Expanded Anemometer Calibration Uncertainty

Rachael V. Coquilla
Chief Engineer, Otech Engineering, Inc.
630 Peña Drive, Suite 800, Davis, CA 95618 USA
Email: rvcoquilla@otechwind.com   Phone: 530-757-2264

***SUMMARY*: Atmospheric wind measurements are critical in the wind energy industry. Thus, it is essential that calibrated anemometers be deployed in field installations. An anemometer calibration produces a transfer function that relates an anemometer raw signal to a corresponding controlled reference wind speed. In order to account for the errors associated in a field wind measurement, it is also important that the uncertainty in the calibration test be estimated. The most widely referred published standard in the wind energy industry that defines the requirements, procedures, and uncertainty method for cup anemometer calibration is IEC 61400-12-1. According to this standard, anemometer calibration uncertainty is reported based on the uncertainty analysis of the controlled reference wind speed. However, the resulting calibration transfer function, which includes errors from the test anemometer output reading, is what is programmed in field data loggers. Thus, the uncertainty in the controlled reference wind speed is just a portion of the total uncertainty in the calibration. The objective of this presentation is to propose a method of extending the anemometer calibration uncertainty to also include the error contributions from the anemometer output signal and the degree of linearity defined from the calibration transfer function. For sample applications, extended uncertainty analysis was performed on calibrations from commonly deployed anemometers in the wind energy industry.**

A. Importance of Field Wind Speed Measurements

Calibration testing is essential for anemometers used in the wind energy industry. Areas of critical wind measurements include 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. 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.

B. Anemometer Calibration Standards

In the wind energy industry, the most commonly referred publication for anemometer calibration protocol is IEC 61400-12-1: “Wind Turbines - Part 12-1: Power performance measurements of electricity producing wind turbines”, released in December 2005. This particular document provides calibration procedures for cup anemometers used in turbine power performance evaluation. Another calibration protocol for both cup and propeller anemometers is also provided in ASTM D 5096-02: “Standard test method for determining the performance of a cup anemometer or propeller anemometer”, 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: “Meteorology – Wind

Measurements – Part 1: Wind tunnel test methods for rotating anemometer performance" was released, which is an international standard for calibration and performance testing of rotating anemometers and, essentially, an extended and updated version of ASTM D 5096-02. Although details in these three standards differ in some ways, a common requirement for anemometer calibration and performance evaluation is that such tests are to be conducted in controlled conditions generated in 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. For this paper, anemometer calibrations were performed in accordance to IEC 61400-12-1.

C. Calibration Test Procedure

Anemometer calibration tests presented in this paper were performed in the Otech Wind Tunnel Laboratory WT3A, which is located in Davis, California, USA (see Figure 1). Otech Engineering, Inc. is an ISO/IEC 17025:2005 accredited laboratory and operates three suction-type (Eiffel-type) wind tunnels, housed in separate laboratory rooms. All of the wind tunnels were designed with a closed test section of similar size 61.0 cm crosswind width x 61.0 cm height x 121.9 cm downwind length. Otech Wind Tunnel WT3A is driven by a 30 hp (22 kW) fan motor, which can generate winds up to 45 m/s. The wind tunnels at Otech are also equipped with National Instruments LabVIEW data acquisition software and supporting hardware, which allows for near-real time, simultaneous measurements of all measuring instruments installed, including measurements of the output from the anemometer undergoing calibration testing.

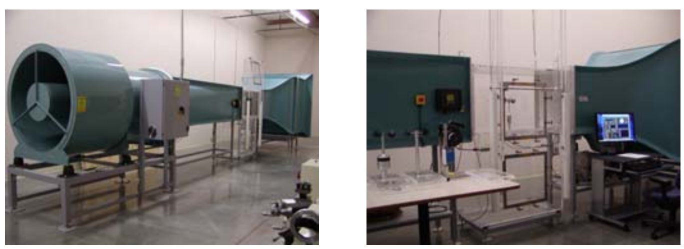

Figure 1: Otech Engineering Wind Tunnel Laboratory, WT3A.

Reference wind speed in the wind tunnel test section is measured using a Pitot-static tube system where the sensing tips of four (4) Pitot-static tubes are positioned at the entrance of the test section. Dynamic and static pressure inputs from the four Pitot-static tubes are ported to a single MKS Barotron type differential pressure transducer as shown in Figure 2 below.

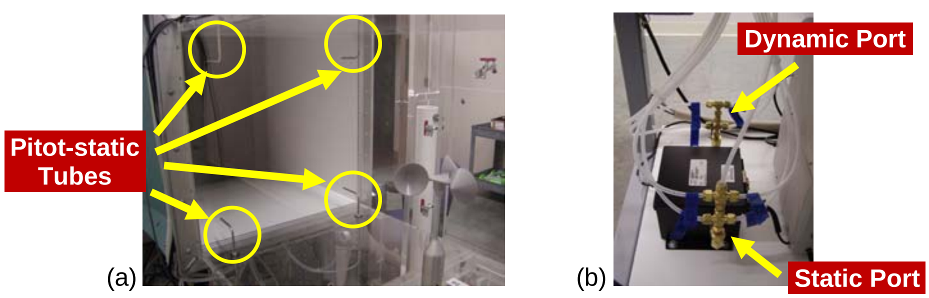

Figure 2: (a) Otech Wind Tunnel WT3A Pitot-static tube system installed in test section and (b) ported to an MKS Barotron differential pressure transducer.

Local conditions in the test section (i.e., ambient pressure, temperature, and relative humidity) are simultaneously measured in order to determine the corresponding local density used to calculate the reference wind speed. Test section ambient pressure is measured through the static ports of the Pitot-static tubes using a Setra Model 270 barometer (Figure 3a). Temperature and relative humidity is sensed by an Omega Model HX 94V probe inserted inside the test section (Figure 3b).

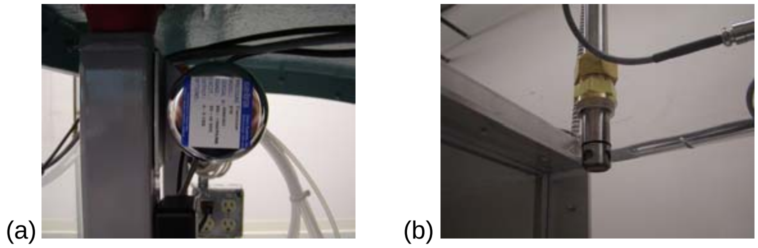

Figure 3: (a) Setra Model 270 Barometer and (b) Omega Model HX 94V Temperature and Relative Humidity probe installed in Otech Wind Tunnel WT3A.

Anemometer output is typically associated to its rate of rotation. Figure 4 below describes the scheme of the data collection and the output analysis from an anemometer signal. From the diagram in Figure 4, a raw signal from the anemometer is generated, which is collected according to the data acquisition sampling scheme. At Otech data acquisition is programmed using the National Instruments LabVIEW software. It is important to provide a sampling rate that would fully capture the anemometer's raw waveform signal. For calibrations performed in this study, a sampling rate of 10 kHz was applied to capture all the wind tunnel measurements. Once the waveform signal is collected, shown as "Anemometer sampled signals" in Figure 4, an FFT analysis or pulse count is applied to determine the frequency output from the anemometer signal. In general, most anemometers deployed in the field output a square-wave pulse signal, where the frequency can be determined using FFT or pulse counting. 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 square-wave pulse or sine signal.

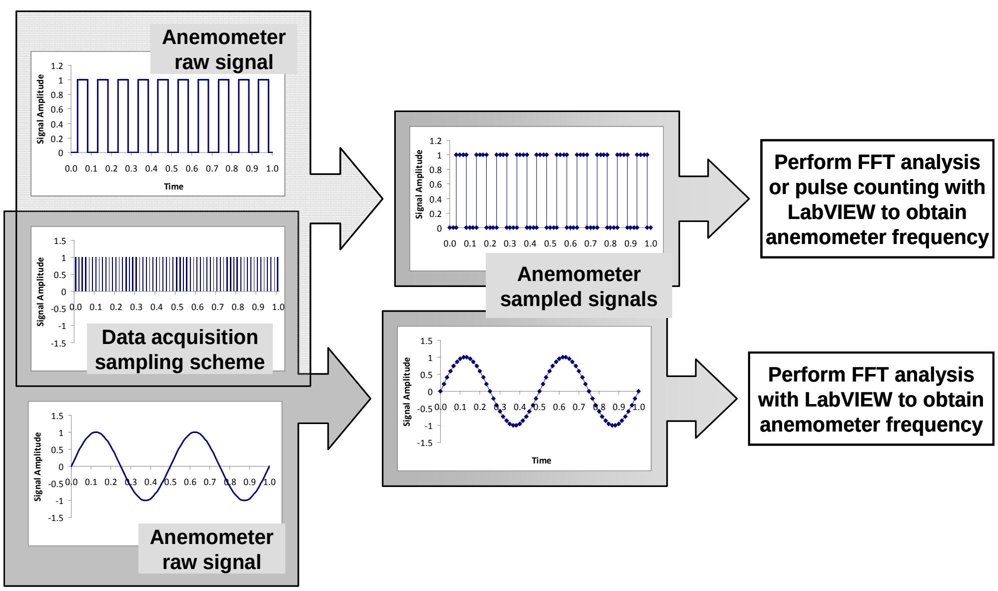

Figure 4: Data acquisition and post-processing of anemometer signal using LabVIEW.

To determine a calibration transfer function, the test anemometer is calibrated for a range of reference wind speeds and a linear regression analysis is performed between the anemometer output and the reference wind speed measurements. According to IEC 61400-12-1, anemometer calibration is performed for a range on 4 to 16 m/s at 1 m/s increments. Ideally, the relationship between the anemometer output and the reference wind speed is linear. As a representation for the degree of linearity, the correlation coefficient, *R*, and the standard error of estimate for the regression, for the slope, and for the offset are also determined from the linear regression analysis. Wind speed residuals are also used to evaluate the linear regression and are determined by finding the difference between the calculated wind speed based on the linear regression equation and the measured reference speed.

Calibration test protocols were performed according to IEC-61400-12-1. From this standard, the calibration test speeds were done from 4 to 16 m/s at 1 m/s increments and ordered in increasing and decreasing steps. Prior to each calibration test, the anemometers were subjected to a five minute “run-in” or pre-spin with a bench fan motor in order to reduce any effects due to mechanical friction of the anemometer bearings (see Figure 5). Test instruments were also installed and positioned in the wind tunnel test section so that the model solid blockage is less than 5%. In this case, solid blockage is defined as the ratio of the projected frontal area of the anemometer plus its mount over the cross-sectional area of the wind tunnel test section. Of the sensors tested for this project, the Thies First Class and Thies First Class Advanced resulted with the highest solid blockage of 4.99%.

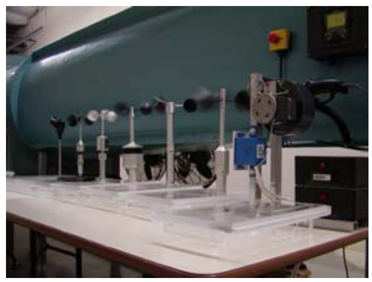

Figure 5: Anemometer “run-in” or pre-spin process.

D. Anemometer Calibration Uncertainty According to IEC 61400-12-1

As specified in IEC 61400-12-1, cup anemometer calibration is done using a wind tunnel test facility that incorporates a Pitot-static tube system to measure the reference wind speed. Thus, anemometer calibration uncertainty is based on the errors accumulated in the reference wind speed measurement from a Pitot-static tube system. For this paper, uncertainty analysis of this wind speed measurement was performed using a method presented by Coleman and Steele (2009)[3]. This approach evaluates the key data reduction equation for the calculation of the wind speed by isolating its independent and dependent variables. With a Pitot-static tube system, wind speed, V, is calculated using the following base equation.

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

Here, Δp is the differential pressure reading from the Pitot-static tube, C_h is the Pitot-static tube head coefficient, ρ 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, ϕ, vapor pressure, P_w, the gas constant for air, R_{air}, and the gas constant for water, R_w, as defined in the following Equation (2), followed by the definitions for the vapor pressure and gas constants, where R is the universal gas constant. M_{air} and M_w are the molecular weights for air and water.

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

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

$$R_{air} = \frac{R}{M_{air}} \qquad \text{Eq. (4)} \qquad\qquad R_w = \frac{R}{M_w} \qquad \text{Eq. (5)}$$

Substituting Equations (2), (3), (4), and (5) into Equation (1) gives the expanded wind speed equation as follows. This form of the wind speed equation in Equation (6) allows a more direct identification of the variables that are most sensitive to the calculation. Thus, it is considered the key data reduction equation (DRE) for uncertainty analysis.

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

Independent variables in Equation (6), 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. According to Equation (6), uncertainty in the wind speed measured by a Pitot-static tube system is a function of the dependent variables k_b (blockage correction), k_c (wind tunnel correction), C_h (Pitot-static tube correction), R (universal gas constant), P (ambient pressure), T (ambient temperature), Δp (Pitot-static tube differential pressure), and ϕ (relative humidity). Uncertainty is defined as:

$$U_V = \sqrt{B_V^2 + \left(t S_V \right)^2} \qquad \text{Eq. (7)}$$

Here, B_V represents the propagation of systematic or bias error contributions and is a function of all the dependent variables in Equation (6). These types of errors are typically considered Type B[4]. The propagation of systematic or bias errors is defined as:

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

In Equation (8) above, B_{k_b}, B_{k_c}, B_{C_h}, B_R, B_P, B_T, $B_{\Delta p}$, and B_ϕ are the bias errors from each of the dependent variables. For the measured variables, P, T, Δp, and ϕ, 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 Equation (7), S_V signifies the propagation of random or precision error contributions which originate from the measured dependent variables, P, T, Δp, and ϕ, and are typically considered Type A[4]. The value of t for 95% confidence at ∞ degrees of freedom is 1.96[5]. The propagation of random errors is defined as according to the following equation.

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

Random errors are the variability in the measured variables, P, T, Δp, and ϕ. Thus, S_P, S_T, $S_{\Delta p}$, and S_ϕ, are the standard deviations of the mean values from the corresponding measured variables.

For both Equations (8) and (9), the partial differentials at the front of each term are the corresponding sensitivity coefficients of each dependent variable. These partial differentials are derived from the expanded wind speed term, Equation (6), and are listed in the following Table 1. Note that by substituting the expanded wind speed term, Equation (6), into each of the partial differentials, the sensitivity coefficient equations can be further simplified to match similar terms given in the sample uncertainty analysis provided in IEC 61400-12-1. There are some differences between the sensitivity analysis presented in this paper to that in IEC 61400-12-1. However, the final accounting of the measurement errors is essentially similar. The sensitivity analysis given in this paper is a direct partial derivation of the key data reduction equation for the reference wind speed. One specific variable that differs from IEC 61400-12-1 is the analysis to the barometer sensitivity. From this method, the barometer sensitivity contributes a positive effect in the uncertainty; whereas in IEC 61400-12-1, this is a negative effect.

For a controlled test, the most dominant variables that affect the uncertainty in the wind speed calculation should originate primarily from the contribution of bias or systematic errors (Type B). Smaller random or precision errors (Type A) implies that the measurements at each test speed are stable (i.e. lower standard deviations in the readings). According to the sensitivity analysis, it is also most critical to choose temperature and differential pressure instruments of the appropriate accuracy and resolution for calibration testing.

Table 1: Sensitivity coefficients for each dependent variable in the wind speed uncertainty.

Variable	Sensitivity Coefficient Equation	Equation
Blockage Coefficient	$\frac{\delta V}{\delta k_b} = \sqrt{\frac{2k_c \Delta pRT}{C_h\left[PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)\right]}} = \frac{V}{k_b}$	Eq. (10)
Pitot-static Tube Head Coefficient	$\frac{\delta V}{\delta C_h} = -\frac{1}{2}\frac{k_b}{C_h^{3/2}}\sqrt{\frac{2k_c \Delta pRT}{PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)}} = -\frac{1}{2}\frac{V}{C_h}$	Eq. (11)
Universal Gas Constant	$\frac{\delta V}{\delta R} = \frac{1}{2}k_b\sqrt{\frac{2k_c \Delta pT}{RC_h\left[PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)\right]}} = \frac{1}{2}\frac{V}{R}$	Eq. (12)
Ambient Pressure	$\frac{\delta V}{\delta P} = -\frac{1}{2}\frac{k_b M_{air}}{\left[PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)\right]^{3/2}}\sqrt{\frac{2k_c \Delta pRT}{C_h}} = -\frac{1}{2}\frac{VM_{air}}{PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)}$	Eq. (13)
Ambient Temperature	$\frac{\delta V}{\delta T} = k_b\sqrt{\frac{2k_c \Delta pR}{C_h}}\,\frac{0.5(T)^{-1/2}\left[PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)\right]^{1/2} - 0.5\left[PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)\right]^{-1/2}(T)^{1/2}\left(-0.0631846\left[2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)\right]\right)}{PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)} = \frac{1}{2}V\left[\frac{1}{T} + \frac{1.295\times10^{-8}\phi e^{0.0631846T}\left(M_{air} - M_w\right)}{PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)}\right]$	Eq. (14)
Differential Pressure	$\frac{\delta V}{\delta \Delta p} = \frac{1}{2}k_b\sqrt{\frac{2k_c RT}{\Delta pC_h\left[PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)\right]}} = \frac{1}{2}\frac{V}{\Delta p}$	Eq. (15)
Relative Humidity	$\frac{\delta V}{\delta \phi} = -\frac{1}{2}\frac{k_b\left[-2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)\right]}{\left[PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)\right]^{3/2}}\sqrt{\frac{2k_c \Delta pRT}{C_h}} = \frac{1}{2}\frac{V\left[-2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)\right]}{PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_w\right)}$	Eq. (16)

An uncertainty analysis using the IEC 61400-12-1 methodology was conducted for the Pitot-static tube system installed in the Otech Engineering Wind Tunnel Facility WT3A. According to IEC 61400-12-1 guidelines, the average uncertainty in the reference wind speed measurement in the Otech Wind Tunnel Facility WT3A for test speeds ranging from 4 to 16 m/s is approximately 0.47%.

E. Expanded Uncertainty Analysis for Anemometer Calibration

In the previous section, a method of uncertainty for an anemometer calibration was conducted and was based on the uncertainty analysis in the reference wind speed measurement as defined in IEC 61400-12-1. However, this uncertainty does not account for the error contributions from measurement of the anemometer signal output. Thus, an uncertainty analysis of the anemometer signal must also be investigated. Since it is common practice to program the linear regression equation into field data loggers, the uncertainty in the regression should also be accounted for in the anemometer calibration. Thus, an expanded uncertainty of the anemometer calibration, U_{cal} as shown in Equation (17), would be the sum of the squares of: 1) the uncertainty in the reference wind speed measurement as defined in IEC 61400-12-1, U_V, 2) the uncertainty in the output of the anemometer under test, U_{IUT}, and 3) the uncertainty in the linear regression fit, U_{LR}.

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

Uncertainty in the output of the test anemometer, U_{IUT}, is essentially the propagation of inherent bias errors, B_{IUT}, and precision errors, S_{IUT}, generated during the calibration test (see Equation 18).

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

Bias errors in the anemometer output are primarily from the data acquisition system and from the methodology of calculating for rate of rotation whether in Hz or rpm. Precision errors are determined from the standard deviation of anemometer output reading during the duration of the data collection. Here, the value of t for 95% confidence at ∞ degrees of freedom is 1.96[3]. 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. In general, the uncertainty in the anemometer output signal signifies the degree of stability in the reading when subjected to steady flow conditions.

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 the correlated or uncorrelated variables or 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 random uncertainty.

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

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

A second classical method 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 Equation (24).

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

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

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

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

For the IEC 61400-12-1 test range of 4 to 16 m/s, the standard error of the regression, STE_V, for various types of anemometers could range from 0.015 m/s to as much as 0.093 m/s. Using the classical method defined in Equation (19), the linear regression uncertainty could vary from 0.4% to 2.2% 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 in Equation (21), the linear regression uncertainty varies from 0.4% to 2.2%, which is similar to the resulting values using the STE_V in Equation (19). In the second classical method, the dominant error source is generally the standard error in the offset. In general, uncertainty in the regression defines the level of linearity for the anemometer calibration.

Anemometer calibrations were performed for a Met One 010C, a Met One 014A, an NRG #40, an NRG IF3, and NRG IF Hybrid, Ornytion 107A, Thies 1st Class, Thies 1st Class Advanced, Vaisala WAA252, Vector A100LK, and Windsensor P2546A. Table 2 presents the resulting calibration transfer function slope and offset and the corresponding standard errors of the linear regression.

Table 2: Calibration transfer function results for various anemometers calibrated in WT3A.

	Otech Calibration		Standard Error		
Anemometer Type	Slope (m/s per Hz)	Offset (m/s)	Regression (m/s)	Slope (m/s per Hz)	Offset (m/s)
Met One 010C	0.041	0.32	0.051	0.00015	0.03929
Met One 014A	0.801	0.28	0.052	0.00307	0.03993
NRG #40	0.784	0.18	0.062	0.00362	0.04856
NRG IF3	0.607	0.18	0.093	0.00421	0.07275
NRG IF Hybrid	0.502	-0.34	0.020	0.00076	0.01664
Ornytion 107A	0.630	0.23	0.026	0.00123	0.02050
Thies 1st Class	0.048	0.22	0.015	0.00005	0.01200
Thies 1st Class Adv	0.045	0.21	0.018	0.00006	0.01414
Vaisala WAA252	0.104	0.21	0.038	0.00029	0.02914
Vector A100LK	0.050	0.21	0.034	0.00013	0.02673
Windsensor P2546A	0.619	0.19	0.018	0.00085	0.01436

The following Table 3 and Figure 7 are a summary and comparison of expanded uncertainty for the various anemometers calibrated according to IEC 61400-12-1 in the Otech Wind Tunnel WT3A. Since the standard error in the linear regression is most commonly and readily provided in calibration reports, the linear regression uncertainty defined in Equation (19) was used to summarize the overall anemometer calibration uncertainty.

Table 3: Summary of expanded uncertainty for various anemometers calibrated in WT3A.

Anemometer Type	Mean Relative Uncertainty (%)				Expanded Uncertainty	
	Reference Wind Speed	Anemometer Output	Regression Case 1	Regression Case 2	Relative (%)	Absolute (m/s)
Met One 010C	0.47%	1.16%	1.19%	1.19%	1.75%	0.15
Met One 014A	0.47%	1.62%	1.21%	1.21%	2.11%	0.19
NRG #40	0.47%	1.25%	1.45%	1.47%	2.02%	0.18
NRG IF3	0.47%	0.77%	2.18%	2.21%	2.41%	0.21
NRG IF Hybrid	0.47%	0.72%	0.48%	0.51%	1.00%	0.10
Ornytion 107A	0.47%	2.56%	0.62%	0.62%	2.68%	0.25
Thies 1st Class	0.47%	2.27%	0.36%	0.37%	2.35%	0.23
Thies 1st Class Adv	0.47%	1.92%	0.43%	0.43%	2.04%	0.20
Vaisala WAA252	0.47%	1.80%	0.88%	0.89%	2.08%	0.20
Vector A100LK	0.47%	2.28%	0.80%	0.81%	2.48%	0.24
Windsensor P2546A	0.47%	1.45%	0.43%	0.44%	1.59%	0.15

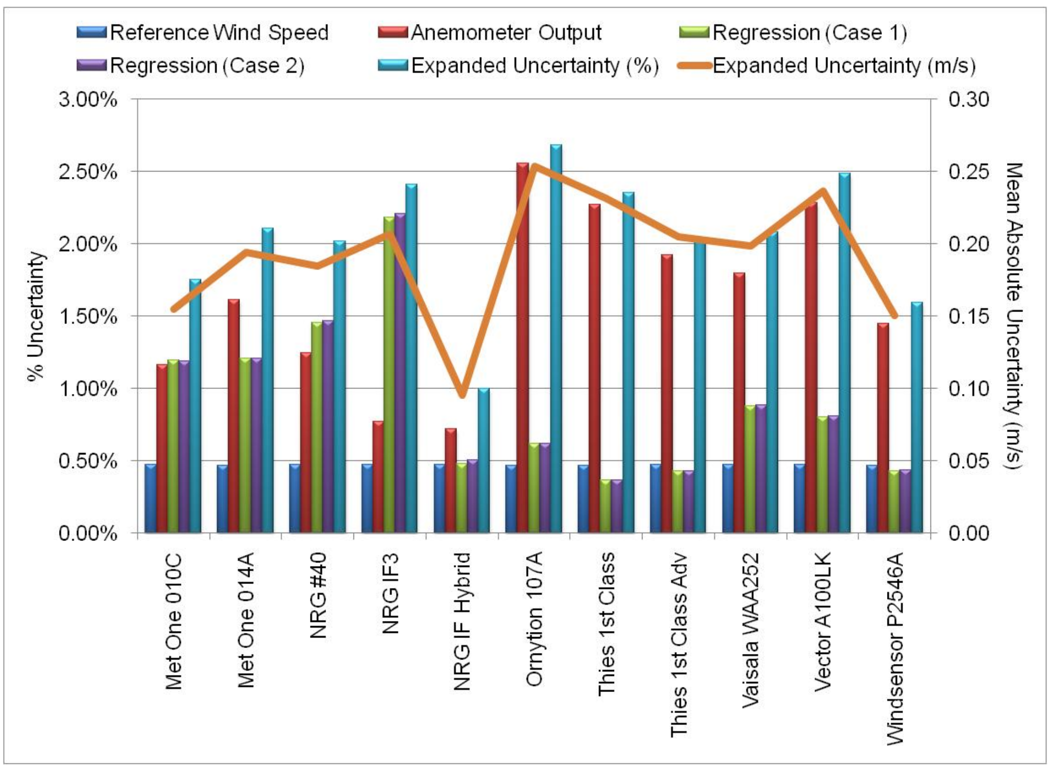

Figure 7: Comparison graph of uncertainty values for various anemometers calibrated in WT3A.

As shown in Table 2 and Figure 7, the uncertainty in the reference wind speed in the Otech Wind Tunnel WT3A is typically the same for all calibration tests, ~ 0.47%. The differences in the calibrations from each sensor type are mainly evident in the uncertainty analysis of the anemometer output and the linear regression, which reveal to be the largest contributors to the overall anemometer calibration uncertainty. The following Table 4 below summarizes the typical range of values for each of the terms involved in an expanded anemometer calibration uncertainty analysis.

Table 4: Summary of equations and corresponding typical values for an expanded uncertainty analysis of a cup anemometer calibration based on IEC 61400-12-1 test speeds of 4 to 16 m/s.

Reference Wind Speed Uncertainty	$U_V = \sqrt{(B_V)^2 + (tS_V)^2}$	~ 0.47%
Anemometer Output Uncertainty	$U_{IUT} = \sqrt{B_{IUT}^2 + (tS_{IUT})^2}$	~ 0.72% to 2.56%
Linear Regression Uncertainty (Case 1)	$U_{LR_{Case1}} = \sqrt{\left(t\dfrac{STE_V}{V_i}\right)^2}$	~ 0.36% to 2.18%
Linear Regression Uncertainty (Case 2)	$U_{LR_{Case2}} = \sqrt{\left(t\dfrac{STE_m}{V_i}f_i\right)^2 + \left(t\dfrac{STE_b}{V_i}\right)^2}$	~ 0.37% to 2.21%
Expanded Anemometer Calibration Uncertainty	$U_{cal} = \sqrt{(U_V)^2 + (U_{IUT})^2 + (U_{LR})^2}$	~ 1.00% to 2.68% or ~ 0.10 to 0.25 m/s

F. Conclusion

Anemometers are essential in several areas in the wind energy industry. 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 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 expanded anemometer calibration uncertainty range approximately from 1.00% to 2.56% (0.10 to 0.25 m/s) for cup anemometers calibrated according to the IEC 61400-12-1 test speeds ranging from 4 to 16 m/s at 1 m/s increments. This expanded uncertainty analysis revealed that errors in a field wind speed reading may originate not only from the controlled reference wind speed offered by a calibration facility, but also from the anemometer output signal and its degree of linearity.

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