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Free-Air Performance Tests of a 5-Metre-Diameter Darrieus Turbine

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FREE-AIR PERFORMANCE TESTS OF A 5-METRE-DIAMETER DARRIEUS TURBINE

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ABSTRACT

A 5-metre-diameter vertical-axis wind turbine has been tested at the Sandia Laboratories Wind Turbine Site. The results of these tests and some of the problems associated with free-air testing of wind turbines are presented. The performance data obtained follow the general trend of data obtained in extensive wind tunnel tests of a 2-metre-diameter turbine. However, the power coefficient data are slightly lower than anticipated. The reasons for this discrepancy are explored in the paper, along with comparisons between experimental data and a computerized aerodynamic prediction model.

ACKNOWLEDGMENTS

The authors are grateful for the support provided by the personnel of the Advanced Energy Projects Division 5715 and R. E. Akins, 5443.

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FIGURES

CONTENTS (cont)

Nomenclature

A_s	Turbine swept area
c	Blade chord
C_{d_o}	Zero wind drag coefficient
C_P	Power coefficient, $\frac{Q_i \omega}{\frac{1}{2} \rho_\infty V_{\infty_i}^3 A_s}$
J	Advance ratio, $\frac{V_{\infty_i}}{R\omega}$
K_p	Power coefficient, $\frac{Q_i \omega}{\frac{1}{2} \rho_\infty A_s (R\omega)^3}$
L	Blade length
m	Number of data records in a data set
n	Total number of data points in the data set
n_i	Number of data points in the ith velocity bin
N	Number of blades
Q	Turbine torque
Q_f	Friction tare torque
Q_i	Average torque in velocity bin i
R	Turbine maximum radius
Re_c	Chord Reynolds number, $\frac{\rho_\infty R\omega c}{\mu_\infty}$
T_j	Turbine torque input to the BINS program, $(Q + Q_f)$
V_{∞_i}	Average freestream velocity in bin i
X	Turbine tip-speed ratio, $\frac{R\omega}{V_{\infty_i}}$

Nomenclature (continued)

μ_∞	Freestream viscosity
ρ_o	Reference density
ρ_∞	Freestream density
ω	Turbine rotational speed
σ	Solidity, $\frac{NcL}{A_s}$

SUMMARY

The Sandia 5-metre vertical-axis wind turbine has been tested in free air at the Sandia Laboratories Wind Turbine Site. The turbine was operated at 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 three blades on the turbine consist of three sections: a circular arc located near the turbine equator with an NACA-0012 airfoil cross section and two straight segments that attach the circular arc to the axis of rotation. The solidity of this system is 0.26.

The performance data were obtained with the aid of a minicomputer and a computer program which utilized statistical methods. The unsteadiness of the winds necessitated the statistical averaging of the data. It was found that the wind turbine performance data are influenced by gusty wind conditions, anemometer location, anemometer response time, and by the inertial effects of the turbine rotor. The "method of bins" computer technique (computer code called BINS) used for averaging the data is, at the present time, the only method by which reasonable performance information has been obtained.

Four data sets for three constant rotational speeds were obtained. The results showed the turbine's performance to be less than anticipated from previous wind tunnel results of a 2-metre turbine and also lower than computer calculations using an aerodynamic prediction model. The maximum power coefficient, C_p, for the turbine was found to be 0.273. A computer analysis shows that the performance of the turbine is degraded by the straight sections of the blades which are not of airfoil cross section. Based on this, the performance data presented here should not be considered to be representative of a vertical-axis wind turbine with blades which are of airfoil cross section from hub-to-hub. Future tests of this 5-metre turbine will be conducted with such blades.

FREE-AIR PERFORMANCE TESTS OF A 5-METRE-DIAMETER DARRIEUS TURBINE

Introduction

The renewed interest in wind energy has brought about a reconsideration of ideas that evolved when wind turbines were more fashionable. One such idea is the vertical-axis wind turbine,[1] which was patented in the United States in 1931 by G. J. M. Darrieus. Sandia Laboratories fabricated a 5-metre-diameter Darrieus wind turbine in 1974. The original turbine design allowed for a variable rotational speed mode of operation. Subsequent studies identified the constant rotational speed/synchronous power grid application as being very promising for the Darrieus turbine. Since early 1976, the Sandia 5-metre turbine has been operating in a synchronous grid mode.

A limited amount of performance data was obtained on the turbine in 1976[2] but data acquisition proved to be difficult and time consuming. At that time, strip charts of the turbine torque and corresponding wind velocity were used to record the performance information. Early in 1977 a minicomputer was installed and programmed to take the turbine performance information and compute the power coefficients. This report presents the performance data obtained to date.

The 5-metre turbine shares the site with a recently erected 17-metre turbine and a 2-metre turbine. Also at the site is a 30-metre-high meteorological tower and an instrumentation building which houses the turbine controls, instrumentation, and Hewlett-Packard minicomputer.

The 5-Metre Vertical-Axis Wind Turbine

The Sandia 5-metre turbine, a proof-of-concept machine fabricated in 1974, was designed to be erected in the shortest possible time at reasonable cost. The three-bladed turbine is shown in Figure 1. Each blade consists of three sections: a circular arc located near the turbine equator and two straight pieces that attach the circular arc to the axis of rotation. 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). The curved part of each blade is a NACA-0012 airfoil section with a 19-cm chord while each straight section is simply steel rolled to a "streamlined" shape with a chord of 10 cm. The solidity, σ, is calculated to be 0.26 assuming the 19-cm chord of the circular arc is continuous to the axis of rotation.

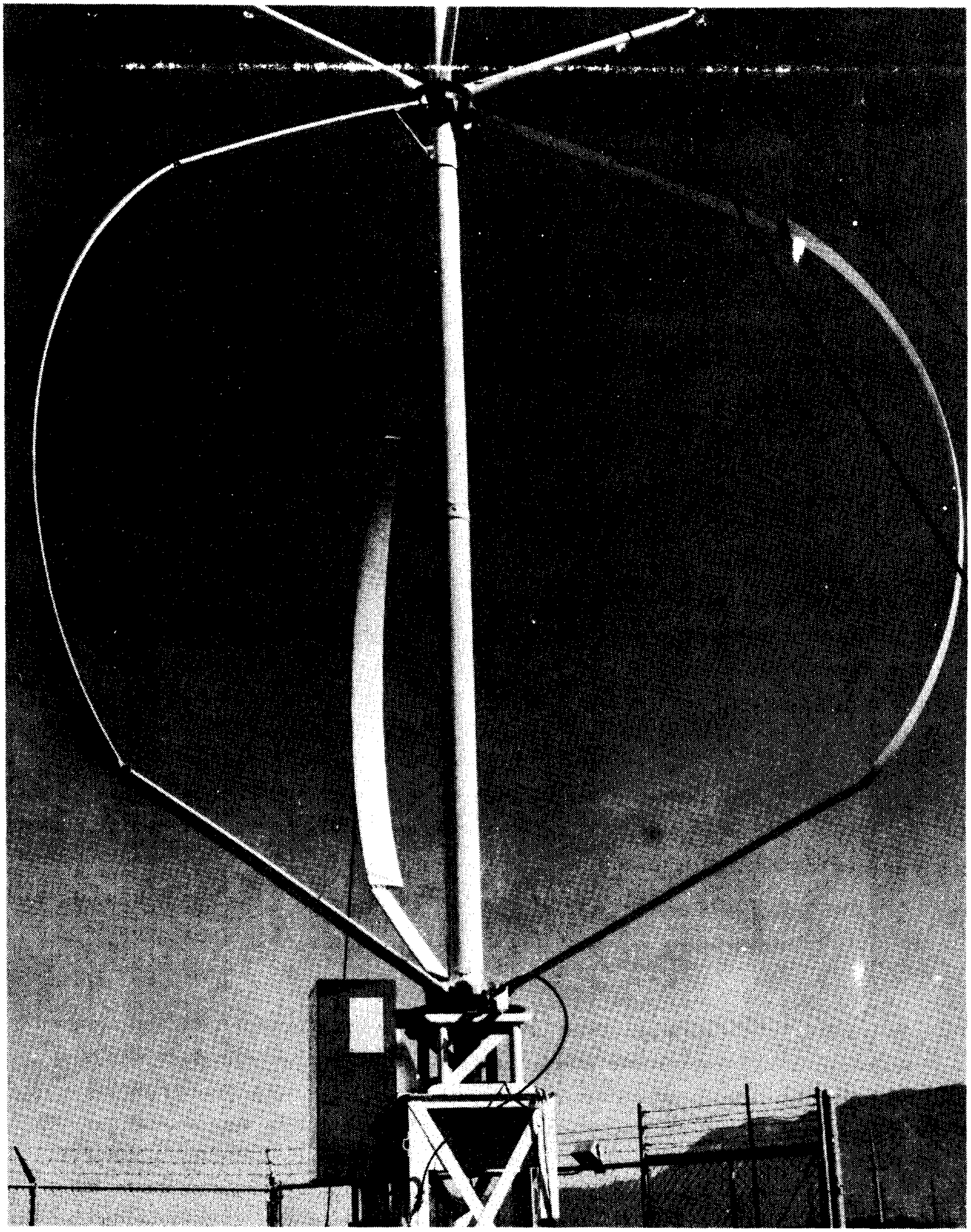

Figure 1. The Sandia 5-Metre Vertical Axis Wind Turbine at the Wind Turbine Site.

The construction of each blade in three sections was done for cost considerations. It was thought at the time that the attachment knuckles and the straight sections would have little influence on the operation and performance of the turbine. In Figure 2, the straight sections and attachment knuckles are clearly visible. The differences in chord length between the circular arc blade and the straight sections can also be seen. It is now believed that this construction technique is detrimental to the performance of the turbine.

The turbine is designed to operate at nearly a constant rotational speed by connecting the turbine shaft, through a two-stage timing belt drive, to an induction motor/generator operating at 3500 rpm. By changing pulleys, the turbine speed can be changed in discrete steps. Figure 3 shows a schematic of the 5-metre 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 relative diameters of the gears. The induction machine can act as either a motor, delivering power to the turbine from the utility line, or a generator, delivering power to the utility line from the turbine.

Testing and Data Acquisition

The atmospheric testing of the 5-metre turbine with the minicomputer began in February 1977. 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 decide the appropriate wind velocity corresponding to a given torque measurement. A representative strip chart record of the wind velocity and turbine torque is shown in Figure 4. The zero wind velocity and torque are at the baseline of the record. The unsteadiness of the wind velocity and torque is quite evident and shows some of the problems of obtaining free-air data from a wind turbine.

Banas[4] and Sullivan[2] have developed a computer program named BINS which uses the "method of bins" to statistically average the wind speed/torque data. 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 miles per hour; i.e., a data point is taken and the wind velocity is determined which in turn locates the velocity bin. The data point is counted and the value of the torque is added to the total 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

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

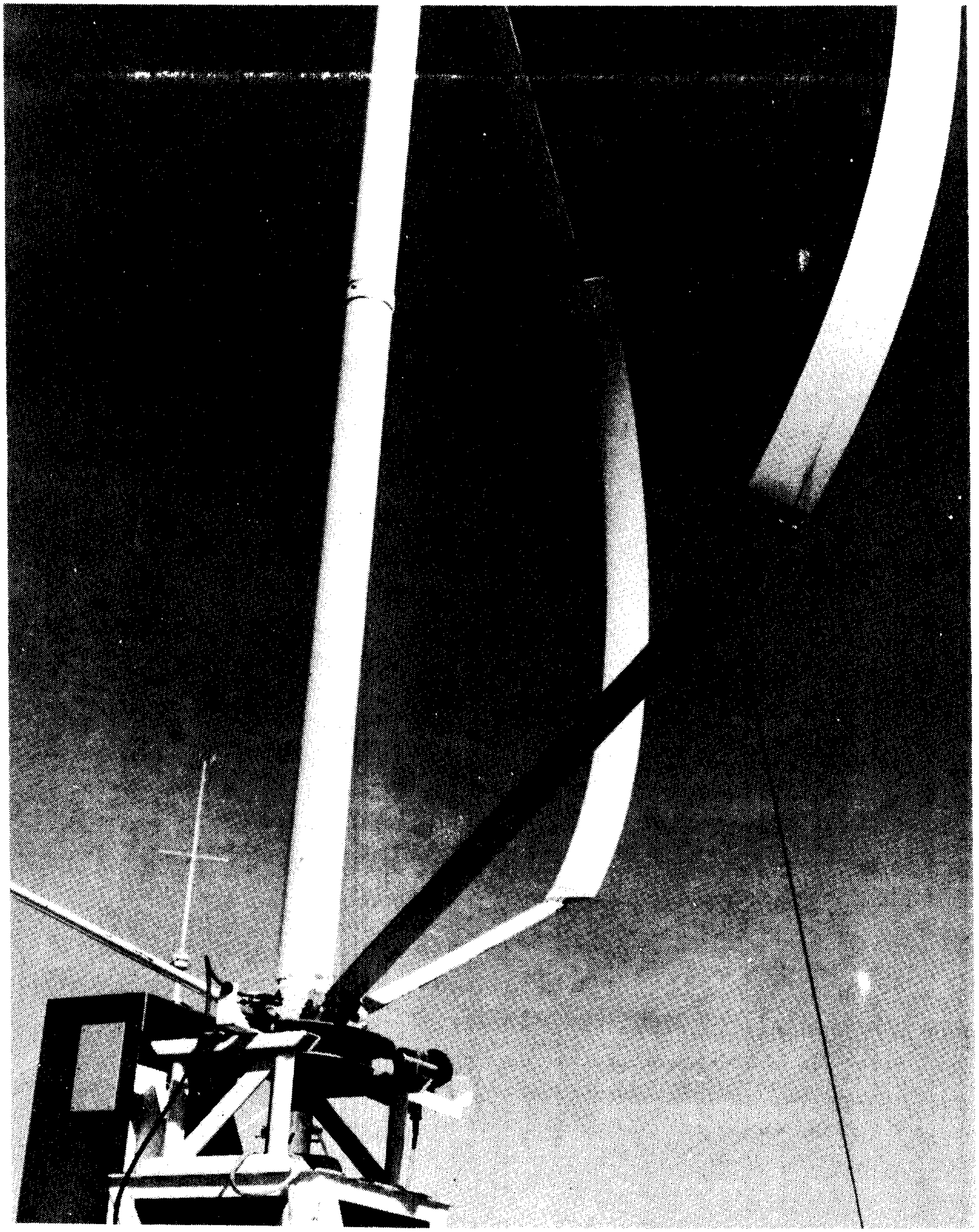

Figure 2. The Present 3-Section Blades on the 5-Metre Turbine.

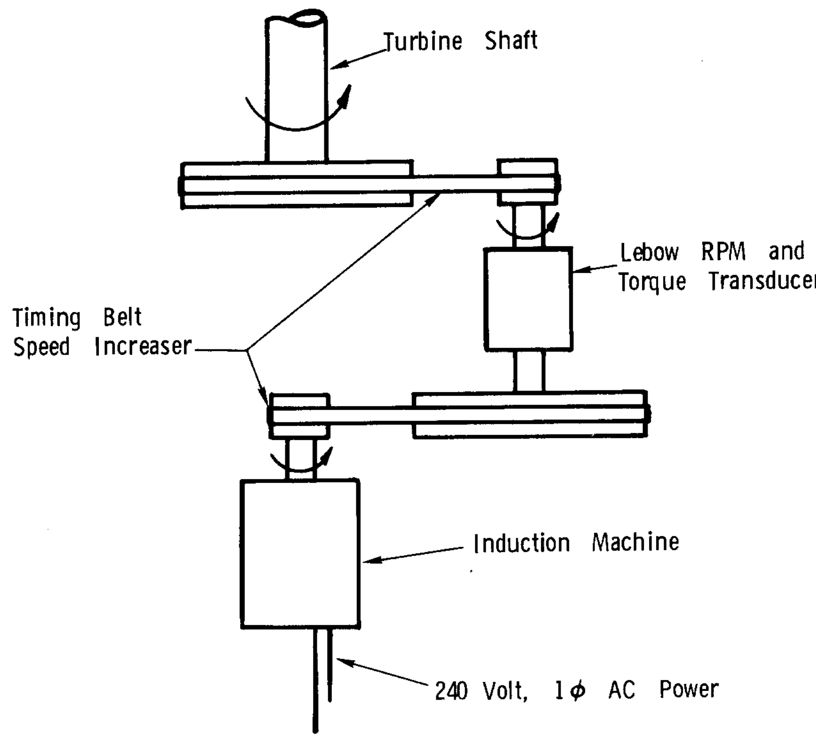

Figure 3. Schematic of the 5-Metre Turbine System.

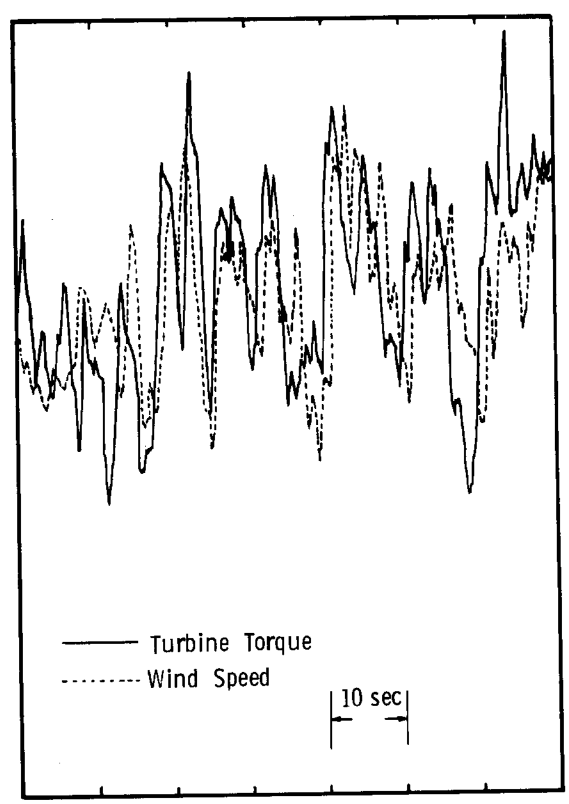

Figure 4. Sample Record of Torque and Wind Speed.

of blades, anemometer identification, wind shear correction factor, temperature, barometric pressure, time of the day, and the turbine tare torque. The turbine tare torque is the torque lost in the turbine due to bearing friction and belt losses.

The computer will accept 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 velocities corresponding to each anemometer. Figure 5 is a photograph of the 5-metre turbine showing two anemometers. One anemometer is directly above the turbine, approximately 2 metres above the blade top attachment point on the turbine axis. The other anemometer is located at the turbine equator height, approximately two turbine diameters south of the turbine axis. That dimension and location were initially chosen because the availability of a corner fence post facilitated mounting the anemometer. The southern direction was chosen because the prevailing winds are generally from the east or west, and the anemometer would not be in the wake of the turbine. The meteorological tower has four anemometers on it and is located approximately 20 turbine diameters west of the 5-metre turbine. The operator has the option of taking wind-velocity data from any of the six available anemometers 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 then performed on a day-to-day basis with the end result being 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 and the performance of the turbine can be computed by the minicomputer in the control building. The summed torque in each velocity bin, i, of a data record is

$$T_i = \sum_{j=1}^{n_i} T_j \tag{1}$$

where n_i equals the total number of data points in the velocity bin, i. When data records are added together, the value of the torque in each bin cannot be directly added because the density of the air when data records are taken will vary from day to day. Thus the value of the torque must be adjusted to account for this using a reference density, ρ_o, and the actual freestream

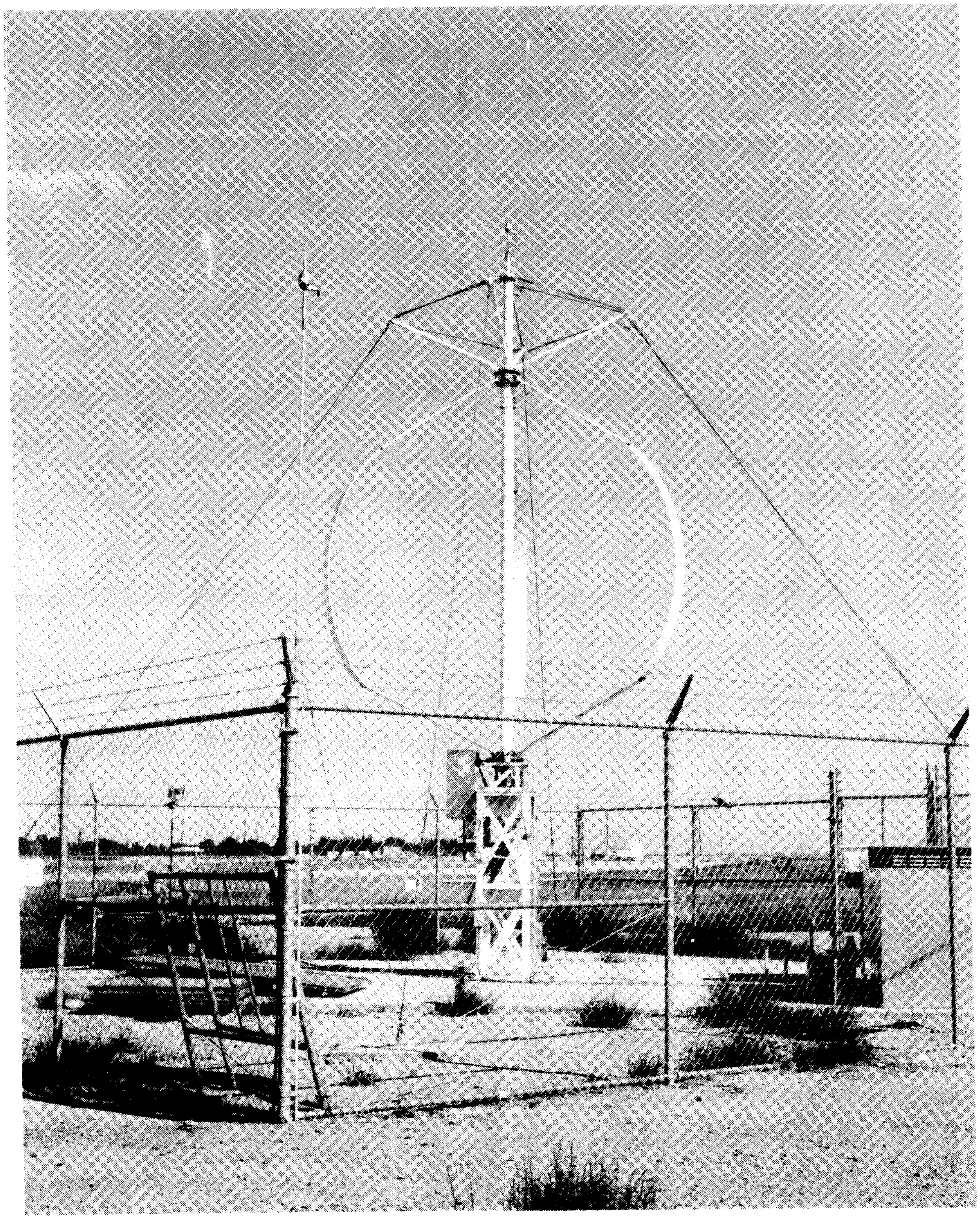

Figure 5. The Location of Two Anemometers with Respect to the 5-Metre Turbine.

density, ρ_∞, for each data record. Thus for each velocity bin, i, a normalized summed torque is determined,

$$\overline{T}_i = T_i \frac{\rho_o}{\rho_\infty} \tag{2}$$

These values of $\overline{T}_i$ for each data record are summed along with the number of data points, n_i, for each velocity bin and an average torque for each velocity bin in a data set is determined as

$$Q_i = \frac{\sum_{k=1}^{m} (\overline{T}_i)_k}{\sum_{k=1}^{m} (n_i)_k} \tag{3}$$

where m is the number of data records being summed in the complete data set. A power coefficient, which is a standard measure of performance, is then calculated by

$$C_p = \frac{Q_i \omega}{\frac{1}{2} \rho_o V_{\infty_i}^3 A_s} \tag{4}$$

where V_{∞_i} is the average velocity of the velocity bin. The velocity bin width on each data record is 0.5 mph. However, the operator may call for the data to be output in 1/2-, 1-, or 2-mph increments. This is done by merely combining adjacent bins and again the velocity is the average velocity of the wider increment; i.e., for a 1-mph increment in velocity, bin 1 and 2 would combine to form a bin with a 1-mph width and the average velocity would be 0.5 mph.

A second power coefficient has been defined by Banas[4] as

$$K_p = \frac{Q_i \omega}{\frac{1}{2} \rho_o A_s (R\omega)^3} \tag{5}$$

where the wind velocity has been replaced by the blade equatorial velocity. This power coefficient was chosen by Banas for three reasons. They are: (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 tip speed ratio is defined as:

$$X = \frac{R\omega}{V_{\infty_i}} \tag{6}$$

A nondimensional freestream velocity, called the advance ratio, is the inverse of Equation 6.

$$J = \frac{V_{\infty_i}}{R\omega} \tag{7}$$

Data will be presented as C_p vs X and K_p vs J.

Four data sets were obtained for the 5-metre turbine. The first data set is for the constant rotational speed of 150 rpm and was obtained in late February and early March 1977. This was followed by a data set for 125 rpm obtained during late March, a data set for 162.5 rpm obtained in June and July, and an additional data set again for 150 rpm obtained in late July and August 1977. The wind speed frequency distributions of the four data sets are presented in Figure 6. The total number of data points in each data set is n. This figure shows the percentage of data points in each velocity bin and indicates how many data points are used to average the torque in each bin. Where the frequency is low, the data may be suspect because only a few data points are used to obtain an average.

The power coefficient, C_p, data for the first two data sets are presented in Figure 7. There are two data sets for 150 rpm; the early data set will be referred to as 150a rpm and the latter set as 150b rpm. The 150a-rpm data set has a maximum C_p of 0.273 while the 125-rpm data set $C_{p_{max}}$ is 0.213. These data are compared with the data[5] obtained for a 2-metre turbine of similar solidity tested in a wind tunnel. The wind tunnel data has a maximum C_p of 0.35 at a lower (2.85×10^5) Reynolds number than the Reynolds number of 4.0×10^5 for the 150a-rpm data. The maximum C_p should increase with increasing Reynolds number.[5] Thus the performance of the 5-metre turbine in free-air is not as good as anticipated. The 125-rpm data are also considerably lower than the wind tunnel data and even lower than would be anticipated by the 15% reduction in Reynolds number to 3.4×10^5 from 4.0×10^5 for the 150a-rpm data. This has caused considerable concern.

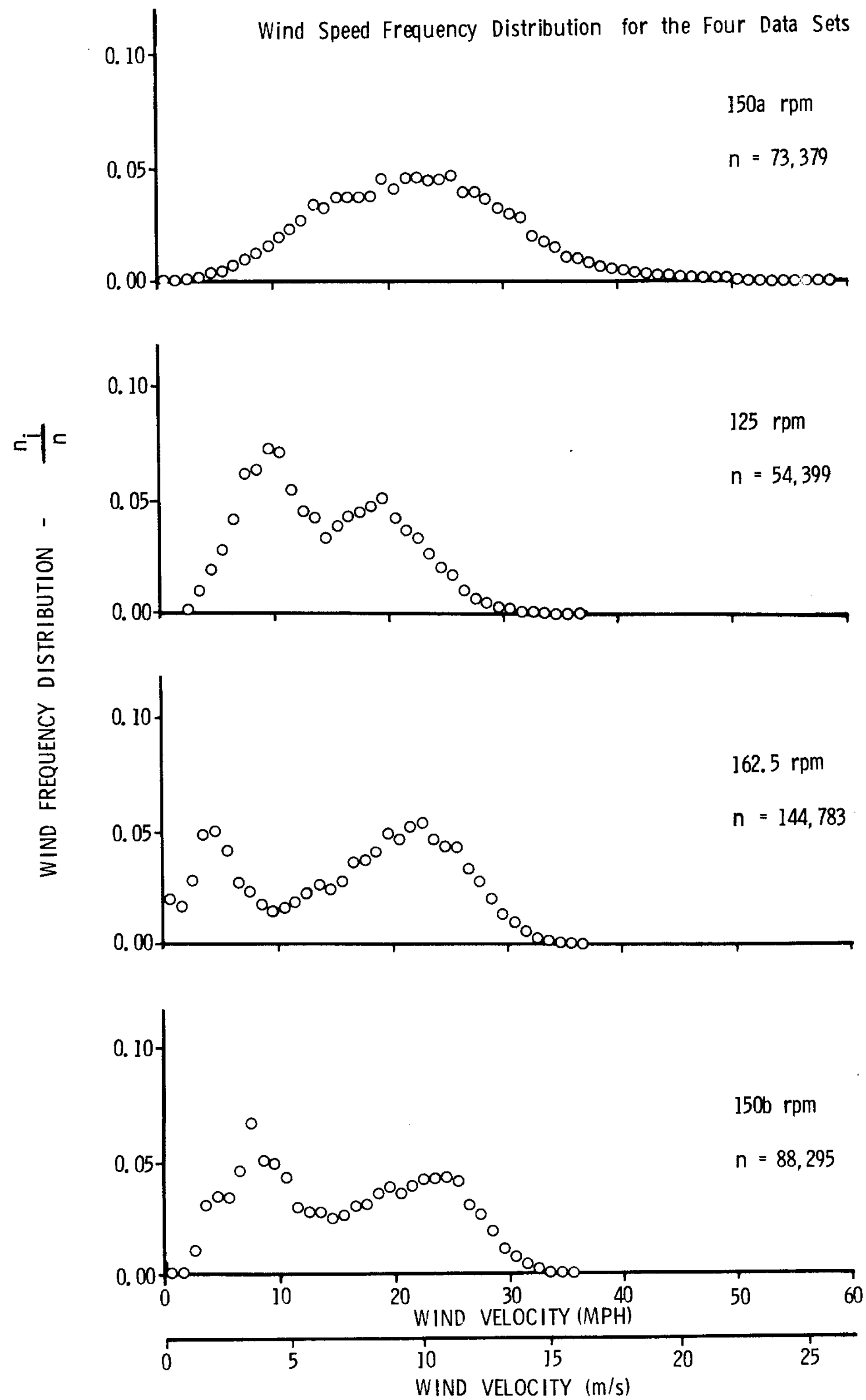

Figure 6. Wind Speed Frequency Distribution for the Four Data Sets.

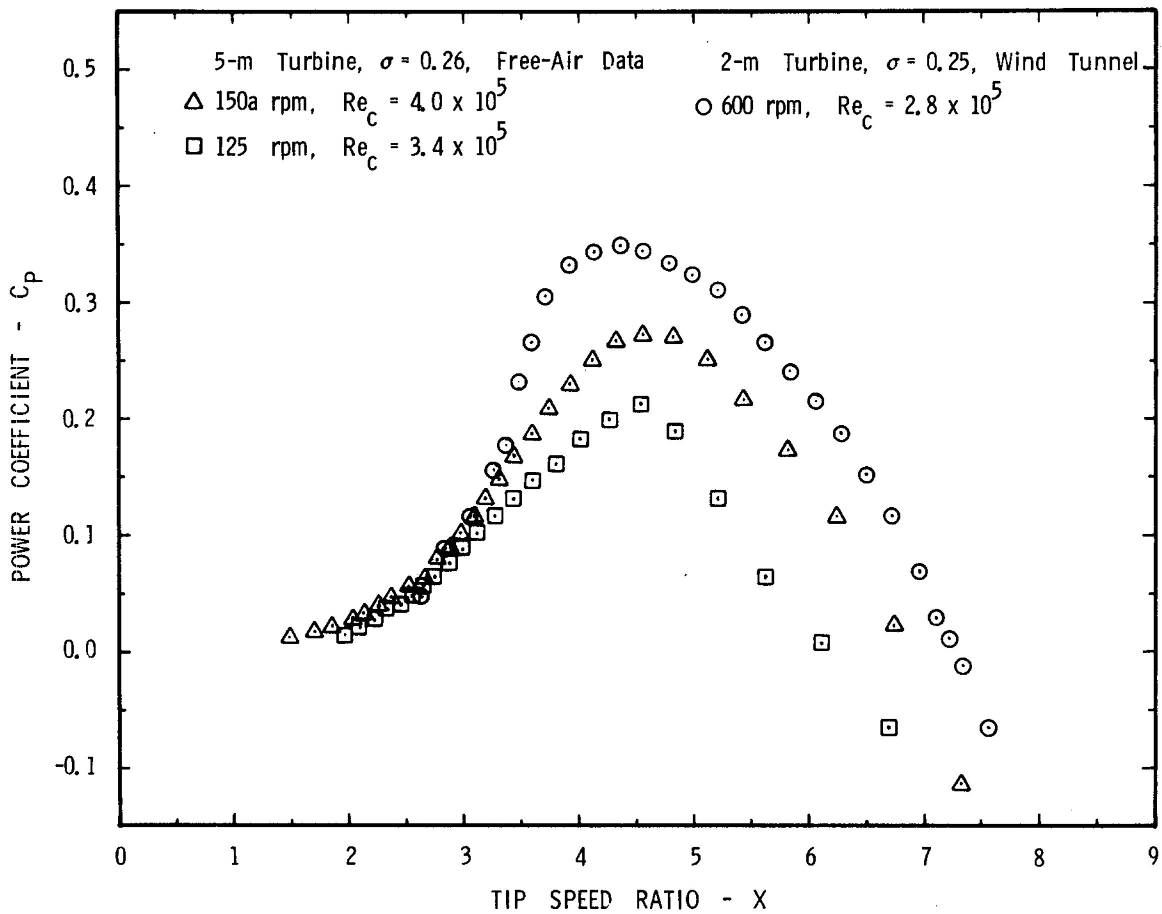

Figure 7. Power Coefficient, C_p, Performance Data of the 5-Metre Turbine at 150a and 125 rpm with Wind Tunnel Data from a 2-Metre Turbine for Comparison.

Figure 8 presents the power coefficient, K_p, as a function of the advance ratio for the first two data sets and compares them with the wind tunnel data of the previous figure. This figure shows that the turbine power does reach a maximum for constant rotational speed as a function of velocity. This figure also shows the inherent self-regulation of the Darrieus turbine operating at constant rotational speed. One point of interest is the free-air data for advance ratios greater than 0.3. The power produced by the 5-metre turbine does not decrease as rapidly past peak K_p as the 2-metre turbine tested in the wind tunnel. This indicates that for larger advance ratios there are some differences between the wind tunnel information and data obtained in free-air testing. Fortunately, this difference is in the form of improved performance for the turbine in free-air.

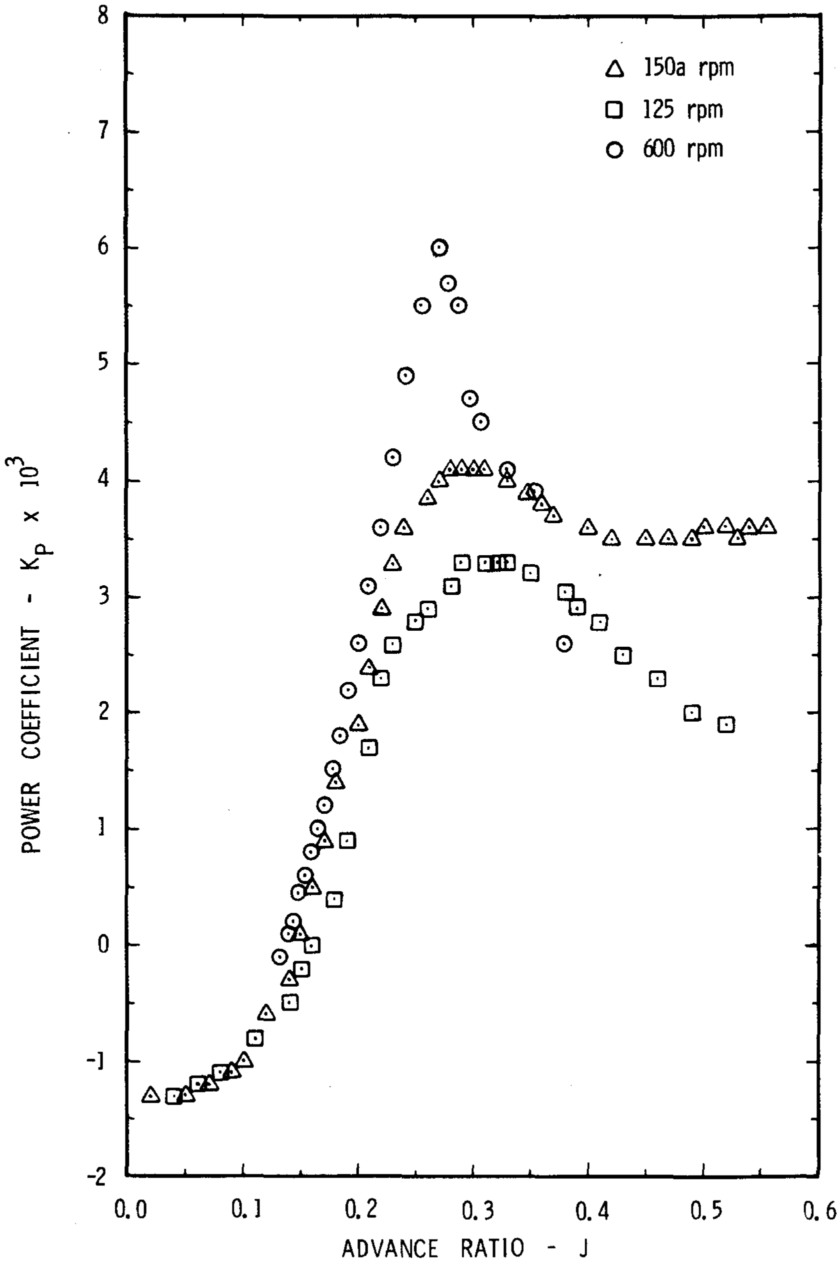

Figure 8. Power Coefficient, K_p, Performance Data of the 5-Metre Turbine at 150a and 125 rpm with Wind Tunnel Data from a 2-Metre Turbine for Comparison.

A compilation of power coefficients, C_p, of all four data sets is shown in Figure 9. This shows a most disturbing result. The data sets for 162.5 and 150b rpm are both lower in C_p than the first data set of 150a rpm. It was because the 162.5-rpm data set was found to be lower than the 150a-rpm set that the 150a-rpm condition was repeated. Examining Figure 6 again shows that the wind speed frequency distribution for the first data set (150a rpm) is much smoother than the other three sets. In reflecting back by memory, without benefit of having taken hard copy data, it is believed that the winds were more steady for that data set. This conclusion, however, is purely subjective and only the smoother wind speed frequency distribution of the first data set can offer any additional support to that conclusion.

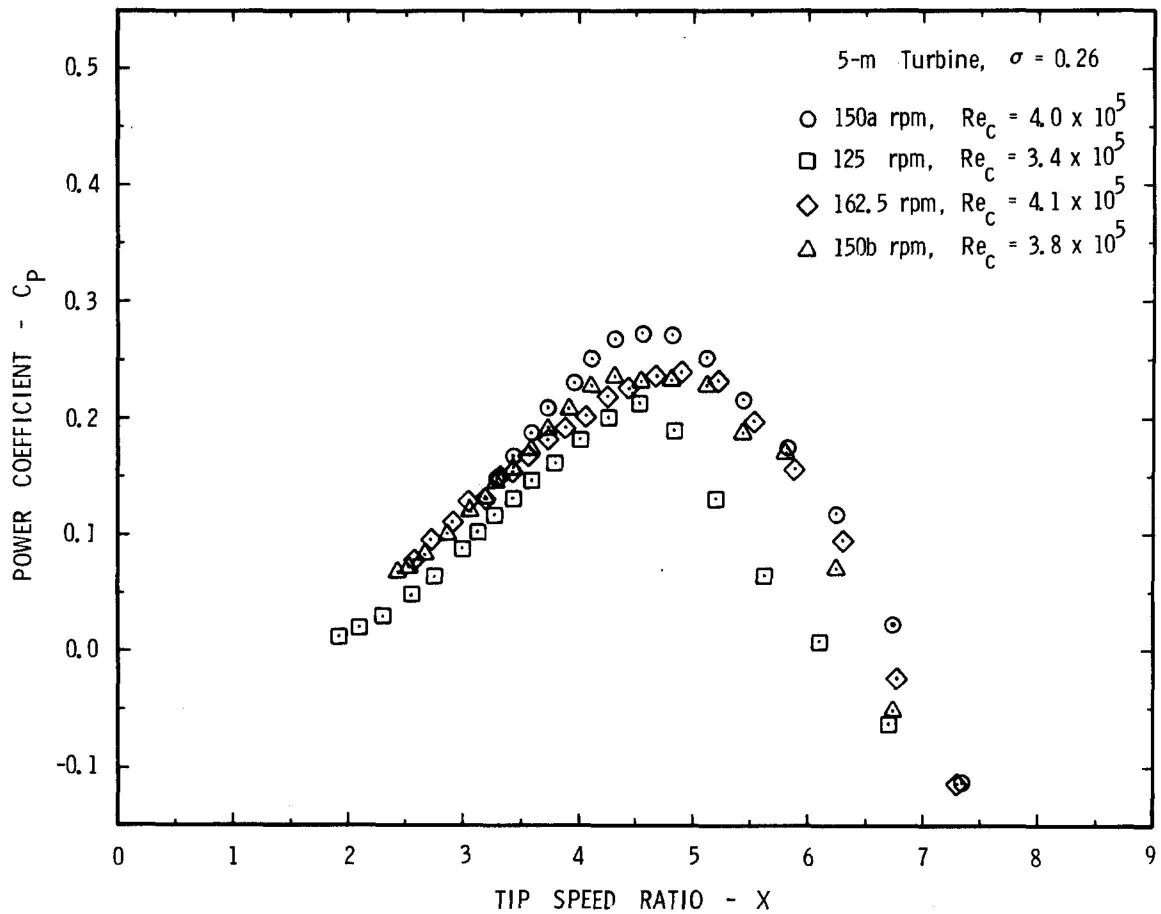

Figure 9. C_p Performance Data of the 5-Metre Turbine at 150a, 125, 162.5, and 150b rpm.

The power coefficients, K_p, for three data sets are shown in Figure 10. The data for all three sets are nearly identical for advance ratios up to 0.3 where there is a divergence in the data. This corresponds to velocities in excess of 26 mph for 150 rpm and 28 mph for 162.5 rpm; the wind speed frequency indicates that the number of data points beyond those speeds drops drastically, thus the averages may be affected. Assuming the divergence is real, then the particular winds of the 162.5- and 150b-rpm data sets were in some way different from the winds of the first (150a rpm) data set. This is not to say that the wind turbine's output is a function of the "quality" of the wind, but rather the problem may be the inability to correctly determine the true wind velocity experienced by the turbine.

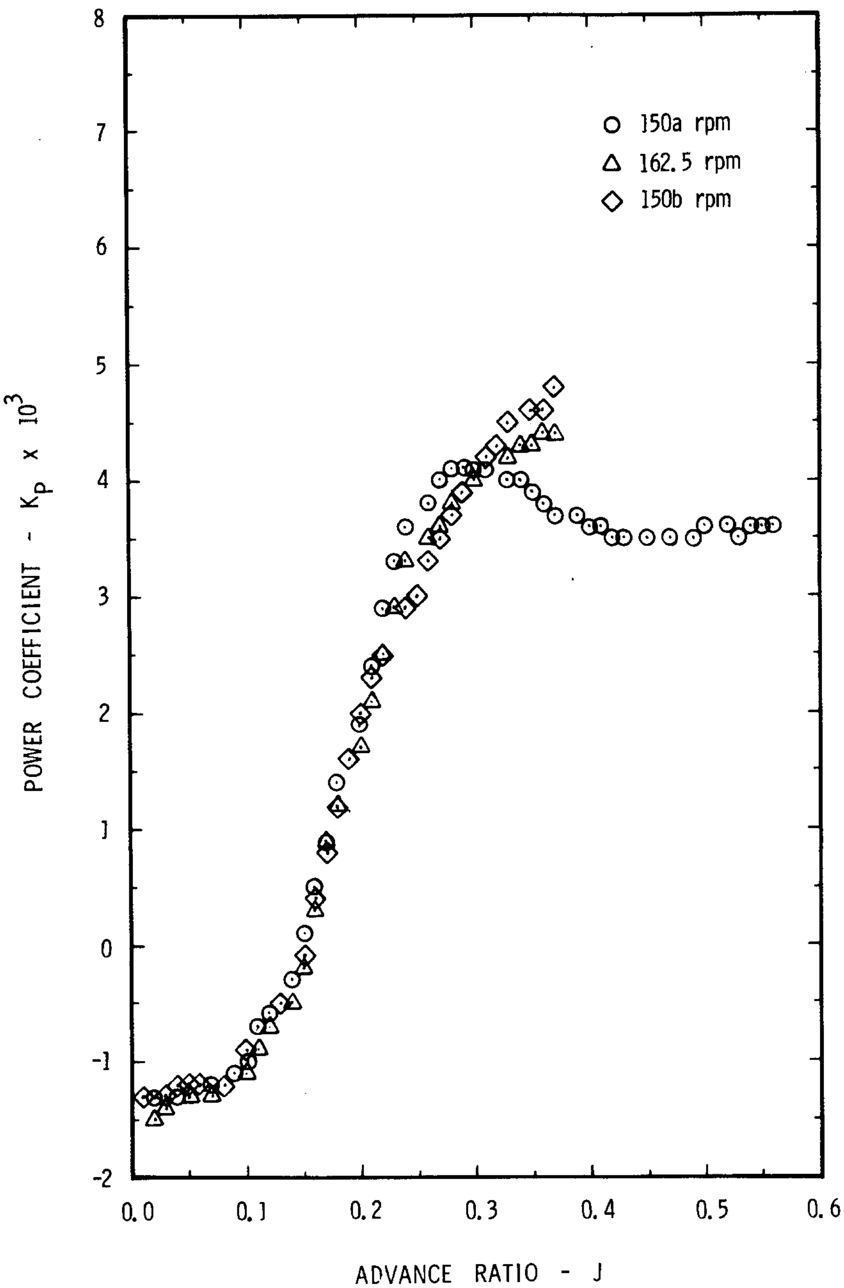

Figure 10. K_p Performance Data of the 5-Metre Turbine at 150a, 162.5, and 150b rpm.

As was mentioned previously, the minicomputer was programmed to accept wind speed data from as many as three anemometers simultaneously. This capability was used extensively. In Figure 5, two of the anemometers are shown; one is 2-metres above the turbine and the second is at the turbine equator height located two turbine diameters south of the turbine axis. The third anemometer that was used is located on the meteorological tower approximately 20 turbine diameters to the west. No satisfactory data correlation was obtained from the third anemometer primarily because of the distance between the turbine and anemometer. All data presented thus far has used the anemometer located on the fence at the turbine equator height. Figure 11 shows a comparison of the data for the two anemometers. It is immediately apparent that the top anemometer is being affected by the turbine. As the tip speed ratio increases, the turbine begins to look more like a solid barrier to the air and more of the air simply accelerates around it causing the top anemometer to indicate a higher wind velocity. This translates to reduced power coefficients. The anemometer on the fence is located sufficiently far away so the influence of the turbine, assuming an east or west wind, is less than 1% of the anemometer indicated wind speed. Figure 12 presents the same information as Figure 11 except it is for the 162.5-rpm data set.

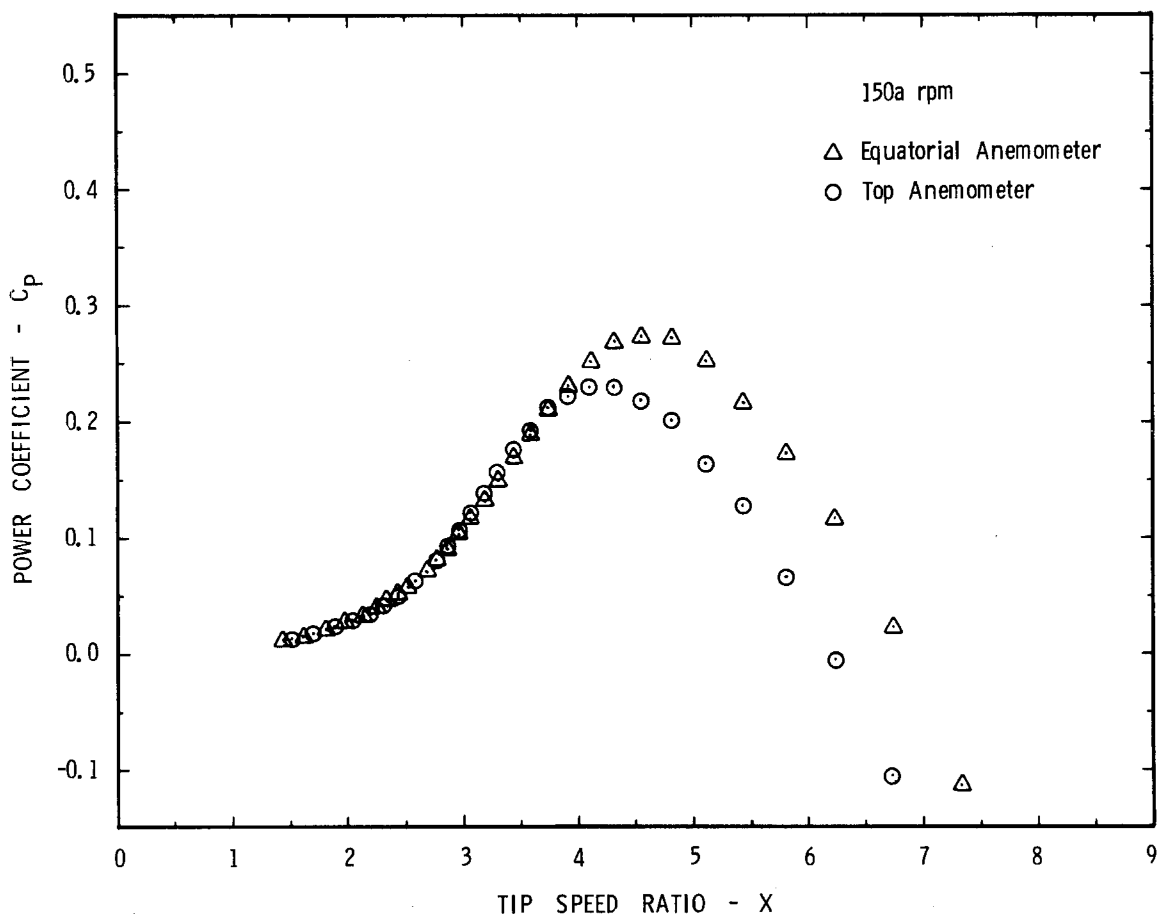

Figure 11. A Comparison of the 150a rpm C_p Data Between the Equatorial and Top Anemometers.

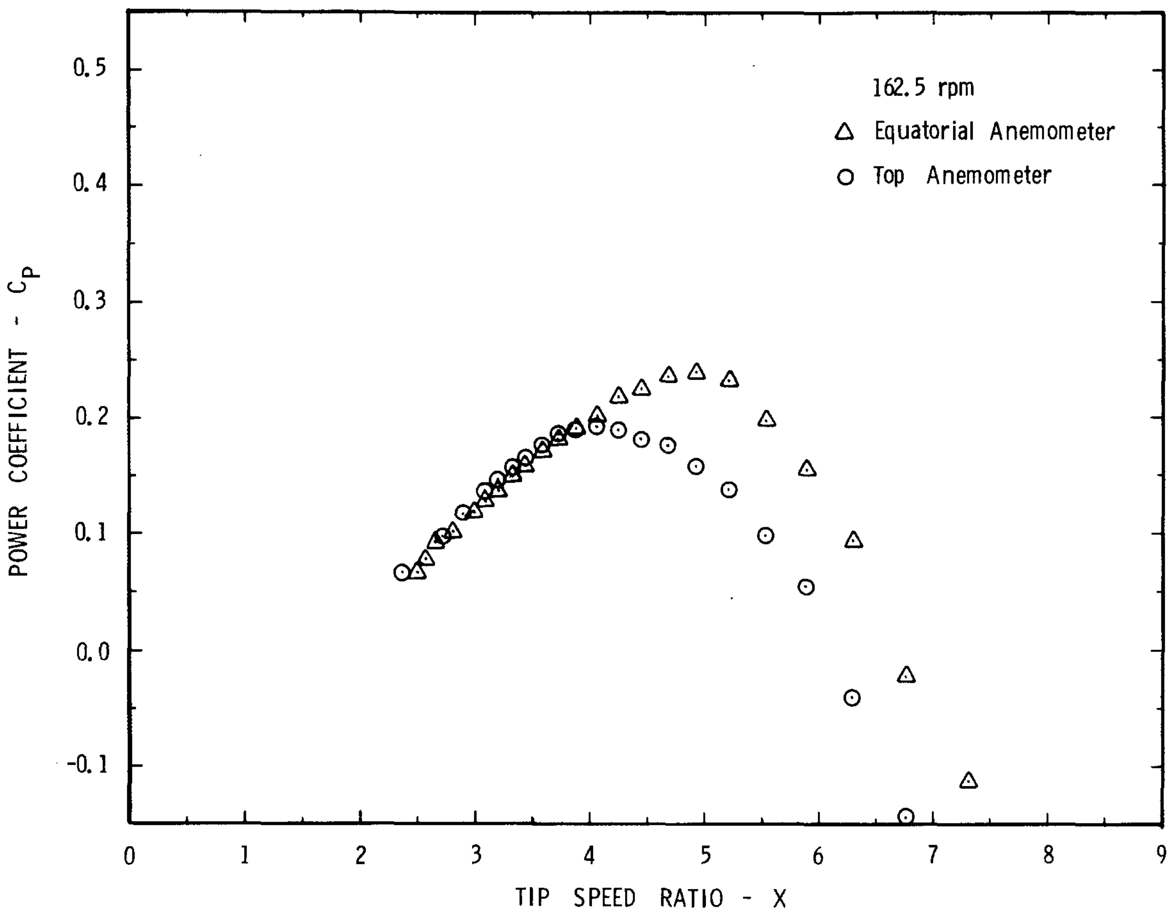

Figure 12. A Comparison of the 162.5 rpm C_p Data Between the Equatorial and Top Anemometers.

When the power coefficient, K_p, is examined for the two anemometers, the large discrepancy is not obvious as shown in Figure 13. This indicates that when the accuracy of the wind velocity is in question, the power coefficient, K_p, for constant rotational speed may be the better indicator to use in assessing a turbine's performance. Also, when two or more turbines are compared, where there is some doubt about the accuracy of the wind measurement, K_p would be the better criteria for making the comparison.

The question of why the 5-metre performance data are lower than expected based upon wind tunnel data and theoretical modeling is still unanswered. In Figure 14, the best 5-metre turbine data (150a rpm) are compared to two computed power coefficient, C_p, curves. As noted previously, the three-section blades of the 5-metre turbine incorporate straight sections which are of rolled steel and not airfoil sections. In the analysis, these sections were assumed to have aerodynamic section characteristics similar to flat plates which have substantially higher drag coefficients than the NACA-0012 airfoil sections. Curve 1 shown in the figure is obtained from the multiple streamtube model[6] with empirical additions based upon wind tunnel results[5] using NACA-0012 airfoil section data for the curved blades and flat plate section data for the straight sections. The calculated C_p curve is similar to but differs from the 5-metre turbine data. Curve 2 shows the anticipated performance of the 5-metre turbine if the blades were airfoils from hub-to-hub.

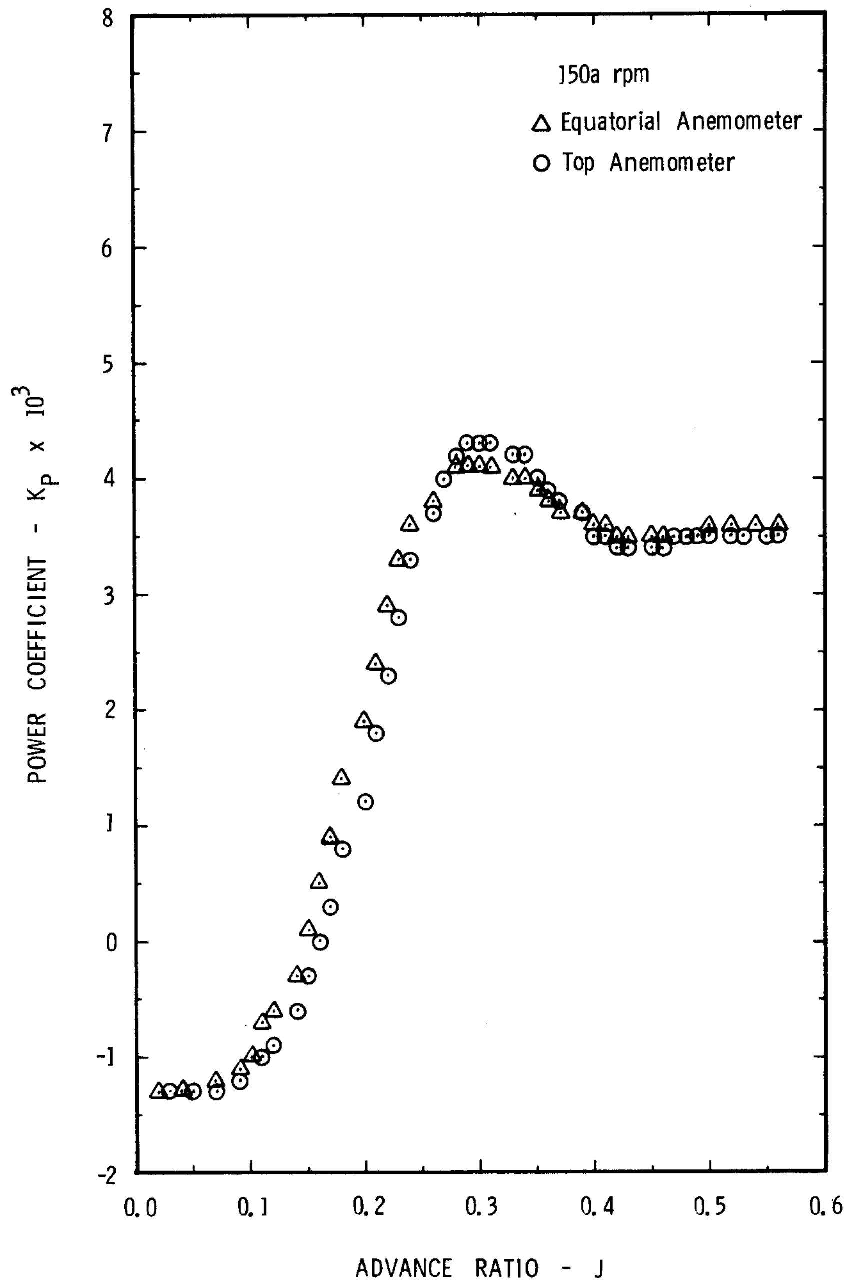

Figure 13. A Comparison of the 150a rpm K_p Data Between the Equatorial and Top Anemometers.

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 calculated. Under the no wind condition, the blades are always operating at zero degree angle-of-attack. Figure 15 shows a comparison of the calculated C_{d_o}'s for the 5-metre turbine, 2-metre turbine, and the zero angle-of-attack drag coefficients for the NACA-0012 airfoil section. The 2-metre model with continuous (hub-to-hub) airfoil blades approaches the value for the NACA-0012 section data, while the C_{d_o}'s for the 5-metre turbine are greater by almost a factor of two. This indicates that there are large differences in the blades between the 5- and 2-metre turbines. It is believed that the difference is primarily caused by the "high drag" straight sections.

Conclusions

The performance data for the 5-metre turbine obtained with the aid of a minicomputer and the computer program BINS shows the performance to be lower than anticipated from previous wind tunnel test results on a 2-metre turbine and also lower than theoretical computer calculations. A computer analysis, Figure 14, shows that the turbine performance is degraded significantly by the straight sections of the blades which are not of airfoil cross section. The zero wind drag coefficients, Figure 15, also indicate that the blades of the 5-metre turbine have a much higher drag coefficient than anticipated. Based on this, the performance data presented here should not be considered to be representative of vertical-axis wind turbines with blades which are of airfoil cross section from hub-to-hub. Future tests of this 5-metre turbine will be conducted with such blades.

In addition to the degradation of the performance caused by the straight sections, the data collection methods may also cause the power coefficients, C_p, to be suppressed below their actual values. The BINS program is, at the present time, the only method by which reasonable performance information has been obtained. There are problems with this technique which are not related to the BINS program but to the anemometry during gusty wind conditions. The anemometers are much smaller than the turbine and are very responsive. They respond to a small volume of air moving past them while the turbine must respond to a much larger volume of air which may not be moving at a uniform velocity. This can lead to errors in recorded wind velocity since the anemometer may not be responding to the same wind velocity which the turbine is responding to. The anemometer also responds faster to increasing wind speeds than to decreasing wind speeds with the net result on the average being a higher indicated wind speed than the actual average. It has been shown in Figures 11 and 12 that anemometer location can have a large effect on the turbine performance data. The anemometer must be far enough from the turbine to be unaffected by the wind speeding up to go around the turbine at higher tip speed ratios and yet close enough to be exposed to the same wind velocity and time variations in the wind as the turbine. Under gusty conditions, it may not be feasible to satisfy both requirements for anemometer placement.

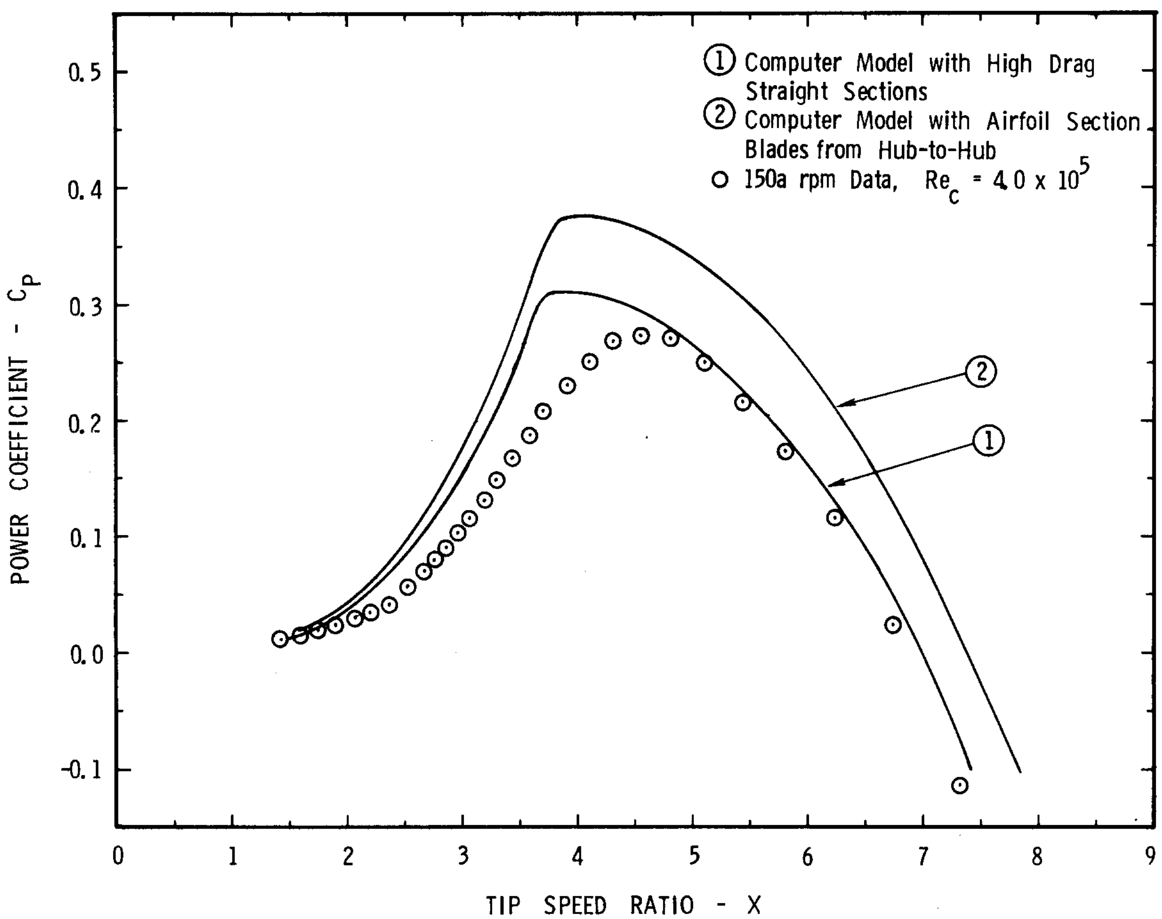

Figure 14. The 150a rpm 5-Metre Turbine Data Compared with Theory.

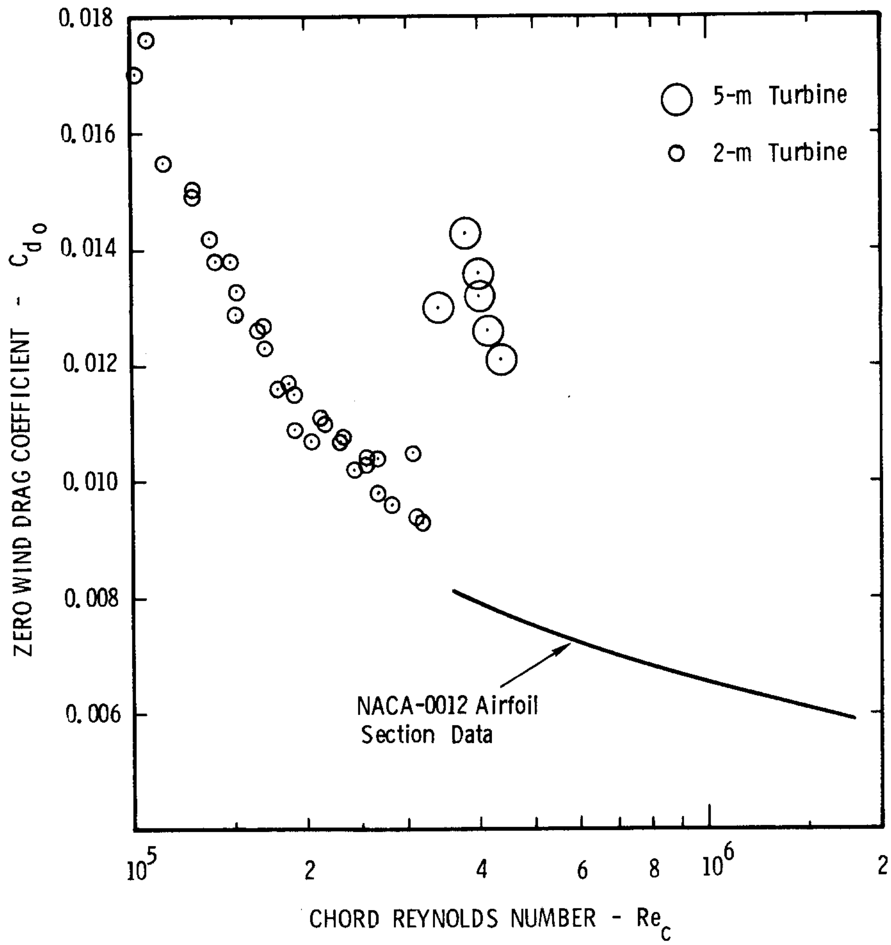

Figure 15. The Zero Wind Drag Coefficient Data of the 5-Metre Turbine Compared with the 2-Metre Turbine and NACA-0012 Airfoil Section Data.

The turbine is held at "nearly" constant rotational speeds; however, slip in the induction machine will allow approximately a ±1-rpm variation of the turbine rotational speed. Any rapid change in the wind velocity will cause a slight change in rotational velocity; thus the inertia of the turbine will affect the torque transducer output. The statistical averaging of the data by the BINS program is assumed to average out inertial effects.

The BINS computer code and the anemometry methods are being reexamined. It is anticipated that the data collecting techniques can be improved to give truer turbine performance data. The 5-metre turbine has demonstrated its present capability and has successfully performed its role as a proof-of-concept machine. Future testing of the turbine will be performed with blades which have an airfoil cross section from hub-to-hub. A 20% or greater increase in performance is expected with the new blades.

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