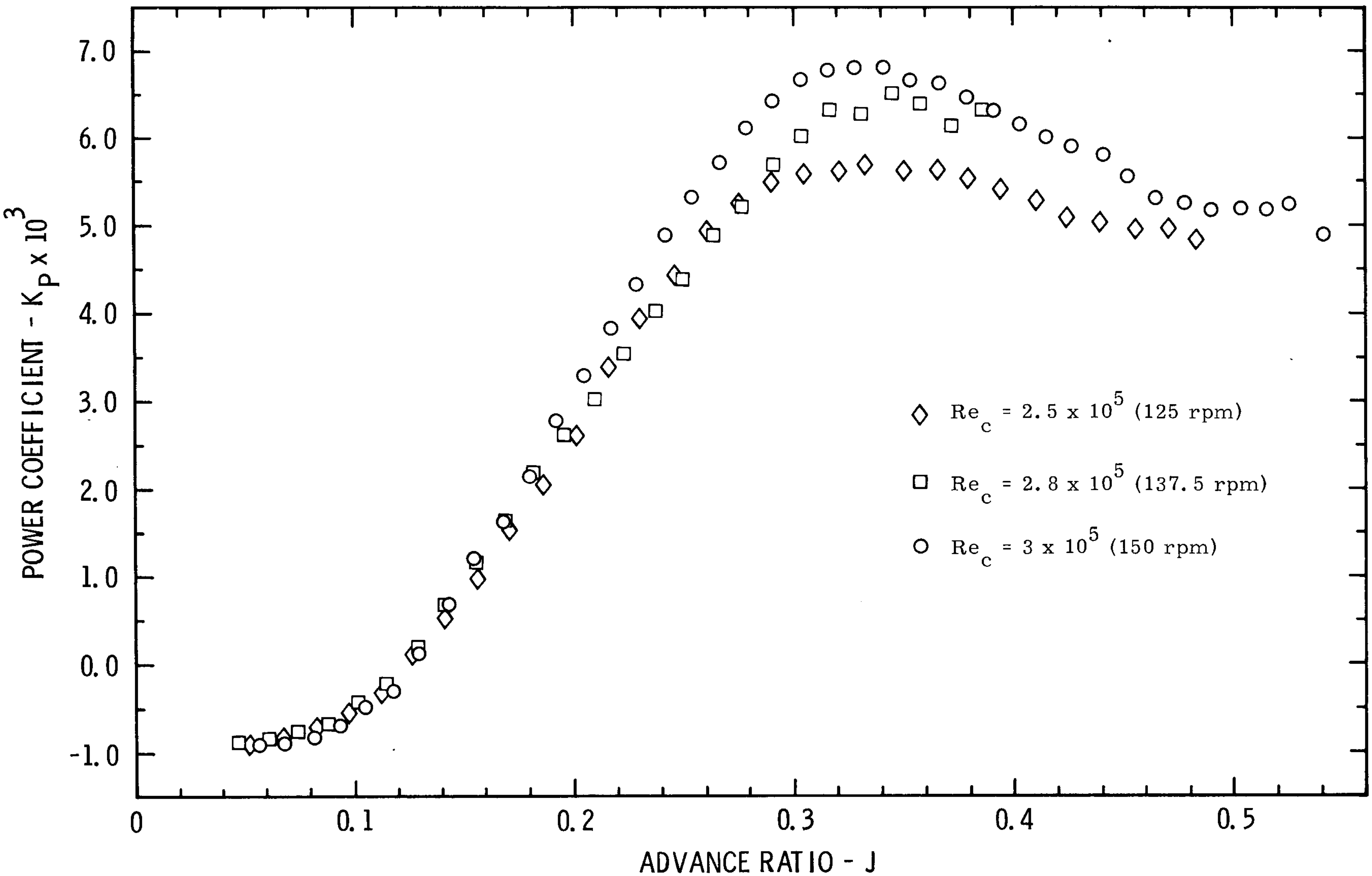

Figure 8. Power Coefficient, K_p, Performance Data for 5-Metre Turbine With Three Extruded NACA-0015 Blades at 125, 137.5, and 150 rpm

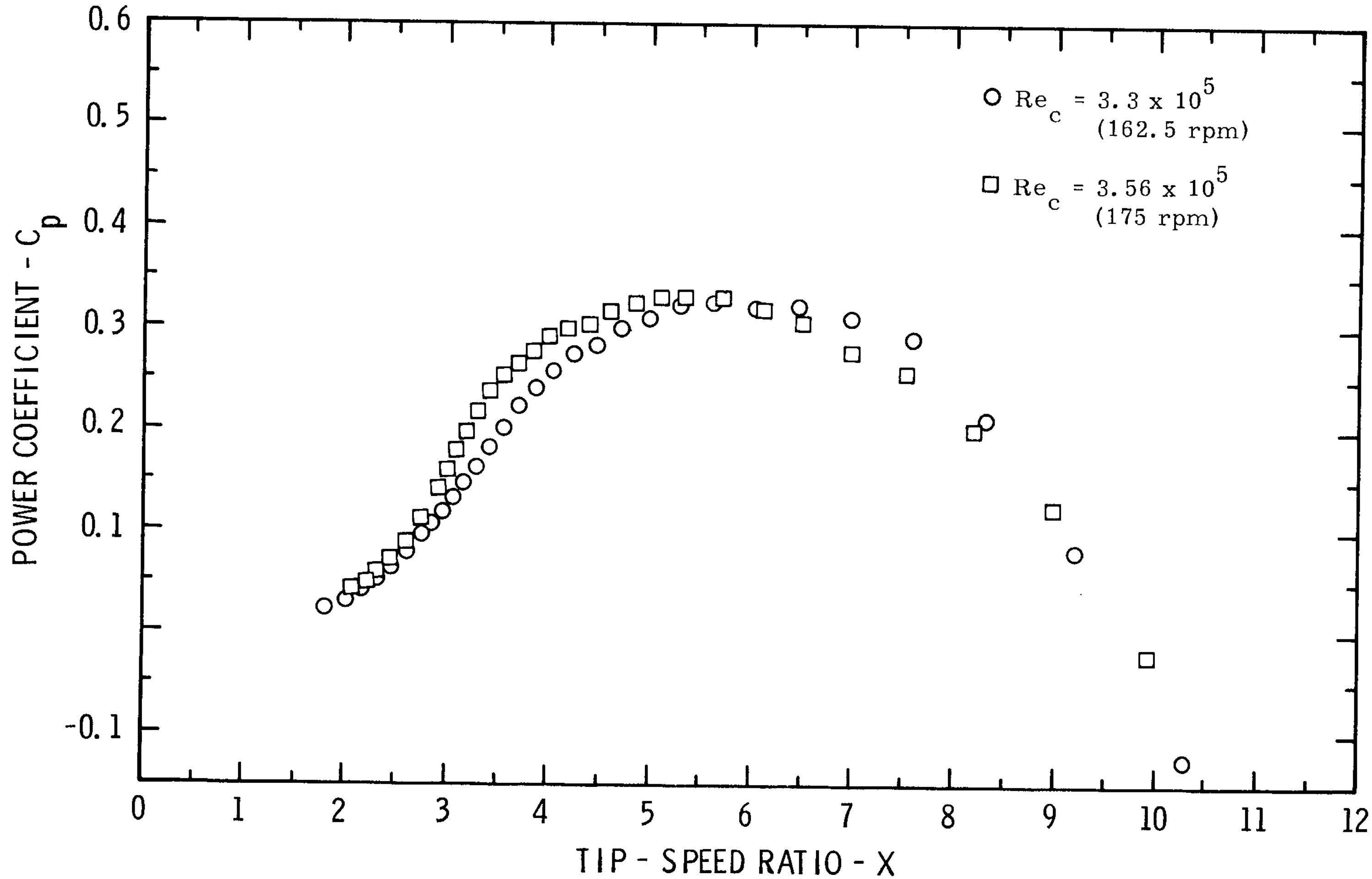

Figure 9. Power Coefficient, C_p, Performance Data of 5-Metre Turbine With Two Extruded NACA-0015 Blades at 162.5 and 175 rpm

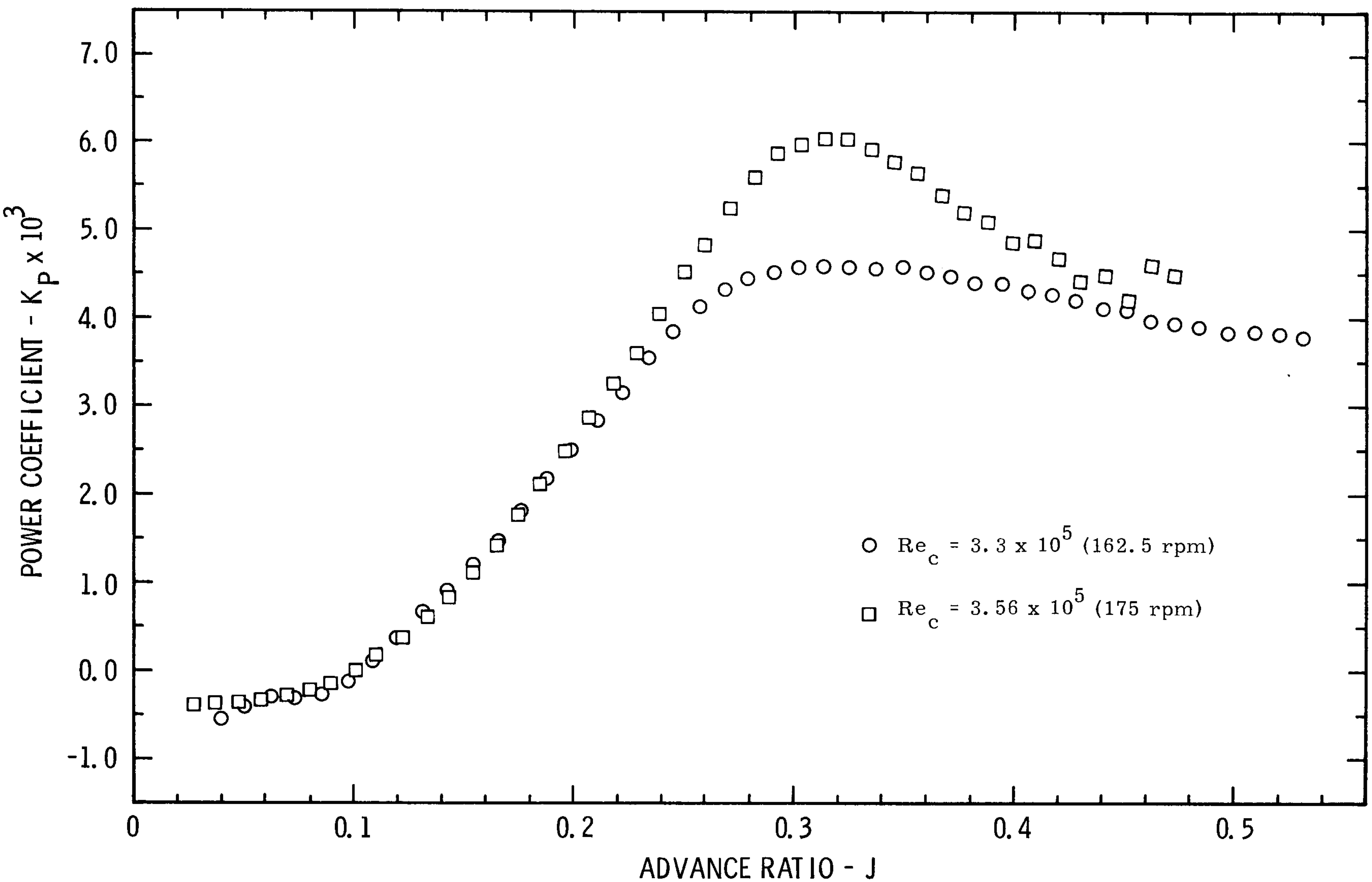

Figure 10. Power Coefficient, K_p, Performance Data of 5-Metre Turbine With Two Extruded NACA-0015 Blades at 162.5 and 175 rpm

exceeded the limitation of the induction motor. This allows the turbine to operate at higher rotational speeds than the synchronous speed which is input to the data reduction program as a constant value. It appears that even at the 175 rpm condition, the induction motor may have been operating with excessive slip. This has the effect of producing higher calculated values of K_p and lower calculated values of C_p because these values are normalized using rotational speeds lower than the actual rotational speed. Thus the large increase in $K_{p_{max}}$ for the 175 rpm condition and the almost insignificant increase in $C_{p_{max}}$ may be due to this excessive slip. This means the 175 rpm data should be used with reservation.

Figures 11 and 12 present the C_p and K_p comparisons between the new and the original blades at a rotational speed of 150 rpm. The improvement in performance is due to the elimination of the nonaerodynamic straight sections and associated knuckles of the original NACA-0012 blades and the better stall characteristics of the NACA-0015 airfoil. The data show an increase in $C_{p_{max}}$ of 44% (from 0.27 to 0.39) and an increase in $K_{p_{max}}$ of 62% (from 0.0042 to 0.0068).

One of the computational tools used at Sandia Laboratories to predict vertical-axis wind turbine performance is a program called VDART, a detailed description of which is found in Ref 15. Briefly, VDART is a vortex/lifting line representation of the turbine blades and the wake they generate. The blades are divided into segments, each of which is modeled by a single "bound" vortex which remains attached to the blade segment and a pair of "trailing" vortices at each of the segment's two extremities. These trailing vortices account for spanwise lift variations and are convected into the turbine wake. Also carried downstream of each segment are "shed" vortices which model timewise variations in the bound vorticity. The sum of velocities induced by the totality of the bound, trailing, and shed vortex systems plus that of the ambient stream define the aerodynamic flowfield. Once this is established at a given operating condition, the lift and drag of the blade segment is obtained with airfoil section data.

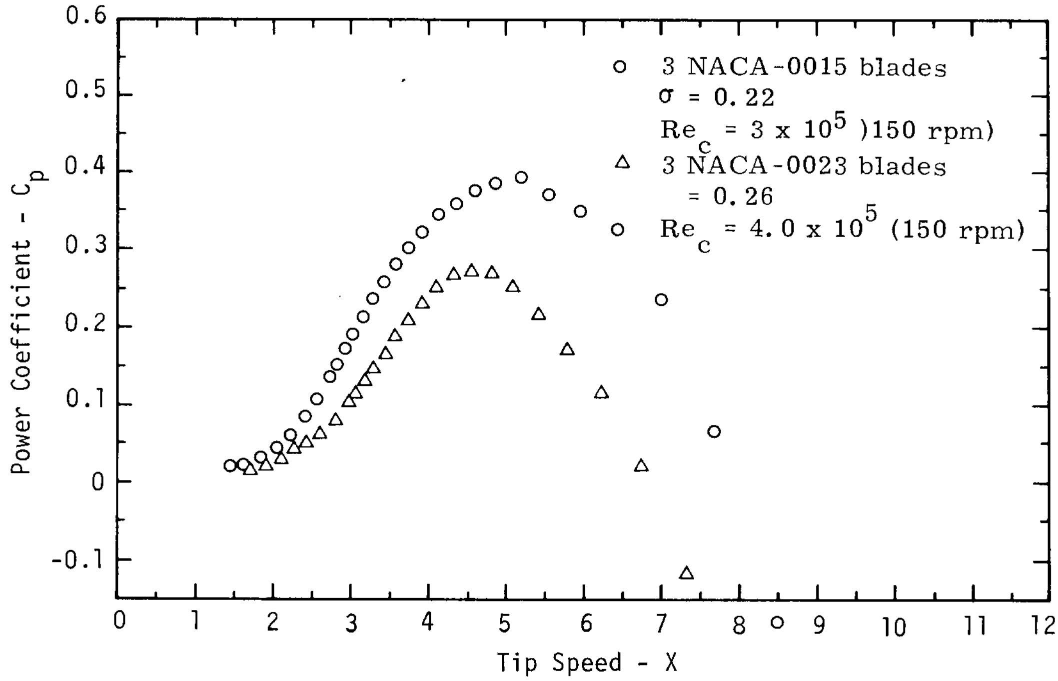

Figure 11. Comparison of the 150 rpm C_p Data Between Original Blade Performance and Extruded Blade Performance of the 5-Metre Turbine

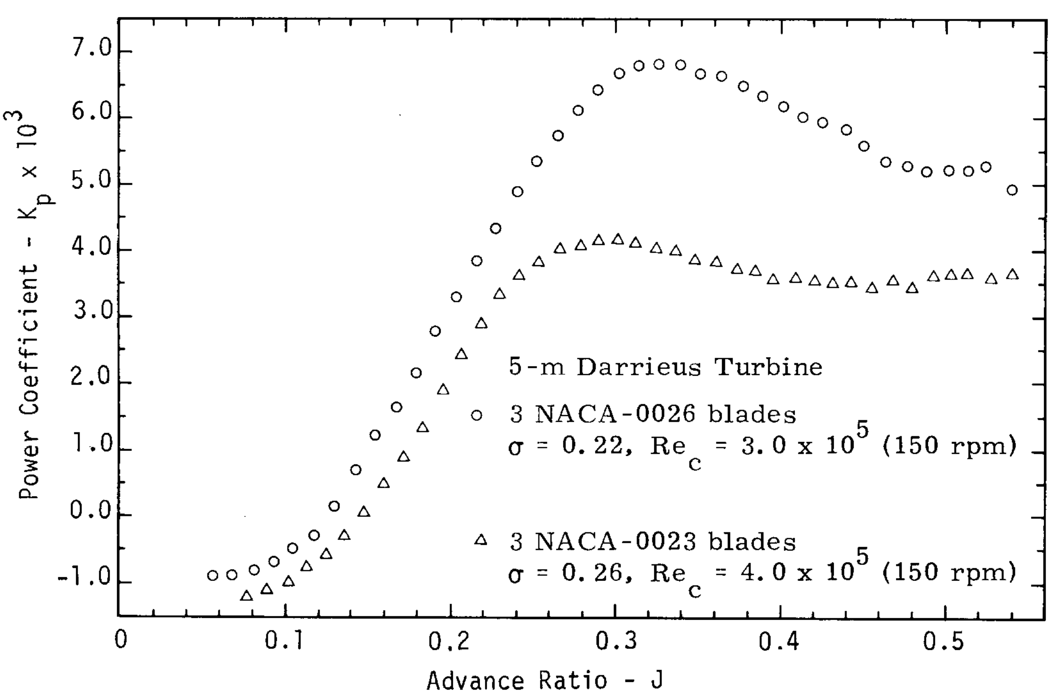

Figure 12. Comparison of the 150 rpm K_p Data Between Original Blade Performance and Extruded Blade Performance of the 5-Metre Turbine

A comparison of the two-bladed 162.5 rpm data with the results of the VDART code is shown in Figure 13. With the exception of the X = 3 point, agreement is quite good. This exception is believed due to the effects of dynamic stall. VDART computer solution convergence for values of X > 8 could not be achieved.

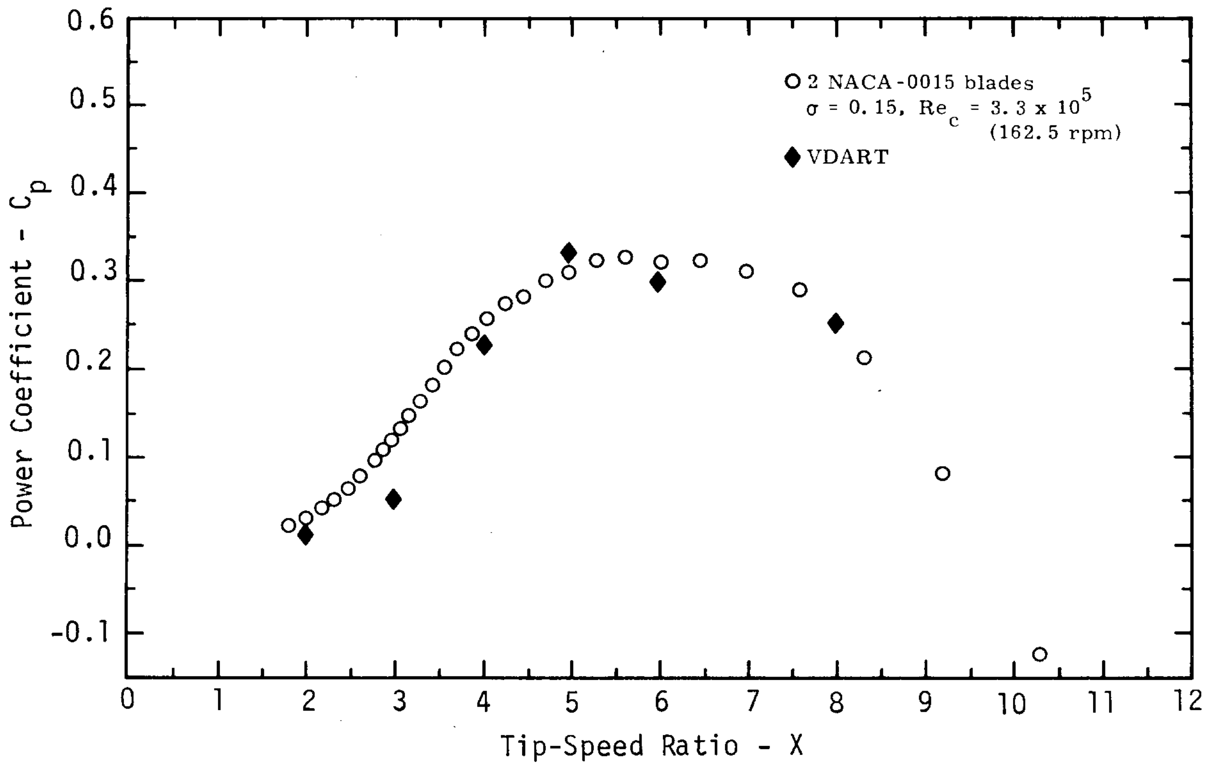

Figure 13. Comparison of Two-Bladed 5-Metre Turbine Performance Data With VDART Computer Program at 162.5 rpm

When the wind turbine is operated (powered) when there is no wind, a value for the zero wind drag coefficient C_{d_o}, can be determined. The value of C_{d_o} as a function of chord Reynolds number is a measure of the turbine's efficiency (high values of C_{d_o} result in low values of C_p). It is therefore of interest to compare the C_{d_o}'s of different configurations and also with the minimum drag of two-dimensional airfoils of the same cross section as the turbine blades. Under the no wind condition, the airfoils are always operating at a geometric angle-of-attack of zero degree. Migliore and Wolfe[16] have shown that airfoils in curvilinear flow actually operate at a virtual angle-of-attack which is different from the geometric angle-of-attack. For the turbine this difference is dependent upon the geometric angle-of-attack, the tip-speed ratio, the blade chord to turbine radius ratio, and the position of the blade in its orbit about the turbine axis. They also show that the effect is reduced for small chord to radius ratios. The chord-to-turbine maximum radius ratio for the 5-m turbine with the extruded blades is 0.067. This results in a virtual angle-of-attack of the order of one degree.[15] This is small, and its effect will be considered insignificant in the calculation of C_{d_o} as a function of chord Reynolds number for the turbine.

A plot of zero-wind drag coefficients as a function of chord Reynolds number is presented in Figure 14. Shown in the figure are C_{d_o} curves for two-dimensional airfoils with the NACA-0012 and -0015 profiles obtained from Eppler's[17] airfoil code, C_{d_o} data for a 2-m-diameter turbine with NACA-0012 blades, and C_{d_o} data for the 5-m turbine with the original NACA-0012 blades and the extruded NACA-0015 blades. The data for the 2-m turbine are shown here because they represent a large amount of data obtained under the most nearly ideal conditions and can be used as a basis for comparison purposes. These data were obtained during spin tests of the 2-m turbine in a large room with the laboratory instrumentation described in Ref 4. The C_{d_o} results of the 5-m turbine with its initial NACA-0012 blades (which performed below expectations) can be seen to be approximately 50% higher than the C_{d_o}'s obtained for the 2-m turbine. The 5-m turbine with the extruded aluminum NACA-0015 blades show a marked reduction of C_{d_o} with accompanying improved performance exhibited by these blades. The results are still higher than the two-dimensional airfoil data from the Eppler code, as can be expected since the chord Reynolds number which the data are plotted against is valid only for that portion of the blade at the turbine equator. The actual Reynolds number everywhere else on the blade is lower, and the accumulated effect of Reynolds number on the minimum drag coefficient (i.e., minimum drag increases with decreasing Reynolds number) can be seen.

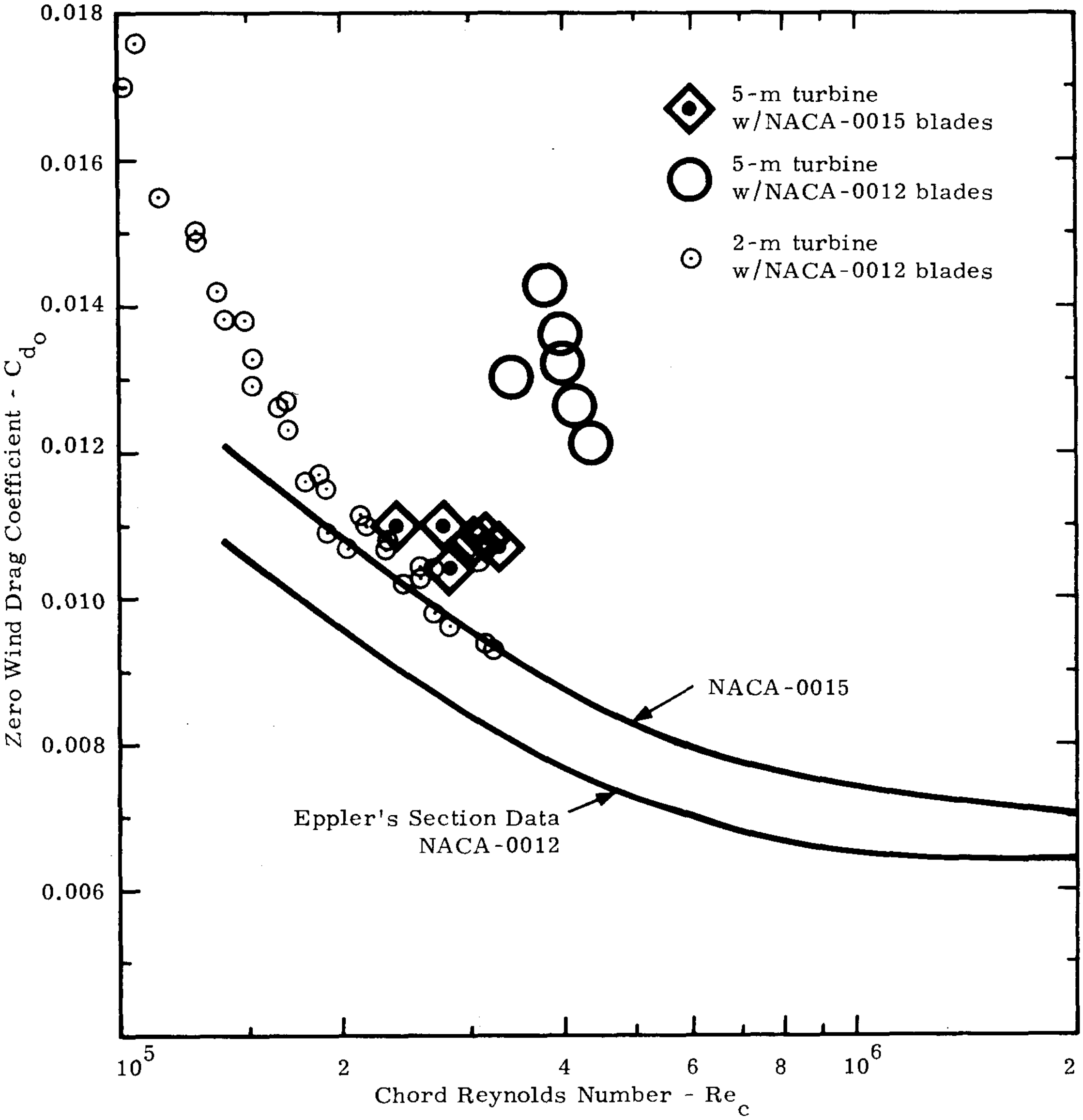

Figure 14. Zero Wind Drag Coefficient Data for Three Configurations of Vertical Axis Wind Turbine

Conclusions

The performance data for the 5-m turbine and the new one-piece extruded aluminum blades with the NACA-0015 airfoil cross section were obtained with the aid of a minicomputer and the computer program BINS. The data show the performance of these blades to be as anticipated and to be considerably improved over that of the original three-piece blades. The highest performance was obtained with three blades at a rotational speed of 150 rpm and produced a $C_{P_{max}}$ of 0.392. This compares with a $C_{P_{max}}$ of 0.273 obtained with three blades at 150 rpm taken during earlier tests with the original three-piece blades. This 44% improvement agrees with wind tunnel data obtained with a 2-m turbine with similar 1-piece blades.

The data obtained at 162.5 rpm with two blades is compared with the results of the computer program VDART and found to be in agreement. VDART is the most sophisticated computer model of the vertical-axis wind turbine performance that is available to Sandia and is considered to offer the best results.

The one-piece extruded aluminum blades are more aerodynamically "clean" than the original three-piece blades, as indicated by the marked reduction of the C_{d_o}'s. This is in spite of the fact that the minimum drag for the NACA-0015 airfoil is slightly higher than the minimum drag for the NACA-0012 airfoil. The turbine with the new blades has demonstrated that the vertical-axis wind turbine can produce power coefficients in the range of 0.4. It is believed that this machine would have exceeded this value if it were not for the fact that the rotational speed of 150 rpm with three blades could not be exceeded due to torque limitations of the timing belts and induction motor.

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