

# Anemometer Calibration for Wind Energy Applications

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Quality wind measurements are critical in evaluating wind turbine power performance, wind energy site assessments, and wind plant operations monitoring. To acquire the necessary precision and to lower the uncertainty in the field measured wind data, it is recommended that calibrated anemometers be deployed on meteorological towers. Calibration of an anemometer relates the raw output from the anemometer under test to a corresponding measure of a controlled reference wind speed in a wind tunnel. In the wind power industry, the most commonly referred standard is IEC 61400-12-1: “Wind Turbines - Part 12-1: Power Performance Measurements of Electricity Producing Wind Turbines”. This paper discusses the anemometer calibration methodology defined in IEC 61400-12-1 combined with recommendations from general meteorology standards. It also includes a detailed uncertainty analysis of the reference wind speed and, for future work, an extended uncertainty analysis that takes into account the uncertainty in the anemometer output signal and in the calibration transfer function.

## A. Introduction

Wind speed measurements are essential in wind energy related applications such as wind plant operations, wind turbine performance evaluations, and wind energy site assessments. In wind plant operations, wind speed measurements are used to validate the power output of the turbine and are also used for controlling the start-up and shut-down of a turbine. For some large turbines, it is necessary to provide a “kick-start” once atmospheric winds are potential for wind power generation. When the winds are too strong, a rotating turbine becomes a safety hazard, thus requiring a shut-down.

In wind turbine power performance evaluation, wind speed readings are matched with corresponding wind turbine power measurements in order to produce a power curve for the turbine (see Figure 1). Power curves represent the overall performance of a particular wind turbine model and are used to determine wind turbine power production.

For wind energy site assessment, the distribution of the measured wind speed and the wind turbine power curves are used to determine the predicted annual energy production, a critical value used in power purchase agreements. Since wind power is proportional to the cube of the wind speed, a slight error in the wind measurement could translate to a much greater error in the predicted annual energy production, emphasizing the importance of having accurate wind speed readings. To ensure the accuracy of atmospheric wind measurements, it is recommended that anemometers or wind measuring instruments be calibrated in accredited wind tunnel test laboratories that provide traceable calibrations along with the associated measurement uncertainties.

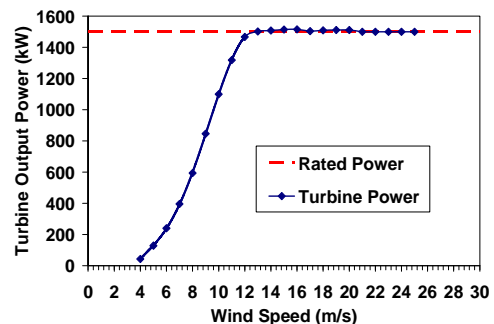


Figure 1: Sample wind turbine power curve.

## B. Anemometer Calibration Protocol

Anemometer calibration defines the relationship between the output of the anemometer, whether a voltage or frequency signal, and the measurement of the reference wind speed. Ideally, this relationship is linear (see Figure 2). During a calibration test, anemometer output is collected for a range of wind speed settings. A regression analysis is then conducted to determine a calibration transfer function. Wind speed residuals can also be determined by finding the difference between the calculated wind speed based on the linear regression equation and the measured reference speed. A sample wind speed

residual graph is presented in Figure 3. From the linear regression analysis, two statistical measures are also calculated and used to represent the degree of linearity between the anemometer output signal and corresponding reference wind speed readings: the correlation coefficient,  $R$ , and the standard error of estimate,  $STE$ .

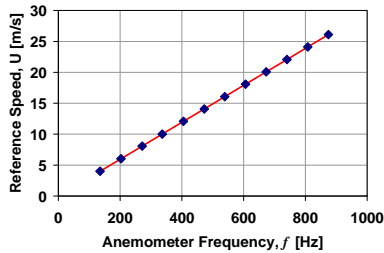


Figure 2: Sample calibration result with linear regression line.

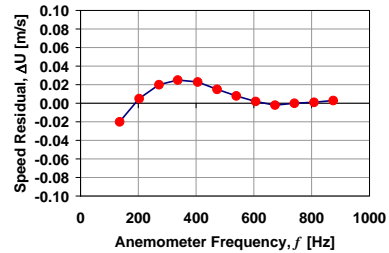


Figure 3: Sample wind speed residual graph of an anemometer calibration.

Several techniques of anemometer calibration have been attempted including using a moving vehicle where the anemometer under test is moved through the air. However, a more controlled test methodology, required by current test standards, is done using a wind tunnel where air is moved across the anemometer under test. Some facilities test one anemometer at a time while there are also those that test multiple anemometers during one calibration cycle. Testing multiple anemometers during one calibration cycle allows a test facility the advantage of getting more anemometers calibrated at once. However, in order to reduce the biases from the disturbance of another object in the test area, standards recommended that anemometers are calibrated one at a time in a wind tunnel.

In the wind energy industry, the most commonly referred publication for anemometer calibration is IEC 61400-12-1, released in December 2005. This particular document provides calibration procedures for cup anemometers used in turbine power performance evaluation. A calibration protocol for both cup and propeller anemometers is also provided in ASTM D 5096-02, originally published in 1990. This particular standard applies to anemometers used for general meteorology applications including wind resource assessment. In May 2007, ISO 17713-1 was released, which is an international standard for calibration and performance testing of rotating anemometers and, essentially, an updated version of ASTM D 5096-02. Although details in these standards differ in some ways, a common requirement for anemometer calibration and performance evaluation is that tests are to be conducted under controlled conditions using a low turbulence, uniform-flow wind tunnel. The difference between these standards is the protocols for calibration test speeds. IEC 61400-12-1 specifically requires a specific set over the range of 4 to 16 m/s. ASTM D 5096-02 and ISO 17713-1, however, requires a range starting from slightly faster than the anemometer threshold speed to as high as the application speed or the speed at which the anemometer would be subjected to during its operational life. Since most wind tunnel test facilities are incapable of meeting anemometer application speeds, ISO 17713-1 states that the top test speed may be the maximum speed of the wind tunnel facility.

### C. Introduction to Uncertainty

Uncertainty of a measured variable is a summarized estimate of the errors in a single measured variable. It includes the propagation of bias,  $\beta$ , and precision,  $\sigma$ , errors that surround a particular measurement as shown in Figure 4. Here,  $X_{true}$  is the true value for a particular variable, such as wind speed, and  $\bar{X}$  is a measured variable from a certain instrument system, such as a wind tunnel Pitot-static tube system. The bias error,  $\beta$ , is the fixed error that defines the offset of  $\bar{X}$  from  $X_{true}$ . Some references identify the bias as systematic errors, which typically fall as Type B errors according to the ISO GUM<sup>(5)</sup> and NIST TN 1297<sup>(9)</sup>. With multiple readings of  $\bar{X}$ , precision errors, based on the

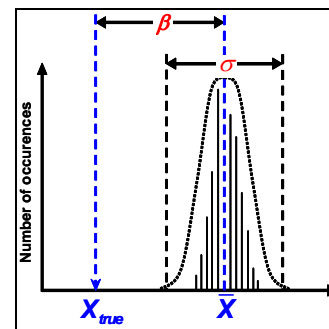


Figure 4: Bias,  $\beta$ , and random error,  $\sigma$ , contributions to uncertainty.

variability of the readings at a particular statistical confidence interval, define repeatability or variability of  $\bar{X}$ . Precision errors are also known as random errors, typically identified as Type A errors according to the GUM<sup>(5)</sup> and NIST TN 1297<sup>(9)</sup>.

Uncertainty is of great importance and can be a powerful tool in the wind energy industry such that it could be used to define whether or not a wind farm project is successful. For developers and finance institutions, the feasibility of a project and the degree of financial risks and returns are predicted partly by wind power uncertainty estimates. For wind energy consultants, an uncertainty analysis can be used to track down sources that generate errors in a wind energy estimate so that recommendations may be made to improve the system. Unfortunately, uncertainty can also be misleading when presented based on incomplete analysis in error propagation or for incorrect use of terminology. At times uncertainty is referred to as a measure of accuracy when, on the contrary, accuracy is a form of bias error,  $\beta$ , that represents only a partial role in uncertainty. By definition, accuracy is a closeness of agreement between a measured value,  $\bar{X}$ , and a true value,  $X_{true}$ .

A common question from end users in the wind energy industry is whether to use uncalibrated or calibrated anemometers to conduct wind measurements. With uncalibrated anemometers, users resort to applying the manufacturer's published transfer function to convert the anemometer output to wind speed. The published transfer function does have a degree of uncertainty which essentially adds only to the bias of the same model anemometer. From the manufacturer's specification, a level of accuracy is also assigned to the anemometer; however, this value also only applies as a bias error. A complete uncertainty analysis investigates not only bias errors but also precision errors, which are related to the repeatability of the wind measurement. It is possible that significant precision errors would be revealed during calibration. In order to gain a better understanding of the uncertainty in the field measured wind speed, calibrated anemometers should be employed. With a calibrated anemometer, error sources of its measurement performance would be accounted for.

#### D. IEC 61400-12-1 Uncertainty Analysis Method

There are several references providing methods in determining the uncertainty of an anemometer calibration. For the wind energy industry, the most widely referred standard is IEC 61400-12-1. This particular document primarily provides the steps in conducting a field evaluation of the performance of a wind turbine. The evaluation includes site measurements of the local wind speed, which is used as part of the power curve of the wind turbine. Within the appendices of this standard are procedures in performing a cup anemometer calibration transfer function test along with other various tests that would evaluate the instrument's sensitivity to certain terrain and atmospheric conditions. The standard also specifies that cup anemometer calibration is conducted using a wind tunnel test facility that incorporates a Pitot-static tube system to measure the reference wind speed. Some test facilities do choose to incorporate other methods to measure the reference speed such as hot wire anemometry, laser Doppler velocimetry, or even propeller or other types of dynamic anemometers. In the IEC standard, however, uncertainty analysis is conducted based on the errors accumulated in the reference wind speed measurement from a Pitot-static tube system.

When an anemometer is calibrated to the wind speed measurement sensed by the Pitot-static tube system, the IEC standard suggests that the uncertainty is presented based on the uncertainty in the reference wind speed,  $V$ , defined in Equation 1.

$$V = k_b \sqrt{\frac{2k_c \Delta p}{C_h \rho}} \quad \text{Eq. (1)}$$

Here,  $\Delta p$  is the differential pressure reading from the Pitot-static tube,  $C_h$  is the Pitot-static tube head coefficient,  $\rho$  is the density,  $k_c$  is the wind tunnel calibration factor, and  $k_b$  is the blockage correction. In more detail, the density can be defined in terms of the ambient pressure,  $P$ , the ambient temperature,  $T$ , the relative humidity,  $\phi$ , vapor pressure,  $P_w$ , the gas constant for air,  $R_{air}$ , and the gas constant for water,  $R_w$ , as defined in Equation 2. Vapor pressure and gas constants for air and water are then defined in the following Equations 3, 4, and 5, respectively.

$$\rho = \frac{1}{T} \left[ \frac{P}{R_{air}} - 0.01\phi P_w \left( \frac{1}{R_{air}} - \frac{1}{R_w} \right) \right] \quad \text{Eq. (2)}$$

$$P_w = 0.0000205 \exp(0.0631846T) \quad \text{Eq. (3)}$$

$$R_{air} = \frac{R}{M_{air}} \quad \text{Eq. (4)}$$

$$R_w = \frac{R}{M_w} \quad \text{Eq. (5)}$$

Here,  $R$  is the universal gas constant.  $M_{air}$  and  $M_w$  are the molecular weights for air and water, respectively. Using the terms listed above, the reference wind speed measured from a Pitot-static tube system previously defined in Equation 1 can be expanded as follows.

$$V = k_b \sqrt{\frac{2k_c \Delta p R T}{C_h [P M_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846T) (M_{air} - M_w)]}} \quad \text{Eq. (6)}$$

This form of the wind speed equation allows a more direct identification of the variables that are most sensitive to the calculation. From Equation 6, the independent variables, terms with exact values as defined in NIST, are found to be  $M_{air}$  and  $M_w$ . Since independent variables have no systematic or random errors, further sensitivity analysis are not required. Dependent variables are essentially measured or pre-calculated parameters which do require further analysis. Thus, from Equation 6, uncertainty in the reference wind speed measured by a Pitot-static tube system is a function of the dependent variables,  $k_b$ ,  $k_c$ ,  $C_h$ ,  $R$ ,  $P$ ,  $T$ ,  $\Delta p$ , and  $\phi$ , and is then defined as:

$$U_V = \sqrt{(B_V)^2 + (tS_V)^2} \quad \text{Eq. (7)}$$

Here,  $B_V$  represents the propagation of systematic or bias error contributions and is a function of all the dependent variables found in Equation 6. Thus, the propagation of systematic errors is defined as:

$$B_V = \sqrt{\left( \frac{\delta V}{\delta k_b} B_{k_b} \right)^2 + \left( \frac{\delta V}{\delta k_c} B_{k_c} \right)^2 + \left( \frac{\delta V}{\delta C_h} B_{C_h} \right)^2 + \left( \frac{\delta V}{\delta R} B_R \right)^2 + \left( \frac{\delta V}{\delta P} B_P \right)^2 + \left( \frac{\delta V}{\delta T} B_T \right)^2 + \left( \frac{\delta V}{\delta \Delta p} B_{\Delta p} \right)^2 + \left( \frac{\delta V}{\delta \phi} B_\phi \right)^2} \quad \text{Eq. (8)}$$

In Equation 8 above,  $B_{k_b}$ ,  $B_{k_c}$ ,  $B_{C_h}$ ,  $B_R$ ,  $B_P$ ,  $B_T$ ,  $B_{\Delta p}$ , and  $B_\phi$  are the bias errors from each of the dependent variables. For the measured variables,  $P$ ,  $T$ ,  $\Delta p$ , and  $\phi$ , bias errors can be found from data acquisition, signal conditioning, and instrument performance such as linearity or accuracy. For the assigned or property variables,  $k_b$ ,  $k_c$ ,  $C_h$ , and  $R$ , "fossilized" errors are generally applied, representing both the random and systematic errors in the determination of such variables.

From the following Equation 9,  $S_V$  signifies the propagation of random or precision error contributions which originate only from the measured dependent variables,  $P$ ,  $T$ ,  $\Delta p$ , and  $\phi$ . The value of  $t$  for 95% confidence at infinite ( $\infty$ ) degrees of freedom is 1.96<sup>(5)</sup>. The propagation of random errors is defined as according to the following equation.

$$S_V = \sqrt{\left( \frac{\delta V}{\delta P} S_P \right)^2 + \left( \frac{\delta V}{\delta T} S_T \right)^2 + \left( \frac{\delta V}{\delta \Delta p} S_{\Delta p} \right)^2 + \left( \frac{\delta V}{\delta \phi} S_\phi \right)^2} \quad \text{Eq. (9)}$$

Random errors are the variability in the measured variables. Thus,  $S_P$ ,  $S_T$ ,  $S_{\Delta p}$ , and  $S_\phi$ , are simply the standard deviations of the mean values from the corresponding measured variables. For both Equations 8 and 9, the partial differentials in front of each term are the corresponding sensitivity coefficients of each dependent variable. These partial differentials are essentially derived from the expanded reference wind speed, Equation 6. Below displays a table of the sensitivity equations required in Equation 6.

**Table 1: Sensitivity coefficient partial differential equations for each dependent variable.**

Dependent Variable	Sensitivity Coefficient Equation	Equation Number
Blockage Coefficient	$\frac{\delta V}{\delta k_b} = \frac{\sqrt{2\Delta p R T}}{C_h [PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)]} = \frac{V}{k_b}$	Eq. (10)
Pitot-static Tube Head Coefficient	$\frac{\delta V}{\delta C_h} = -\frac{1}{2} \frac{k_b}{C_h^{3/2}} \sqrt{\frac{2\Delta p R T}{PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)}} = -\frac{1}{2} \frac{V}{C_h}$	Eq. (11)
Universal Gas Constant	$\frac{\delta V}{\delta R} = \frac{1}{2} k_b \sqrt{\frac{2\Delta p T}{RC_h [PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)]}} = \frac{1}{2} \frac{V}{R}$	Eq. (12)
Ambient Pressure	$\begin{aligned} \frac{\delta V}{\delta P} &= -\frac{1}{2} \frac{k_b M_{air}}{[PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)]^{3/2}} \sqrt{\frac{2\Delta p R T}{C_h}} \\ &= -\frac{1}{2} \frac{VM_{air}}{PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)} \end{aligned}$	Eq. (13)
Ambient Temperature	$\begin{aligned} \frac{\delta V}{\delta T_K} &= k_b \sqrt{\frac{2\Delta p R}{C_h}} \frac{0.5(T_K)^{-1/2} [PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)]^{1/2} - 0.5 [PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)]^{-1/2} (T)^{1/2}}{PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)} \\ &= \frac{1}{2} V \left[ \frac{1}{T} + \frac{1.295 \times 10^{-8} \phi \exp(0.0631846 T)(M_{air} - M_w)}{PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)} \right] \end{aligned}$	Eq. (14)
Differential Pressure	$\frac{\delta V}{\delta \Delta p} = \frac{1}{2} k_b \sqrt{\frac{2RT}{\Delta p C_h [PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)]}} = \frac{1}{2} \frac{V}{\Delta p}$	Eq. (15)
Relative Humidity	$\begin{aligned} \frac{\delta V}{\delta \phi} &= -\frac{1}{2} \frac{k_b [-2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)]}{[PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)]^{3/2}} \sqrt{\frac{2\Delta p R T}{C_h}} \\ &= \frac{1}{2} \frac{V [-2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)]}{PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846 T)(M_{air} - M_w)} \end{aligned}$	Eq. (16)

An uncertainty analysis using the methodology defined in IEC 61400-12-1 was conducted for the Otech Engineering Wind Tunnel Facilities (see Figure 5). Otech operates three suction-type, uniform-flow, and low-turbulence wind tunnels with test sections of size 0.6 m width by 0.6 m height by 1.2 m length

(see Figure 6). With this size most anemometers occupy a blockage ratio of less than 0.3%. Wind speed is measured in the test section using a Pitot-static tube system, which includes simultaneous measurements of the differential pressure sensed from the Pitot-static tube, the barometric pressure, temperature, and relative humidity.



Figure 5: Otech Engineering Wind Tunnel Facilities located at Davis, CA.

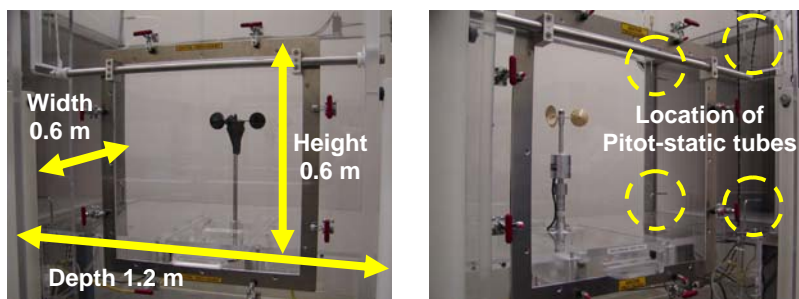


Figure 6: Anemometer calibration testing using a Pitot-static tube system.

Anemometer output is essentially associated to its rate of rotation. More commonly, it is collected as a TTL or square-wave pulse signal, of which the frequency of the pulse, determined from a pulse count method or an FFT analysis, is the anemometer's rate of rotation (see Figure 7). In some cases, the output is a sine wave signal, which requires an FFT analysis to determine the frequency. There are also some anemometers that output a voltage signal, which is an internally processed conversion from the pulse or sine signal.

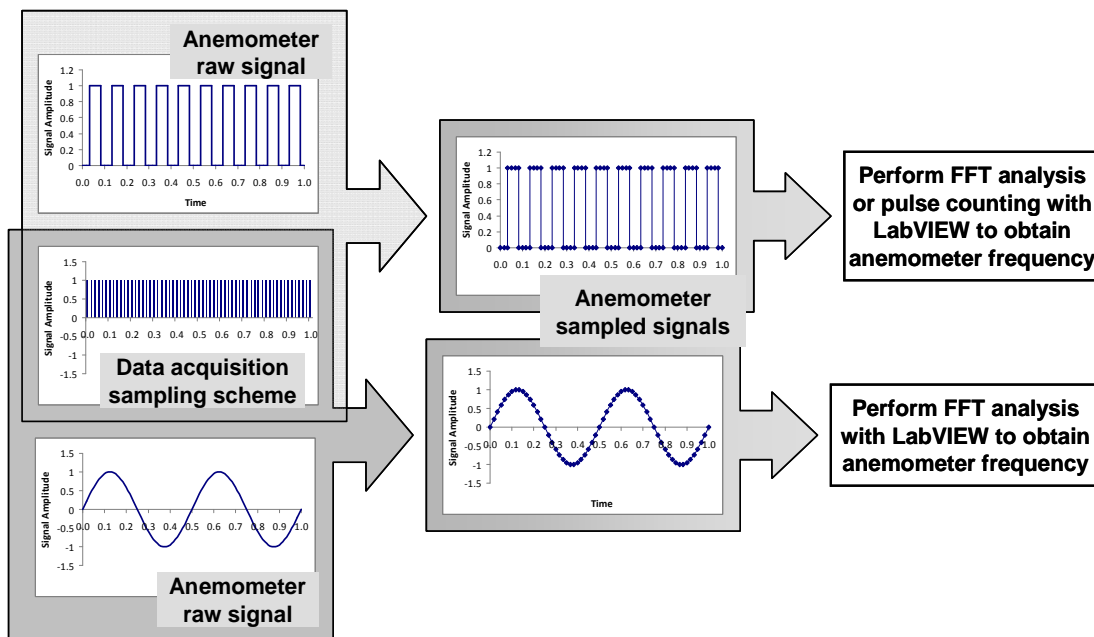


Figure 7: Data acquisition and post-processing of anemometer signal using LabVIEW.

In order to time correlate the calibration test, signal from a test anemometer and the corresponding controlled reference wind speed are measured simultaneously. This is made possible with a LabVIEW data acquisition system, which provides a near-real time view of a calibration (see Figure 8).



**Figure 8: Calibration testing using LabVIEW wind tunnel control system and data acquisition.**

A data set from a sample anemometer calibration is shown in the following Figure 9. From the data table, a column of the corresponding uncertainty for each wind speed is presented, and calculated based on the method according to IEC 61400-12-1 guidelines. For this case, the average relative uncertainty in the reference wind speed measurement for test speeds ranging from 4 to 26 m/s is approximately 0.5%.



Wind Speed (m/s)	Anemometer Output (Hz)	Wind Speed STD (m/s)	Wind Speed Bias Error (m/s)	Wind Speed Random Error (m/s)	Wind Speed Uncertainty (m/s)	Relative Wind Speed Uncertainty
3.99	6.25	0.003	0.019	0.003	0.020	0.51%
5.97	9.40	0.005	0.028	0.005	0.030	0.50%
7.96	12.59	0.004	0.037	0.004	0.038	0.48%
9.94	15.76	0.007	0.047	0.007	0.049	0.49%
11.92	18.96	0.007	0.056	0.007	0.057	0.48%
13.92	22.23	0.010	0.065	0.010	0.068	0.49%
15.91	25.56	0.011	0.075	0.011	0.078	0.49%
17.90	28.73	0.012	0.084	0.012	0.087	0.49%
19.90	32.02	0.011	0.093	0.011	0.096	0.48%
21.87	35.13	0.012	0.102	0.012	0.105	0.48%
23.87	38.42	0.014	0.112	0.014	0.115	0.48%
25.84	41.53	0.013	0.121	0.013	0.124	0.48%

**Figure 9: Sample anemometer calibration data generated at Otech Engineering.**

### E. Expanded Uncertainty Analysis for Anemometer Calibration

In the previous section, uncertainty presented in an anemometer calibration report was based on the uncertainty analysis in the reference wind speed measurement as defined in IEC 61400-12-1. However, this uncertainty presentation does not include error contributions from the measurement of the anemometer signal; thus, the presentation does not completely define the uncertainty in the calibration or the relationship between the anemometer signal to the corresponding reference wind speed. Since anemometer calibration also relies on the output of the anemometer itself, an uncertainty analysis of the anemometer signal must also be investigated. According to IEC 61400-12-1, the linear transfer function of the anemometer calibration must also be presented. If the linear regression equation is used to convert anemometer measurements in the field, which is commonly done in the wind energy and general meteorology industry, the uncertainty in the regression would also need to be presented in the anemometer calibration report. As defined in the following Equation 17, an expanded uncertainty of the anemometer calibration,  $U_{cal}$ , would be the sum of the squares of the uncertainty in the reference wind speed measurement as defined in IEC 61400-12-1,  $U_V$ , plus the uncertainty in the output of the anemometer under test,  $U_{IUT}$ , and the uncertainty in the linear regression fit,  $U_{LR}$ .

$$U_{cal} = \sqrt{(U_V)^2 + (U_{IUT})^2 + (U_{LR})^2} \quad \text{Eq. (17)}$$

Uncertainty in the output of the test anemometer,  $U_{IUT}$ , is essentially the propagation of inherent bias errors,  $B_{IUT}$ , and precision errors generated during the calibration test,  $S_{IUT}$ , as shown in see Equation 18. Bias errors in the anemometer output are primarily from the data acquisition system and, for the pulse output anemometer, the methodology of calculating for rate of rotation whether in Hz or rpm. The precision errors are accounted for in the standard deviation of anemometer output reading during the duration of the data collection. Again, the value of  $t$  for 95% confidence at  $\infty$  degrees of freedom is 1.96<sup>(6)</sup>. Bias errors are typically dominated by the method of determining the anemometer's rate of rotation. For instance, with a pulse count method, a bias error is associated with the least significant count. Precision errors may vary largely based on the standard deviations in the anemometer output at each wind speed. Typically, the range in the anemometer output uncertainty could vary from 0.5% to 1.5%.

$$U_{IUT} = \sqrt{B_{IUT}^2 + (tS_{IUT})^2} \quad \text{Eq. (18)}$$

Linear regression uncertainty,  $U_{LR}$ , may be approached in one of two options: 1) the comprehensive method which involves the uncertainty in the slope and offset of the linear regression along with a detailed evaluation of the corresponding sensitivities and 2) the classical method which involves statistical variables normally presented in calibration test reports, or may be calculated from data presented in calibration reports, and would provide a valid and conservative representation of the linear regression uncertainty. This paper presents the uncertainty analysis of the linear regression using the classical method, which can be done in one of two ways. One way involves the application of the standard error of estimate in the regression ( $STE_V$ ) as shown in Equation 19, where  $STE_V$  is defined in Equation 20. Here,  $STE_V$  is the major contributor to the calibration random uncertainty.

$$U_{LR_{Case1}} = \sqrt{\left( t \frac{STE_V}{V_i} \right)^2} \quad \text{Eq. (19)}$$

$$STE_V = \sqrt{\frac{\sum_{i=1}^N (V_i - mf_i - b)^2}{N - 2}} \quad \text{Eq. (20)}$$

A second way involves the standard error in the slope,  $STE_m$ , and in the offset,  $STE_b$ , where the uncertainty in the linear regression can then be calculated using Equation 21. To determine  $STE_m$  and  $STE_b$ , the standard error in the regression,  $STE_V$ , is also required as defined in Equations 22 and 23. Here, the term  $SS_f$  is the sum of the squares of the anemometer readings measured at each test wind speed defined in the following Equation 24.

$$U_{LR_{Case2}} = \sqrt{\left( t \frac{STE_m}{V_i} f_i \right)^2 + \left( t \frac{STE_b}{V_i} \right)^2} \quad \text{Eq. (21)}$$

$$STE_m = \sqrt{\frac{STE_V^2}{SS_f}} \quad \text{Eq. (22)}$$

$$STE_b = \sqrt{STE_V^2 \left( \frac{1}{N} + \frac{\bar{f}^2}{SS_f} \right)} \quad \text{Eq. (23)}$$

$$SS_f = \sum_{i=1}^N f_i^2 - \frac{\left( \sum_{i=1}^N f_i \right)^2}{N} \quad \text{Eq. (24)}$$

For a test range of 4 to 26 m/s, values of the standard error of the regression,  $STE_V$ , for various types of anemometers could range from 0.02 m/s to as much as 0.15 m/s. Thus, with the classical method defined in Equation 19, the linear regression uncertainty could vary from 0.2% to 5.0% depending on the  $STE_V$ . In most anemometer calibrations,  $STE_m$  and  $STE_b$  are much smaller compared to  $STE_V$ . However, when applied using the second classical method defined in Equation 21, the linear regression uncertainty varies from 0.2% to 5.0% similar to the calculations using the  $STE_V$  in Equation 19. As a note, in the second classical method, the dominant error source is generally the standard error in the offset. The following Table 2 is a summary of the equations required for an expanded uncertainty analysis of an anemometer calibration. Since the standard error in the linear regression is most commonly provided in calibration reports, Case 1 in the table below would provide an acceptable expression for linear regression uncertainty.

**Table 2: Summary of equations for anemometer calibration expanded uncertainty analysis.**

Anemometer Calibration Uncertainty	$U_{cal} = \sqrt{(U_V)^2 + (U_{IUT})^2 + (U_{LR})^2}$	~ 0.7% to 5.2%
Reference Wind Speed Uncertainty	$U_V = \sqrt{(B_V)^2 + (tS_V)^2}$	~ 0.5%
Anemometer Output Uncertainty	$U_{IUT} = \sqrt{B_{IUT}^2 + (tS_{IUT})^2}$	~ 0.5% to 1.5%
Linear Regression Uncertainty (Case 1)	$U_{LR_{Case1}} = \sqrt{\left(t \frac{STE_V}{V_i}\right)^2}$	~ 0.2% to 5.0 %
Linear Regression Uncertainty (Case 2)	$U_{LR_{Case2}} = \sqrt{\left(t \frac{STE_m}{V_i} f_i\right)^2 + \left(t \frac{STE_b}{V_i}\right)^2}$	~ 0.2% to 5.0 %

An expanded uncertainty analysis, shown in the following Table 3, was performed for the data presented in the sample calibration previously given in Figure . In this example, the uncertainty in the reference wind speed was presented. In Table 3, the anemometer output uncertainty is displayed in column 8, the regression uncertainty is shown in column 9, and the anemometer calibration uncertainty in column 10. Bias in the anemometer output measurement uncertainty was based on the errors in the data acquisition system while the random error was generated from the standard deviation of the readings. For this analysis, the linear regression uncertainty was calculated using the classical method, Case 1, shown in Table 2, which requires the standard error of estimate,  $STE_V$ . From the sample calibration case,  $STE_V$  was 0.031 m/s revealing a highly linear sensor. A lower standard error value generally corresponds to a more linear anemometer. Figure 10 displays the linear regression and speed residual plot for this sample calibration. Overall, the average anemometer calibration uncertainty for the sample test given in Figure 9 and for a test speed range of 4 to 26 m/s was found to be 1.5%, which was found to be primarily driven by the uncertainty in the anemometer output. Since it was found to be a highly linear sensor, there was little contribution from the linear regression uncertainty.

**Table 3: Expanded uncertainty analysis for sample calibration given in Figure 9.**

Wind Speed (m/s)	Wind Speed Uncertainty	Anem. Output (Hz)	Anem. STD (Hz)	Anemometer DAQ Bias Error (Hz)	Anemometer Random Error (Hz)	Anemometer Output Uncertainty	Case 1 Regression Uncertainty	Case 2 Regression Uncertainty	Anemometer Calibration Uncertainty
3.99	0.51%	6.25	0.061	0.00063	0.061	1.94%	1.52%	1.07%	2.52%
5.97	0.50%	9.40	0.082	0.00094	0.082	1.74%	1.02%	0.74%	2.08%
7.96	0.48%	12.59	0.119	0.00126	0.119	1.90%	0.76%	0.58%	2.10%
9.94	0.49%	15.76	0.111	0.00158	0.111	1.41%	0.61%	0.49%	1.62%
11.92	0.48%	18.96	0.116	0.00190	0.116	1.22%	0.51%	0.43%	1.41%
13.92	0.49%	22.23	0.130	0.00222	0.130	1.17%	0.44%	0.39%	1.34%
15.91	0.49%	25.56	0.145	0.00256	0.145	1.13%	0.38%	0.36%	1.29%
17.90	0.49%	28.73	0.169	0.00287	0.169	1.18%	0.34%	0.34%	1.32%
19.90	0.48%	32.02	0.172	0.00320	0.172	1.08%	0.30%	0.33%	1.22%
21.87	0.48%	35.13	0.172	0.00351	0.172	0.98%	0.28%	0.32%	1.13%
23.87	0.48%	38.42	0.174	0.00384	0.174	0.91%	0.25%	0.31%	1.06%
25.84	0.48%	41.53	0.208	0.00415	0.208	1.00%	0.23%	0.30%	1.13%

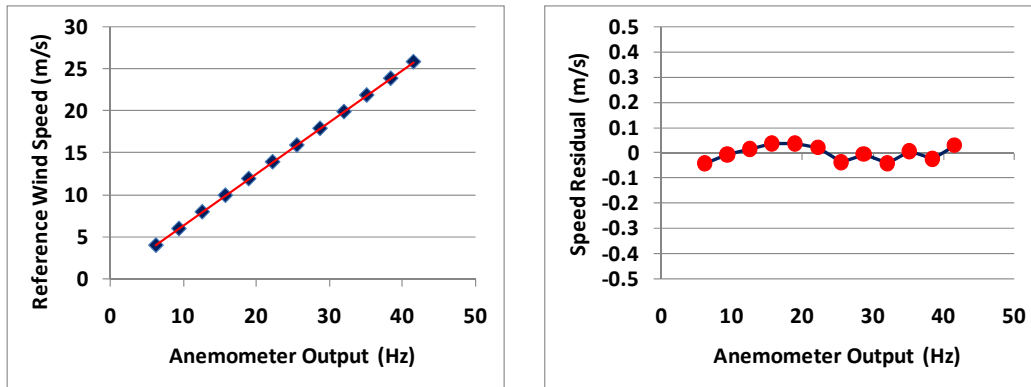


Figure 10: Linear regression and speed residual plots of sample calibration given in Figure 9.

## F. Conclusion

Anemometers are essential in several areas in the wind energy industry. Field wind measurements from anemometers are critical in determining the power production estimates for a wind turbine plant. In order to obtain the highest level of precision, calibrated anemometers must be deployed in meteorological towers. Anemometer calibration is essentially the method of relating the raw output of an anemometer of wind measuring instrument to a controlled reference wind speed. Under IEC 61400-12-1, the most commonly referred standard in the wind energy industry, anemometer calibration uncertainty is presented based only on the uncertainty of the reference wind speed measured at the test facility. For field applications, a more useful value would be an expanded uncertainty analysis of the anemometer calibration which not only includes the test facility wind speed uncertainty but also the uncertainty in the anemometer output measured in the test facility and, if applied, the uncertainty in the use of the calibration linear transfer function equation. This paper presented the classical approach to the uncertainty in linear regression equation, which provides a valid yet conservative estimate of the linear regression uncertainty. Overall, typical values for an anemometer calibration uncertainty range from approximately from 0.7% to 5.2%. This expanded uncertainty analysis revealed that errors in a field wind speed reading not only may be contributed to the controlled reference wind speed offered by a calibration facility, but also to the output of the anemometer under test and its degree of linearity.

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