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ABSTRACT

During the first phase of the U.S. Department of Energy's turbulence characterization program, important discoveries were made about the field application of propeller-vane and cup anemometers under very turbulent conditions. First, averaged speeds measured by the propeller-vane anemometer were consistently lower than those from the cup anemometer, even though both registered virtually the same during wind-tunnel calibration testing. Second, the propeller-vane anemometers suffered from structural failures much more frequently than the cup anemometers.

The difficulties associated with the use of the propeller-vane motivated us to consider the cup anemometer for turbulence measurements. At fast sample rates, the output of the cup anemometer is severely degraded by discretization error that stems from pulse counting demodulation. However, we found that a low-pass Gaussian filter could be applied to the time series of wind speed derived from the cup anemometer to yield time series and frequency spectra that compared very favorably with those obtained from the propeller-vane anemometer. This finding suggests that the cup anemometer may prove to be an inexpensive and rugged sensor appropriate for turbulence measurements for wind-energy applications.

INTRODUCTION

A turbulence characterization program was initiated in the U.S. Department of Energy's Wind Energy Program to establish turbulence parameter values for the design of advanced wind turbines and to provide a basis for the development of an efficient and cost-effective turbulence characterization scheme. To accomplish these objectives, Pacific Northwest Laboratory (PNL) developed a measurement and analysis program (1) in an effort to work jointly with the wind energy community to characterize wind turbulence in a variety of complex terrains at existing or potential sites of wind turbine installation.

To characterize the turbulence, the configuration of sensors shown in Figure 1 was chosen. This configuration not only provides vertical and horizontal wind shear data at a site, it also provides the opportunity to examine the effect of rotational sampling of the turbulent wind. The combination of propeller-vane and vertical propeller anemometers was selected as a lower-cost, more-durable alternative to the uvw propeller anemometers used in previous short-term turbulence measurement studies by PNL. The propeller-vane (prop-vane) anemometer uses a miniature tachometer generator to produce a DC-voltage signal that is linearly proportional to wind speed. The propeller has a distance constant of 2.1 m. The vane assembly has a delay distance of 1.3 m and a damping ratio of 0.25.

A cup anemometer and wind direction vane were mounted near the propeller-vane anemometer at the top of the 30-m tower to provide an independent measurement of the wind speed and direction. The cup anemometer produces a sine wave voltage through a single coil by a four-pole magnet. For all practical purposes, the frequency of the AC signal is linearly proportional to wind speed. The distance constant of the cup is 3.0 m.

A data collection scheme was established to measure the horizontal and vertical components of the wind speed from the four locations at a rate of five samples per second during any time period when the average wind speed

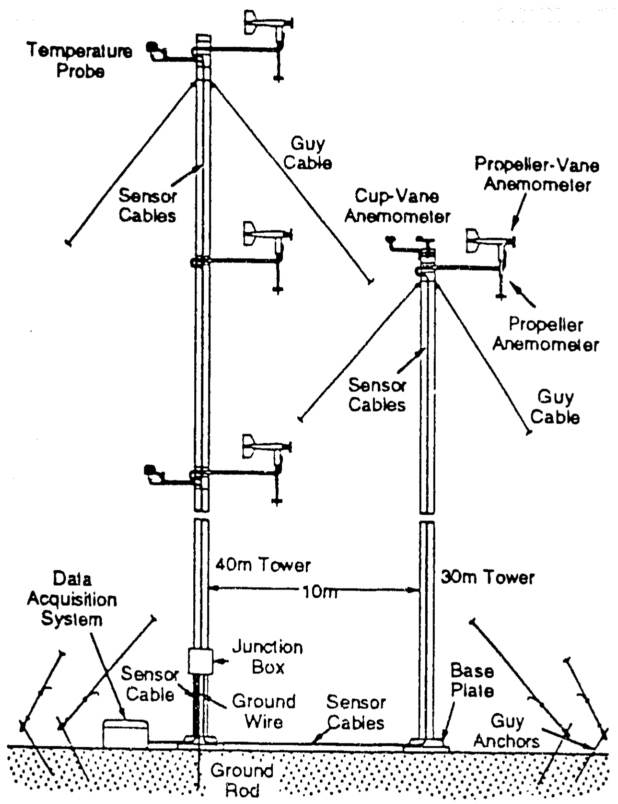

FIG. 1. SCHEMATIC OF COMPONENTS OF TURBULENCE CHARACTERIZATION SYSTEM (not to scale)

is greater than or equal to 5 m/s. The speed and direction data from the cup and vane are collected as 10-min averages of 1-s samples for all wind speeds.

As a quality assurance check, the 5-Hz data are averaged over 10-min intervals for comparison with the 10-min average data. Scatter plots are produced that provide an ongoing comparison between the prop-vane anemometer and the cup anemometer and vane on the 30-m tower at each site. These plots provide a convenient check for sensor problems such as icing, bearing wear, or physical damage. The measurements from the two types of sensors were also compared to evaluate the turbulence intensity parameter commonly derived from wind measurements made with the low-cost cup anemometer.

FIELD PERFORMANCE OF ANEMOMETERS

During the first phase of the turbulence characterization program, important discoveries were made about the field performance of prop-vane and cup anemometers under very turbulent conditions. The scatter plot analyses in Figure 2 showed higher 10-min average speeds measured by the cup anemometer than the prop-vane anemometer; this difference was as great as 4% at the higher wind speeds. This discrepancy was first thought to be due to an error in calibration of one of the sensors used at the particular site that was being studied. However, the same problem was found at all six sites. The discrepancy was also shown to be independent of wind direction, eliminating the possibility of tower or anemometer shadow effects. The cause was then suspected to be the manufacturer-supplied calibration coefficients for one or both types of anemometers. However, wind tunnel calibration tests performed at PNL showed that the two anemometers registered virtually the same speed in the nonturbulent flow of the tunnel (Figure 3).

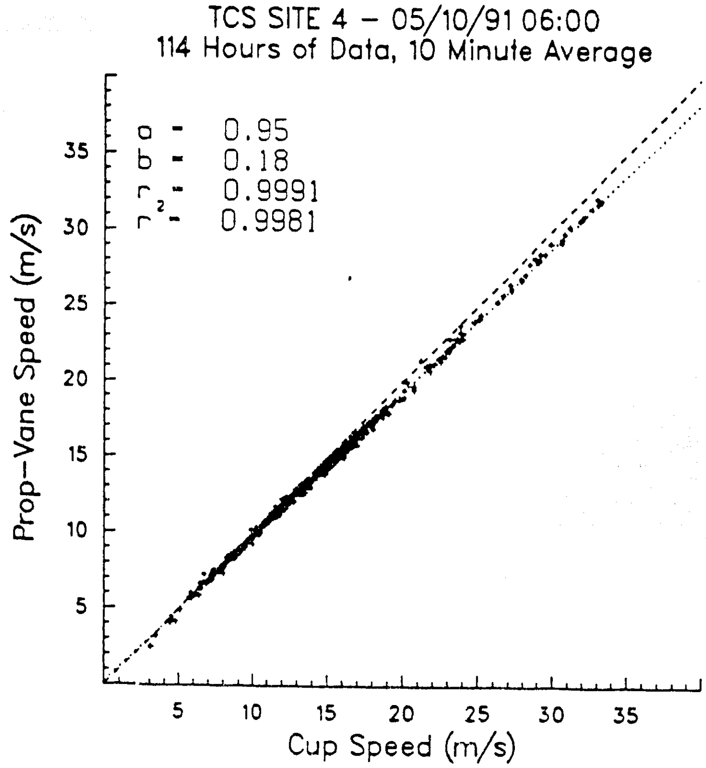

FIG. 2. SCATTERPLOT OF 10-MIN AVERAGE WIND SPEEDS FROM PROPELLER-VANE ANEMOMETER VS. CUP ANEMOMETER. Plot represents 4 days and 18 hours of data or 684 points.

Since significant vertical wind velocities were measured at some of the sites, it was thought that the non-cosine response of the prop-vane anemometer to the vertical component of the wind might contribute to a reduced horizontal wind speed measured by the prop-vane. An algorithm similar to that used to correct the response of a uvw propeller anemometer (2) was applied to the horizontal and vertical wind measurements. This attempt toreduce the discrepancy between the measurements of the cup and prop-vane anemometers was unsuccessful. Even in cases in which the angle-of-attack of the wind was up to 15° from horizontal, the correction to the horizontal component of the wind was negligible.

These hypotheses were expected to uncover a site-dependent problem or a problem with use of the anemometers (i.e., calibration or mounting). Once assured that the calibration and mounting procedures were free from serious error, it was then conjectured that the source of the speed discrepancy might stem from the dynamic interaction of the anemometers with the turbulent wind.

Pursuing this lead, it was first asked if cup overspeeding could cause the cup wind speed measurements to be larger than the actual wind speed, thus accounting for some or all of the 4% difference. Overspeeding errors have been estimated (3,4) suggesting that for cup anemometers with relatively small distance constants, overspeeding errors tend to be small and probably cannot fully account for the difference. [For example, Hunter (4) estimated the overspeeding error to be only about 0.3% for one particular type of cup anemometer deployed at the 10-m level in "open moorland".] Therefore, it was assumed that the overspeeding was small, and another reason for the discrepancy was proposed: the dynamic behavior of the prop-vane in turbulent environments.

That the prop-vane's dynamic behavior in turbulent environments may be less than satisfactory has been demonstrated by Tangler et al. (5). In this study, three anemometers - a sonic, a cup, and a prop-vane - were used to determine the power curve of a wind turbine. The power curves derived by the cup and sonic

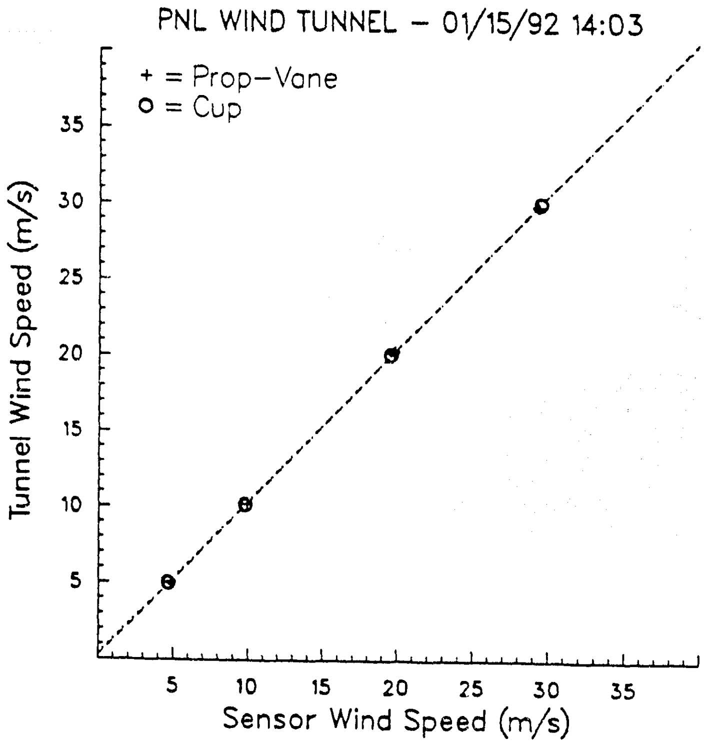

FIG. 3. SCATTERPLOT OF WIND TUNNEL SPEED VS. WIND SPEED DERIVED BY SENSOR OUTPUT USING MANUFACTURER'S CALIBRATION COEFFICIENTS FOR PROPELLER-VANE (+) AND CUP (o) ANEMOMETER. Measurements were made at approximately 5, 10, 20, and 30 m/s. Dashed line is wind tunnel derived calibration of prop-vane. Dotted line is calibration of cup.

anemometer agreed with theoretical predictions of the power curve. In contrast, poor results were achieved with prop-vane anemometers: the maximum turbine power occurred at measured wind speeds that were unreasonably low, thereby resulting in a power coefficient (C_p) that exceeded the Betz limit! The prop-vane's propensity to register lower wind speeds appears to be caused by its inability to remain aligned with theinstantaneous wind vector during turbulent conditions. This misalignment is analogous to the cosine "yaw error" experienced by wind turbines attempting to follow fluctuations in wind direction. Tangler's findings are consistent with our observations and substantiate the idea that the wind speed discrepancy is caused by prop-vane underspeeding.

This characteristic of the prop-vane was not the only difficulty experienced with the instrument. The structural performances of the prop-vane anemometer and cup anemometer and vane also differed. The prop-vane suffered a high incidence of damage in the turbulent wind at the selected sites, while the cup and vane survived even the most violently turbulent episodes, endured winds gusting to 43 m/s, and was not damaged during heavy icing conditions. Wind tunnel tests of a used prop-vane and a used cup anemometer supplied further evidence of the structural superiority of the inexpensive cup anemometer. A prop-vane that had been used at a low-turbulence site for 18 months showed a significant change in calibration, primarily because of bearing wear. A cup anemometer that was used at a moderately turbulent site for about 4 years gave virtually the same calibration as a new anemometer. (The cost of repairing each of the prop-vanes with the least amount of damage was more than the cost of a new cup and vane.)

UTILIZATION OF AN AC-OUTPUT ANEMOMETER FOR TURBULENCE MEASUREMENTS

Because of the excellent service record of the cup anemometer and its lower cost, an effort was begun to determine whether the cup anemometer could replace the prop-vane anemometer for turbulence measurements. Such replacement required the consideration of several factors. First, if turbulence measurements from the prop-vane and cup anemometers are to be (roughly) equivalent, then the distance constants of the two anemometers must be about the same. This is the case for the anemometers discussed in this paper; the distance constant of the cup anemometer is 3.0 m, while the prop-vane's distance constant is 2.1 m. Second, one must be cognizant of the fact that turbulence measurements obtained from the cup anemometer cannot capture the full frequency range of the spectrum associated with many turbulent flows, because the distance constant of the cup is simply too large. However, the low-frequency end of the spectrum - most relevant to the wind energy community - can be measured. Third, the nature of the signal emanating from the anemometers may complicate or even prevent the use of certain types of anemometers for turbulence measurements. These complications arise only at sampling rates fast enough to follow the turbulent variation in the wind.

For anemometers that produce a DC-voltage signal, including the prop-vane considered here, the electrical output is directly proportional to the wind speed. These anemometers may be sampled at relatively fast rates with little difficulty. Unfortunately this is not the case for anemometers that produce an AC-voltage signal, a class of which the cup anemometer is a member. For such anemometers, the electrical output is a frequency-modulated sine wave, the frequency of the sine wave being a measure of the wind speed. (In approximate terms, the frequency is directly proportional to the wind speed.) To recover the wind speed from the output voltage, a demodulation scheme must be devised.

Pulse-counting demodulation is one very common way of recovering the wind speed. In simplified terms, each maximum ("pulse") of the sine wave is counted within the specified time interval. The number of pulses that occur in the sampling interval is a measure of the sine wave's frequency, which in turn is related to the wind speed. The more pulses that occur in the sampling interval, the greater the speed. Because the number of pulses is a discrete rather than a continuous variable, the speed can only be registered at discrete speed intervals, and AC output anemometers that use pulse-counting demodulation suffer from discretization error. When the discretization error is large - as it must be for the fast sampling rates required for turbulence measurements - time series and spectra derived from the cup anemometer become so degraded that the cup anemometer's output is simply not suitable for turbulence measurements.

As mentioned previously, the cup anemometer possesses several advantages over the prop-vane anemometer. These considerations would make the cup the preferred choice for turbulence measurements if the discretization error could be reduced or eliminated. One way of removing the discretization error involves the use of a filter. When convolved with the time series obtained using pulse-counting demodulation, the appropriate filter may, for all practical purposes, eliminate the discretization error.

To evaluate the possibility of sampling the AC signal of the cup anemometer at higher rates while reducing the discretization error, a prop-vane and a cup anemometer were mounted less than a meter apart on a cross beam elevated 6 m above the ground. The cup anemometer used in this study produces a signal with twice the frequency of the standard sensor used in the first phase of the turbulence characterization program. The signals from both anemometers were sampled at 5 Hz. At this sampling rate, the pulsed output of the cup anemometer yields a discretization error equivalent to 1.9 m/s. Different numerical filters were applied to the speeds measured by the cup anemometer in an attempt to derive measurements similar to that produced by the DC-output prop-vane. It was discovered that a Gaussian filter applied to the cup's discrete output did indeed reduce the discretization error so that the filtered time series and spectra became virtually indistinguishable from the corresponding time series and spectra obtained from the prop-vane anemometer.

The filtering process is illustrated in Figure 4. Figure 4a shows a 7-min segment of winds as measured by the prop-vane, while Figure 4b shows the same wind regime as measured by the cup anemometer. The discrete nature of the cup's measured wind speed is vividly apparent and is a direct result of the pulse-counting demodulation used to extract the speed from the sine wave carrier. Even the most cursory comparison of

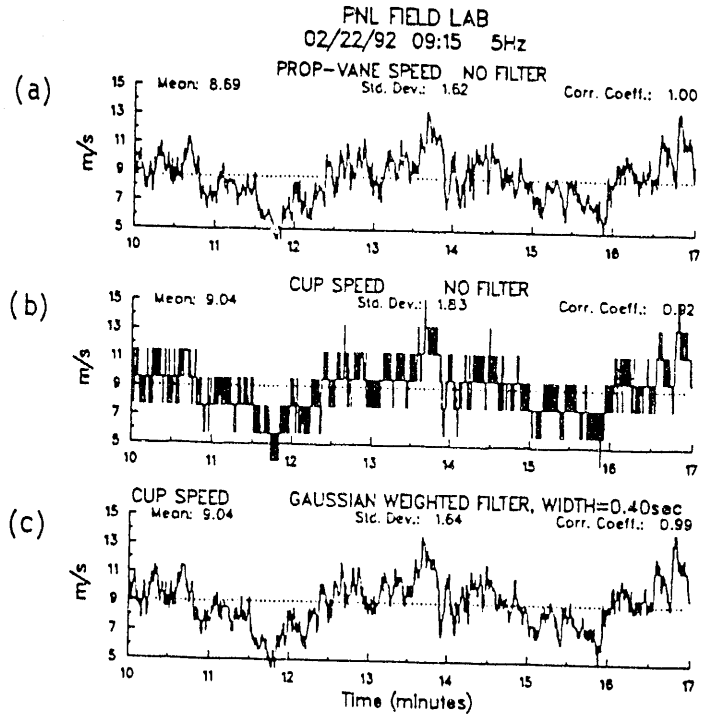

FIG. 4. TIME SERIES OF WIND SPEED MEASURED BY (a) PROPELLER-VANE ANEMOMETER, (b) CUP ANEMOMETER, AND (c) CUP ANEMOMETER AFTER APPLYING GAUSSIAN FILTER. Sensors were sampled at rate of 5 Hz.

Figure 4a and 4b demonstrates that the DC-output prop-vane produces a much more realistic time series than the AC-output cup.

This situation changes dramatically, however, when the Gaussian filter is applied to the cup's time series. The resulting, filtered time series is depicted in Figure 4c. Now, although the difference in mean speeds between the cup and prop-vane is still evident, the fluctuations about the mean are virtually identical.

This close similarity holds true for the power spectra as well. Figure 5a shows spectra derived from the prop-vane and the cup anemometers before the filter is applied to the cup's output. For frequencies greater than about 1 Hz, the cup's spectrum exhibits a peculiar "tail" uncharacteristic of the true behavior of the turbulent wind. This tail is caused by the aliasing of high-frequency noise into the spectrum; the high-frequency noise is a result of the pulse-counting demodulation. The same spectra are shown in Figure 5b, after the output of the cup anemometer has been filtered. Clearly, the correspondence between the cup anemometer's spectrum and the prop-vane's spectrum is now very close. This finding suggests that reliable turbulence measurements for wind energy applications can be obtained from an inexpensive and rugged cup anemometer.

CONCLUSIONS

The conclusions of this study may be summarized as follows:

- Prop-vane anemometer underspeeding can cause significant errors in the measurement of wind speeds (as great as 4%).

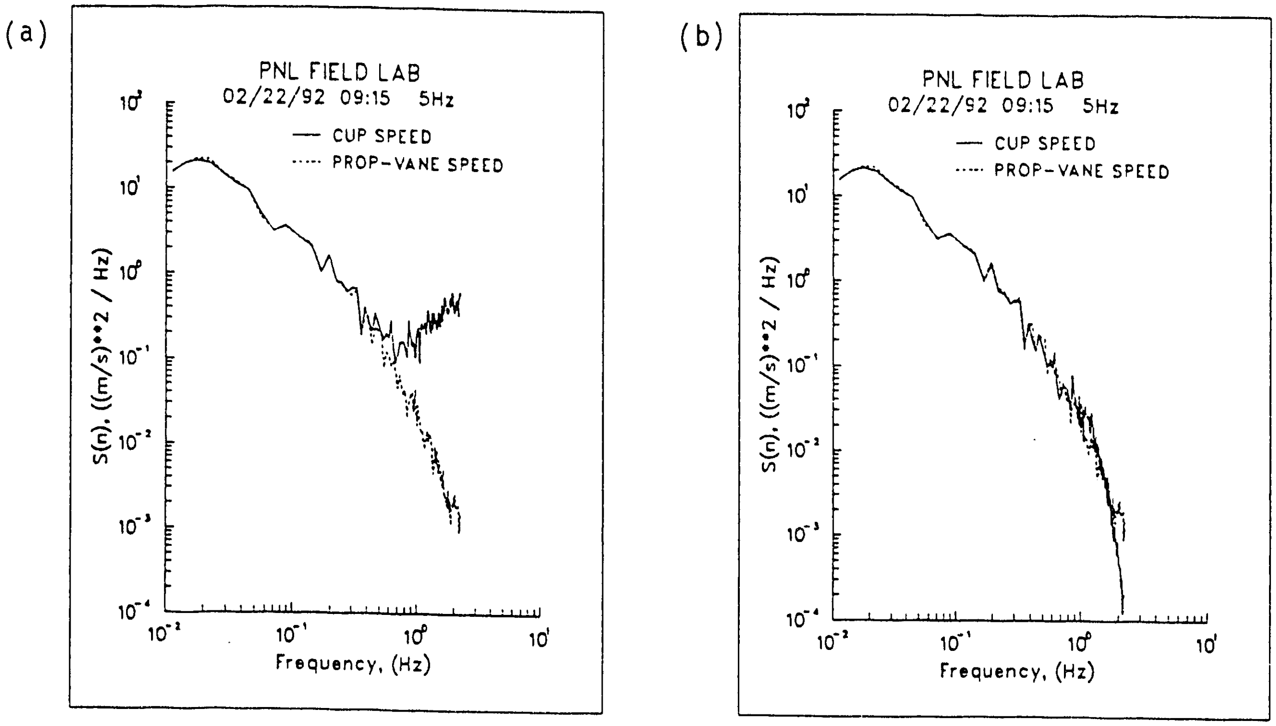

FIG. 5. SPECTRUM OF WIND MEASURED BY PROPELLER-VANE ANEMOMETER (dashed line) AND CUP ANEMOMETER (solid line) (a) BEFORE AND (b) AFTER APPLYING GAUSSIAN FILTER. Spectra are for same time segment as in Figure 4.

- The cup anemometers considered in this study were structurally sound and did not sustain significant damage or bearing wear in turbulent wind regimes. In contrast, the prop-vane's ability to withstand the turbulent stress imposed by the wind was not nearly as good.

- Although anemometers that use pulse-counting demodulation to measure wind speeds, such as the cup anemometer, suffer from a large discretization error when sampled at fast rates, the error may be virtually eliminated by the use of a Gaussian filter (which is convolved with the demodulated time series). When the error is eliminated, the rugged and inexpensive cup anemometer becomes an attractive alternative to the prop-vane for turbulence measurements.

These findings have led to the replacement of the propeller-vane anemometers used in the first phase of the turbulence characterization program with cup anemometers and wind direction vanes at three sites of the second phase of the program.

The sites in the turbulence characterization program were deliberately selected at locations where turbulence was suspected of causing structural damage to wind turbines. The prop-vane anemometer used in this study has been an acceptable instrument with which to measure the wind at locations where the turbulence is not as severe. In fact, no structural problems occurred with the prop-vanes used at the site with the least turbulence and lowest annual average wind speed.

ACKNOWLEDGMENTS

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