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Error Analysis in Wind Turbine Field Testing

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ERROR ANALYSIS in WIND TURBINE FIELD TESTING

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OBJECTIVE

In wind turbine field testing, one of the most important issues is understanding and accounting for data errors. Extended dynamic testing of wind turbines requires a thorough uncertainty analysis and a regimen of quality assurance steps in order to preserve accuracy. Test objectives need to be identified to determine the accuracy requirements of any data measurement, collection, and analysis process. Frequently, the uncertainty analysis reveals that the major sources of error can be allowed for with careful calibration and signal drift tracking procedures.

This paper offers a basis for the discussion and development of a repeatable and accurate process to track errors and account for them in data processing.

1.0 INTRODUCTION

Wind turbine testing generally uses basic scientific technique: a question is posed; theories offered; and "solutions" are tested and verified. The approach is universal, as are the basic problems of assuring data "honesty". It is important that the accuracy of the process meets the accuracy needs to answer the questions posed. Careful physical calibrations and a thorough error accounting can determine if the accuracy needs are being met. Frequently, test results are put forth in many scientific papers without such accounting for test errors. We are hoping to lay a foundation for discussion of of a generally accepted procedure for doing this.

The discussion below first tackles the issue of full uncertainty analysis, including an example for clarity. The uncertainty analysis shows that the most significant error sources are under the control of the test engineer and can be reduced with careful planning and good test procedures. The details of such planning and procedures are put forth and discussed in the second half of the paper.

2.0 ESTIMATING MEASUREMENT UNCERTAINTY

Required measurement accuracy depends on what is to be done with the acquired data. It is typically the test engineer's job to specify equipment and define procedures to ensure that each measurement is made to the necessary level of accuracy.

After data objectives have been determined, an uncertainty analysis can be conducted to estimate attainable levels of measurement accuracy. In such an analysis the test engineer makes his or her best estimate of the largest error that may be reasonably expected for each part of a measurement process. Measurement error is composed of random errors (also called repeatability, precision, or sampling errors) and bias errors as illustrated in Figure 1 (Beckwith and Maragoni, 1990). Typically, a random

error increases the scatter in the final test results. A bias error causes the measured data to be offset by some amount from the "true" (NIST-traceable) value. Uncertainty estimates are based on instrumentation and equipment specifications, test measurements, and experience. Major error sources are data acquisition components, calibration procedures, and data reduction systems.

2.1 Common Sources of Signal Error

It is often difficult to perform an uncertainty analysis because of the significant number of potential error sources. Typical error sources for strain-gauge measurements are identified in Figure 2 (Taylor, 1989).

2.2 Measurement Uncertainty Analysis Example

The following is an example of an uncertainty analysis for a hypothetical strain-gauge-based bending moment measurement. It is assumed that the sensors and equipment are exposed to a wide variation in temperature. Manufacturer specifications for sensors, wires, signal conditioning, and data acquisition system components are used to estimate intrinsic errors. These are listed in Figure 3 and presented in terms of percent full-scale (FS) random or bias error. Individual contributing sources of uncertainty are then summed together to calculate total error for each component. Next, errors from all sources of uncertainty are root-sum-squared (RSS) to determine total random and bias errors.

A summary of this process is shown in Figure 4. The intrinsic errors from manufacturer equipment specifications are listed first. Effects from other error sources are listed next. Total measurement error is the sum of the random and bias RSS components.

The other error sources listed in the summary are based on test engineer estimates. As is indicated, it is often the case that such errors are significantly larger than any intrinsic errors. It is usually difficult to estimate accurate values for these components. These error sources can be determined from: results of tests designed to directly measure their error contribution; previous measurement experience; or transducer performance history.

3.0 ENSURING DATA ACCURACY : Calibration

It is obvious from the above example that data collection is susceptible to many sources of error. It also is very unlikely that an uncertainty analysis based solely on manufacturer specifications and estimated errors would accurately predict actual measurement error. The only way to quantify data errors is to directly measure the major error components. This allows error estimates to be verified with known data values, thereby increasing confidence in measured data values. The largest potential sources of error are signal drift and sensor installation. These two sources can be reasonably quantified with careful signal calibration and drift tracking procedures.

3.1 Calibration Procedures

The test engineer should design step-by-step calibration procedures to ensure that errors are kept within limits prescribed by the test objectives. It is preferable that these calibrations are performed with the same instrumentation used to record the test data. This quantifies measurement uncertainty of all components along the data measurement path including sensors, cables, signal conditioner, and A/D converter. It is also advisable to perform multiple calibrations under conditions similar to those expected during actual data measurement. Calibrations are typically performed using the whole data path ("end to end") or a component-by-component process.

3.1.1. ***Direct or "end-to-end" calibrations.*** The best way to calibrate a channel is to directly measure the full channel response using an external reference that produces a known result. With this technique, all the components along the data path are calibrated together and the accuracy of the full data path can be determined. An example is a blade pull to calibrate strain-gauge bending moment. In a blade pull, a known mechanical moment is applied to the strain gauge bridge sensing element. The resulting response, which reflects errors from the complete data path, is recorded on the data acquisition system.

3.1.2. ***Component calibrations.*** For many types of measurements, it is not possible to directly calibrate the full measurement data path simultaneously. The alternative requires system components to be calibrated separately. This is often done in two distinct steps:

1) calibrate the electronics, and
2) calibrate the transducer.

The response of the electronic portion of the signal path (mainly the signal conditioning and A/D conversion system.) is determined by replacing the sensor input signal with a known reference. The accuracy of the transducer is determined by external pre-test and post-test calibrations to ensure that it remained within tolerance during use. An example of this is a strain-gauge shunt calibration where the measurement electronics are frequently calibrated to compensate for voltage drift by switching in a known precision resistance in place of the strain gauge. It is still required that the strain-gauge itself be calibrated after installation by applying a known load and measuring the response. In this case, the overall measurement uncertainty can be verified by comparing component calibration results with estimated values from the uncertainty analysis.

3.2 Using Regression Statistics to Quantify Error. In the above calibrations, the reference input load is varied over the measurement range, and corresponding raw output values (e.g.,volts) are recorded. Using known input load values, a least-squares linear (or higher order) regression is performed to obtain calibration coefficients. Regression statistics can be checked to ensure that results are within uncertainty limits.

For example, assume a blade pull is used determine the slope and offset of a blade bending moment channel. Voltage X is read from the data acquisition system when known moment ,Y, is applied:

Read in n measured values into vector X:

$$X = \{X_1, X_2, X_3, ..., X_n)$$

Get n corresponding known reference values Y:

$$Y = (Y_1, Y_2, Y_3, ..., Y_n\}$$

Calculate least squares coefficients for m=slope and b=offset:

$$m=(n\Sigma XY-\Sigma X\Sigma Y)/(n\Sigma X^2-(\Sigma X)^2)$$

$$b=(\Sigma Y\Sigma X^2-\Sigma X\Sigma XY)/(n\Sigma X^2-(\Sigma X)^2)$$

Calculate standard error of estimate Y on X, S_{yx}:

$$S_{yx}= \sqrt{(\Sigma(Y-Y_{est})^2/n)}$$

where $Y_{est} = \{mX_1+b, mX_2+b, mX_3+b, ..., mX_n+b)$

The standard error of estimate S_{yx} is a direct indication of random error. A 95% statistical degree of confidence defined as $\pm 2S_{yx}$ is recommended for calibrations. This reflects errors associated with the full data measurement path and engineering unit conversion procedure. These can be root-sum-squared with errors associated with obtaining the reference values to determine overall measurement error.

Differences in offset obtained from consecutive calibrations are direct measurements of relative bias errors. Alternatively, bias errors can be determined previous to the collection of each data set, as described later in this paper.

3.3 Other Calibration Strategies

Whenever possible, it is advisable to make redundant measurements to ensure that a system component has not failed during an experiment. This is especially true for measurements from transducers which are infrequently calibrated. Consider, for example, a scenario in which a strain gauge is slightly damaged during use, and the calibration slope shifts 10%. It would be very difficult to ascertain that any change in measurement accuracy has occurred by simply observing time-series data values. In-situ electronics calibrations would not reveal any problem. Since most experiments involve making measurements under various system configurations, the 10% shift could easily be erroneously attributed to a configuration change. Chances are, the effect would not be noticed until a post calibration was performed. However, if two redundant strain-gauge measurements were available, they could be periodically compared to each other to ensure that values remained within acceptable uncertainty limits.

Another recommended practice is to repeat calibrations at periodic intervals during an experiment with the system restored to a standard configuration. Results from repeated calibrations are then compared to earlier ones to see if results are still within the acceptable uncertainty limits. It is often difficult to determine how often the calibration procedures should be performed. Calibrations should be repeated at time intervals sufficient to ensure the accuracy of intermediate data, and is usually based on manufacturer recommendations and test experience. These time intervals may vary from minutes to months, depending on the transducer or system component being calibrated and required channel accuracy.

At least two calibrations, a pre-test and post-test, are necessary. The pre-test calibration establishes a baseline and helps to determine if the measurement range is adequate, and if values are within acceptable uncertainty limits. A post-test calibration is performed after all data are collected. These calibrations should be performed on all components of the data measurement path. Measurement uncertainty limits are often revised to reflect results obtained from post-test calibrations.

4.0 ENSURING DATA ACCURACY: Signal Drift Tracking

Strain-gauge measurements usually exhibit large bias errors over time. These are caused by a variety of factors such as electronics drift, temperature effects, gauge adhesive breakdown, etc. To ensure accurate measurements and reduce measurement uncertainty, frequent calibrations to track drift (bias error) are performed.

Ideally, all sensors should be periodically positioned at some zero load reference point and the output voltage adjusted to zero. Unfortunately, this is rarely feasible. There are techniques used to identify the drift of different sensors and specific applications. Diligent test engineers provide for such operations to be performed at the beginning of all data sets. Frequently, this involves carefully identifying a repeatable process by which most sensors are positioned at a known load, raw data is collected, and the deviation from the known load output at initial calibration is considered as drift. The range of variation of this drift during the test period is the combined bias error. Bias shifts can be taken into account by either:

- updating calibration offsets in data processing or
- verifying that the bias error is within the prescribed range.

4.1 Long Term Drift Analysis

All signals should be slowly sampled over a couple of typical diurnal cycles (in low winds) to quantify the effect of temperature on all sensors. It is recommended that this drift due to temperature should be sampled and then preaveraged to about half the data set period. Each sensor will have different time constants and careful data analysis should reveal the preaverage period at which the standard deviation of temperature begins to converge. A curve fit of each channel output versus temperature (as noted in Calibration above) can quantify the direct temperature errors.

4.2 Pre-Test Techniques for Quantifying Drift

Most signal drift can be tracked and accounted for by identifying and revisiting known load positions (as described above) as frequently as is practical. Different signal drift tracking processes are required for different types of sensors and signals. Some of these are discussed below. A possible way for integrating some of these approaches is shown in flowchart form in Figure 5.

4.2.1 ***Slow Rotation*** Slow rotation of a turbine rotor in little or no wind can be used to identify the no load outputs of in-plane and out-of-plane blade bending moments and main shaft bending moments. Rotor azimuth can also be used to identify when the rotor is at a no-load position for these various sensors. Binning slow rotation data versus azimuth can be quite useful for automating the process of drift checking and accounting.

4.2.2 ***Parked Rotor*** Parked rotor loads can also be measured in very little or no wind. With a blade parked in a horizontal position out-of-plane loads should be zero. In a vertical position, in plane loads should be zero. Shaft bending moments should be zero when the associated neutral axis is vertical. Torque should be zero horizontal to wind.

4.2.3 ***Parked Yaw (Tower and Mainframe Loads)*** Moving the turbine to incremental fixed yaw positions can be used to identify drift in some tower and rotor loads. In our experience two yaw positions exactly 90 degrees from each other (e.g., coincidental to the tower bending gauges' neutral axes) can be useful when indicated with marks or proximity sensors.

4.4 Uncertainty Introduced in Accounting for Signal Drift

Uncertainty is, of course, further introduced into the process by any step introduced into the data processing pathway. Difficulty arises when the wind is blowing and the known load position is difficult to determine during pre-test drift checks. This can be troublesome since most testing takes place during moderate and high winds. Parked rotor loads versus wind speed can identify signals which are susceptible to drift check error in these conditions.

Acceleration during slow rotation introduces odd signal attenuation which can be allowed for. The latter only seems to be an issue when averaging a number of rotations for a sensor with large gravity cyclic loads.

5.0 CONCLUSIONS and RECOMMENDATIONS

To determine if data accuracy requirements are being met, a thorough uncertainty analysis is useful. However, due to its complexity, such a process is open to error itself. It is recommended that the errors be directly measured and tracked with careful calibrations and signal drift tracking. Signal calibrations curve fit statistics can be used to quantify some signal errors. It is recommended that signal drift be tracked with a repeatable process as frequently as practical.

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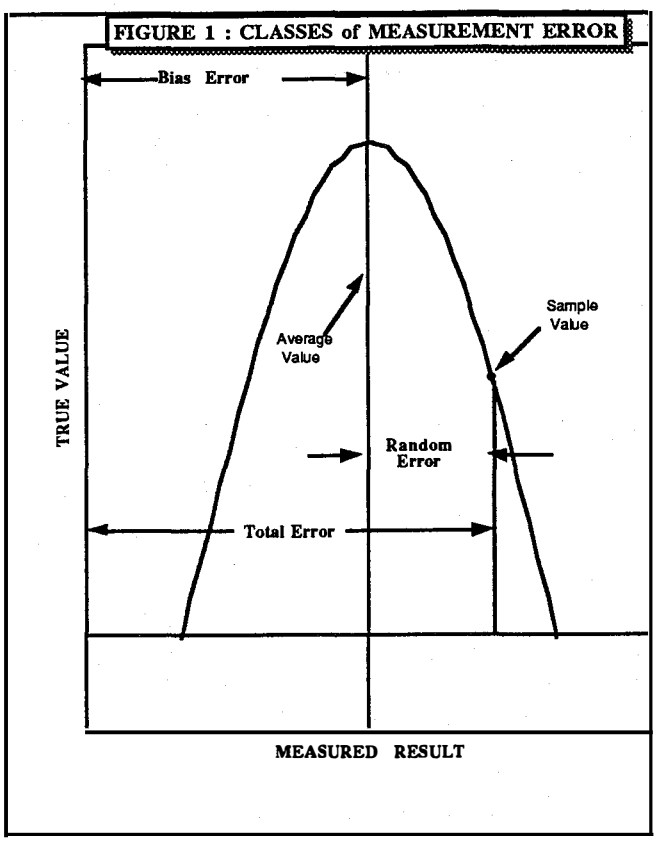


FIGURE 5 : AUTOMATIC DRIFT TRACKING PROCESS

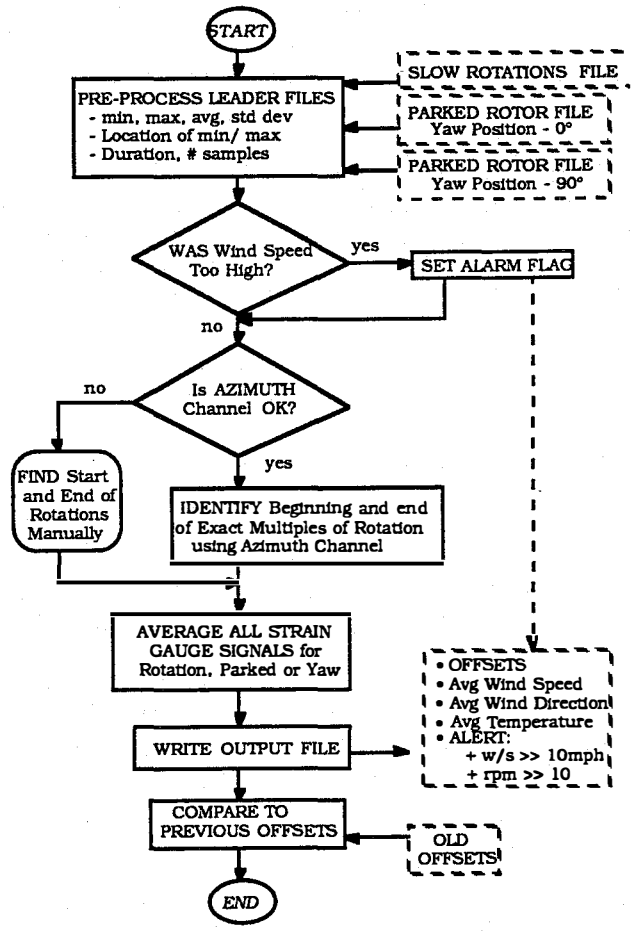
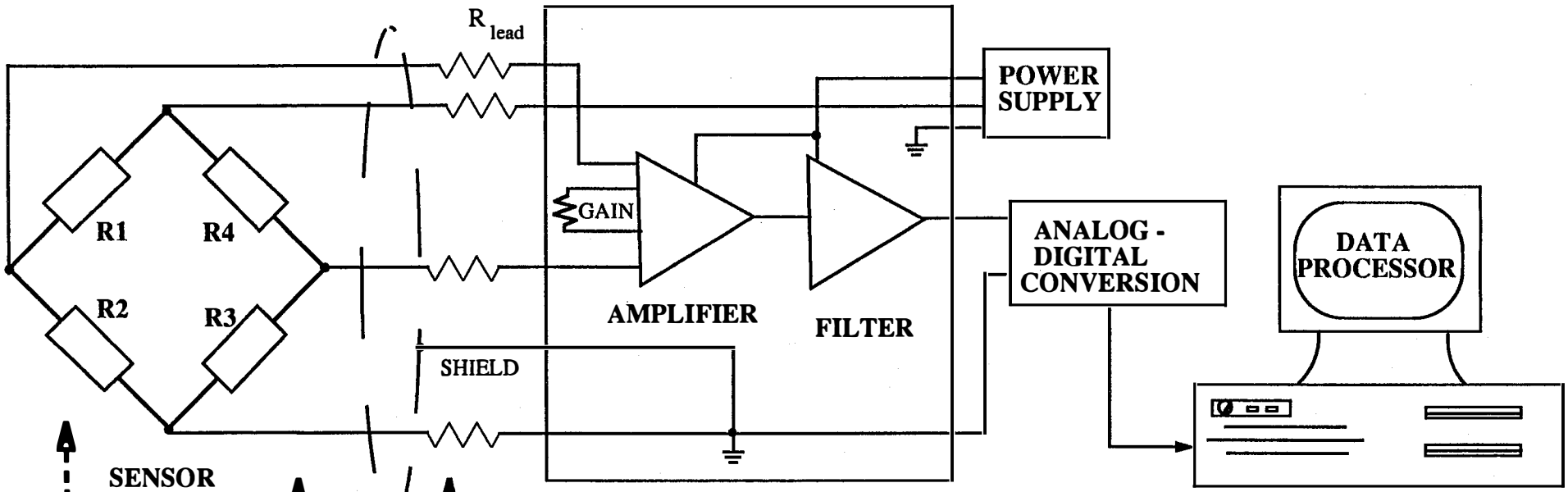


FIGURE 4: SUMMARY of UNCERTAINTY EXAMPLE

Sources of Uncertainty	Type of Error: Bias (N-m)	Bias (%FS)	Random (N-m)	Random (%FS)
Intrinsic errors (mfg specs):				
Strain Gages	±103	±1.61%	±12.8	±0.20%
Lead wires	±5.8	±0.09%	±3.2	±0.05%
Signal conditioning	±57.6	±0.90%	-	-
A/D converter	±26.9	±0.42%	±7.04	±0.11%
Other error sources:				
Off-axis gage alignment	±260	*±4.06%*	-	-
Drift between calibrations	±500	*±7.81%*	-	-
Root-sum-squared	±576		±15.0	
Total Error	±591 N-m	9.23%		

FIGURE 2 : ERROR SOURCES in DATA PATHWAY



Sensing Errors:
- Gage location
- Gage orientation
- Surface preparation
- Adhesive + coating

Sensors:
- Misallignment
- Non-linearity
- Hysteresis
- Temperature Effects
- Repeatability
- Sensitivity

Wires:
- Resistance
- Capacitance Effects
- Noise Pickup
- Temperature Effects

Signal Amplification:
- Amplifier non-linearity, sensitivity, noise
- Temperature Effects

Excitation Voltage
- Balance loading
- Power supply ripple, regulation, and stability
- Temperature Effects

A/D Conversion
- Stability
- Linearity
- Calibration Resolution
- Measurement Resolution
- Aliasing
- Noise
- Temperature Effects

Data Collection and Reduction:
- Linear conversion errors
- Calibration determination errors
- Sample skew
- Filter gain and phase effects

FIGURE 3 : UNCERTAINTY ANALYSIS EXAMPLE

Strain Gages:

Type:	Full bridge, 10 VDC excite
FS Measurement Range:	3200 N-m
FS Output:	5 mv
Operating Temperature:	-20 to +60 deg C
Sensitivity:	0.50% FS, bias
Hysteresis:	0.25% FS, bias
Linearity:	0.30% FS, bias
Repeatability	0.20% FS, random
Thermal offset:	0.005% FS/degC, bias (0.005%*80°C = 0.40% FS)
Thermal sensitivity:	0.002% FS/degC, bias (0.002%*80°C = 0.16% FS)

Total Error	Bias:	1.61% of 6400 N-m	*103 N-m*
	Random:	0.20% of 6400 N-m	*12.8 N-m*

Lead Wires:

Resistance:	0.05% FS, bias
Capacitance:	Assumed negligible
Noise	0.05% FS, random
Thermal sensitivity: (80°C range)	0.002% FS/°C, bias (.0005%*80°C =0.04% FS)

Total Error	Bias:	0.09% of 6400 N-m	*5.8 N-m*
	Random:	0.05% of 6400 N-m	*3.2 N-m*

Signal conditioning:

Output:	0 to 5 VDC for 3200 N-m
Linearity:	0.1% FS, bias
Thermal sensitivity:	.01% FS/°C, bias (.01%*80°C = 0.80% FS)

Total Error	Bias:	0.90% of 6400 N-m	*57.6 N-m*

Analog to digital (A/D) conversion:

Measurement Range:	0 to 5 Vdc to 12-bits
Stability:	0.06% FS, bias
Linearity:	1/2 LSB =0.012% FS, bias
Calibration resolution:	1 LSB = 0.024% FS, bias
Thermal sensitivity:	.004% FS/°C, bias (.004%*80°C=0.32%)
Noise	5 mV rms =0.1% FS,random
Resolution:	1/2 LSB = .012% FS, random

Total Error	Bias:	0.42% of 6400 N-m	*26.9 N-m*
	Random:	0.11% of 6400 N-m	*7.04 N-m*