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Wind Characteristics for Field Testing of Wind Energy Conversion Systems

Robert E. Akins

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WIND CHARACTERISTICS FOR FIELD TESTING OF WIND ENERGY CONVERSION SYSTEMS

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ABSTRACT

Techniques are presented to determine placement of instrumentation to be used in measurement of wind characteristics for field testing of Wind Energy Conversion Systems (WECS). Potential errors in the measurement of a reference wind velocity as a result of physical separation between an anemometer and a WECS and interference between the WECS and the reference anemometer are outlined. Methods of correcting errors caused by both of these sources are developed.

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1. INTRODUCTION

The successful commercial development of wind energy conversion systems (WECS) is dependent upon accurate prediction of their performance. However, because present techniques [1] involve many simplifications, there is a definite need to verify WECS performance predictions with field measurements. Such measurements are of interest both to researchers in order to verify analysis techniques and to manufacturers in order to ensure that their products will perform as advertised. An important part of such field measurements is the determination of the wind characteristics (e.g. wind speed, wind direction, density of the air) which must be utilized in order to measure performance. Such field measurements are difficult to make because of rapid variations of both wind speed and direction. These variations require careful interpretation of wind characteristics used in WECS performance measurements.

Two separate but important aspects of performance measurement are: the establishment and verification of the performance of a particular WECS. For a production system the manufacturer can <u>establish</u> performance using a prototype version. As a part of the development effort of the Federal Wind Energy Program, establishment of performance of some WECS is being conducted by groups involved in the development of technologies which will be later utilized by private industry [2-4]. The establishment of the performance of a particular WECS requires careful measurement of the wind characteristics very close to the location of the turbine.

Verification of performance would normally be of interest to a utility, a farmer or a home owner who has purchased a WECS and is interested in verifying that the system is performing as predicted. The wind characteristics that must be measured to verify performance are less complicated and require less sophisticated equipment than the wind characteristics required for establishing performance.

While there is interplay between the wind characteristics used for performance evaluation and the corresponding measure of WECS output (e.g. output power or energy produced) this report will focus on the wind characteristics that must be utilized in performance evaluation and verification.

The following sections explain the need for a reference velocity measurement, factors that could introduce errors in the reference velocity, methods for reducing errors in the reference velocity, instrument selection, and additional measurements of wind characteristics necessary for performance evaluation.

II. REFERENCE WIND VELOCITY MEASUREMENT

A common method for specifying WECS performance provides a plot of output in KW as a function of wind speed. This wind speed, a scalar, is often specified at the hub height of a horizontal-axis WECS or at the centerline (or equator) of a vertical-axis WECS. Such a point measurement is a convenient reference that corresponds with the form of most existing meteorological records. Because of vertical wind shear and temporal variation of wind velocity, such a point measurement is

not an exact measure of the instantaneous wind speed experienced over the entire WECS. A recent program involving field measurements and associated analysis has indicated that the use of a point measurement on the average introduces very little error [5]. However, an instantaneous point measurement can vary significantly from the instantaneous spatially averaged speed over the swept area of a WECS. In an actual situation, the WECS disturbs the flow field when it is operating, and neither a point measurement nor a spatial average measurement can be made that will correspond to the WECS location. Most aerodynamic models for predicting performance of WECS also use a reference wind speed measured at hub or equator height [6, 7].

The use of a reference wind speed, a scalar quantity, instead of a reference wind velocity, a vector quantity with both a magnitude and direction, requires some explanation. A wind speed can be measured with an inexpensive instrument and the interpretation of a wind speed record is straightforward. However, the performance of some WECS is dependent on relative wind direction as well as wind speed. This situation corresponds to a WECS that must yaw into the wind for maximum performance and that has a relatively slow yaw rate. Such a WECS would not always be in an optimum position and the incident wind velocity normal to the WECS will at times be less than the ambient wind speed. For this condition, performance prediction using aerodynamic models and a measured wind speed could overpredict WECS output.

There are two approaches to dealing with the problem of an incident velocity which is not normal to the plane of a WECS.

The first would be to specify the performance of the WECS as a function of wind speed only. Any effect as a result of misalignment of the WECS in the incident wind would be included in the performance specification. Such an approach would only require a measurement of a reference wind speed. Performance specifications in terms of a reference wind speed could be combined with existing long-term climatological records to provide estimates of annual output of a particular WECS.

The second approach would be to specify the performance of a WECS as a function of the component of the incident wind velocity normal to a reference plane. In the case of a conventional horizontal-axis WECS, this reference plane would be the plane in which the blades rotate. This measurement of the normal component would be more complicated than measurement of a wind speed, but in some cases it may be more appropriate. Data reduction using the normal-component approach would require a more sophisticated technique than the wind-speed approach because both an instantaneous orientation of the WECS and wind direction would have to be monitored in addition to wind speed. The decision to use one of these approaches will be made by the organization establishing the performance of a particular WECS. Once an approach has been selected to define performance, any measurement made to verify that performance should use the same technique of measuring a reference wind speed or velocity as was used in the establishment of performance.

In the remainder of this report, the term "reference velocity" will be used to indicate a measurement of wind velocity or wind speed used in specifying performance.

III. FACTORS THAT AFFECT THE REFERENCE VELOCITY

Two major sources of error result from the placement of an instrument used to determine reference velocity. The first is caused by the physical separation between the instrument and the WECS. Because of the random nature of turbulent fluctuation in the atmosphere, the time history of velocity at two different locations will be different. In some instances statistical measures, such as the mean and standard deviation of velocity, may be equal at two different locations, but instantaneous velocity fluctuations may show very little correlation. The second source of error is the potential modification of the incident flow field by the presence of an operating WECS. This effect is similar to that caused by flow around a fixed obstacle. Such a flow results in some regions of increased velocity and other regions of decreased velocity.

Physical separation between a WECS and an instrument used to establish a reference velocity is unfortunately necessary. Yet ideally, the reference velocity is the velocity which would be measured at the location of the WECS if the WECS were not present. The exact measurement of such an instantaneous reference velocity is impossible. Any choice of location for a reference anemometer will introduce some error into the measurement. The reference anemometer and the center of the WECS may be separated

in both horizontal and vertical directions. A vertical separation occurs when a reference anemometer is mounted either above or below a WECS on the same tower. If there is no interference between the WECS and the reference anemometer, a vertical separation will introduce an error in the mean reference velocity because of wind shear. It is possible to correct for the wind shear in time-averaged velocity measurements, although the correction will not be exact for instantaneous measurements, for time-averaged values for less than a period of approximately one minute, or for long-term averages.

In most instances, a horizontal separation between the center of a WECS and reference anemometer will not introduce significant error into the time-averaged or mean velocity measurement. However, if the horizontal separation is large (greater than 500 m), or if the exposure at the two locations is different because of trees, buildings, or topographical features, a substantial difference may occur in the mean reference velocity measured at the two locations.

The direction of horizontal separation of a reference instrument from a WECS is important. In general, an upwind placement is desirable with the reference anemometer far enough upwind to be clear of any interference from the WECS. Because a reference anemometer must be mounted on some sort of tower, the physical location of the reference anemometer must be fixed relative to the WECS. Therefore, in some instances the reference anemometer will be upwind, in some cases it will be acrosswind, and in some cases it will actually be downwind

of the WECS. The validity of the data will vary as a function of wind direction. For a downwind location, the reference anemometer could be in the wake of the WECS. Measured reference velocities may be of limited value in this case.

If the WECS had no effect on the incident flow field when it was operating it would seem appropriate to place the reference anemometer as close as possible to the center of the WECS. Unfortunately, an operating WECS has a significant influence on the flow field in the vicinity of the WECS. In some regions this influence casues an increase in velocity while in other regions a decrease. A sketch of flow through and around an operating WECS is shown in Figure 1. The magnitude of the change in reference velocity is difficult to predict as a function of position. An integrated measure of the influence of the wind turbine on the flow field is the drag coefficient of the WECS. A drag coefficient is a non-dimensional method of expressing the drag or alongwind force on a WECS. The drag coefficient is defined:

$$C_D = \frac{D}{\frac{1}{2}\rho \; V_R^2 \; A} \tag{1}$$

where C_D is the drag coefficient

D is the drag force

ρ is the density of air

V_R is a reference velocity

A is a reference area, usually the swept area for a horizontal-axis WECS or the projected area for a vertical-axis WECS.

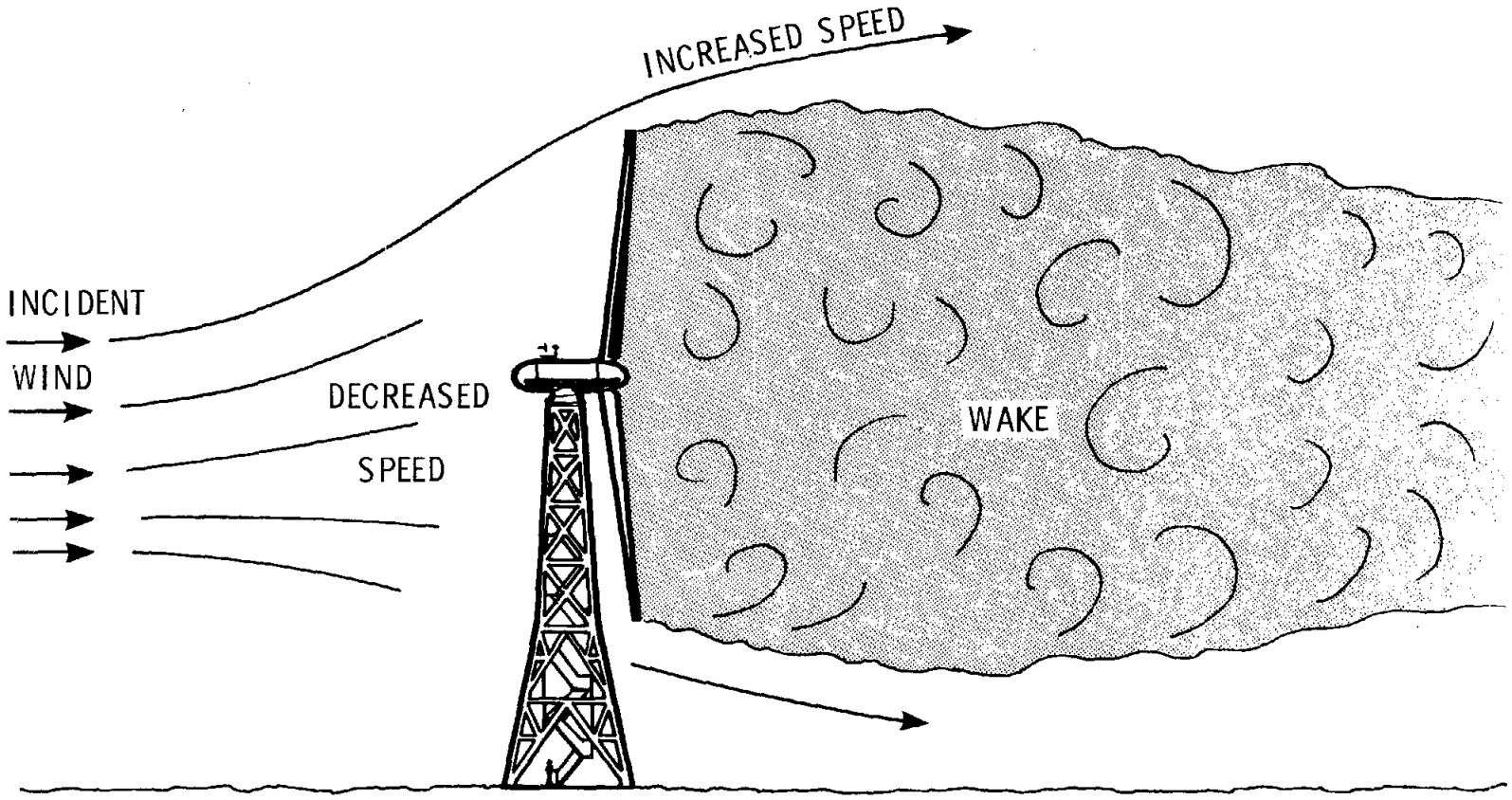


FIGURE 1. SCHEMATIC OF INTERACTION OF WECS WITH INCIDENT WIND FIELD.

The drag coefficient is a function of the operating condition of the WECS. For instance, for constant rpm operation, the drag coefficient is a function of the tip-speed ratio (ratio of the maximum speed of a blade to the reference velocity). At low tip-speed ratios the drag coefficient is relatively low; at high tip-speed ratios the drag coefficient increases. Physically this corresponds to the WECS turning at a faster rate and looking more like a solid body. Figure 2 is a plot of the drag coefficient for a Darrieus vertical-axis WECS for a number of different solidities (solidity is the ratio of blade chord area to swept area)[8]. The drag coefficient for a horizontal-axis WECS follows the same trends with tip-speed ratio. This wide variation in drag coefficient with tip-speed ratio means that the influence a WECS will have on velocity near the blades will also vary with tip-speed ratio. Any attempts to correct a reference anemometer to account for possible interference caused by the WECS would have to include a variation with tip-speed ratio. Such a correction would be very difficult to incorporate into a test procedure.

In summary, the two main factors which can create errors in a reference velocity measurement are the physical separation of the anemometer and the WECS and possible interference between the WECS and the reference anemometer. The following section describes methods of predicting these errors, and suggests methods for reducing these errors.

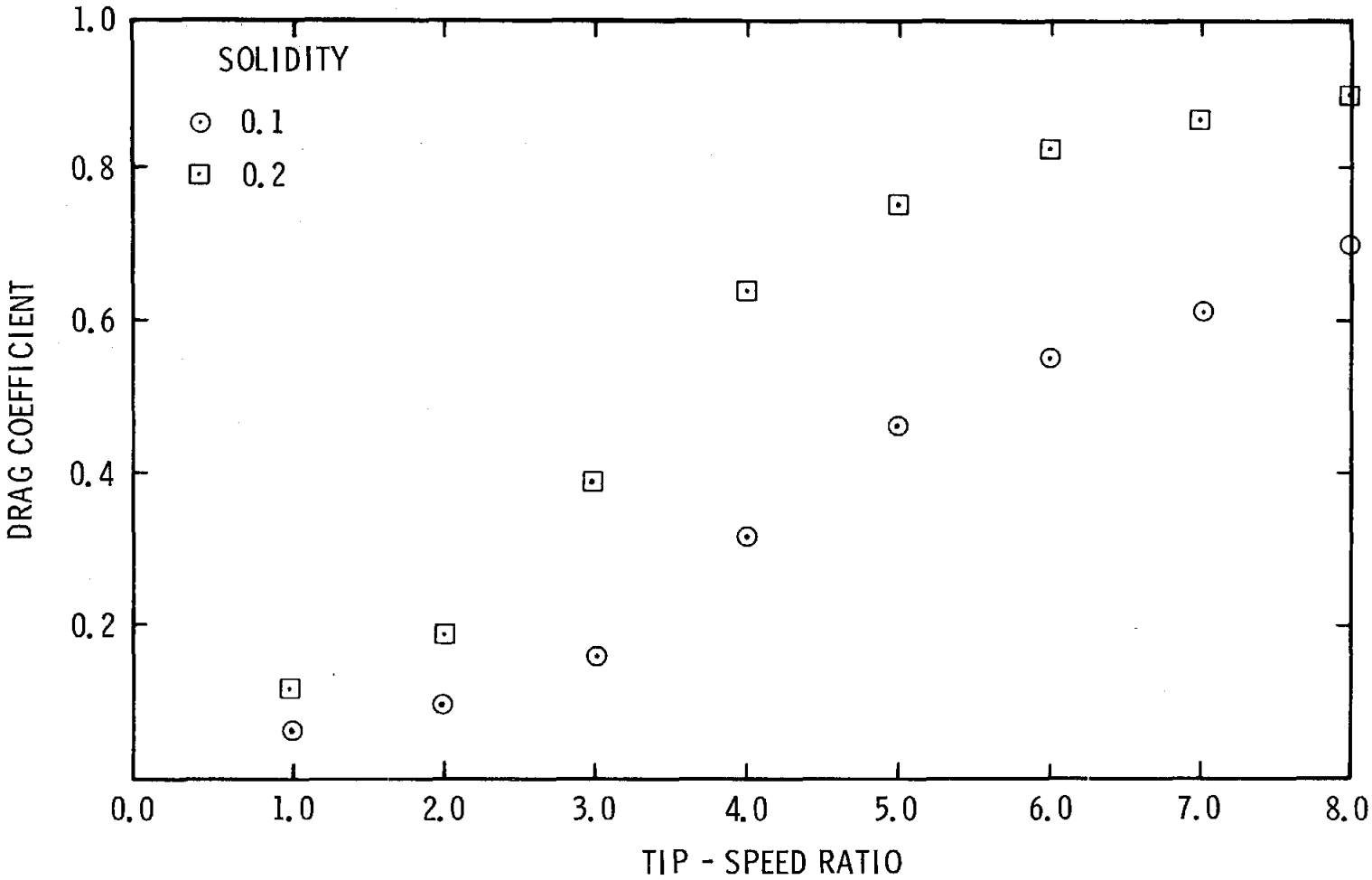


FIGURE 2. DRAG COEFFICIENT ON A DARRIEUS WIND TURBINE (9).

IV. METHODS OF ESTIMATING AND CORRECTING ERRORS IN MEASUREMENT OF A REFERENCE VELOCITY

With a basic understanding of the causes of error in a measured reference velocity, it is possible to develop techniques which may be used to both estimate and correct these errors. In considering techniques for correcting errors, it is important to recall the distinction between the establishment and the verification of performance for a WECS. The verification of performance requires less sophisticated equipment and allows much greater freedom in placing a reference anemometer than does the establishment of performance. This section deals separately with errors caused by physical separation and by interference, and addresses the needs of both verification and establishment for each source of error. As part of the discussion of correction methods, examples are provided when possible. These examples utilize measurements made at the DOE/Sandia VAWT test facility. These measurements were made in support of testing of the DOE/Sandia 17 meter VAWT.

ESTIMATING ERRORS CAUSED BY PHYSICAL SEPARATION

One method of estimating error in measurement of a reference velocity is to mount a separate anemometer at the centerline of the WECS and compare the readings from this instrument with those from the reference instrument. The location of the second instrument must be selected near the WECS in order to minimize any interference effects of the WECS or its supporting tower. Such a comparison would be accomplished with the WECS in a nonoperating or parked condition. The mean wind shear as

a function of height can be measured directly. Values from both anemometers can be averaged for periods of 5 minutes over a range of wind speed and direction. The ratio of these values can be used to obtain a shear correction that may be applied to the reading of the reference anemometer to correct it to the appropriate value at the centerline of the WECS. In most instances this correction would be a single ratio independent of wind speed or direction. The use of a single ratio will in most cases be an approximation. Conditions may occur which require the shear correction to be a function of either wind speed, or direction, or both. The setup for this measurement is shown in a diagram in Figure 3. The reference anemometer is shown mounted on a separate tower at an elevation Z_R. The elevation of the centerline of the WECS is Z_{CL}. There is a horizontal separation of X_s between the center of the WECS and the reference anemometer. The correction for the mean wind speed between elevations Z_R and Z_{CL} can be expressed as:

$$C = \frac{U(Z_{CL})}{U(Z_R)} \tag{2}$$

where C is the correction, and U(Z) is the mean wind speed for a period of 5 minutes. This correction C may be considered as $C(U,\theta)$ if a large variation is observed as a function of wind speed or direction.

One can also make use of a power-law expression for the variation of mean wind speed with height [9]. The power-law is

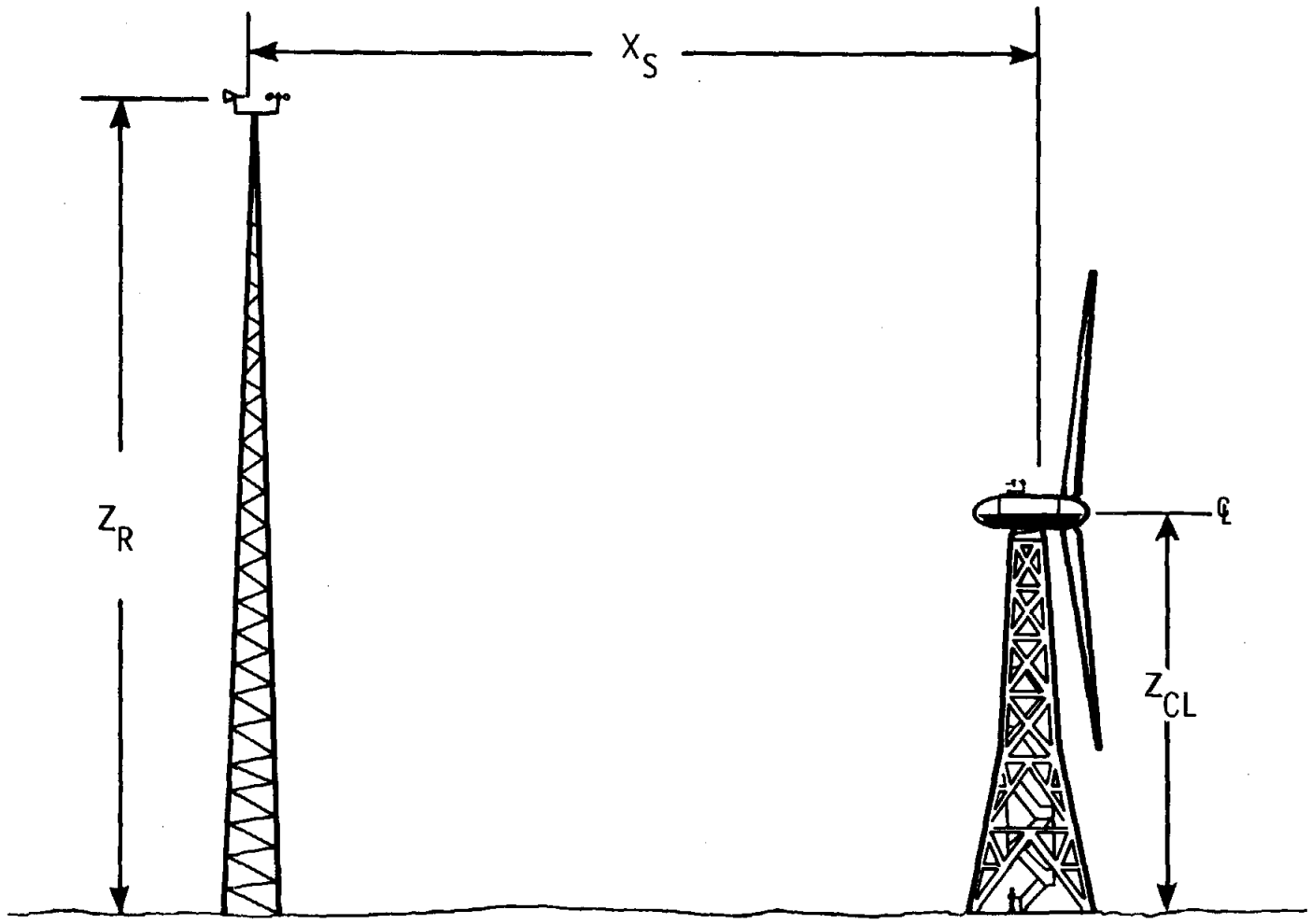


FIGURE 3. VERTICAL AND HORIZONTAL SEPARATION BETWEEN A WECS AND A REFERENCE ANEMOMETER.

$$\frac{U(Z_R)}{U(Z_{CL})} = \left(\frac{Z_R}{Z_{CL}}\right)^{\alpha} \tag{3}$$

where α is the exponent of the power-law. In combining Equations (2) and (3) the correction for a reference wind speed as a function of Z becomes:

$$C = \left(\frac{Z_{CL}}{Z_R}\right)^{\alpha} \tag{4}$$

If α is assumed constant for a particular location this expression is independent of wind speed and direction.

The preceding discussion assumes that a second anemometer may be mounted and that adequate instrumentation is available to make a simultaneous measurement of $U(Z_R)$ and $U(Z_{CL})$. If such resources are not available, a value of α may be selected, based on a physical description of the terrain in the vicinity of the WECS. Many methods of selecting α for different terrains exist [9, 10]. The scheme used in Ref. 10 is shown in Table 1. Use of this table or a comparable method should be approached with some caution. Local topography can have a significant effect on α. If a question exists in the estimation of α, limited field measurements may be necessary.

The second source of error caused by physical separation is the lack of correlation between wind speed fluctuations at physically separated locations. The physical separation can be in either the horizontal or vertical direction as indicated in Figure 3 by X_S and $Z_R - Z_{CL}$. The methods that exist for estimation of the cross-correlation coefficient for wind speed fluctuations are quite complicated. In

TABLE 1 - VALUES OF POWER-LAW EXPONENT FOR DIFFERENT TERRAINS (10)

TERRAIN DESCRIPTION	POWER-LAW EXPONENT
Large expanses of water, flat coastal areas with off-sea wind, desert	0.12
Flat or gently rolling open country with very few obstructions	0.15
Terrain with more numerous small obstructions such as hedges, trees and buildings	0.19
Terrain well covered by numerous obstructions (e.g. suburbs of large towns and cities)	0.26
Centers of large towns and cities with concentrations of large buildings	0.35

order to apply these methods, an advanced understanding of turbulent flows is required [11-13].

CORRECTING ERRORS CAUSED BY PHYSICAL SEPARATION - PERFORMANCE VERIFICATION

The most important measure of reference velocity used in performance verification is the probability density function (PDF) of the wind speed. The PDF describes the probability that the wind speed will assume a value within some defined range at any instant of time. For a fixed period of time, a year for instance, the PDF can provide the number of hours the wind can be expected to be between two fixed values. The PDF may be measured for any period of time, from 5 minutes to a year or longer. The verification of performance requires a knowledge of the output of a WECS as a function of wind speed, P(V), and a measured PDF of wind speed p(V). The output of the WECS during the period, t, in which p(V) is measured is given by,

$$\text{OUTPUT} = t\int_0^{V_{MAX}} P(V)p(V)dV, \tag{5}$$

where V_{MAX} is the cut-out speed limit. It may be assumed that P(V) is provided by the manufacturer of the WECS and the only measurement required to compute the energy produced by the WECS is the PDF, p(V).

The PDF is a statistical measure of wind speed variation, and for a fixed height it should not vary significantly over an area at least 1 km in diameter, provided there are no obstructions or nearby major topographic features. No error should

be introduced in the PDF due to horizontal separation between a reference anemometer and a WECS.

Vertical separation between the reference anemometer and the WECS centerline will introduce error in the reference velocity as a result of wind shear. Correction for wind shear may be made using equations (2) - (4) by two different methods. Instantaneous readings of reference wind velocity may be corrected for wind shear before a PDF is determined; or if one of the commercially available units is used to obtain the PDFs (these units are called wind speed compilators), the shear correction may be applied to the measured probability density. This correction is not exact and some error is introduced.

Corrections for vertical separation may be better understood if considered in connection with the methodology for determining a PDF. If a time series of N readings of wind speed,

$$V_i, \; i = 1, N \tag{6}$$

is taken at a particular site at equally spaced time intervals, the PDF may be obtained by separating the range of readings into 1 m/s increments. The number of readings in each increment is determined by examining each V_i and summing the number for each increment. Once this operation is completed, the number of readings in each increment is divided by the total number of readings, N, to obtain the PDF. When this procedure is used, the shear correction may be applied to the time series V_i prior to the determination of the PDF.

Figure 4 is an example of the PDFs obtained simultaneously at three separate locations (indicated by different symbols) in the same vicinity, but separated both horizontally and vertically. All have been corrected for wind shear to a common reference height. The readings were taken at 0.1 s intervals for 15 minutes. All three PDFs are similar.

CORRECTING ERRORS CAUSED BY PHYSICAL SEPARATION - PERFORMANCE ESTABLISHMENT

Error in reference velocity measurement caused by physical separation is more critical in performance establishment than in performance verification. This difference is due to the fact that in performance evaluation there is a need to know the instantaneous wind speed which is driving the WECS. The two major sources of error in the measurement of a reference velocity are 1) wind shear because of vertical separation, and 2) a cross-correlation coefficient between wind speed fluctuations which is less than unity for spatial separations in both the horizontal and vertical directions.

Techniques for correcting error caused by wind shear have been discussed in the preceding section concerning performance verification. These methods can also be applied to correcting error in a reference velocity in performance evaluation.

Error in a measured reference velocity, caused by a cross-correlation coefficient between speed fluctuations at two separate locations being less than unity, is more difficult to correct. No methods exist for completely removing this error. One technique which allows a reduction in the error, but not a

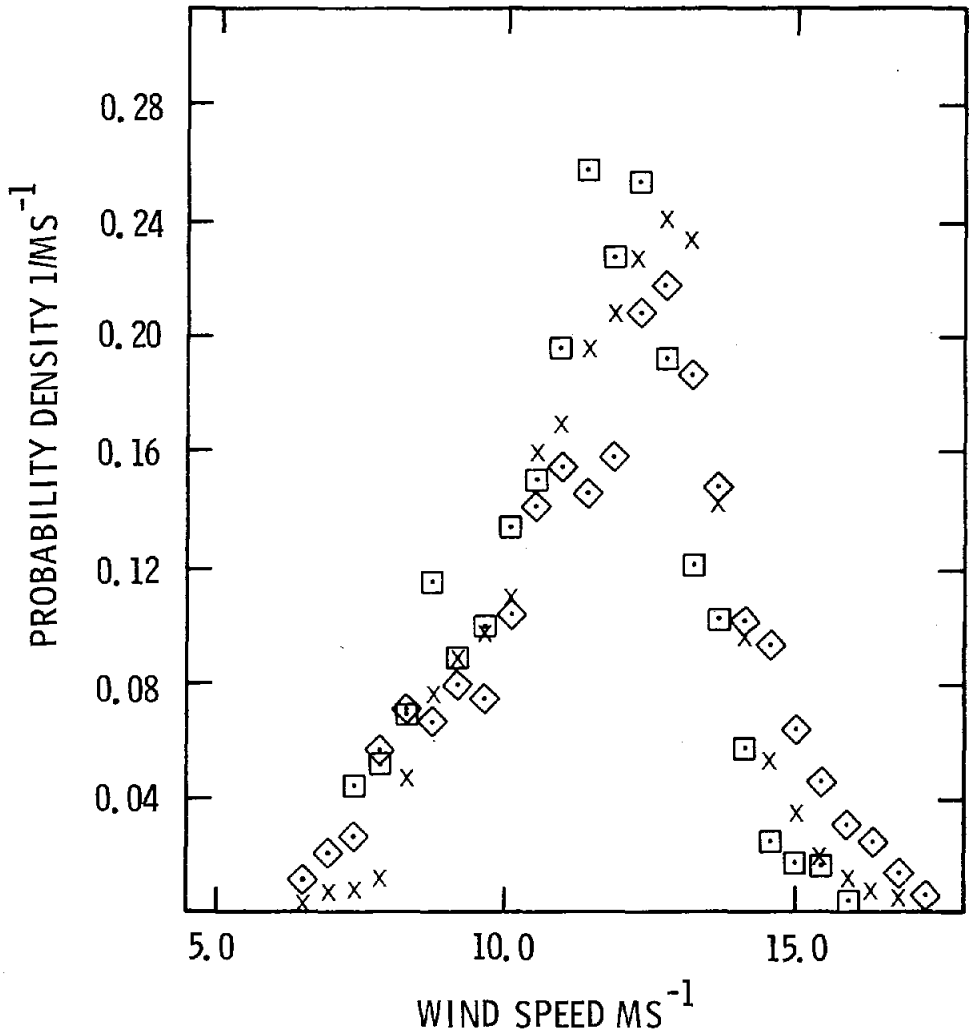


FIGURE 4. WIND SPEED PROBABILITY DENSITY, DATA CORRECTED FOR SHEAR TO A COMMON HEIGHT.

complete removal, averages both the reference velocity and the power output of the WECS for a period of time before they are used to measure the performance the WECS. This averaging technique was developed as part of the research reported in this document; therefore it has received limited use. Cases to which the technique has been applied all resulted in a more accurate measure of performance than if the technique had not been used.

The cross-correlation coefficient between two physically separated anemometers (see Figure 3) can be increased by averaging the instantaneous output of the two instruments for short periods of time prior to computing the cross-correlation coefficient. This averaging has the effect of filtering the high frequency (small scale) fluctuations in the measured wind speed. Such filtering is appropriate when using an anemometer, which has a relatively small effective measurement volume, for the measurement of an effective wind speed over the larger swept volume of a WECS. No exact criteria were determined for averaging wind speeds prior to calculation of a cross-correlation. The data used in the demonstration were taken at 10 samples per second, or a sample interval of 0.1 seconds. Cross-correlations were computed for two anemometers with a horizontal separation of 80 m. Figure 5 is a plot of measured cross-correlation coefficients for a 0.1-second sample interval and for averaged 1-second and 5-second intervals. The increase in the cross-correlation coefficient with increased averaging time is significant. At a zero time

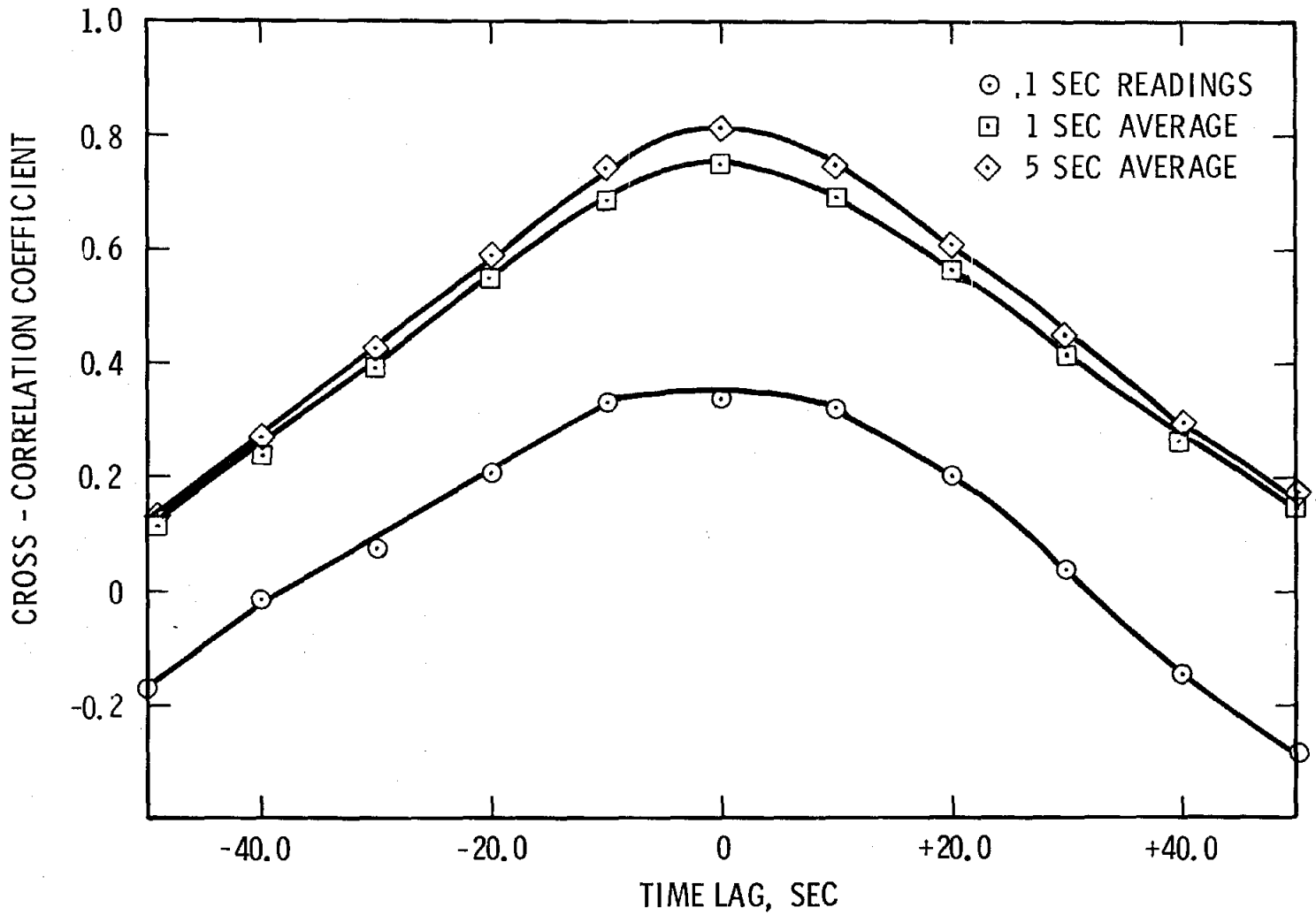


FIGURE 5. EFFECT OF AVERAGING TIME ON WIND SPEED CROSS-CORRELATION COEFFICIENTS.

lag, the cross-correlation coefficient increases from 0.34 for 0.1-second readings to 0.82 for 5-second averaged readings. Only one second of averaging accomplishes most of the increase in the cross-correlation coefficient. Figure 6 is a plot of the zero time lag cross-correlation coefficient as a function of averaging time. The zero averaging time corresponds to the 0.1-second readings. These data again show that most of the increase in cross-correlation is obtained by averaging for only one second.

Data used in these examples were taken at the DOE/Sandia VAWT Test Facility. Increases in cross-correlation coefficient with averaging time were observed for all cases for which the calculation was carried out. The spectral density of the longitudinal velocity fluctuations at the test facility agrees well with measurements at other locations [14], so these results may be expected to be applicable at other locations. The exact amount of increase in the cross-correlation coefficient with time averaging will naturally be a function of separation and, to some degree, location. However, the trend of increasing cross-correlation with time averaging should be present at any location.

The value of this increased cross correlation can only be assessed in the context of an actual performance evaluation. This assessment was done in a situation where a reference anemometer was located directly above a vertical-axis wind turbine. Sufficient experience had been obtained with a reference anemometer at this location to enable the output of the WECS,

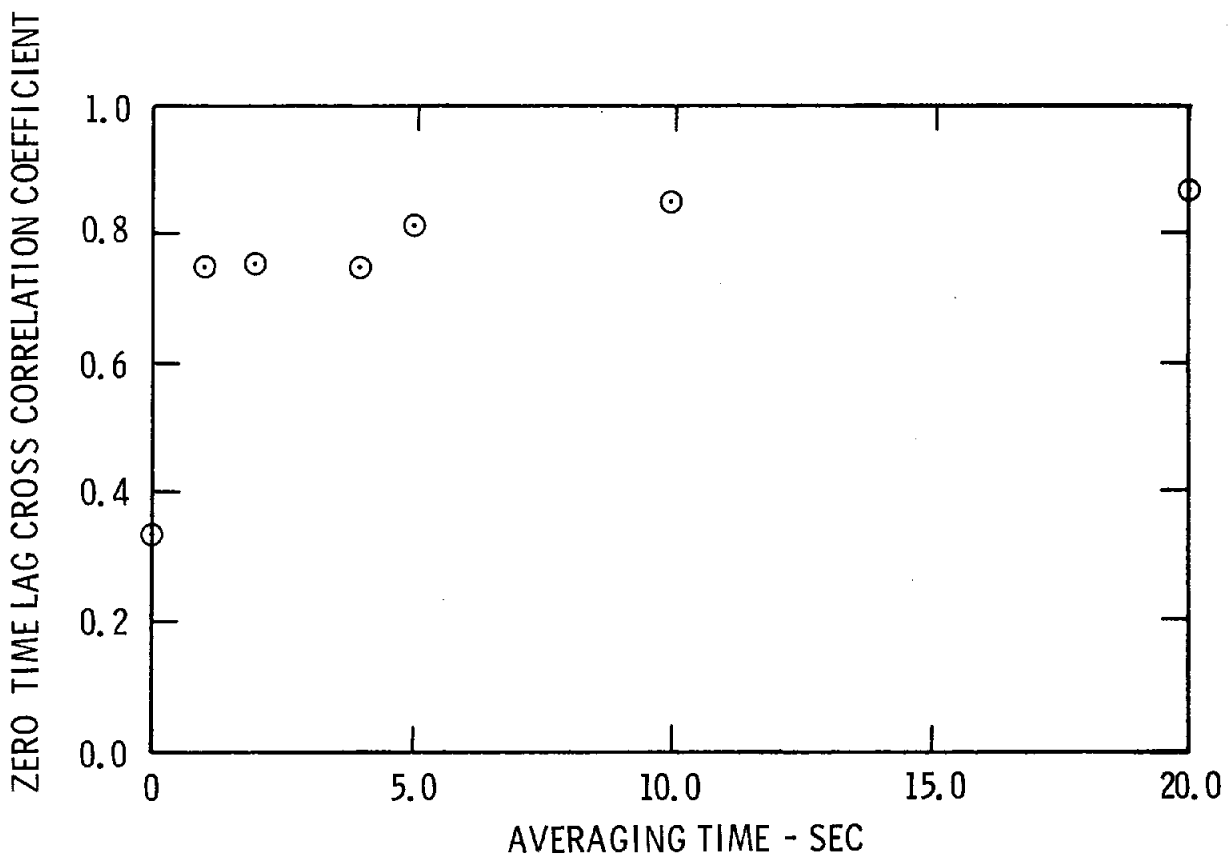
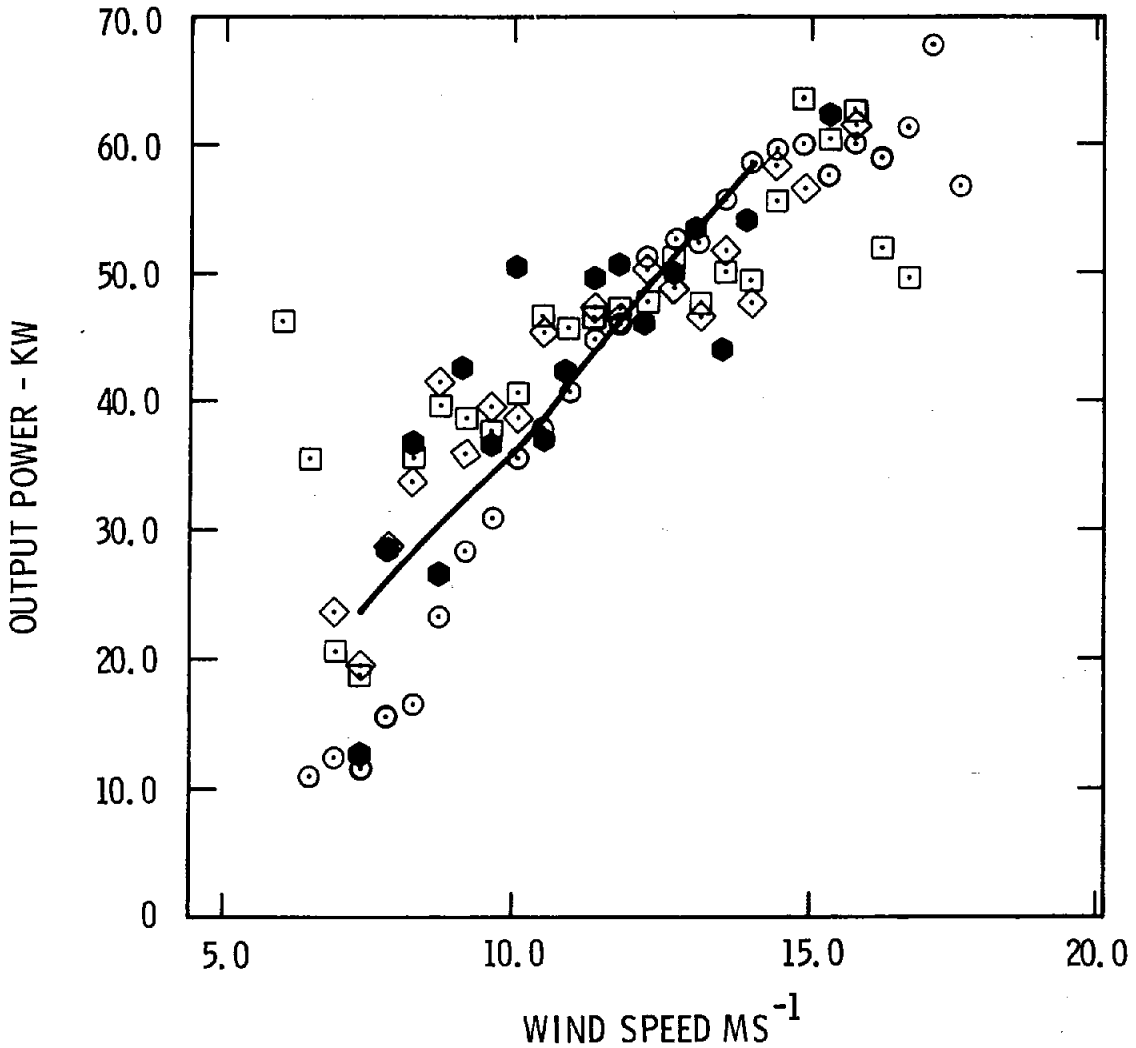


FIGURE 6. EFFECT OF AVERAGING TIME ON ZERO TIME LAG CROSS-CORRELATION COEFFICIENT.

as a function of wind speed measured with this anemometer, to be considered accurate. Performance measurements were made using the "methods of bins" [15, 16]. This method is a straightforward technique in which velocity is scaled into increments of, for instance, 1 m/s. As readings of WECS output and reference velocity are taken (either instantaneous or averages), they are recorded in two sets of bins. One set contains a number that is the total number of readings which have fallen in the 1 m/s velocity increment. The second set of bins contains the sum of the power readings taken when the reference velocity falls within the range of values with which each bin is associated. At the conclusion of a period of data collection, the sum of power readings is divided by the number of readings and an average power for that velocity increment is obtained. Once data are obtained for the entire operating range of a WECS, the output of the WECS as a function of reference velocity is determined. See Reference 16 for a more detailed description of the technique.

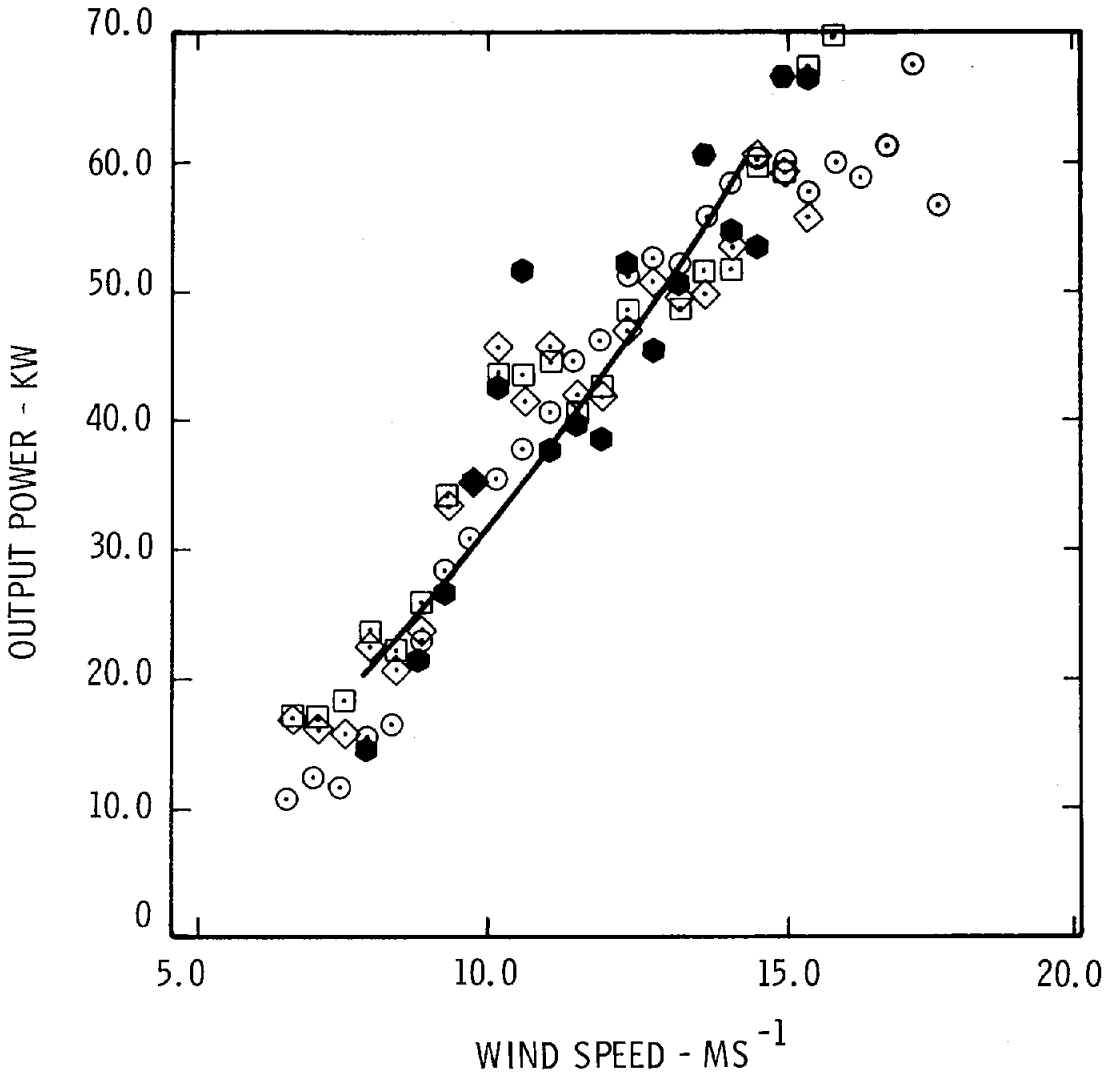
In using a technique of performance evaluation such as the method of bins, it is clear that if an incorrect reading of reference velocity is used, the data concerning WECS output as a function wind speed will also be incorrect. In order to have an accurate measure of reference wind velocity, both the mean correction must be accurate, and the cross-correlation between fluctuations at the reference location and the WECS center must be as large as possible. The cross-correlation

may be increased by averaging reference velocity readings for a short (1-5 sec.) period of time, as described in the preceding paragraphs. In a performance evaluation situation, the measure of output should also be averaged for the same period. In this case the time averaged values of both reference velocity and WECS output should be used in the method of bins or other comparable technique instead of instantaneous readings. Examples of this application are shown in Figures 7 and 8. These figures are based on fifteen minute records of data. Some of the data scatter in these figures is due to this short length of record. In both figures, circles indicate data taken with a reference anemometer placed in a reliable location (16 m above the center of the turbine). This anemometer location is called Location 1 in the figures. Data denoted by circles were obtained using 0.1 second readings with no averaging. In Figure 7, these data are compared to those obtained using a reference anemometer located on a meteorological tower 110 m away from the center of the WECS, called Location 2. The squares represent data obtained using the anemometer at Location 2 as a reference, 0.1-second readings, and no averaging. These data exhibit considerable scatter, overestimate the power for low wind speeds, and underestimate the power for higher wind speeds. The diamonds and hexagons represent data obtained with averaging periods of 1 second and 6 seconds, respectively. While scatter still exists, averaging does produce data that are closer to the results obtained from a reference anemometer at Location 1. The solid line in Figure 7 was



SYMBOL	LOCATION	TIME INCREMENT(S)	VERTICAL SEPARATION(M)	HORIZONTAL SEPARATION(M)
⊙	1	0.1 (RAW)	16	0
⊡	2	0.1 (RAW)	0	110
◇	2	1.0 (AVG)	0	110
⬢	2	6.0 (AVG)	0	110
—	POWER LAW CURVE FIT TO ⬢			

FIGURE 7. WECS OUTPUT POWER MEASURED USING TWO SEPARATE REFERENCE ANEMOMETERS.



SYMBOL	LOCATION	TIME INCREMENT(S)	VERTICAL SEPARATION(M)	HORIZONTAL SEPARATION(M)
⊙	1	0.1 (RAW)	16	0
⊡	3	0.1 (RAW)	17	110
◇	3	1.0 (AVG)	17	110
⬢	3	6.0 (AVG)	17	110
—	POWER LAW CURVE FIT TO ⬢			

FIGURE 8. WECS OUTPUT POWER MEASURED USING TWO SEPARATE REFERENCE ANEMOMETERS.

obtained from a least-squares power-law fit to the data from Location 2 with 6-second averaging. For wind speeds between 10 and 15 m/s the curve-fit agrees well with Location 1 data. The mean wind speed at the WECS centerline height for this record was 11.6 m/s.

Data in Figure 8 correspond to similar conditions as shown in Figure 7 except that a second reference anemometer location was used. This Location 3 was separated from the center of the WECS by 110 m horizontally and 17 m vertically. A mean correction for wind shear has been employed. Averaging techniques are denoted by the same symbols as were used in Figure 7. The power-law curve fit of the 6-second average data from Location 3 again agrees well with the Location 1 data.

Another technique may be employed to check an output power versus wind speed relationship. This technique can be used to verify a relationship, but if error is indicated, the technique cannot provide a direct indication of the source of the error (physical separation, interference, or some other cause). The technique entails using a known power versus wind speed relationship and a measured wind speed PDF for a specified period. These two quantities can be combined to predict the output energy of the WECS for the period of time during which the wind speed PDF was measured. The measured output of the WECS for the same period can also be obtained by an independent means, for instance a kilowatt-hour meter. If the predicted and measured energy

productions agree, confidence may be obtained in the location of the reference anemometer used in the performance establishment (see Reference 16).

ESTIMATING ERRORS CAUSED BY INTERFERENCE

A straightforward method of estimating errors in a reference velocity caused by interference treats the WECS as a solid body in a uniform flow. A horizontal-axis WECS is treated as a solid disc, while a Darrieus vertical-axis WECS is treated as a sphere. The analysis was limited to these two shapes although the techniques could be easily applied to other configurations. The solid body case is limiting in that as the tip-speed ratio of a WECS increases, the rotor appears more solid to the approaching flow. Not only is this concept correct intuitively, but the increase in drag coefficient with tip-speed ratio shown in Figure 2 is evidence of a tendency toward solid body behavior with increasing tip-speed ratio. Axisymmetric potential flow solutions for flow past a disc and a sphere were obtained to identify upstream regions of both increased and decreased velocity [17, 18]. Downstream of a WECS, wake effects will dominate for at least three to five diameters. The prediction of velocity reduction in a wake is a complicated problem and no simple technique is available to estimate the flow field in the wake. Consequently, estimates of interference will only be made upwind of a WECS.

Figure 9 is a diagram of regions upwind of a solid disc that experience greater than a five percent speed-up or

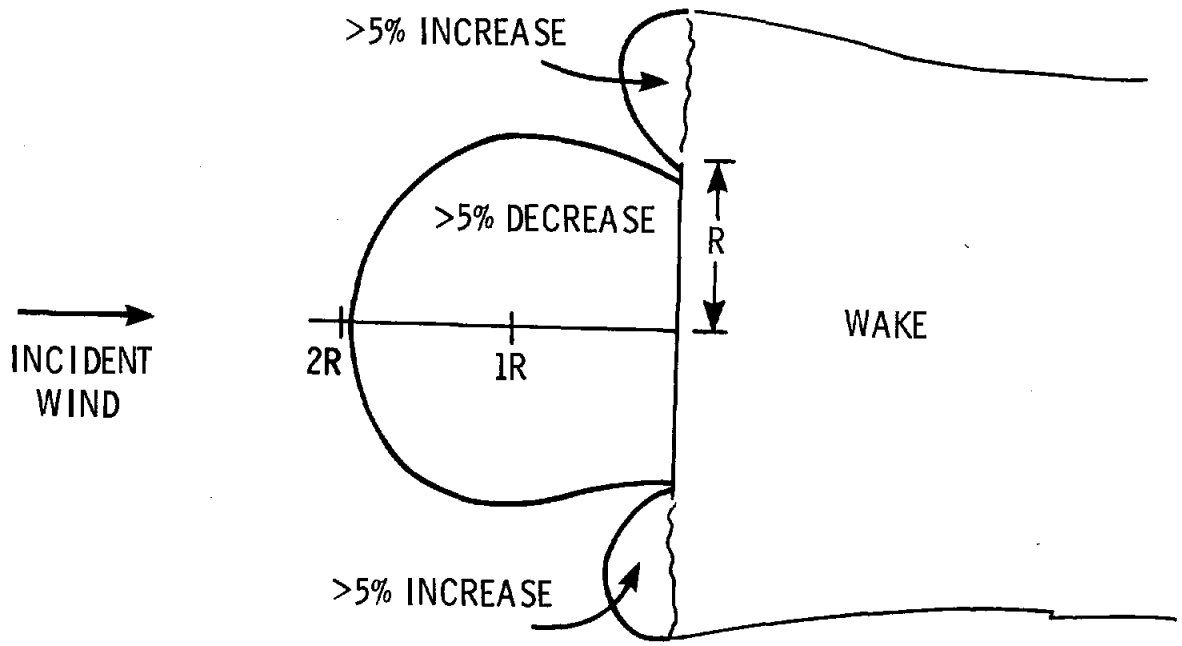


FIGURE 9. REGIONS OF POSSIBLE SIGNIFICANT ERROR IN REFERENCE VELOCITY MEASUREMENT FOR POTENTIAL FLOW PAST A DISC.

reduction of wind speed in a uniform flow. These regions are shown in a nondimensional format in terms of the radius of the disc. Significant interference effects may be assumed to be limited to these regions. In many operating conditions of a WECS, the areas of speed-up or reduction in wind speed will be smaller. It is not possible to quantify interference effects as a function of operating condition. Figure 9 can be used most effectively to identify regions of potential problems. If a reference anemometer must be placed in a region where interference effects may occur, efforts should be made to insure that an accurate reference speed is obtained. Techniques that may be used to determine if any interference problems are affecting a reference anemometer are outlined in the two following sections.

Figure 10 is a diagram of regions upwind of a solid sphere that experience greater than a five percent speed-up or reduction of wind speed in a uniform flow. These regions are also shown in a nondimensional format based on the radius of the sphere. As for the disc (Figure 9), significant interference effects may be assumed to be limited to these regions. Many operating conditions may result in much less interference.

CORRECTING ERRORS CAUSED BY INTERFERENCE - PERFORMANCE VERIFICATION

Because the requirements for performance verification do not require close physical proximity between the WECS and the reference anemometer, the best solution to anemometer placement is to locate the reference instrument upwind of the WECS and outside

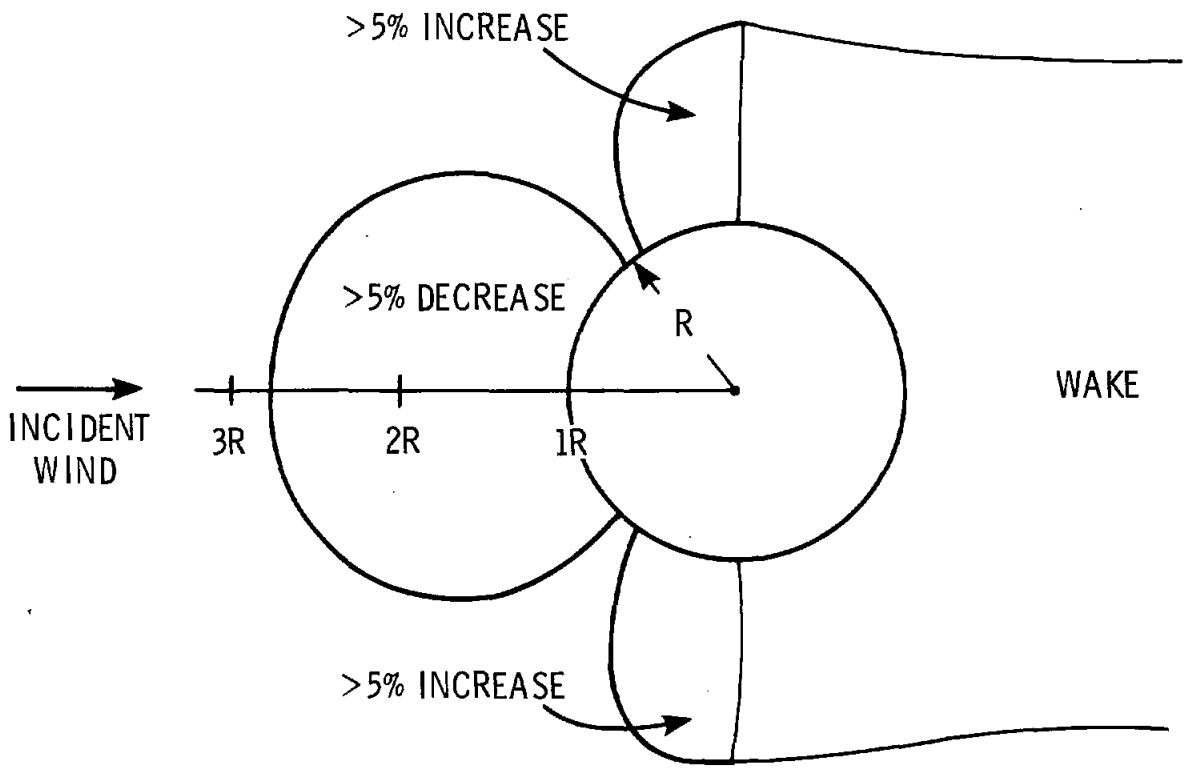


FIGURE 10. REGIONS OF POSSIBLE SIGNIFICANT ERROR IN REFERENCE VELOCITY MEASUREMENT FOR POTENTIAL FLOW PAST A SPHERE.

of the regions of influence shown in Figures 9 and 10. If for some reason such a separation is not possible, no proven techniques exist for correcting a reference anemometer output for interference. Some methods are available that allow the accuracy to be estimated for a reference anemometer that may be subject to interference from a WECS. These methods are discussed in the following section dealing with errors in performance establishment caused by interference.

CORRECTING ERRORS CAUSED BY INTERFERENCE - PERFORMANCE ESTABLISHMENT

Because of errors introduced in the measurement of a reference velocity caused by physical separation, applications involving performance establishment usually require that the reference anemometer be placed as close to the WECS as practical. In addition, in many cases it is convenient to mount the reference anemometer on the same structure or tower that supports the WECS. Any situation in which a reference anemometer is mounted within regions of possible interference, shown in Figures 9 and 10, must be dealt with carefully. Because interference effects are a function of the operating condition of the WECS, no straightforward methods of correcting exist. The best approach is to determine if an error in the reference velocity exists, and then move the reference anemometer to remove the error.

A second anemometer may be used to check the output of the reference anemometer. For instance, if the reference anemometer is located in a region of potential interference, a second anemometer may be mounted some distance away in a region where no interference exists. Optimally, the second anemometer can be

mounted at the same elevation as the primary reference anemometer. Readings of average values for periods of five minutes to one hour from the two anemometers can be compared when the WECS is not operating. These values of average velocity should be very nearly equal. The same process can be repeated while the WECS is operating, preferably in a condition with a high tip-speed ratio. If any differences in measured velocities appear, they are an indication that interference is present and the location of the reference anemometer should be changed.

A second method of detecting error in the reference anemometer as a result of interference is to compare the predicted output energy of the WECS with the actual energy produced. Interference could make the predicted energy either greater or less than the actual energy produced, depending on whether the reference anemometer is located in a region experiencing an increase or decrease in wind speed caused by interference.

Figure 11 is an example of interference effects on a measured performance curve. This figure is taken from a report on field-testing of a small vertical-axis wind turbine at Sandia Laboratories [19]. Two sets of data are shown in the figure. The circles represent data taken with an anemometer mounted above the WECS in the region where, according to figure 10, interference is probable. The data represented by the triangles were obtained with a second reference anemometer that was not influenced by the operation of the WECS. Output of the WECS is presented in terms of a nondimensional quantity called the power coefficient. The power coefficient is defined as

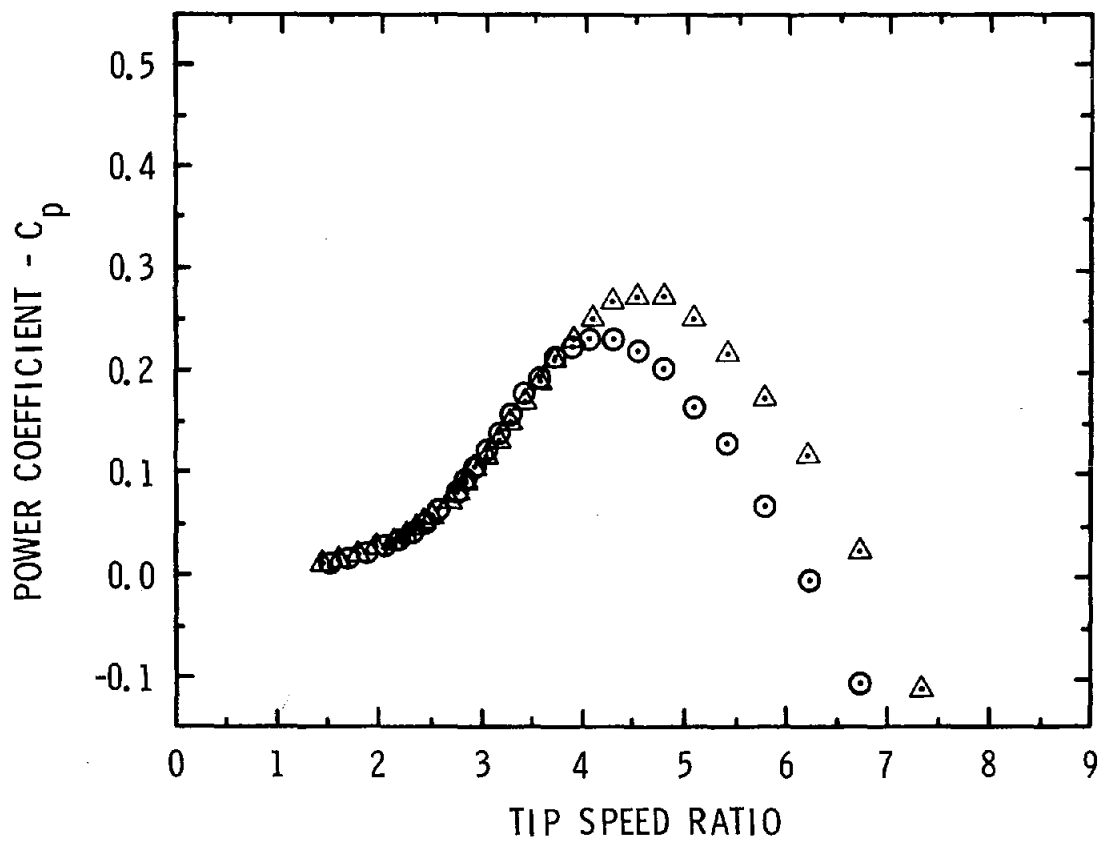


FIGURE 11. EXAMPLE OF INTEREFENCE EFFECTS ON MEASURED POWER COEFFICIENTS (19).

$$C_P = \frac{P}{\frac{1}{2}\rho \ V^3 A} \tag{7}$$

where P is the output power

ρ is the density of air

V is the reference velocity at the WECS center line

A is the swept area of the WECS

At the higher tip-speed ratios, the anemometer above the WECS (circles in the figure) provides a lower value of C_P than the second reference anemometer. From Figure 10, the region above the WECS should be an area of increased wind speed. This increase would result in a smaller C_P as shown in the figure. Such a comparison cannot be made unless a reliable location for a reference anemometer is available.

V. INSTRUMENT SELECTION

A wide variety of instrumentation is available which is suitable for the field testing of WECS. They range from familiar cup anemometers to sophisticated laser-doppler velocimeter systems. Each individual application will entail different requirements and hence different instrument selection. Three important factors in instrument selection are durability, frequency response, and the ability to resolve wind components. These criteria will be discussed briefly in the following section. More detailed information concerning meteorological instruments may be found in References 20 and 21.

The frequency response of an instrument is normally stated as the highest frequency of oscillating input that the instrument can accurately measure. The frequency response of a cup or propellor anemometer is stated in terms of a distance constant. The distance constant represents the length of a column of air that must pass the anemometer before it indicates 1-1/e, or 63%, of a change. For any anemometer, the distance constant is independent of wind speed. The frequency response will therefore increase with wind speed. An anemometer with a distance constant of 1 m would have a nominal frequency response of 10 Hz in a 10 m/s wind. The method of data collection will set requirements for the frequency response of an anemometer. If readings are averaged for a set period, for instance 1 s, then a frequency response near 1 Hz would be appropriate. If instantaneous readings are used a more responsive instrument (possibly 10 Hz) would be desirable. The speed at which these frequencies are determined could correspond to the rated wind speed for a horizontal-axis machine or the wind speed at which the peak C_p occurs for a vertical-axis machine.

Durability of the instrument should be a prime factor in selection of a reference anemometer. In many installations some form of crane will be required to service the unit. The rental cost of the crane will probably exceed the cost of the instrument many times over. Frequent servicing of the anemometer is therfore not economical. In some instances it may be necessary to compromise somewhat in anemometer selection, with increased durability gained at the expense of frequency response.

This trade-off may be necessary because instruments with higher frequency response tend to also be more fragile and hence less durable.

The wind is a vector having both a magnitude (speed) and a direction. As a minimum, it might be sufficient in some cases to merely measure speed. In an application of performance verification a speed measurement will generally be adequate. In an application involving performance establishment, the ability to measure not only wind speed, but also wind direction is important. Errors in a measured reference speed, due to physical separation or interference, may be a function of wind direction, making the ability to determine a wind direction important. In addition, the ability to measure wind characteristics described in the following section is dependent on an ability to resolve a wind speed into components.

VI. OTHER IMPORTANT MEASUREMENTS

In addition to a reference velocity, a number of other wind characteristics are important in either performance verification or evaluation. The density of the ambient air is important in that WECS output is directly proportional to density. A measurement of ambient temperature and barometric pressure allows the calculation of density, using the ideal gas law. Measurements can be made at a particular location using relatively inexpensive instruments. If proper instruments are not available, temperatures and pressures could also be obtained from a nearby weather station. A reported power

versus wind speed relationship can be corrected to another density using the relationship

$$\frac{P_1}{\rho_1} = \frac{P_2}{\rho_2} \quad \text{or} \qquad (9)$$

$$P_2 = \frac{P_1 \rho_2}{\rho_1}$$

where P_1 corresponds to the measured power produced at density ρ_1, and P_2 corresponds to the power produced at density ρ_2.

A number of additional wind characteristics should be reported as a part of performance establishment. These characteristics include turbulence intensities in the alongwind, crosswind, and vertical directions, and the longitudinal velocity spectra. Detailed reviews of these quantities in atmospheric boundary layers may be found in Ref. 9 and 12. Ref. 14 is an example of the documentation of wind characteristics at a particular WECS test facility.

VII. SUMMARY

The most important measurement of wind characteristics in field testing of WECS is the reference wind velocity. Requirements for the measurement of a reference wind velocity differ for the establishment of the performance of a particular WECS and the verification of the performance of a WECS. Error may be present in the reference wind speed due to the physical separation between the WECS and the reference anemometer, and due to interference between the WECs and the reference anemometer. Error caused by physical separation can be corrected by a constant correction due to vertical variation of mean wind velocity and by time averaging

to reduce errors caused by wind velocity fluctuations. Error caused by interference between the WECS and the reference anemometer is difficult to correct and is best avoided by an understanding of the locations at which such error can be important. Instrument selection for a reference anemometer should be influenced by durability and frequency response.

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4715 W. N. Sullivan
4720 V. L. Dugan
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5624 L. V. Feltz
5630 R. C. Maydew
5633 R. E. Sheldahl
6010 T. F. Marker
8000 T. B. Cook, Jr.
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