Calibration Speed Range for Rotating Anemometers used in Wind Energy Applications

Rachael V. Coquilla[1] and John Obermeier[2]
Otech Engineering, Inc., Davis, CA 95618

A rotating anemometer is designed so that its spin rate is directly related to the magnitude of the incoming wind. An anemometer calibration is performed when the spin rate is tabulated for a range of controlled wind speeds. In some end uses, this calibration table is used as a "look up" table, where given a raw anemometer signal reading from the field, the local wind speed is interpolated from the calibration table. For most field applications however, a transfer function, determined through regression analysis on the calibration table, is employed. Regardless of its end use, the value of an anemometer calibration is largely dependent on the range of controlled test speeds. Generally, if an anemometer is not calibrated to a particular speed, its performance is unknown at those wind conditions. According to the most widely referred standard for conducting wind turbine power performance measurements, IEC 61400-12-1, anemometer calibration is to be specifically performed at 4 to 16 m/s speed range at increments of 1 m/s. The problem with this speed range is that the resulting calibration does not represent the wind regime that an anemometer would sense in the field. In most turbine sites, wind gusts are known to reach much greater than 16 m/s. In addition, a mean speed of 16 m/s in the field is determined from a wind distribution having much higher speeds. A calibration at 4 to 16 m/s does not necessarily guarantee a correct measure of wind speeds much higher than 16 m/s. Thus, a factor that should influence the deciding test speed range is the wind conditions at which the anemometer is subjected to. According to the most recently released standard, ISO 17713-1, anemometer calibration is to be performed to the application range (i.e., the speeds at which the anemometer would sense). This paper presents an investigation of the calibration speed range for field installed rotating anemometers used in wind energy applications. There are two possible sources that may generate errors in the anemometer calibration data: 1) anemometer not calibrated for wind speed distribution at the site and 2) anemometer linear performance for a specific test speed range.

A. Introduction

Most rotating anemometers sold today, cup or propeller type, are commonly provided with a manufacturer's published transfer function. This transfer function is typically obtained through various calibration tests and performance evaluations, which may well represent the output for the particular model sensor. However, the individual calibration transfer function of any one rotating anemometer may vary 1% to 3% from its published transfer function depending on the manufacturer's quality control and the test speed range at which the published or individual transfer function was generated from. Accurate wind readings are critical in wind turbine power performance testing and site assessment. In power performance evaluation, a series of measured turbine power at various corresponding measured wind speed is used to produce a power curve for the turbine. In site assessment, the distribution of measured wind speed is used to determine the predicted annual energy production from the wind. Since wind power is proportional to the cube of the wind speed, a slight error in the wind reading could translate to a much greater error in the predicted wind energy, which emphasizes the importance of having accurate wind speed readings. To acquire such precision and better accuracy in the wind data, it is recommended that calibrated anemometers along with its calibration transfer function be employed. It is also important that the anemometers be calibrated at the appropriate test speed range commonly seen in the field.

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[1] Associate Engineer, Otech Engineering, Inc., 630 Peña Dr, Suite 200, Davis, CA 95618, and AIAA Member.
[2] President, Otech Engineering, Inc., 630 Peña Dr, Suite 200, Davis, CA 95618.

B. Review of Current Calibration Standards

Several types of anemometers are currently being used in the wind energy industry from the classic rotating cups or propellers to the newer sonic sensors. Since rotating anemometers are the most commonly used, this paper will only address calibration standards related to such instruments. Currently, there are three standards that present procedures for calibration of rotating anemometers using a wind tunnel facility. The most widely referred standard in the wind energy industry is the IEC 61400-12-1, first edition, 2005-12: "Power Performance Measurements of Electricity Producing Wind Turbines", which was published through the International Electrotechnical Committee (IEC) and initially introduced by MEASNET (the international Measuring Network of Wind Energy Institutes). The purpose of this document is to provide the steps in conducting the performance evaluation of a wind turbine. It is intended to assist manufacturers, purchasers, operators, and planners in the evaluation of wind turbines. One of the most important measurements that the IEC standard requires is the wind speed. As specified, the wind speed shall be measured using a cup anemometer mounted on a meteorological tower positioned at a location near the wind turbine but undisturbed from the turbine's dynamics. Along with other atmospheric variables, the wind speed is acquired simultaneously with turbine power output in order to generate the wind turbine power curve, which is then used to determine the annual energy production (AEP). Due to this direct relationship to power output, the wind speed measurement is critical in the evaluation of a wind turbine. Since cup anemometers have proven to be the most durable instruments to measure wind speed in wind turbine applications, this IEC standard requires its use and also provides the guidelines for its calibration and classification. The purpose of IEC classification is to define a class number based on the performance of an anemometer under certain terrain environments. This involves three types of sensitivity tests: 1) angular response, 2) dynamic effects due to rotor torque acceleration and deceleration, and 3) bearing friction torque for a range of environmental temperature conditions. Such classification tests are generally conducted only once per anemometer type prior to field installation and turbine testing and require the use of the initial calibration test results. This IEC guideline provides several details for calibration and classification procedures; however, a key note relating to the topic of this paper is that the IEC specifies a calibration wind speed range of 4 to 16 m/s.

A second anemometer test protocol, intended for general meteorology applications, is the ASTM D 5096-02: "Standard Test Method for Determining the Performance of a Cup Anemometer or Propeller Anemometer", which was originally published in 1996 by the American Society for Testing and Materials (ASTM). Like the IEC document, this standard also defines a method of obtaining the anemometer transfer function and the sensitivity tests to determine its overall performance. This standard not only provides the procedures for calibration but also methods in evaluating the performance of a cup or propeller anemometer, which include determining the starting threshold, the off-axis (angular) response, and the distance constant. Other than the angle response test, IEC and ASTM require different sensitivity tests to determine the performance of an anemometer. IEC also defines a method of classification while the ASTM standard does not. A major difference is that ASTM requires anemometer calibration beginning at a speed two times the anemometer starting threshold, the lowest speed in which the anemometer would begin to continually rotate, to the one-half maximum speed predicted at the installation site.

A third and more recently released standard, which originated from ASTM D 5096-02, is ISO 17713-1: "Meteorology—Wind Instruments—Part 1: Wind Tunnel Test Methods for Rotating Anemometer Performance", published through the International Organization for Standardization (ISO). This publication is also directed for general meteorology. It not only updates the test protocols defined in ASTM D 5096-02 but also introduces the ASTM guidelines as an international standard for performance testing of rotating anemometers. As one of the key revisions from the ASTM standard, ISO suggests conducting anemometer calibration for a range starting at two times the anemometer starting threshold up to the maximum application speed.

C. Test Speed Range Based on Wind Speed Distribution in the Field

Regardless of the magnitude of the wind, a functional rotating anemometer will give a raw signal or spin rate to all incoming winds. In order to convert this raw signal into an accurate wind speed value, the anemometer must be calibrated to the range of wind speeds sensed in the field. Calibration procedures in the IEC 61400-12-1 are primarily written for cup anemometers used for turbine performance evaluation. This standard has also been suggested for calibrating all rotating anemometers used in other applications such as wind power site assessments, turbine control monitoring, and even general meteorology studies. However, regardless of the type of anemometer or application, one of the main challenges with this IEC standard is that the specified calibration test speeds only span 4 to 16 m/s. This particular test speed range does not cover the range of winds seen in the field.

According to a Rayleigh annual wind speed distribution, mean winds greater than 16 m/s commonly occur. Figure 1 displays sample graphs of Rayleigh wind distributions for various mean speeds, which roughly represent wind sites in California according to public wind resource maps in the California Energy Commission website (http://www.energy.ca.gov/maps/wind.html). In Figure 1, a wind distribution at a mean annual speed of 5 m/s could represent a speed range of up to 16 m/s. However for distributions representing higher mean speeds, the probability of winds greater than 16 m/s increases. Additionally, measured winds also could often range from calm (1 to 2 m/s) to as much as 2-sec gusts of 40 to 50 m/s. Even without gusts, steady winds at wind turbine sites such as Tehachapi, California could reach to about 50 m/s during a one hour period.

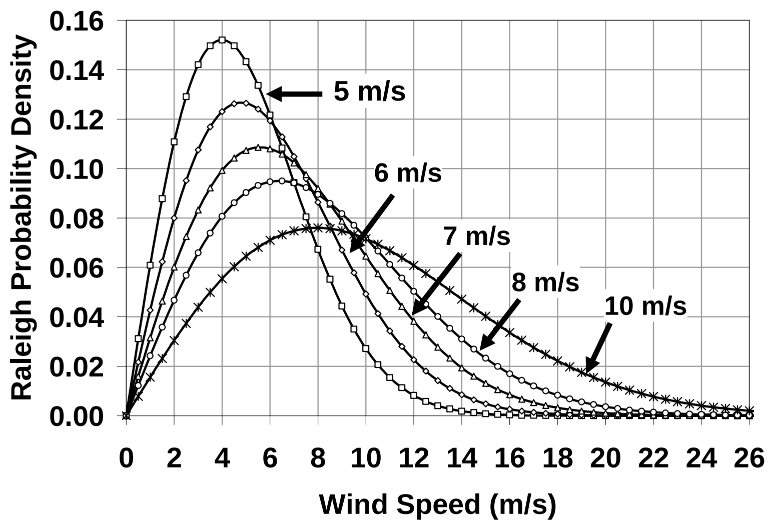

Figure 1: Sample Rayleigh wind speed distributions.

Most field anemometry systems today employ data loggers that acquire 10-min averages of atmospheric variables such as temperature, humidity, wind direction, or wind speed. For some loggers this average is generated from a set of 2-sec anemometer readings collected for 10 minutes. With data loggers reporting 10-min averages, wind speeds sensed beyond the anemometer calibration range may add a bias to the 10-min mean. For example, to measure a 10-min averaged wind speed of 16 m/s would require a wind distribution that includes winds and gusts moving much faster than 16 m/s. An anemometer calibrated at the 4 to 16 m/s IEC test range may not necessarily guarantee the measurement of winds faster than 16 m/s. Thus, in order to develop a better accuracy in the field measured wind speed, it is recommended that anemometers be calibrated to the range of wind speeds predicted at a particular site.

A more practical guideline for determining the anemometer calibration test speed range is presented in the ASTM D 5096-02 and ISO 17713-1 standards. ASTM D 5096-02 first introduced the idea of a speed range starting near anemometer threshold up to 50% of the application speed. The standard also recommended not extrapolating beyond the range at which the anemometer was tested. An updated recommendation from ISO 17713-1 suggests performing the range given in ASTM plus additional speeds up to the application speed. If a particular facility cannot perform the required speed range, it is to be noted in the calibration report. According to ASTM and ISO, it is not recommended to extrapolate wind data beyond the anemometer calibration test range.

D. Test Speed Range Based on Anemometer Performance

Anemometers are calibrated to equate the raw signal from the sensor to a reference wind speed magnitude. Since rotating anemometers are ideally designed so that its raw signal is, to a certain degree, linearly related to the mean local wind speed, it is commonly assumed that an anemometer calibrated at any speed range can provide a linear interpolation of speeds outside of the test range. However, most rotating anemometers respond non-linearly for certain speed ranges, particularly near the anemometer threshold speed and sometimes at higher application speeds. Due to bearing friction, anemometers are non-linear at the lower spin rates or lower wind speeds. Anemometers may also be non-linear at higher speeds due to changes in aerodynamics.

In order to investigate the effect of wind speed range in the calibration results of an anemometer, tests were conducted in the wind tunnel facility at Otech Engineering, Inc, Davis, CA. The Otech facility is an open-circuit, suction-type wind tunnel which is primarily used to calibrate one anemometer at a time in an enclosed test section of size 0.61 m x 0.61 m x 1.22 m (2' x 2' x 4'). The wind is driven by a 15 hp fan motor capable of generating speeds up to 36 m/s in the test section. Current test speed protocols range from 4 to 26 m/s. This speed range was chosen based on the cut-in and cut-out speeds for a typical wind turbine. Although the lowest test speed is slightly higher than a typical anemometer threshold speed, the range of speeds up to 26 m/s does include the highest probability of winds sensed in the field. Wind tunnel speed is determined using four equally positioned Pitot-static tubes at the entrance into the test section. Environmental conditions (i.e., ambient pressure, temperature, and humidity) are also simultaneously measured. Flow quality in the test section is also uniformly maintained to within +/- 0.1% with turbulence levels less than 0.1%. Using this Pitot-static tube system, the uncertainty in the reference speed averages to about 0.5% for all test speeds. According to current standards, uncertainty in the calibration is based on the uncertainty in the reference wind speed. Thus, in the Otech wind tunnel facility, anemometers calibrated for this investigation are associated with a standard uncertainty of 0.5% for all test speeds.

For this investigation, calibration tests were performed on four types of anemometers, three cup anemometers, designated as Cup Anemometer #1, #2, and #3, and a propeller anemometer. For this paper, generic numbers were assigned to the anemometer models. Each instrument was calibrated for a range of 4 to 26 m/s at 2 m/s increments. Linear transfer functions were then determined for the 4 to 26 m/s range and for the range of 4 to 16 m/s. The following plots present the calibration data, the resulting transfer functions, and the residuals at each wind speed. Figures 2, 4, 6, and 8 are plots of the calibration data at 4 to 26 m/s along with the corresponding wind speed residuals from the linear transfer function. Figures 3, 5, 7, and 9 are plots of the calibration data at 4 to 16 m/s along with the extrapolated wind speeds up to 26 m/s and the corresponding residuals.

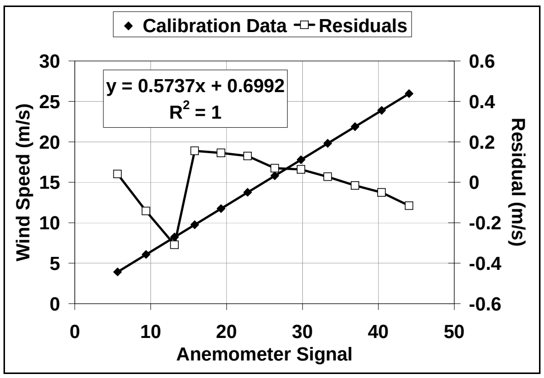

Figure 2: Calibration for Cup Anemometer #2 at 4 to 26 m/s test speed range.

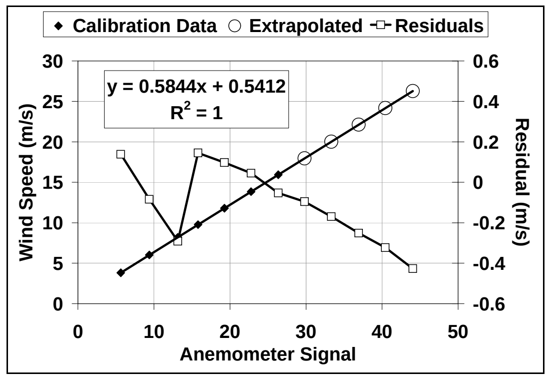

Figure 3: Cup Anemometer #2 resulting residuals for wind speeds interpolated using a transfer function generated at 4 to 16 m/s.

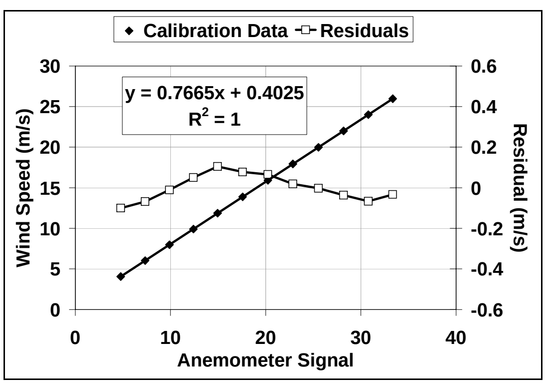

Figure 4: Calibration for Cup Anemometer #1 at 4 to 26 m/s test speed range.

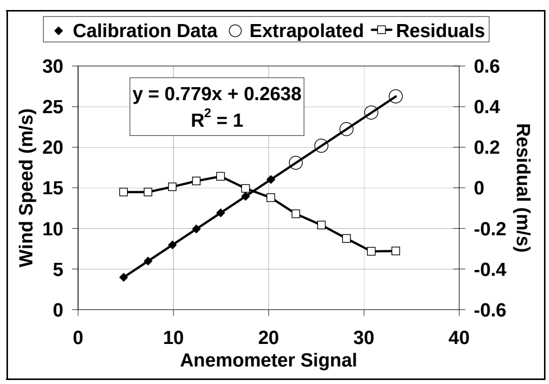

Figure 5: Cup Anemometer #1 resulting residuals for wind speeds interpolated using a transfer function generated at 4 to 16 m/s.

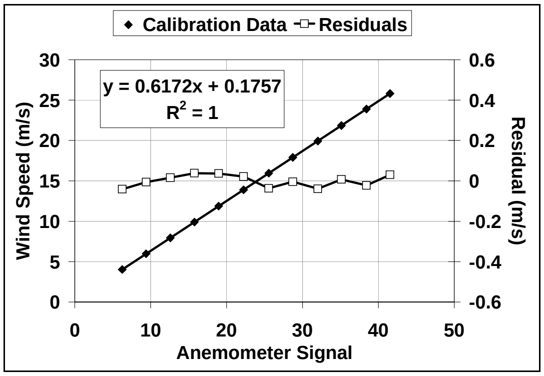

Figure 6: Calibration for Cup Anemometer #3 at 4 to 26 m/s test speed range.

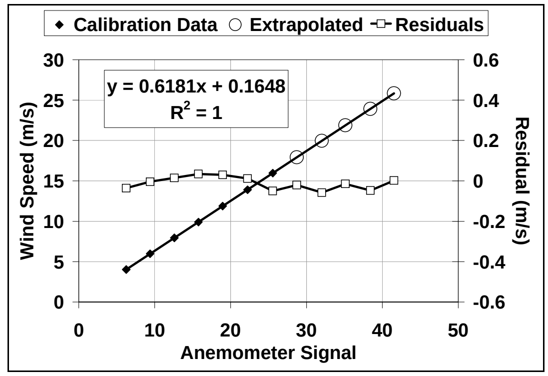

Figure 7: Cup Anemometer #3 resulting residuals for wind speeds interpolated using a transfer function generated at 4 to 16 m/s.

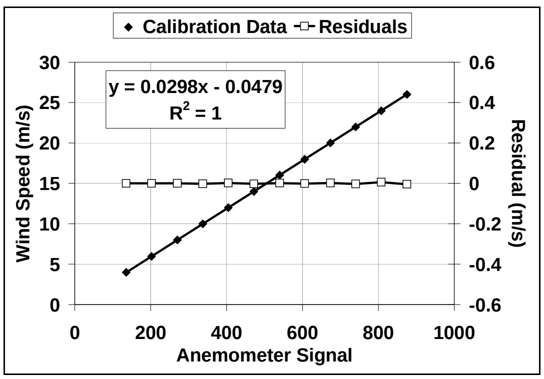

Figure 8: Calibration for Propeller Anemometer at 4 to 26 m/s test speed range.

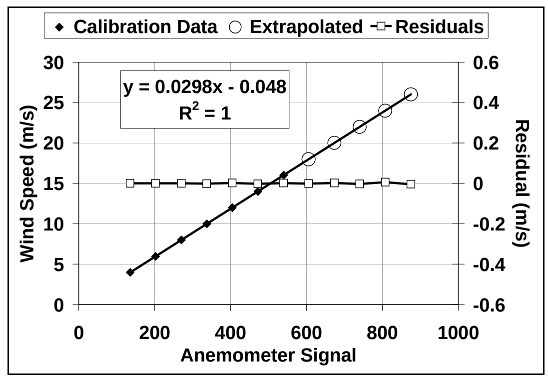

Figure 9: Propeller Anemometer resulting residuals for wind speeds interpolated using a transfer function generated at 4 to 16 m/s.

An overall comparison between the residual graphs generated using the 4 to 26 m/s versus 4 to 16 m/s transfer functions for each anemometer reveals that the propeller anemometer remains highly linear regardless of the test speed range as shown in Figures 8 and 9. However, for the cup anemometers, the linearity varies with speed range for different models.

In the extreme case of Cup Anemometer #1, the highly non-linear feature in the low wind speeds develops large errors in all speed ranges as shown in Figure 2. In addition, when using the transfer function generated from the low speeds, errors in the extrapolation of higher wind speeds increased (see Figure 3). This is also evident for a more common anemometer response shown in Figures 3 and 4 for Cup Anemometer #2. In this case, the anemometer's linearity redirects at 12 m/s (see Figure 3), which is possibly due to changes in the rotational aerodynamics at this particular speed. Thus, using a transfer function calculated at 4 to 16 m/s does increase errors in wind speeds extrapolated beyond the calibration range. In Figure 4, for example, the transfer function generated from 4 to 26 m/s resulted with a residual of approximately -0.01 m/s at 26 m/s. The transfer function obtained from 4 to 16 m/s, however, increased the residual to -0.3 m/s. Based on these first two cup anemometer cases, it is recommended that the calibration speed range cover the range sensed in the field in order to gain better accuracy in regions of non-linearity.

Fortunately, some cup anemometers are more ideally linear, as in the case of Cup Anemometer #3. According to Figures 6 and 7, this particular sensor shows that same residual response for any calibration speed range. Regardless of the performance, it is still essential to calibrate anemometers to the speed range sensed in the field to increase the accuracy of the wind speed reading.

E. Conclusion

In this study, a review of the current anemometer calibration standards was presented. Three standards for calibration guidelines currently published are the IEC 61400-12-1, ASTM D 5096-02, and ISO 17713-1. The IEC standard is specifically for turbine power performance, while the ASTM and ISO standard encompasses general meteorology. An important note is that the IEC standard specifies a calibration test range of 4 to 16 m/s. The ASTM and ISO standard covers a much broader test range which covers the entire spectrum of winds an anemometer could encounter in the field. Thus, the test speed range should be considered based on the historic wind distribution for a particular site. The anemometer calibration range should also be determined based on the performance of the anemometer. Based on a comparison of three anemometers, the linear transfer function from a more non-linear anemometer was determined to be most sensitive to the selection of test speeds. Due to the variation in calibration results for the same type of anemometer and at different speed ranges, it is highly recommended that each instrument be calibrated and that the calibration test speeds should cover an array generated in the free atmosphere.

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