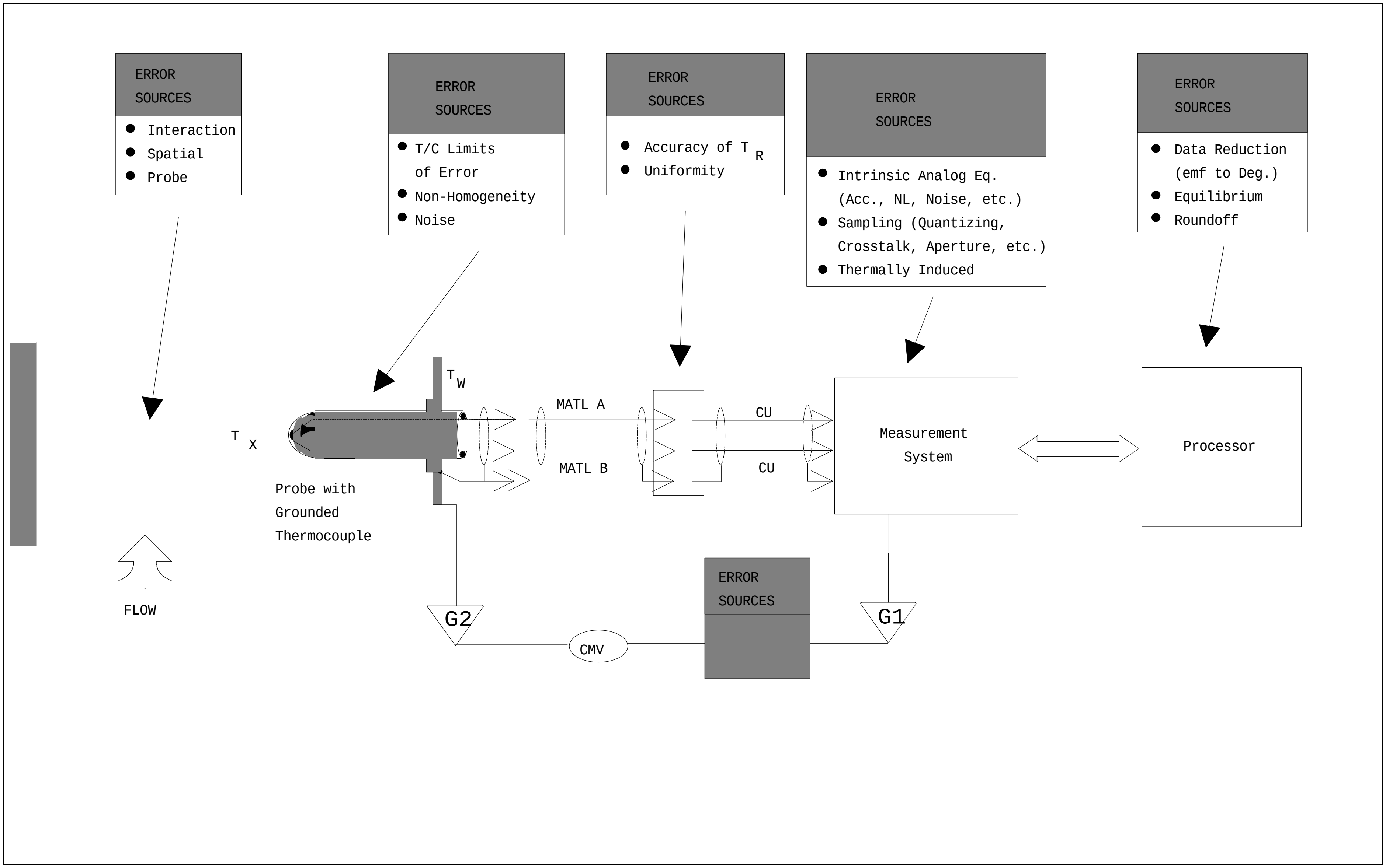
APPLICATION NOTE 505

Predicting Measurement Uncertainty Using Manufacturer's Specifications

SECTION 1 INTRODUCTION

The lack of standards associated with terminology, manufacturer's reporting of error and analytical methods for combining elemental errors has complicated our ability to accurately predict the static accuracy performance of a system comprised of an integration of equipment from multiple manufacturers. This application note presents a discussion of elemental error sources within a measurement chain and introduces analytical methods for combining errors.

An estimate of total measurement error can be established for a specific configuration based on knowledge of the measurement chain and on the performance specifications of the candidate equipment. We should emphasize from the outset that the inherent errors associated with the equipment are in all likelihood small when compared to other potential error sources such as installation and application errors. However, because equipment errors are published whereas the other error sources are generally not acknowledged or quantified, estimates of total measurement error are generally restricted to analyzing published equipment errors. Unfortunately, the lack of industry standards with regard to both error definitions and error reporting techniques complicates the prediction of total measurement error.


ERROR SOURCES
Interaction
Spatial
Probe
ERROR SOURCES
T/C Limits of Error
Non-Homogeneity
Noise
ERROR SOURCES
Accuracy of T R
Uniformity
ERROR SOURCES
Intrinsic Analog Eq. (Acc., NL, Noise, etc.)
Sampling (Quantizing, Crosstalk, Aperture, etc.)
Thermally Induced
ERROR SOURCES
Data Reduction (emf to Deg.)
Equilibrium
Roundoff
T X
T W
MATL A
MATL B
CU
CU
Measurement System
Processor
Probe with Grounded Thermocouple
FLOW
G2
CMV
ERROR SOURCES
G1

SECTION 2
CONSTRUCTING AN ERROR MODEL

2.1 Overview

Our approach in developing a static error model is based on the following six steps:

Step 1. Draw a simple schematic block diagram of the total measurement chain indicating sensor, measurement system and processor.
Step 2. Establish sensor output signal levels and required system gain;
Step 3. Identify and quantify intrinsic equipment errors;
Step 4. Choose consistent units for all errors;
Step 5. Identify and quantify other error sources such as installation related errors and application related errors;
Step 6. Combine elemental errors.

Our approach in estimating total measurement error is restricted to analyzing the effects of equipment error only. However, for completeness, we illustrate the other potential error sources. Figure 1 illustrates typical errors encountered with a thermocouple measurement.

2.2 Error Components

If at a constant known input we make repeated observations of the input, we will observe scatter in the results. Assuming constant temperature, constant input and no AC common mode voltage, the observed scatter is caused by noise. This assumes that the measurement system has adequate resolution to detect the noise. The fixed difference between the known input and the average of all measurements is a measure of the system's bias error at this set of conditions. Since noise has a random distribution, the measurement system's scatter can be quantified using statistics. The Students and Chi Square Distributions in conjunction with the Central Limit Theorem provide a mechanism for determining the required number of observations. This component of measurement error is called random error and is quantified using the population variance statistic. Thus, we see (Figure 2) that there are two components of measurement error -- bias error and random error.

2.3 Interpreting Manufacturer's Errors

To interpret manufacturer's performance specifications, we must first of all establish a reasonable definition and then inquire as to whether at a constant input this contributes to the fixed error or random error. The key is to apply the definition at one specific input. The following definitions are offered for the more fundamental errors:

Non-Linearity. The deviation of the output of a device from a straight line where the straight line may be defined using end points, terminal points, or best fit.
Hysteresis. The variation in a device's output for a specific input when the input is approached from different directions.
Gain Accuracy. Ratio of the true measurement gain to the nominal gain.
Zero Offset. The deviation in the output from true zero for a zero input.
Temperature Coefficient. A quantitative measure of the effects of a variation in operating temperature on a device's zero and sensitivity. This is typically reported by equipment manufacturers in terms of %FS/°C.
Resolution. The value of the smallest detectable signal that a system can measure.
Noise. Any extraneous or unwanted signal which contaminates the measurement. For measurement systems, noise consists of random noise (thermal processes within conductors), white noise (thermal processes within resistors) and systematic noise (line frequency, power supply ripple, EMI, etc.).

Crosstalk. For a multiplexed measurement system the interaction between consecutively scanned channels caused by a difference in voltage between channels. This system attribute is generally expressed in terms of dB.

.**Common Mode Rejection Ratio (CMRR).** The ratio of signal gain to the ratio of normal mode voltage to CMV expressed as:

$$\mathbf{CMRR = Gain/(e_{cmv}}/e_{cmv})$$

where e_{cmv} is the normal mode voltage appearing at the device's output and e_{cmv} is the CMV.

Based on the above definitions, it can be seen that each of the intrinsic errors with the exception of noise contributes to the fixed error. If a different constant input is applied, we postulate that the total fixed error will be different as a result of different contributions from each elemental error. In other words, elemental errors such as non-linearity introduce a fixed error at a constant input. However, this fixed error is not constant over the range. Based on this observation, we postulate that manufacturers report maximum ranges for each of the intrinsic errors. For example, a specification for non-linearity of ±0.1%FS is interpreted to mean that the maximum deviation from a specified straight line is less than ±0.1%FS over the entire range. If the non-linearity at any point within the range is observed to be greater than ±0.1%, the device is not performing to published specifications.

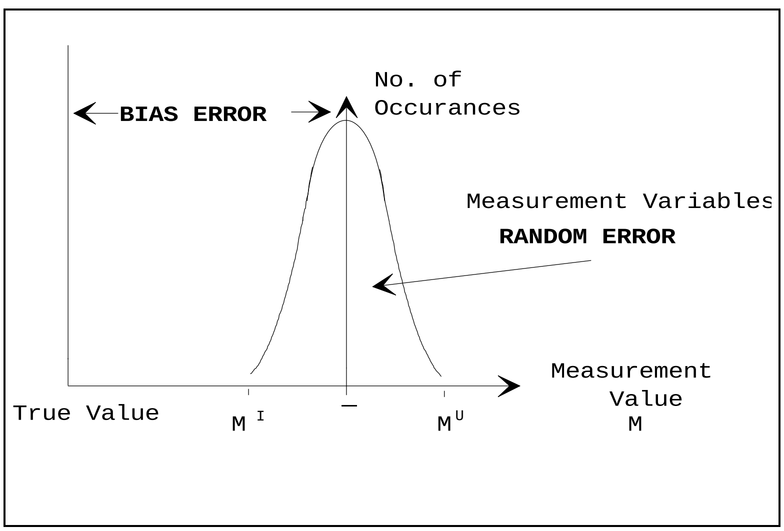


Figure 2. The Two Components of Measurement Error

SECTION 3
COMPUTING TOTAL ERROR

3.1 Overview

For a given configuration with candidate equipment, we can compute the total error attributable to the intrinsic equipment errors as follows:
- Extract from the performance specifications all pertinent performance specifications.
- Establish input/output levels and use to compute system gain. This is required to convert all specifications which are stated in RTI and RTO terms to consistent units such as %FS.
- Establish maximum operating temperature excursion for sensor and data acquisition system. This is used with temperature coefficients to establish maximum error bands for both zero and gain.
- Establish maximum common mode voltage (CMV). Note that strain gage transducers which use grounded power supplies introduce a CMV of one-half the excitation voltage.
- For multiplexed systems, establish maximum channel-to-channel voltage difference for use with crosstalk calculations.
- Determine total system bias based on the elemental errors. The Root-Sum-Square (RSS) technique is considered to be a fair and conservative method of estimating total bias.
- Convert noise specifications to units consistent with the bias term.
- Estimate total measurement uncertainty as a function of bias and random Crosstalk.

3.1 Calculations

Static Crosstalk

$$\text{Error, \%FS} = \{[\text{Gain} \bullet \delta V \bullet \log^{-1}(-\text{Crosstalk in dB}/20)]/\text{FS}) \bullet 100$$

where δV = differential voltage between Channel N and Channel N + 1;
Crosstalk = manufacturer's specification in terms of dB;
Gain = post multiplexer gain for Channel N + 1;
FS = full scale output voltage.

Common Mode Voltage

$$\text{Error, \%FS} = ([\text{Gain} \bullet \text{CMV} \bullet \log^{-1}(-\text{CMRR}/20)]/\text{FS} \bullet 100$$

where Gain = gain of input differential amplifier;
CMV = estimate of common mode voltage in volts;
CMRR = manufacturer's specification in terms of dB;
FS = full scale output voltage.

Zero Stability Attributable to Temperature

$$\text{Error, \%FS} = ([\text{Gain} \bullet \text{RTI} \bullet \delta T + \text{RTO} \bullet \delta T]/\text{FS} \bullet 100$$

where Gain = gain of device;
RTI = element of temperature coefficient in terms relative to input;
RTO = element of temperature coefficient in terms relative to output.
δT = maximum expected temperature excursion.

Zero Offset (Low Level Multiplexed Systems)

$$\text{Error, \%FS} = ([\text{Zero Offset Spec} \bullet \text{Gain}]/\text{FS}) \bullet 100$$

where Gain = gain of channel;
FS = full scale output voltage;

and the Zero Offset Specification is in absolute unit such as μV.

Noise

Noise should be stated as a function of both bandwidth and gain. Typically, noise is reported as 3-sigma noise and is in terms of RTI and RTO.

$$\text{Error, \%FS} = ([\text{Gain} \bullet \text{RTI} + \text{RTO}]/\text{FS}) \bullet 100$$

3.3 Establishing the Estimate

As stated previously, considerable care should be taken to ensure that all errors are in consistent units and that the errors are calculated at the proper gain level. It should be noted that several of the bias errors (offset, gain accuracy, etc.) Can be effectively eliminated using calibration or software techniques. Having done so, the estimate of total uncertainty is:

Uncertainty, %FS = ±(Total Bias Error + Random Noise)

where Total Bias Error = $[b_1^2 + b_2^2 + \bullet \quad \bullet \quad + b_n^2]^{1/2}$ and Random Noise = 3-sigma Error.

This provides a 99.7% confidence interval for uncertainty. If a different confidence level is desired, noise should be divided by three to obtain one-sigma. Any desired multiplier can then be used.

SECTION 4
SUMMARY

Manufacturer's specifications can be used to predict total measurement uncertainty based on a specific configuration and on candidate equipment. While this does not provide an accurate estimate of the expected total error since it does not address installation and application errors, the technique does provide a mechanism for comparing candidate systems.

Reference

Taylor, James; *Fundamentals of Measurement Error*, Neff Instrument Corporation; Monrovia, California