Review of Anemometer Calibration Standards

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Anemometer calibration defines a relationship between the measured signals from a test anemometer to a simultaneously collected reference wind speed generated in a controlled test facility. There are three published standards that present test protocols for rotating anemometers: ASTM D 5096-02, ISO 17713-1, and IEC 61400-12-1. For sonic anemometers, two published standards are referenced: ASTM D 6011-96 and ISO 16622. A common requirement from all of these standards is that anemometer calibration is to be conducted in a steady state wind tunnel, in which local conditions would isolate the performance of the sensor from disturbances such as vibrations and off-angle winds. Procedures in IEC 61400-12-1 also specify that the wind tunnel reference speeds are to be measured using a Pitot tube system. Requirements in ASTM D 5096-02, ISO 17713-1, ASTM D 6011-96, and ISO 16622 allow the possibility of incorporating other types of reference wind measurement systems. This paper is a supplement for the poster presented in CANWEA 2009 and provides a review and comparison of current anemometer calibration standards as a guide for instrument manufacturers, distributors, and end users in defining appropriate test protocols for certain types of anemometers.

A. Introduction

Rotating anemometers are designed so that its rotation rate is related to the magnitude of the incoming wind. Typical methods of generating an output signal from a rotating anemometer can be done through a reed switch or through the pole interaction of a magnet to a coil. In general, a rotating anemometer is also ideally designed so that it is most sensitive to the horizontal wind component in the atmosphere. Thus, calibration is essentially performed in test facilities maintaining steady horizontal winds. Currently, there are three published standards that define the procedures for calibrating rotating anemometers, both cup and propeller type: ASTM D 5096-02 and ISO 17713-1, which is referenced for rotating anemometers applied in general meteorology applications, and IEC 61400-12-1, which is recommended for anemometers used in wind turbine performance testing.

Wind measurement from sonic anemometers is determined from the change in the propagation of sound waves between a sound transmitter and a receiver due to the magnitude of the incoming flow of atmospheric wind. Since these types of sensors are dependent on the speed of sound, they are essentially most sensitive to the local atmospheric density and to the angle of the incoming wind. Base calibration for sonic anemometers is performed in a zero-wind chamber, which involves the measurement of the acoustic pathlength and transient times. To fully complete the performance test of a sonic sensor, it is also necessary to evaluate the sensor through various temperature and pressure environments in the zero-wind chamber and to measure the response the sensor when subjected to various angles of incoming flow simulated in a wind tunnel. Two standards that define procedures for sonic anemometer testing are ASTM D 6011-96 and ISO 16622.

All published standards require the presentation of the uncertainty in the reference wind speed in the final anemometer calibration report. Currently, IEC 61400-12-1 is the sole standard that defines a method of anemometer calibration for the wind energy industry and particularly advises the deployment of cup anemometers specifically for wind turbine testing. This standard also defines the tests involved in determining the classification of a cup anemometer as a qualifier for a valid instrument to be used for wind turbine testing.

B. IEC 61400-12-1 Cup Anemometer Test Procedures

The International Electrotechnical Commission (IEC) is a global standards organization that consists of committees that review operational practices in electrical and electronic industry and research. The IEC also publishes international standards in collaboration with the International Organization for Standardization (ISO). A key publication related to the wind energy industry is IEC 61400-12-1, ed. 1, released in 2005. This particular standard was first introduced to the IEC by MEASNET (the International Measuring Network of Wind Energy Institutes). The purpose of this standard is “to provide uniform methodology that will ensure consistency, accuracy, and reproducibility in the measurement and analysis of power performance by wind turbines.” It was intended to specifically aid manufacturers, purchasers, and installers in the design and verification of the power performance of a wind turbine.

Wind power is proportional to the cube of wind speed, thus, wind speed measurement is critical in the performance evaluation of a wind turbine. Along with local atmospheric conditions, wind speed is to be acquired simultaneously with turbine power output in order to generate a wind turbine power curve. This power curve is then used to estimate annual energy production. In the IEC standard, cup anemometers are the preferred sensors for measuring the wind speeds used for power performance measurements since they provide the lowest uncertainty and have proven to be the most durable open-air instruments in wind turbine applications. As specified in section 5 of IEC 61400-12-1, cup anemometers are to be mounted on a meteorological tower positioned at a particular location near the wind turbine but undisturbed from the turbine’s dynamics.

Anemometer calibration is conducted to determine the transfer function that converts the instrument’s analog voltage or frequency output to wind speed. According to the IEC standard, cup anemometer calibration is to be conducted in a uniform, horizontal, steady-state flow of low turbulence levels. Such controlled conditions are best achieved in a controlled wind tunnel facility. The following table lists the IEC minimum performance requirements for a wind tunnel anemometer calibration facility.

Table 1: Wind tunnel requirements for IEC 61400-12-1 cup anemometer calibration testing.

Wind Tunnel Characteristic	*Description*	*Minimum Requirement*
Blockage Ratio	Ratio of the anemometer plus mount frontal area to the total wind tunnel test section area	Not to exceed 0.1 for open test sections, 0.05 for closed sections
Flow Uniformity	Percent difference in wind speed within the test section volume	Less than 0.2% in the longitudinal, transversal, and vertical directions
Horizontal Wind Gradient	Dynamic pressure differential at the area covered by the rotating cup anemometer	Must be less than 0.2%
Turbulence Intensity	Ratio between the wind speed standard deviation to the mean speed	Must be less than 2%

Based on these IEC wind tunnel requirements, anemometer calibration is to be performed with steady-state, uniform horizontal flow conditions across the anemometer. Thus, there should be no cross or vertical flow conditions and more importantly, the wind tunnel test section should maintain minimum to near-zero turbulence. In addition, the cup anemometers are to be specifically calibrated to a Pitot-static tube system, which itself is also calibrated to the appropriate test speed range. Pitot tubes are installed allowing for a maximum deviation of 1º from the incoming flow. From the IEC standard, the reference wind speed from a Pitot-static tube system is calculated using the differential pressure measured at the inlet of the Pitot-static tube and also the measurements of the local conditions inside the wind tunnel test section (i.e. ambient pressure, temperature, humidity). IEC requires that equipment used to measure the differential pressure from the Pitot-static tube, the ambient pressure, temperature, and relative humidity must be traceable to a national standards authority such as NIST (National Institute for Standards and Testing) in the United States. The data acquisition system designed to collect such measurements must also be of minimal interference and noise in that the calculated velocity from the Pitot tube system maintains a resolution of at least 0.02 m/s. The following is a list of required conditions, defined in IEC 61400-12-1, to be included in a cup anemometer calibration procedure.

1) The test anemometer shall be installed on a mounting stand similar to that used in field installation and shall be positioned to the incoming flow at a maximum declination of 1°.

2) Prior to every calibration round, the integrity of the experimental set-up shall be verified by means of comparative calibration of a “reference anemometer”.

3) Prior to calibration, the anemometer “shall be run in for about 5 minutes to avoid the effect that large temperature variations may have on the mechanical friction of the anemometer bearings”.

4) Calibration will be conducted for a wind speed range of 4 m/s to 16 m/s at a 1 m/s interval, according to the following sequence of test speeds: 4, 6, 8, 10, 12, 14, 16, 15, 13, 11, 9, 7, and 5 m/s. This rising and falling speed sequence is to identify any hysteresis during the test.

5) Before test data acquisition, the wind tunnel must be given adequate time to stabilize to the set wind speed. According to the IEC, “wind tunnel stability can be assumed if two successive 30 sec means are within 0.05 m/s of each other”.

6) For test data collection at the desired speed, the sampling frequency shall be at least 1 Hz at a sampling interval of 30 seconds, which could be increased for low resolution anemometers.

7) Anemometer calibration shall be reported with a thorough assessment of calibration uncertainty (i.e., wind tunnel speed), according to ISO guidelines.

To verify the integrity of the wind tunnel test facility, the IEC standard recommends that the facility designate a reference anemometer that would undergo at least five calibration tests at various times and environmental conditions. The IEC standard requires that repeatability must be maintained less than 0.5% at 10 m/s. A second IEC recommendation is for the facility to participate in “round robin” testing with other calibration facilities using a designated reference anemometer. The average calibration of the reference anemometer should agree with those of other facilities within 1% over the range of 4 to 16 m/s.

IEC 61400-12-1 also defines the test procedures required to determine cup anemometer classification, which provides a rating for the anemometer based on its performance characteristics in a particular environment. A classification number is used to help turbine evaluators determine a suitable anemometer for power performance testing. Classification involves sensitivity tests designed to evaluate the response of an instrument when subjected to various conditions such as atmospheric flow complexity, turbulence, and density changes. Through the IEC standard, cup anemometers are classified based on the combined results from 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. IEC cup anemometer classification is also calculated primarily for two types of terrain, Class A and Class B, the latter being the more complex. A number preceding the class letter is the classification number calculated from the prescribed sensitivity tests. More specifically, this number identifies the relative error in the anemometer’s indicated wind speed. For turbine power performance evaluation, the IEC standard recommends that an anemometer of Class 1.7A or Class 2.5B or lower shall be employed depending on terrain conditions at the turbine test site. For conditions not specified under Class A or B terrain, an anemometer of Class 1.7S or lower is suggested.

C. ASTM D 5096-02 Cup and Propeller Anemometer Test Procedures

ASTM (American Society for Testing Materials) is one of the world’s largest non-profit, voluntary standards development organizations. ASTM develops and publishes standards which provide consensus in the manufacture of materials and products and also establish protocols in systems and services. A guideline for performance testing of cup or propeller anemometers used for general meteorology applications is defined in ASTM D 5096-02, originally published in 1990. The purpose of this standard is not only to provide a method of calibration that produces a transfer function but also to determine certain performance characteristics (i.e., starting threshold, distance constant, and off-axis response) for cup or propeller anemometers using a wind tunnel facility. The following table lists the wind tunnel requirements specified by ASTM D 5096-02.

Table 2: Wind tunnel requirements for ASTM cup and propeller anemometer testing.

Wind Tunnel Characteristic	*Minimum Requirement*
Blockage	Anemometer front area is less than 5% of the test section cross-section area
Wind Speed Capability	Must be capable of reaching speeds up to at least 50% of the application range and must maintain speed within +/- 0.2 m/s
Flow Uniformity	Flow profile in the test section must be constant to within 1%
Turbulence	Must be less than 1% in the test section
Air Density Uniformity	Density profile in test section must be less than 3% difference
Wind Speed Reading	Maintain a relative accuracy of 0.1 m/s to its traceable source

Air density is a function of the local conditions. Thus, during tests the ambient pressure and temperature in the test section are to be monitored and reported. Similar to the IEC standard, all instruments used to measure the wind speed and the local conditions must be traceable to NIST or any other internationally recognized standards body. Following is a list of the critical steps and requirements from the ASTM calibration procedure or transfer-function test.

1) Install the anemometer at an angle of attack maintained within 0.5°.

2) Acquire wind tunnel speed and anemometer rotation rate along with test section environmental conditions. Collect data for 30 to 100 seconds at each test speed and at a sampling rate of at least 100 Hz. Ensure that the wind tunnel has stabilized to each test speed before collecting data. The time to stabilize depends on the anemometer distance constant.

3) Calibration is conducted for a speed range starting at two times the anemometer threshold, U_o, up to 0.5 times the maximum application speed, U_{max}. Incremental test speeds are then defined according to the following table of ascending and descending speeds, giving a total number of 20 test speeds.

Table 3: ASTM D 5096-02 Calibration Test Speed Protocol

Ascending Speeds	*Descending Speeds*
2 times U_o	0.5 times U_{max}
3 times U_o	0.4 times U_{max}
4 times U_o	0.3 times U_{max}
5 times U_o	0.2 times U_{max}
6 times U_o	0.1 times U_{max}
0.1 times U_{max}	6 times U_o
0.2 times U_{max}	5 times U_o
0.3 times U_{max}	4 times U_o
0.4 times U_{max}	3 times U_o
0.5 times U_{max}	2 times U_o

4) Conduct a least squares regression analysis using the collected wind speed and anemometer rotation data set to determine and report the slope and offset of the calibration transfer function.

5) Calculate and report the wind speed residuals by first determining a predicted wind speed value for a range of anemometer rotation rates using the determined linear transfer function and then subtracting this predicted value from the measured wind speed.

6) "Extrapolation of data beyond the range of actual measurement is not recommended…" Thus, if the maximum test speed is 50% of U_{max}, then the transfer function only applies to that particular speed range.

Along with procedures to calibrate an anemometer, ASTM also specifies methods of determining three types of anemometer performance characteristics: 1) starting threshold, 2) distance constant and 3) off-axis response. Starting threshold is the wind speed at which the anemometer starts to rotate. Distance constant, directly analogous to time constant, is the distance that air passes an anemometer as the anemometer reaches a certain equilibrium speed. In order to have an anemometer most sensitive or responsive to the incoming wind, the instrument is typically designed with the lowest distance constant. The off-axis response evaluation is an angular response test similar to that specified in IEC 61400-12-1. For this type of test, the anemometer is subjected to various vertical angle rotations to determine its sensitivity to upslope and downslope winds as evident in complex terrain.

D. ISO 17713-1 Cup and Propeller Anemometer Test Procedures

ISO 17713-1, released in May 2007, is an international standard for performance testing rotating anemometers. This standard was based on ASTM D 5096-02 with updates to certain procedures. Requirements for the wind tunnel facility are similar. For anemometer calibration testing, a method of determining wind speed measurement resolution was added, adding a guideline in the data acquisition time interval for each test speed. ISO 17713-1 requires that a measurement resolution of 0.1 m/s or better be maintained. For anemometer pulse count technique, measurement resolution is calculated based on the wind distance passage per output pulse divided by the data acquisition time interval.

ISO 17713-1 also redefined the test speed range so that it would primarily cover the full range of intended use for the anemometer but also address the working range of the wind tunnel test facility. This test speed protocol also includes 5 points in the non-linear range of the anemometer (i.e., near threshold, U_o). In the ASTM standard, calibration was performed up to 50% of the application speed. ISO 17713-1 requires that at least five additional test speeds evenly spaced up to the application speed be included and that linear regression or transfer function analysis should not take into account test data acquired near the anemometer threshold speed. Similar to the recommendation from ASTM, ISO 17713-1 suggests not using the resulting calibration transfer function to extrapolate beyond the calibration test range since this would result to increased measurement uncertainties. A typical test speed protocol offered by ISO 17713-1 is as follows:

Table 4: ISO 17713-1 Calibration Test Speed Protocol

2 times U_o	0.5 times U_{max}	0.6 times U_{max}
3 times U_o	0.4 times U_{max}	0.7 times U_{max}
4 times U_o	0.3 times U_{max}	0.8 times U_{max}
5 times U_o	0.2 times U_{max}	0.9 times U_{max}
6 times U_o	0.1 times U_{max}	U_{max}

E. ASTM D 6011-96, Sonic Anemometer Test Procedures

ASTM D 6011-96 is a published standard for sonic anemometer performance testing procedures. Sonic anemometers evaluated under this standard will obtain the calibration transfer characteristics necessary for general meteorological applications. One of the most difficult challenges is that sonic anemometers are essentially three-dimensional sensors in which the horizontal wind speed reading is greatly affected by vertical or off-axis flow. Thus, performance testing proves to be much more complicated than that for cup or propeller anemometers. This ASTM standard provides a method for assessing the performance of sonic anemometers “that use inverse time solutions to measure wind velocity components and the speed of sound”. It is primarily intended to assist instrument manufacturers in the design and development of a sonic anemometer. However, it may also be used as a guide for test facilities and users in evaluating the performance for specific wind reading applications.

Wind tunnel requirements for sonic anemometer performance evaluation are similar to those defined in ASTM D 5096-02 for cup or propeller anemometer testing. An added requirement is that wind tunnel speeds from 1.0 to 10 m/s be maintained at +/- 0.1 m/s or better.

In order to understand the performance characteristics of a newly designed sonic anemometer, ASTM D 6011-96 recommends measurements of the: 1) acoustic pathlength, 2) system delay, 3) system delay mismatch, 4) thermal stability range, 5) velocity resolution, 6) shadow correction, 7) velocity calibration range, and 8) the acceptance angle. The first five performance tests are conducted in a zero-wind chamber, in which the calibration transfer characteristics of the instrument are obtained. Shadow correction, velocity calibration range, and the acceptance angle criteria are evaluated in a controlled wind tunnel facility to verify the response of the sonic anemometer.

Due to the three-dimensional sensitivity of sonic anemometers, shadow correction must be performed in a wind tunnel facility. This test process defines the sonic anemometer response or deviation at multiple orientations around the horizontal and vertical plane with respect to the incoming wind. For this testing, it is required that an apparatus that would rotate the anemometer around the horizontal and vertical plane be maintained with an angular alignment resolution of 0.5°. Shadow correction creates a "look-up" table or correction function, which may be used to adjust the sonic anemometer wind speed output according to its sensitivity to the particular off-angle position from the incoming flow. The following steps summarize the procedures in ASTM D 6011-96 to conduct sonic performance tests in a wind tunnel facility.

Step 1: With the sensor positioned vertically at zero angle of attack, select a low wind speed (about 2 m/s or lower) to test for orientations +/- 60 deg around its vertical axis at 10 deg increments. Repeat this procedure for a mid-range speed (about 5 to 6 m/s) and then for a high wind speed (about 10 m/s or greater).

Step 2: Repeat Step 1 for angles of attack at 5 deg increments starting with the sensor tilted 15 deg into the wind to 15 deg tilted away from the wind.

F. ISO 16622 Sonic Anemometer Test Procedures

An international standard for conducting performance testing on sonic anemometers is ISO 16622, which was released in September 2002. The goal of this standard is similar to that of ASTM D 6011-96 in that it provides the procedures that capture the three-dimensional response of a sonic anemometer. ISO 16622 defines four test methods:

1) Zero wind chamber test, which determines the zero wind offset for the instrument.
2) Wind tunnel test, which characterizes the deviation of the wind speed due to the angle of the incoming flow (i.e. shadow correction testing)
3) Pressure chamber test, which defines the operational air density range for the instrument.
4) Field test, which evaluates the sensor under possible adverse environmental conditions difficult to simulate in a laboratory.

Requirements for a wind tunnel facility are similar to that in ASTM D 6011-96. However, ISO 16622 requires that the wind tunnel be capable of producing wind speeds that cover the full application range of the sonic anemometer to be calibrated. Each steady setting of the wind speed must be maintained to within +/- 0.2 m/s, preferably +/- 0.1 m/s. For angle testing, the rotating fixture must have a 1° angular resolutions and +/- 0.5° repeatability. The wind tunnel test protocol in ISO 16622 is defined as follows:

Step 1: With the sensor positioned vertically at zero angle of attack, select a low wind speed (about 10% of the maximum test speed) to test for orientation +/- 360 deg around its vertical axis at 5 deg increments. Repeat step for 18%, 32%, 56%, and 100% of the maximum test speed.

Step 2: With the sensor positioned vertically at zero angle of attack and rotated at the worst case orientation (where the sensor reading is most disturbed by support structures), perform tests at 1%, 1.7%, 2.8%, 4.6%, 7.7%, 13%, 21%, 36%, 60%, and 100% of the maximum test speed. If such a wind speed range is not feasible for the wind tunnel lab, perform tests at 2%, 3%, 5%, 7%, 11%, 18%, 27%, 42%, 65%, and 100% of the maximum test speed. Repeat step for the best case orientation (where the sensor is least disturbed by support structures).

Step 3: Repeat Steps 1 and 2 with the sensor tilted 15 deg into the wind and then tilted 15 deg away from the wind.

G. Conclusion

In summary, five published standards that define anemometer calibration procedures were reviewed and summarized: IEC 61400-12-1, ASTM D 5096-02, and ISO 17713-1 for rotating anemometers and ASTM D 6011-96 and ISO 16622 for sonic anemometers. A summary of the wind tunnel facility requirements and anemometer test protocols is presented in the appendix. Of these standards, IEC 61400-12-1 is the only publication specifically related to the wind industry, in particular, the performance testing and classification of cup anemometers used for wind turbine power performance testing. Overall, most test facilities are capable of performing anemometer test procedures from these standards; however, some may be limited in wind speed test range. Recommended sonic anemometer test procedures define the necessary steps to understand the complete response of a newly design sonic sensor; however, such procedures prove to be quite rigorous for most test facilities, particularly, if performing calibration checks of field installed anemometers. In most cases, sonic procedures from standards are normally revised according to the application of the sensor and its manufacturer recommendations.

Appendix A: Summary of Wind Tunnel Requirements for Anemometer Testing

Wind Tunnel Characteristic	*Description*	*Summary of Minimum Requirements from Standards*
Blockage	Ratio of the projected area of the anemometer plus mount to the test section cross-sectional area	IEC 61400-12-1: not to exceed 10% for open test sections and 5% for closed test sections ASTM & ISO: less than 5%, preferably closer to 1%
Wind Speed Capability	Controlled wind speed range	IEC 61400-12-1: generate controlled speeds from 4 to 16 m/s ASTM D 5096-02, ISO 17713-1: produce speeds at least from 0 to 50% of the application speed for the anemometer under test with the controlled steady speed maintained within +/- 0.2 m/s ASTM D 6011-96: generate speeds of at least 1 to 10 m/s within +/- 0.1 m/s or better ISO 16622: produce speeds over full application range for the anemometer under test with the controlled steady speed maintained within +/- 0.2 m/s, preferably +/- 0.1 m/s
Flow Uniformity	Percent difference in wind speed or velocity profile within the test section volume	IEC 61400-12-1: less than 0.2% ASTM & ISO: uniform velocity profile to within 1%
Horizontal Wind Gradient	Pressure differential at the area covered by a rotating sensor	IEC 61400-12-1: must be less than 0.2%
Turbulence Intensity	Ratio between the wind speed standard deviation to its mean	IEC 61400-12-1: must be less than 2% ASTM & ISO: must be less than 1%
Air Density Uniformity	Percent difference in density within test section volume	ASTM D 5096-02 & ISO 17713-1: less than 3% difference
Data Acquisition	Method of collecting reference wind speed data	IEC 61400-12-1: maintain resolution of 0.02 m/s, sample frequency of at least 1 Hz for 30 sec ASTM & ISO: maintain resolution of 0.02 m/s, sample frequency of at least 10 Hz for 30 to 100 sec

Appendix B: Summary of Wind Tunnel Test Protocols for Rotating Anemometers

Standard	*Test Speed Protocol for Rotating Anemometers*
IEC 61400-12-1	4 to 16 m/s at 1 m/s increasing & decreasing increments (i.e. 4, 6, 8, 10, 12, 14, 16, 15, 13, 11, 9, 7, and 5 m/s)
ASTM D 5096-02	Test speeds start at 2 times the anemometer threshold, U_o, up to 0.5 times the maximum application speed, U_{max}, in the following ascending to descending speeds: Ascending Speeds / Descending Speeds 2 times U_o / 0.5 times U_{max} 3 times U_o / 0.4 times U_{max} 4 times U_o / 0.3 times U_{max} 5 times U_o / 0.2 times U_{max} 6 times U_o / 0.1 times U_{max} 0.1 times U_{max} / 6 times U_o 0.2 times U_{max} / 5 times U_o 0.3 times U_{max} / 4 times U_o 0.4 times U_{max} / 3 times U_o 0.5 times U_{max} / 2 times U_o
ISO 17713-1	Test speeds cover the range of intended use for the anemometer and the working range of the wind tunnel, which includes 5 points in the non-linear range of the anemometer (near threshold, U_o). Typical test protocols are as follows: 2 times U_o / 0.1 times U_{max} / 0.6 times U_{max} 3 times U_o / 0.2 times U_{max} / 0.7 times U_{max} 4 times U_o / 0.3 times U_{max} / 0.8 times U_{max} 5 times U_o / 0.4 times U_{max} / 0.9 times U_{max} 6 times U_o / 0.5 times U_{max} / U_{max}

Appendix C: Summary of Wind Tunnel Test Protocols for Sonic Anemometers

Standard	Wind Tunnel Test Protocol for Sonic Anemometers
ASTM D 6011-96	Step 1: With the sensor positioned vertically at zero angle of attack, select a low wind speed (~ 2 m/s or lower) to test for orientations +/- 60 deg around its vertical axis at 10 deg increments. Repeat this procedure for a mid-range speed (~ 5 to 6 m/s) and then for a high wind speed (~ 10 m/s or greater). Step 2: Repeat Step 1 for angles of attack at 5 deg increments starting with the sensor tilted 15 deg into the wind to 15 deg tilted away from the wind.
ISO 16622	Step 1: With the sensor positioned vertically at zero angle of attack, select a low wind speed (about 10% of the maximum test speed) to test for orientation +/- 360 deg around its vertical axis at 5 deg increments. Repeat step for 18%, 32%, 56%, and 100% of the maximum test speed. Step 2: With the sensor positioned vertically at zero angle of attack and rotated at the worst case orientation (where the sensor reading is most disturbed by support structures), perform tests at 1%, 1.7%, 2.8%, 4.6%, 7.7%, 13%, 21%, 36%, 60%, and 100% of the maximum test speed. If such a wind speed range is not feasible for the wind tunnel lab, perform tests at 2%, 3%, 5%, 7%, 11%, 18%, 27%, 42%, 65%, and 100% of the maximum test speed. Repeat step for the best case orientation (where the sensor is least disturbed by support structures). Step 3: Repeat Steps 1 and 2 with the sensor tilted 15 into the wind and then 15 deg away from the wind.

References

(1) ASTM D 5096-02 (2007). Standard test method for determining the performance of a cup anemometer or propeller anemometer. American Society for Testing and Materials.

(2) ASTM D 6011-96 (2008). Standard test method for determining the performance of a sonic anemometer/thermometer. American Society for Testing and Materials.

(3) IEC 61400-12-1 1st ed 2005-12 (2005). Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines. International Electrotechnical Committee (IEC).

(4) ISO 16622 (2002). Meteorology – Sonic anemometers/thermometers – Acceptance test methods for mean wind measurements. International Organization for Standardization (ISO).

(5) ISO 17713-1 (2007). Meteorology – Wind Measurements – Part 1: Wind tunnel test methods for rotating anemometer performance. International Organization for Standardization (ISO).