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Abstract

A 2-m-dia Darrieus Vertical Axis Wind Turbine with NACA-0012 blades was extensively tested in the Vought Corporation Low Speed Wind Tunnel. This same turbine was installed in the field at the Sandia National Laboratories Wind Turbine Test Site and operated to determine if field data corresponded to data obtained in the wind tunnel. It is believed that the accuracy of the wind tunnel test data was verified and thus the credibility of that data base was further established.

Acknowledgment

The efforts of the personnel in Sandia National Laboratories' Advanced Energy Projects Division are greatly appreciated.

Nomenclature

A_s	Turbine swept area
c	Blade chord length
C_p	Power Coefficient, $\frac{Q\omega}{\frac{1}{2}\rho_\infty V_\infty^3 A_s}$
J	Advance ratio, $\frac{V_\infty}{R\omega}$
K_p	Performance coefficient, $\frac{Q\omega}{\frac{1}{2}\rho_\infty A_s (R\omega)^3}$
L	Blade length
N	Number of blades
Q	Turbine aerodynamic torque
R	Turbine maximum radius
Re_c	Chord Reynolds number, $\frac{\rho_\infty R\omega c}{\mu_\infty}$
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, $\frac{NcL}{A_s}$

Comparison of Field and Wind Tunnel Darrieus Wind Turbine Data

Introduction

A 2-m-dia Darrieus Vertical Axis Wind Turbine with NACA-0012 airfoil blades was extensively tested in the Vought Corporation Low Speed Wind Tunnel.[1,2] The data obtained from these tests were used as the data base for the development of other turbines. Concern about the applicability of wind-tunnel data, obtained under ideal conditions, to turbines operating in the field precipitated the installation of the wind-tunnel model in the field at the Sandia National Laboratories Wind Turbine Site. The 2-m turbine was operated for a limited amount of time to determine if field data corresponded to data obtained in the wind tunnel. The results of this direct comparison are presented.

Test Model and Facilities

Figure 1 shows a downstream view of the 2-m-dia model in the 4.6- x 6.1-m (15- x 20-ft) wind-tunnel test section. Controls for both the wind turbine and the wind tunnel are located behind the windows shown on the right side of the figure. The turbine blades attached to the rotating tower were machined from a high-strength aluminum alloy (7075-T6) to the NACA-0012 airfoil section as a flat ribbon and then formed to the curved shape. The shape is a straight line/circular arc approximation of the troposkien.[1,2] The height of the turbine blades is 2 m (distance between upper and lower virtual intersections of the blades with the turbine axis), with a maximum radius at the equator of 0.98 m.

The rotating tower is attached to the power and instrumentation train that consists of a precision torque and rotation transducer, a right-angle gear transmission with a 2:1 gear ratio, and a speed-controlled 3.7 kW (5-hp) electric motor/generator. The 2:1 gearbox allowed a better match between the wind turbine and the motor/generator load characteristics. The motor/generator speed was controlled by a Morse LTV-5 ac adjustable speed controller. This same 2-m system was later installed at the Wind Turbine Test Site at Sandia Laboratories (Figure 2). The 2-m turbine, standing in the foreground, shares the test site with the Sandia 5-m and 17-m turbines and suitable anemometry for each turbine. The controls and instrumentation for the turbines are located in a nearby control building[3,4] that also houses a minicomputer and recording system to reduce the raw data to usable form and record the data for future use.

Testing and Data Acquisition

The test procedures in the wind tunnel were conventional.[1,2] The turbine was rotated at a rotational speed which was determined and controlled by the speed controller. The wind velocity was adjusted to a predetermined value; the steady-state turbine torque was measured and recorded along with the wind-tunnel conditions and turbine-rotational speed. This defined one data point. The procedure was repeated with new wind speeds until sufficient steady-state data points were obtained to define the performance of the turbine (Figures 3 and 4).

The testing of turbines in the field offers problems not usually encountered in wind-tunnel testing. In particular, although the turbine rotational speed can be held constant by the speed controller, the atmospheric wind speed seldom remains constant for any appreciable length of time. Consequently, it is difficult to assign an appropirate wind velocity corresponding to a given torque measurement. Computer code BINS,[5] which uses the "method of bins" to statistically average the wind speed and torque data, was developed to assist the data acquisition. The

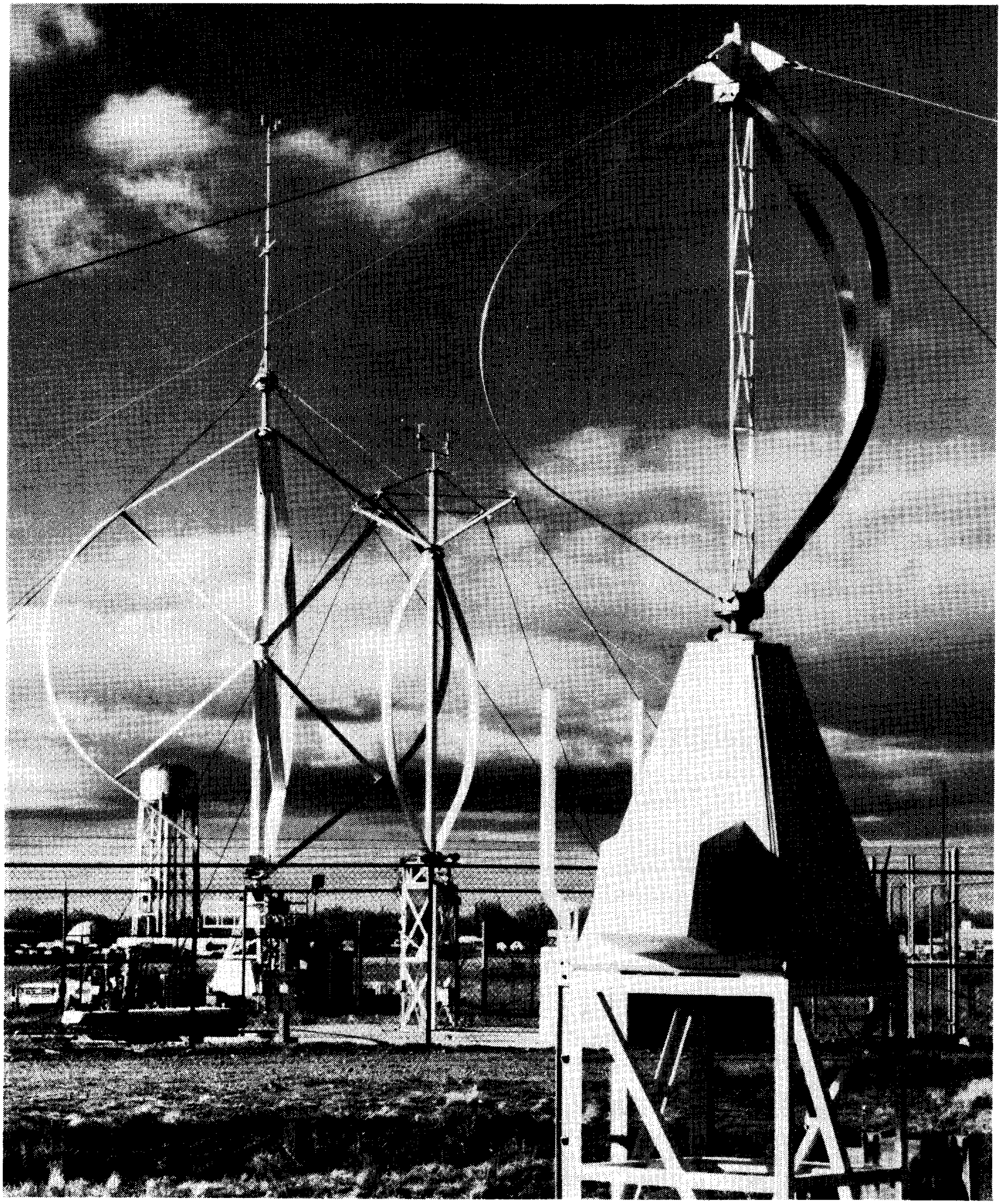

Figure 1. Photograph of 2-m Model in Wind Tunnel.

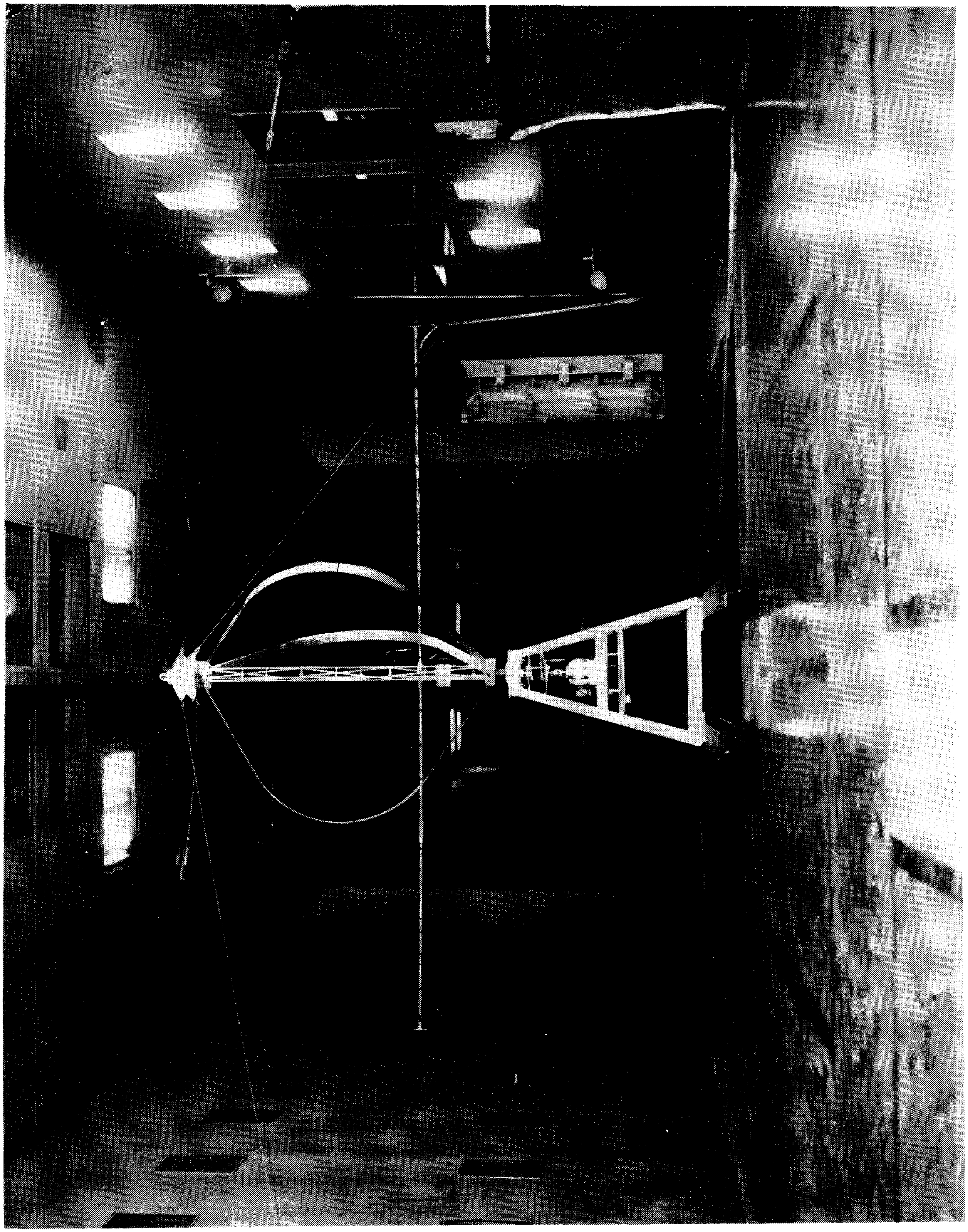

Figure 2. Photograph of 2-m Model at the Sandia Laboratories Wind Turbine Test Site.

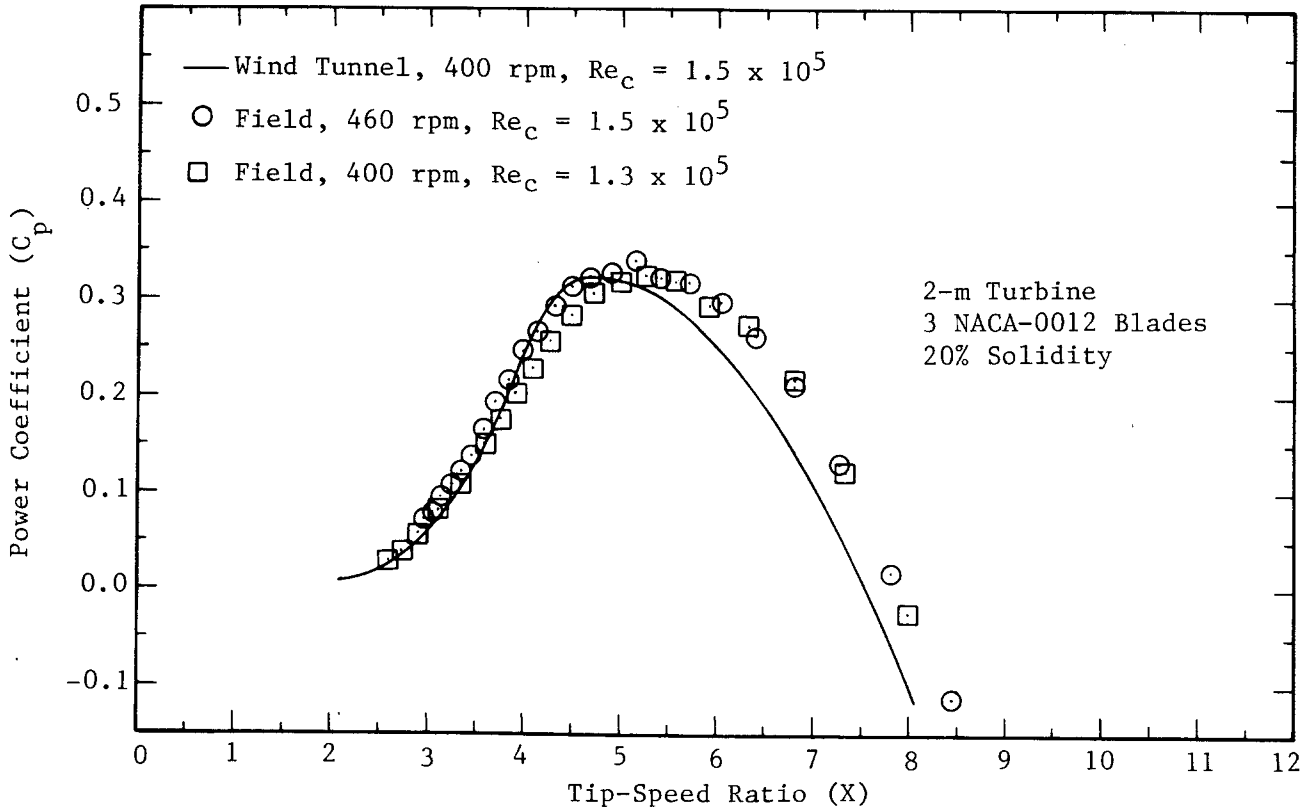

Figure 3. Comparison of Power Coefficients for the 2-m Turbine in the Field and Wind Tunnel.

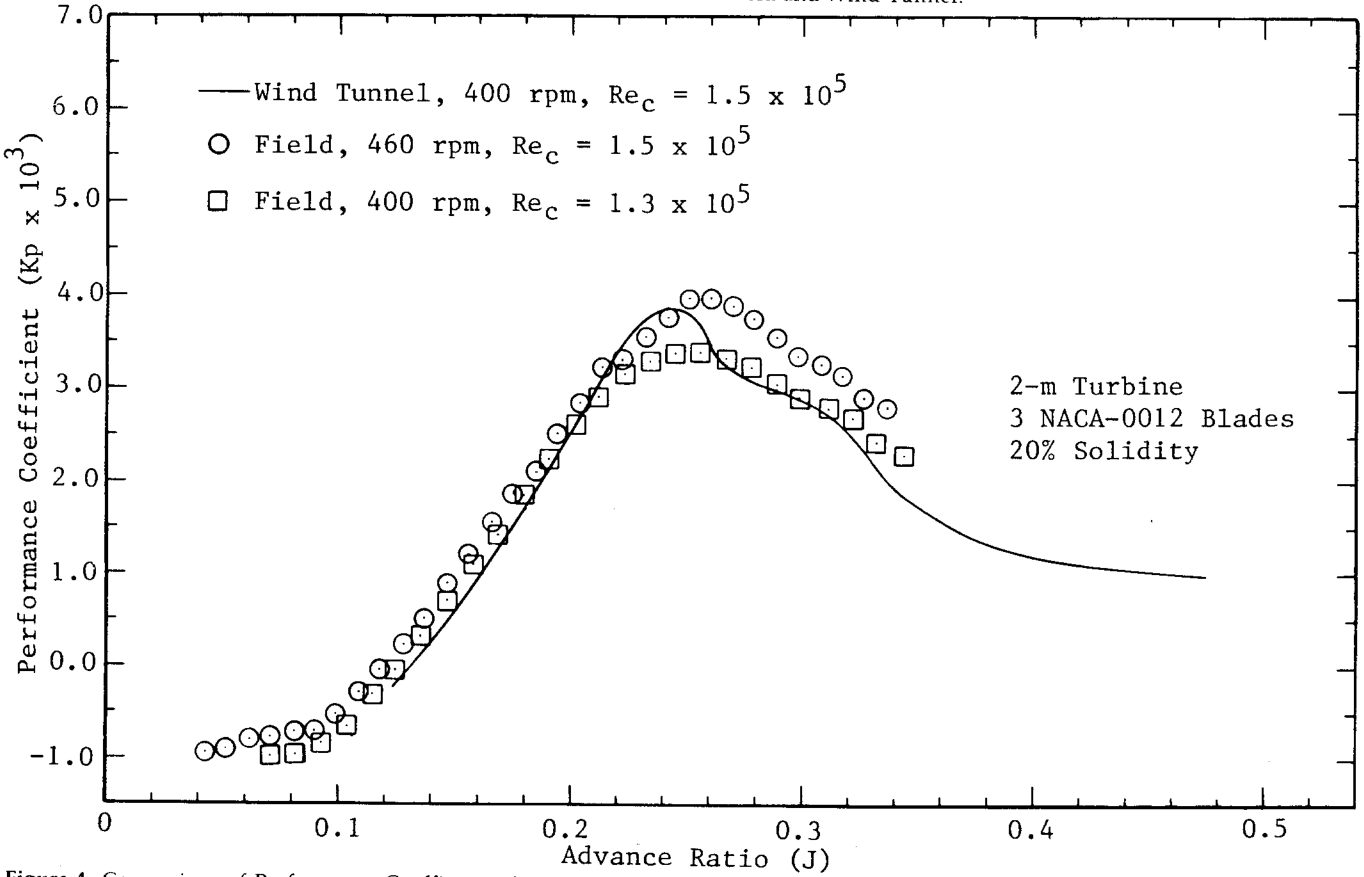

Figure 4. Comparison of Performance Coefficients for the 2-m Turbine in the Field and Wind Tunnel.

wind speed and torque are recorded at sample rates chosen by the operator, generally from 1 to 20 data samples per second. 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 gear losses.

Data are taken when winds are available, so a test may be a few minutes long or extend past an hour. These tests were performed on a day-to-day basis; the end result was a large amount of data taken for a wide range of wind conditions over many days. These data for a given rotational speed 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; the results of the summed data records are presented in the form of power coefficient as a function of tip-speed ratio and performance coefficient as a function of advance ratio.

The 2-m turbine was configured in the field with three blades (chord length = 5.877 cm) producing a solidity of 20%. This initial configuration was chosen because 40% of the data obtained in the wind tunnel were with a turbine solidity of 20%. Two anemometers were placed near the turbine at equator height and at a sufficient distance from the turbine (two turbine diameters) to minimize the effect of potential flow about the turbine and yet close enough to measure accurately the wind velocity in the vicinity of the turbine.[6]

Results and Discussion

The data obtained from tests of the 2-m turbine in the wind tunnel and in the field are presented in the form of power coefficient, C_p, as a function of tip-speed ratio, X (Figure 3). The power coefficient is a standard measure of the turbine's performance. The data also are presented in the form of performance coefficient, K_p, as a function of advance ratio, J (Figure 4). This performance coefficient also is a power coefficient, where the wind velocity of the power coefficient, C_p, has been replaced by the blade equatorial velocity. The performance coefficient was developed for three reasons: (1) K_p shows that power reaches a maximum at a particular value of J (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 turbine was initially operated in the field at a rotational speed of 460 rpm with three blades (5.877-cm chord) and a solidity of 20% to produce a chord Reynolds number (Re_c) of 1.5×10^5. These data are compared with the wind-tunnel data obtained with the identical configuration and Re_c but with a rotational speed of 400 rpm. The difference in rotational speeds required to match the Re_c was due to differences in test conditions between the wind tunnel and the wind turbine test site. Following the acquisition of the 460-rpm data in the field, the rotational speed was lowered to 400 rpm to match the rotational speed of the turbine when it was in the wind tunnel. The Re_c was thus lowered to 1.3×10^5. These two sets of field data are presented and compared with the wind-tunnel data in Figures 3 and 4. The maximum value of C_p for the wind-tunnel data was 0.32 at $X = 4.70$ which compares to 0.34 at $X = 5.15$ for 460 rpm and 0.32 at $X = 5.25$ for 400 rpm in the field. The field data in Figure 3 shows improved performance (larger values of C_p) over the wind-tunnel data for tip-speed ratios greater than 5 (lower wind speeds). This may be a result of the blockage correction factor used to correct the wind-tunnel velocity due to model solid and wake blockage or it may be a real difference between wind-tunnel and field-turbine performance.

As mentioned previously, K_p with its reduced dependency on the wind velocity is an attractive coefficient with which to compare turbine performance. The K_p as a function of the advance ratio is shown in Figure 4. The maximum value of K_p for the wind tunnel is approximately 3.8×10^{-3} at $J = 0.24$ which compares to 4.0×10^{-3} at $J = 0.25$ for 460 rpm and 3.4×10^{-3} at $J = 0.25$ for 400 rpm in the field. Note the close agreement in $K_{p_{max}}$ values for the wind-tunnel data and 460-rpm field data when both are obtained at a Re_c of 1.5×10^5. The 400-rpm field data exhibit a slightly lower $K_{p_{max}}$ with its slightly lower Re_c. Note also the good agreement of K_p for J less than 0.25 (low wind speeds), with the field data slightly higher than the wind-tunnel data. It was concluded that the performance of the 2-m turbine in the wind tunnel was accurate for this operating condition, and there was no reason to expect that the results for other operating conditions would not be the same. Testing of the 2-m turbine for the purpose of direct data comparisons therefore was terminated.

Conclusions

The 2-m-dia Darrieus Vertical Axis Wind Turbine was tested in the field at the Sandia National Laboratories Wind Turbine Site for a limited number of conditions to make a direct comparison with the data obtained previously with the same identically configured turbine in a wind tunnel. One comparison with the wind-tunnel data was made with field data of equivalent Re_c. A second comparison was made at an equivalent rotational speed. The maximum values of the power coefficients compared very favorably; the $C_{p_{max}}$ for the wind tunnel was 0.32, and the $C_{p_{max}}$ of the field data at equivalent Re_c (1.5×10^5) was 0.34. The slight difference is within the experimental accuracy of the measurements. The second set of field data at equivalent rotational speed (400 rpm) shows identical values for $C_{p_{max}}$. It is believed that comparisons should be made on the basis of equivalent Re_c; however, the equivalent rotational speed was included for completeness. The field data show improved (higher) values of C_p over the wind-tunnel data for tip-speed ratios in excess of 5.0. This may be due to the blockage correction factor used to correct the wind-tunnel velocity or it may be a real difference (although slight) between wind-tunnel and field-turbine performance.

An examination of performance coefficients which do not have the cubed dependence on wind speed shows again the excellent agreement between the wind tunnel and field data. The value of $K_{p_{max}}$ from the wind-tunnel test was 3.8×10^{-3} whereas $K_{p_{max}}$ for the equivalent Re_c in the field was 4.0×10^{-3}. $K_{p_{max}}$ for the equivalent rotational speed was 3.4×10^{-3}. This lower value of performance coefficient was expected because it was obtained with the turbine operating at a lower Re_c.

Field testing of the 2-m turbine for direct data comparison was terminated due to the excellent agreement of the first two field-data sets with the wind-tunnel data. It is believed that the accuracy of the wind-tunnel test data was verified and the credibility of that data base was further established.

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