Anemometer Calibration Requirements for Wind Energy Applications

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Outline

- Importance of Wind Sensors in Wind Energy
- Wind Sensors Used in Wind Power
- Basic Anemometer Calibration
- Applicable Test Standards
- Test Facility Requirements
- Facility Performance Evaluation
- Calibration Uncertainty
- Summary
Importance of Wind Sensors in Wind Energy

- **Wind Plant Operations**
  - Validate wind turbine power output
  - Control start-up and shut-down

- **Wind Turbine Performance Evaluations**
  - Power curve (wind turbine power output as a function of wind speed)

- **Wind Energy Site Assessments**
  - Use power curves and wind distributions to estimate annual energy production for power purchase agreements

**Sample Turbine Power Curve**

- 1.5 MW rated power reached at ~12 m/s
- Power estimated at lower wind speeds can be as much as 30% error depending on curve
Wind Sensors Used in Wind Power

- **Cup Anemometers**
- **Propeller Anemometers**
- **Ultra-Sonic Anemometers**

- Wind turbines are designed to generate power from direct incoming flow.
- Key measure from a wind sensor is the magnitude of the horizontal wind speed component.
Basic Anemometer Calibration

Anemometer Output ⇔ Controlled Reference Speed

Rotation rate (i.e., Hz or rpm)

Wind generated from a controlled wind tunnel

Analog voltage or conditioned digital signal

Reference Pitot-static tubes

Perform a Least Squares Fit
⇒ Linear Transfer Function
Applicable Test Standards

- ASTM D5096-02, “Standard test method for determining the performance of a cup anemometer or propeller anemometer”
- IEC 61400-12-1, “Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines”

General requirement is to perform anemometer calibrations in a uniform-flow, low-turbulence wind tunnel.
# Test Facility Requirements

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<td>Speed Range</td>
<td>IEC 61400-12-1 (4-16 m/s); Others based on % of application speed</td>
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<td>Flow Uniformity</td>
<td>IEC 61400-12-1 (&lt;0.2%); Others (&lt;1%)</td>
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<td>Wind Gradient</td>
<td>IEC 61400-12-1 (&lt;0.2%)</td>
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<td>Turbulence Intensity</td>
<td>IEC 61400-12-1 (&lt;2%); Others (&lt;1%)</td>
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<tr>
<td>Density Uniformity</td>
<td>ASTM D5096-2, ISO 17713-1 (&lt;3%)</td>
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<td>Data Acquisition</td>
<td>Resolution 0.02 m/s, minimum sampling 10 Hz, duration 30-100 sec</td>
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<td>Model Blockage</td>
<td>10% max for open test sections, 5% max for closed test sections</td>
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<td>Repeatability</td>
<td>IEC 61400-12-1 (&lt;0.5% at 10 m/s test speed)</td>
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Test Facility Requirements

Common Wind Tunnel Configurations

Open-circuit, suction or Eiffel-type

Open-circuit, blower-type

Closed-circuit
General concept is to define dynamic pressure in test section according to the pressure drop generated by the wind tunnel contraction section.
Facility Performance Evaluation

Reference speed measurement:

*Pitot-static tube system*
(as defined by IEC 61400-12-1)

Four Pitot tubes with sensing tips positioned at test section inlet where total and reference ports connected to an MKS 120AD transducer.
Facility Performance Evaluation

Pitot-Static Tube System
General Velocity Equation

\[ V = \sqrt{\frac{2 \Delta p}{\rho}} \]

Differential pressure from Pitot-static tube
Density of humid air

\[ \rho = \frac{1}{R \cdot T} \left[ P M_{air} - 2.05 \times 10^{-7} \phi e^{0.0631846T} (M_{air} - M_w) \right] \]

Ambient pressure
Relative humidity

Ambient temperature
Facility Performance Evaluation

1) Profiles mean speed settings from 4 to 26 m/s showed an average test section uniformity within +/-0.2%.
2) Preliminary indication of less than 0.2% turbulence.
3) Difference in wind speed between center of test section to reference Pitot-static tubes at inlet averages to +0.014%.
Facility Performance Evaluation

Blockage Ratio
\[ \frac{A_{C3}}{A_{TS}} \leq 2\% \]

Empirical Blockage Correction
\[ k_b = 1 + \frac{1}{4} \frac{A_{C3}}{A_{TS}} = 1.005 \]

Test performance requirements according to IEC 61400-12-1
- Calibration test speeds: 4 to 16 m/s at 1 m/s increments
- Repeatability (<0.5% at 10 m/s) ⇒ within 0.2% for 5 repeated tests
- Interlaboratory Comparison (+/-1% at 4-16 m/s) ⇒ 1% average variation in comparison to an accredited wind tunnel laboratory in Denmark
Calibration Uncertainty

Anemometer calibration uncertainty consists of the propagation of errors from three general areas:

$$U_{cal} = \sqrt{(U_v)^2 + (U_{IUT})^2 + (U_{LR})^2}$$

Reference wind speed

Test sensor output

Calibration linearity

Uncertainty in each area includes systematic or Type B errors ($B_i$) and random or Type A errors ($S_i$):

$$U_i = \sqrt{B_i^2 + (tS_i)^2}$$

Coverage factor at 95% confidence
Calibration Uncertainty

Uncertainty in reference wind speed

\[ U_V = \sqrt{B_V^2 + (tS_V)^2} \]

Analyzed from Pitot-static tube velocity equation

\[
V = \sqrt{\frac{2\Delta p}{\rho}} \\
V = C_h k_b k_c \sqrt{\frac{2\Delta p}{\rho}} \\
\rho = \frac{1}{R^*T} \left[ P M_{air} - 2.05 \times 10^{-7} \phi e^{0.0631846T} (M_{air} - M_w) \right] \\
V = f(M_{air}, M_w, k_b, k_c, C_h, R^*, P, T_K, \Delta p, \phi)
\]
Calibration Uncertainty

**Uncertainty in reference wind speed**

\[ U_V = \sqrt{B_V^2 + (tS_V)^2} \]

**INDEPENDENT VARIABLES**

(exact values defined by NIST)

\[ M_{air} \text{ and } M_w \]

**DEPENDENT VARIABLES**

Measured

\[ P, T, \phi, \Delta p \]

Analyzed

\[ k_b, k_c, C_h, R^* \]

\[
B_V = \sqrt{\left( \frac{\partial V}{\partial k_b} B_{k_b} \right)^2 + \left( \frac{\partial V}{\partial k_c} B_{k_c} \right)^2 + \left( \frac{\partial V}{\partial c_h} B_{c_h} \right)^2 + \left( \frac{\partial V}{\partial R^*} B_{R^*} \right)^2}
\]

\[
\quad + \left( \frac{\partial V}{\partial P} B_P \right)^2 + \left( \frac{\partial V}{\partial T} B_T \right)^2 + \left( \frac{\partial V}{\partial \Delta p} B_{\Delta p} \right)^2 + \left( \frac{\partial V}{\partial \phi} B_\phi \right)^2
\]

\[
S_V = \sqrt{\left( \frac{\partial V}{\partial P} S_P \right)^2 + \left( \frac{\partial V}{\partial T} S_T \right)^2 + \left( \frac{\partial V}{\partial \Delta p} S_{\Delta p} \right)^2 + \left( \frac{\partial V}{\partial \phi} S_{\phi} \right)^2}
\]
Calibration Uncertainty

Uncertainty in test sensor output

\[ U_{IUT} = \sqrt{B_{IUT}^2 + (tS_{IUT})^2} \]

- Type B errors are acquired from data acquisition system.
- Type A errors are quantified by the standard deviations in the test sensor reading.

Uncertainty in calibration linearity

\[ U_{LR} = \sqrt{(tV_{res})^2} \]
Calibration Uncertainty

Calibration Uncertainty for the C3 Anemometer

- **Reference Speed:**
  - 0.07 m/s
  - 0.21 m/s

- **C3 Output**

- **Transfer Function**

- **Overall**

**Graph Details:**
- **Y-axis:** Uncertainty (m/s)
- **X-axis:** Reference Speed (m/s)
Summary

Key Considerations for an Anemometer Calibration Program

1) Perform tests in a controlled, uniform-flow, low-turbulence wind tunnel as required by test standards

2) Verify wind tunnel performance through velocity surveys

3) Qualify ability to perform wind sensor calibrations
   - Blockage evaluation
   - Test repeatability
   - Interlaboratory comparison

4) Document the uncertainty analysis

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