

Interpreting and Applying Equipment Specifications¹

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Abstract

Ideally, manufacturer specifications provide performance characteristics that can be used to evaluate the suitability of measuring and test equipment (MTE) for a given application. However, understanding specifications and using them to compare equipment from different manufacturers or vendors can be a perplexing task. This primarily results from inconsistent terminology, units, and methods used to develop and report equipment specifications.

This paper discusses how manufacturer specifications are obtained, interpreted and used to assess MTE performance and reliability. Recommended practices are presented and illustrative examples are given for combining specifications.

1 Introduction

Manufacturer specifications are an important element of cost and quality control for testing, calibration and other measurement processes. They are used for MTE selection or establishing equipment substitutions for a given measurement application. In addition, manufacturer specified tolerances are used to compute test uncertainty ratios and estimate bias uncertainties.

MTE are calibrated periodically to determine if they are performing within manufacturer specified tolerance limits. In fact, the elapsed-time or interval between calibrations is often based on in-tolerance or out-of-tolerance data acquired from periodic calibrations. Therefore, it is important that manufacturer specifications are properly interpreted and applied.

2 Measuring and Test Equipment

Before we delve into defining and interpreting specifications, it is important to clarify what constitutes MTE. For the purposes of uncertainty analysis, MTE include artifacts, instruments, sensors and transducers, signal conditioners, data acquisition units, data processors and output displays.

2.1 Artifacts

Artifacts constitute passive devices such as mass standards, standard resistors, pure and certified reference materials, gage blocks, etc. Accordingly, artifacts have stated outputs or nominal values and associated specifications.

2.2 Instruments

Instruments constitute equipment or devices that are used to measure and/or provide a specified output. They include, but are not limited to, oscilloscopes, wave and spectrum analyzers, Josephson junctions, frequency counters, multimeters, signal generators, simulators and calibrators, inclinometers, graduated cylinders and pipettes, spectrometers and chromatographs, micrometers and calipers, coordinate measuring machines, balances and scales. Accordingly, instruments can consist of various components and associated specifications.

2.2 Sensors and Transducers

Sensors constitute equipment or devices that respond to a physical input (i.e., pressure, acceleration, temperature or sound). The terms sensor and transducer are often used interchangeably. Transducers more generally refer to devices that convert one form of energy to another. Consequently, actuators that convert an electrical signal to a physical output are also considered to be transducers. For the purposes of this paper, discussion will be limited to sensors and transducers that convert a physical input to an electrical output.

Note: Transmitters constitute sensors coupled with internal signal conditioning and/or data processing components, as well as an output display.

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Some sensors and transducers convert the physical input directly to an electrical output, while others require an external excitation voltage or current. Sensors and transducers encompass a wide array of operating principles (i.e., optical, chemical, electrical) and materials of construction. Consequently, their characteristics and associated specifications can cover a broad spectrum of detail and complexity. A selected list of sensors and transducers is shown in Table 1.

Table 1 Sensors and Transducers

Input	Sensor/Transducer	Output	Excitation
Temperature	Thermocouple	Voltage	
	RTD	Resistance	Current
	Thermistor	Resistance	Current, Voltage
Pressure and Sound	Strain Gauge	Resistance	
	Piezoelectric	Voltage	Voltage
Force and Torque	Strain Gauge	Voltage	Voltage
	Piezoelectric	Voltage	
Acceleration/Vibration	Strain Gage	Voltage	Voltage
	Piezoelectric	Charge	
	Variable Capacitance	Voltage	Voltage
Position/Displacement	LVDT and RVDT	AC Voltage	Voltage
	Potentiometer	Voltage	Voltage
Light Intensity	Photodiode	Current	
Flow Rate	Coriolis	Frequency	
	Vortex Shedding	Pulse/Frequency	Voltage
	Turbine	Pulse/Frequency	
pH	Electrode	Voltage	

2.3 Signal Conditioners

Signal conditioners constitute devices or equipment that are employed to modify the characteristic of a signal. Conditioning equipment include attenuators, amplifiers, bridge circuits, filters, analog-to-digital and digital-to-analog converters, excitation voltage or current, reference temperature junctions, voltage to frequency and frequency to voltage converters, multiplexers and linearizers. A representative list of signal conditioning methods and functions is provided in Table 2.

Table 2 Signal Conditioning Methods

Type	Function
Analog-to-Digital Conversion (ADC)	Quantization of continuous signal.
Amplification	Increase signal level.
Attenuation	Decrease signal level.
Bridge Circuit	Increase resistance output.
Charge Amplification	Convert charge to voltage.
Cold Junction Compensation	Provide temperature correction for thermocouple connection points.
Digital-to-Analog Conversion (DAC)	Convert discrete signal to continuous signal
Excitation	Provide voltage or current to transducer.
Filter	Provide frequency cutoffs and noise reduction
Isolation	Block high voltage and current surges.

Type	Function
Linearization	Convert non-linear signal to representative linear output.
Multiplexing	Provide sequential routing of multiple signals.

2.4 Data Acquisition

Data acquisition (DAQ) equipment provide the interface between the signal and the data processor or computer. DAQ equipment include high-speed timers, random access memory (RAM) and cards containing signal conditioning components.

2.5 Data Processors

Data processors constitute equipment or methods used to implement necessary calculations. Data processors include totalizers and counters, statistical methods, regression or curve fitting algorithms, interpolation schemes, measurement unit conversion or other computations. Error sources resulting from data reduction and analysis are often overlooked in the assessment of measurement uncertainty.

2.6 Output Displays

Output display devices constitute equipment used to visually present processed data. Display devices can be analog or digital in nature. Analog devices include chart recorders, plotters and printers, dials and gages, cathode ray tube (CRT) panels and screens. Digital devices include light-emitting diode (LED) and liquid crystal display (LCD) panels and screens. Resolution is a primary source of error for digital and analog displays.

3 Performance Characteristics

Manufacturer specifications should provide information about MTE performance characteristics. Some manufacturers may provide ample information detailing individual performance specifications, while others may only provide a single specification for overall accuracy. In some instances, specifications can be complex, including numerous time or range dependent characteristics. And, since specification documents are also a means for manufacturers to market their products, they often contain additional information about features, operating condition limits, or other qualifiers.

3.1 Static Characteristics

Static performance characteristics provide an indication of how an instrument, transducer or signal conditioning device responds to a steady-state input at one particular time. In addition to sensitivity (or gain) and zero offset, other static characteristics include nonlinearity, repeatability, hysteresis, resolution, noise, transverse sensitivity, acceleration sensitivity, thermal stability, thermal sensitivity shift, temperature drift, thermal zero shift, temperature coefficient, and accuracy.²

3.2 Dynamic Characteristics

Dynamic performance characteristics provide an indication of how an instrument, transducer or signal conditioning device responds to changes in input over time. Dynamic characteristics include warm-up time, response time, time constant, settling time, zero drift, sensitivity drift, stability, upper and lower cutoff frequencies, bandwidth, resonant frequency, frequency response, damping, phase shift, and reliability.³

3.3 Other Characteristics

Other characteristics are often included with performance specifications to indicate input and output ranges, environmental operating conditions, external power requirements, weight, dimensions and other physical aspects of the device. These other characteristics include rated output, full scale output, range, span, dynamic input range, threshold, dead band, operating temperature range, operating pressure range, operating humidity range, storage temperature range, thermal compensation, temperature compensation range, vibration sensitivity, excitation voltage or current, weight, length, height, and width.

² Accuracy is typically reported as a combined specification that accounts for nonlinearity, hysteresis, and repeatability.

³ Reliability specifications typically refer to performance over an extended time-period or maximum number of cycles.

4 Obtaining Specifications

Manufacturers publish MTE specifications on their web pages, in product data sheets, technical notes, control drawings, and operating manuals. Some manufacturers also maintain an archive of specification information for discontinued products. In some instances, manufacturers will only provide MTE specification information upon formal request by phone, fax or email. In general, however, published specifications are relatively easy to find via an internet search. In searching for specifications, it is helpful to know the relevant industry-specific, or manufacturer-specific, terminology. Further discussion regarding terms, definitions and abbreviations is provided in section 5.1.

5 Interpreting Specifications

Ultimately, the MTE user must determine which specifications are relevant to their application. Therefore, a basic understanding of the fundamental operating principles of the MTE is an important requirement for proper interpretation of performance specifications. In some cases, first-hand experience about the MTE may be gained through calibration and testing. In other cases, detailed knowledge about the MTE may be obtained from operating manuals, training courses, patents and other technical documents provided by the manufacturer.

MTE specifications should provide adequate details about the expected performance characteristics of a representative group of identical devices or items (i.e., a specific manufacturer and model). This information should be reported in a logical format, using consistent terms, abbreviations and units that clearly convey pertinent performance characteristics.

For the most part, manufacturer specifications are intended to convey tolerances or limits that are expected to bound the MTE performance characteristics. For example, these limits may correspond to temperature, shock and vibration parameters that affect the sensitivity and/or zero offset of a sensing device.

Unfortunately, there is no universal guide or standard regarding the development and reporting of MTE specifications. Inconsistency in the methods used to develop and report performance specifications, and in the terms and units used to convey this information, create obstacles to the proper understanding and interpretation of MTE specifications.

In select instances, the information included in a specification document may follow a standardized format.⁴ However, the vast majority of specification documents fall short of providing crucial information about the confidence levels associated with reported specification limits. MTE manufacturers also don't indicate the applicable statistical distribution for a particular performance characteristic.

Consequently, it is difficult to estimate uncertainties from MTE specifications without gaining further clarification or making some underlying assumptions. It is a good practice to

1. Review the specifications and highlight the MTE characteristics that need clarification.
2. Check the operating manual and associated technical documents for other useful details.
3. Request additional information and clarification from the manufacturer's technical department.

5.1 Terms, Definitions and Abbreviations

Technical organizations, such as ISA and SMA, have published documents that adopt standardized instrumentation terms and definitions.^{5,6} However, there is a need for further clarification and consistency in the general terms and definitions used in the reporting of MTE specifications. There are particular terms and abbreviations that require further discussion.

⁴ See for example, ISA-RP37.2-1982-(R1995): *Specifications and Tests for Strain Gauge Pressure Transducers*.

⁵ ISA-37.1-1975 (R1982): *Electrical Transducer Nomenclature and Terminology*, The Instrumentation, Systems and Automation Society.

⁶ SMA LCS 04-99: *Standard Load Cell Specification*, Scale Manufacturers Association.

For example, some MTE specifications may convey performance characteristics as “typical” or “maximum” values. However, the basis for these classifications is not often apparent and introduces confusion about which specification (typical or maximum) is applicable. In addition, since associated confidence levels, containment probabilities or coverage factors are not often provided, it is difficult to clearly interpret either set of specifications. Consequently, manufacturers must be contacted for further clarification.

MTE specifications commonly include the use of abbreviations such as FS, FSO, FSI, RDG, RO, RC and BSL. The abbreviation FS (or F.S.) refers to full scale. Similarly, the abbreviation FSO (or F.S.O.) refers to full scale output and the abbreviation FSI (or F.S.I.) refers to full scale input. Specifications that are reported as % FS (or ppm FS) generally refer to full scale output. When in doubt, however, contact the manufacturer for clarification.

The abbreviation RDG refers to reading or output value. The abbreviation RO (or R.O.) refers to rated output and the abbreviation RC (or R.C.) refers to rated capacity. In some cases, the abbreviation BSL (or B.S.L.) is used to indicate that a combined non-linearity, hysteresis, and repeatability specification is based on observed deviations from a best-fit straight line. Abbreviations commonly used in MTE specification documents are listed in Table 3.

Table 3 Common MTE Abbreviations

Abbreviation	Description	Abbreviation	Description
ADC	Analog to Digital Converter	NMV	Normal-Mode Voltage
BSL	Best-fit Straight Line	ppb	Parts per billion
CMR	Common-Mode Rejection	ppm	Parts per million
CMRR	Common-Mode Rejection Ratio	RDG	Reading
CMV	Common-Mode Voltage	RF	Radio Frequency
CTE	Coefficient of Thermal Expansion	RH	Relative Humidity
DAC	Digital to analog converter	RO	Rated Output
FS	Full Scale	RSS	1) Root-sum-square 2) Residual sum of squares
FSI	Full Scale Input	RTI	Referred to Input
FSO	Full Scale Output	RTO	Referred to Output
FSR	Full Scale Range	TRS	Transverse Rupture Strength
LSB	Least Significant Bit	VAC	Alternating Current Volts
LSD	Least Significant Digit	VDC	Direct Current Volts
NMRR	Normal-Mode Rejection Ratio		

5.2 Qualifications, Stipulations and Warnings

Most MTE specifications describe the performance characteristics covered by the manufacturer’s product warranty. These reported specifications also often include qualifications, clarifications and/or caveats. Therefore, it is a good practice to read all notes and footnotes carefully to determine which, if any, are relevant to the specifications.

For example, MTE specification documents commonly include a footnote warning that the values are subject to change or modification without notice. Manufacturers do not generally modify existing MTE specifications unless significant changes in components or materials of construction warrant the establishment of new specifications. However, it may be necessary to contact the manufacturer to ensure that the appropriate MTE specification documents are obtained and applied.⁷

MTE specifications may state a recommended range of environmental operating conditions to ensure proper performance. They may also include a qualification indicating that all listed specifications are typical values

⁷ That is, the published specifications considered by the manufacturer to be applicable at the time the MTE was purchased.

referenced to standard conditions (e.g., 25 °C and 10 VDC excitation). This qualification implies that the primary performance specifications were developed from tests conducted under a particular set of conditions.

If so, additional specifications, such as thermal zero shift, thermal sensitivity shift and thermal transient response error, are included to account for the variation in actual MTE operating conditions from standard conditions. The MTE user must then consider whether or not these additional specifications are relevant to the MTE application.

5.3 Specification Units

As with terms and definitions, specification units can vary between manufacturers of similar MTE models. In addition, specification units can vary from one performance characteristic to another for a given MTE manufacturer model.

For example, display resolution specifications can be expressed in digits, counts, percent (%) or other units such as mV or °C. Nonlinearity, hysteresis and repeatability specifications can be expressed as % FS, ppm FS, % RDG, ppm RDG, % RO or other units. Sensitivity specifications can be expressed as mV/psi, mV/g, $\mu\text{V}/^\circ\text{F}$, pC/g or other units.

Specifications related to environmental conditions can be expressed as % FS/ $^\circ\text{F}$, % RO/ $^\circ\text{C}$, ppm/ $^\circ\text{C}$, % FS/g, psi/g, psi/ $^\circ\text{F}$, mV/ $^\circ\text{C}$, %Load/ $^\circ\text{F}$, etc. Noise specifications such as Normal Mode Rejection Ratio (NMRR) and Common Mode Rejection Ratio (CMRR) are generally specified in decibels (dB) at specified frequencies (usually 50 and 60 Hz).

Different specification units can make it especially difficult to interpret specifications. In most cases, units conversion is required before specifications can be properly applied. Selected specification conversion factors are listed in Table 4 for illustration. Additional calculations may be required before specifications can be properly used to estimate MTE parameter bias uncertainty and tolerance limits.

Table 4 Specification Conversion Factors

Percent	ppm	dB	Relative to 10 V	Relative to 100 psi	Relative to 10 kg/ $^\circ\text{C}$
1%	10000	-40	100 mV	1 psi	100 g/ $^\circ\text{C}$
0.1%	1000	-60	10 mV	0.1 psi	10 g/ $^\circ\text{C}$
0.01%	100	-80	1 mV	0.01 psi	1 g/ $^\circ\text{C}$
0.001%	10	-100	100 μV	0.001 psi	100 mg/ $^\circ\text{C}$
0.0001%	1	-120	10 μV	0.0001 psi	10 mg/ $^\circ\text{C}$

Note: A decibel (dB) is a dimensionless unit for expressing the ratio of two values of power, P_1 and P_2 , where $\text{dB} = 10 \log(P_2/P_1)$. The dB values in Table 4 are computed for P_2/P_1 ratios corresponding to the percent and ppm values listed. For electrical power, it is important to note that power is proportional to the square of voltage, V , so that $\text{dB}_V = 10 \log(V_1^2/V_2^2) = 20 \log(V_1/V_2)$. Similarly, acoustical power is proportional to the square of sound pressure, p , so that $\text{dB}_A = 10 \log(p_1^2/p_2^2) = 20 \log(p_1/p_2)$.

6 Applying Specifications

Manufacturer specifications can be used to purchase or substitute MTE for a given measurement application, estimate bias uncertainties and establish tolerance limits for calibration and testing. Therefore, MTE users must be proficient at identifying applicable specifications and in interpreting and combining them.

It is also important that manufacturers and users have a good understanding and assessment of the confidence levels and error distributions applicable to MTE specifications. This is a crucial part of the process and requires some further discussion.

6.1 Confidence Levels

As previously discussed, some manufacturer MTE specifications are established by testing a selected sample of the produced model population. Since the test results are applied to the entire MTE model population, limits are

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developed to ensure that a large percentage of the MTE model population will perform as specified. Consequently, the specifications are confidence limits with associated confidence levels.⁸

That is, the limits specified for an MTE performance characteristic are established for a particular confidence level and degrees of freedom (or sample size). Confidence limits, $\pm L_x$, for values of a specific performance characteristic, x , are expressed as

$$\pm L_x = \pm t_{\alpha/2, \nu} s_x \quad (1)$$

where

$$\begin{aligned} t_{\alpha/2, \nu} &= \text{t-statistic} \\ \alpha &= \text{significance level} = 1 - C/100 \\ C &= \text{confidence level (\%)} \\ \nu &= \text{degrees of freedom} = n - 1 \\ n &= \text{sample size} \\ s_x &= \text{sample standard deviation.} \end{aligned}$$

Ideally, confidence levels should be commensurate with what MTE manufacturers consider to be the maximum allowable false accept risk (FAR).⁹ The general requirement is to minimize the probability of shipping an MTE item with nonconforming (or out-of-compliance) performance characteristics. In this regard, the primary factor in setting the maximum allowable FAR may be the costs associated with shipping nonconforming products.

For example, an MTE manufacturer may require a maximum allowable FAR of 1% for all performance specifications. In this case, a 99% confidence level would be used to establish the MTE specification limits. Similarly, if the maximum allowable FAR is 5%, then a 95% confidence level should be used to establish the specification limits.

Unfortunately, manufacturers don't commonly report confidence levels for their MTE specifications. In fact, the criteria and motives used by manufacturers to establish MTE specifications are not often apparent. Most MTE manufacturers see the benefits, to themselves and their customers, of establishing specifications with high confidence levels. However, specsmanship between MTE manufacturers can result in tighter specifications and increased out-of-tolerance occurrences.¹⁰

Alternatively, some manufacturers may test the entire produced MTE model population to ensure that individual items are performing within specified limits prior to shipment. However, this compliance testing process does not ensure a 100% probability (or confidence level) that the customer will receive an in-tolerance item. The reasons for this include

1. Measurement uncertainty associated with the manufacturer MTE compliance testing process.
2. MTE bias drift or shift resulting from shock, vibration and other environmental extremes during shipping and handling.

Manufacturers may attempt to mitigate this problem by increasing the MTE specification limits. This can be accomplished by using a higher confidence level (e.g., 99.9%) to establish larger specification limits. Alternatively, some manufacturers may employ arbitrary guardbanding¹¹ methods and multiplying factors. In either case, the resulting MTE specifications are not equivalent to 100% confidence limits.

⁸ In this context, confidence level and containment probability are synonymous, as are confidence limits and containment limits.

⁹ See for example, Castrup, H.: "Risk Analysis Methods for Complying with NCSLI Z540.3."

¹⁰ See for example, Deaver, D.: "Having Confidence in Specifications."

¹¹ Guardbands are supplemental limits used to reduce false accept risk.

6.2 Error Distributions

MTE performance characteristics, such as nonlinearity, repeatability, hysteresis, resolution, noise, thermal stability and zero shift constitute sources of measurement error. Measurement errors are random variables that can be characterized by statistical distributions. Therefore, MTE performance characteristics are also considered to be random variables that follow statistical distributions.

The statistical distribution for a type of measurement error is a mathematical description that relates the frequency of occurrence of values to the values themselves. Error distributions include, but are not limited to normal, lognormal, uniform (rectangular), triangular, quadratic, cosine, exponential, u-shaped and trapezoidal.

This concept is important to the interpretation and application of MTE specifications because an error distribution allows us to determine the probability that a performance characteristic is in conformance or compliance with its specification.

Some manufacturers may state that specifications simply bound the value of an MTE characteristic and do not imply any underlying statistical distribution. Yet, when asked for clarification, many manufacturers indicate that the normal distribution is used as the underlying performance distribution.

For the sampled MTE model specifications described in section 6.1, the performance characteristics of an individual MTE model may vary from the population mean. However, the majority of the units should perform well within their specification limits. As such, a central tendency exists that can be described by the normal distribution.

If the limits are asymmetric about a specified nominal value, it is still reasonable to assume that individual MTE performance characteristics will tend to be distributed near the nominal value. In this case, the normal distribution may be applicable. However, the lognormal or other asymmetric distribution may be more applicable.

There are a couple of exceptions when the uniform distribution would be applicable. These include digital output resolution error and quantization error resulting from the digital conversion of an analog signal. In these instances, the specifications limits, $\pm L_{res}$ and $\pm L_{quan}$, would be 100% confidence limits defined as

$$\pm L_{res} = \pm \frac{h}{2} \quad (2)$$

and

$$\pm L_{quan} = \pm \frac{A}{2^{n+1}} \quad (3)$$

where

- h = least significant display digit
- A = full scale range of analog to digital converter
- n = quantization significant bits.

6.3 Combining Specifications

In testing and calibration processes, an MTE performance characteristic is identified as being in-tolerance or out-of-tolerance. In some cases, the tolerance limits are determined from a combination of MTE specifications. For example, consider the accuracy specifications for the DC voltage function of a digital multimeter listed in Table 5.

Table 5 8062A Digital Multimeter DC Voltage Specifications¹²

Specification	Value
200 mV Range Resolution	0.01 mV
200 mV Range Accuracy	0.05% of Reading + 2 digits
2 V Range Resolution	0.1 mV
2 V Range Accuracy	0.05% of Reading + 2 digits
20 V Range Resolution	1 mV
20 V Range Accuracy	0.07% of Reading + 2 digits

¹² Specifications from 8062A Instruction Manual downloaded from www.fluke.com

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For illustration purposes, assume that a 5 V output is read with the DC voltage function of the multimeter. Therefore, the appropriate accuracy specification would be $\pm (0.07\% \text{ Reading} + 2 \text{ mV})$.¹³ To compute the combined accuracy specification, we must convert the % Reading to a value in units of mV.

$$0.07\% \text{ Reading} = (0.07/100) \times 5 \text{ V} \times 1000 \text{ mV/V} = 3.5 \text{ mV}$$

The total accuracy specification for the 5 V output reading would then be $\pm 5.5 \text{ mV}$. Combined accuracy specifications for different voltage ranges and output readings are summarized in Table 6 for comparison.

Table 6 DC Voltage Accuracy Specifications

Output Reading		200 mV Range	2 V Range	20 V Range
50 mV	0.05 V	$\pm 0.05 \text{ mV}$	$\pm 0.23 \text{ mV}$	$\pm 2.04 \text{ mV}$
100 mV	0.1 V	$\pm 0.07 \text{ mV}$	$\pm 0.25 \text{ mV}$	$\pm 2.07 \text{ mV}$
200 mV	0.2 V	$\pm 0.12 \text{ mV}$	$\pm 0.30 \text{ mV}$	$\pm 2.14 \text{ mV}$
500 mV	0.5 V		$\pm 0.45 \text{ mV}$	$\pm 2.35 \text{ mV}$
1000 mV	1 V		$\pm 0.70 \text{ mV}$	$\pm 2.70 \text{ mV}$
2000 mV	2 V		$\pm 1.20 \text{ mV}$	$\pm 3.40 \text{ mV}$
5000 mV	5 V			$\pm 5.50 \text{ mV}$
10000 mV	10 V			$\pm 9.00 \text{ mV}$

For another example, let us consider the tolerance specifications for different gage block grades published by NIST.¹⁴ A subset of the data are listed in Tables 7 and 8.

Table 7 Tolerance Grades for Metric Gage Blocks (μm)

Nominal	Grade .5	Grade 1	Grade 2	Grade 3
< 10 mm	0.03	0.05	+0.10, -0.05	+0.20, -0.10
< 25 mm	0.03	0.05	+0.10, -0.05	+0.30, -0.15
< 50 mm	0.05	0.10	+0.20, -0.10	+0.40, -0.20
< 75 mm	0.08	0.13	+0.25, -0.13	+0.45, -0.23
< 100 mm	0.10	0.15	+0.30, -0.15	+0.60, -0.30

Table 8 Additional Tolerance for Length, Flatness, and Parallelism (μm)

Nominal	Grade .5	Grade 1	Grade 2	Grade 3
< 100 mm	± 0.03	± 0.05	± 0.08	± 0.10
< 200 mm		± 0.08	± 0.15	± 0.20
< 300 mm		± 0.10	± 0.20	± 0.25
< 500 mm		± 0.13	± 0.25	± 0.30

Suppose we want to compute the combined tolerance limits for a Grade 2 gage block with 20 mm nominal length. The first specification limits (+0.10 μm , -0.05 μm) are asymmetric, while the second specification limits ($\pm 0.08 \mu\text{m}$) are symmetric. Consequently, the combined tolerance limits will be asymmetric and we need to compute upper and lower tolerances (e.g., $+L_1$, $-L_2$).

There are two possible ways to compute values for L_1 and L_2 from the specifications: linear combination or root-sum-square (RSS) combination.

¹³ Understanding Specifications for Precision Multimeters, Application Note Pub_ID 11066-eng Rev 01, ©2006 Fluke Corporation.

¹⁴ The Gage Block Handbook, NIST Monograph 180, 1995.

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1. Linear Combination

$$L_1 = 0.10 + 0.08 = 0.18$$

$$L_2 = 0.05 + 0.08 = 0.13$$

2. RSS Combination

$$L_1 = \sqrt{(0.10)^2 + (0.08)^2} = \sqrt{0.0164} = 0.13$$

$$L_2 = \sqrt{(0.05)^2 + (0.08)^2} = \sqrt{0.0089} = 0.09$$

If the specifications are interpreted to be additive, then the combined tolerance limits for the 20 mm Grade 2 gage block are +0.18 μm , -0.13 μm . Alternatively, if they are to be combined in RSS, then the resulting tolerance limits are +0.13 μm , -0.09 μm .

Linear or RSS specification combination cannot be used for MTE that have complex performance characteristics. For example, consider the load cell specifications¹⁵ listed in Table 9.

Table 9 MDB-5-T Load Cell Specifications

Specification	Value	Units
Rated Output (R.O.)	2 (nominal)	mV/V
Maximum Load	5	lb _f
Nonlinearity	0.05% of R.O.	mV/V
Hysteresis	0.05% of R.O.	mV/V
Nonrepeatability (Noise)	0.05% of R.O.	mV/V
Zero Balance (Zero Offset)	1.0% of R.O.	mV/V
Compensated Temp. Range	60 to 160	°F
Temperature Effect on Output	0.005% of Load/°F	lb _f /°F
Temperature Effect on Zero	0.005% of R.O./°F	mV/V/°F
Required Excitation	10	VDC

The load cell sensing element is a resistance-based strain gage that requires an external excitation voltage. The load cell has a rated output of 2 mV/V for loads up to 5 lb_f which equates to a nominal sensitivity of 0.4 mV/V/lb_f. Therefore, the load cell output is a function of the excitation voltage and the applied load.

$$LC_{out} = W \times S \times V_{Ex} \quad (4)$$

where

- W = Applied load or weight
- S = Load cell sensitivity
- V_{Ex} = Excitation voltage

Equation (4) shows the mathematical relationship between the physical input (i.e., weight) and the electrical output (i.e., voltage) of the load cell.¹⁶ This relationship is called a transfer function.

According to the specifications, the load cell output will be affected by the following error sources:

- Excitation Voltage
- Nonlinearity
- Hysteresis
- Noise
- Zero Balance
- Temperature Effect on Output

¹⁵ Specifications obtained from www.tloadcells.com/mdb-load-cell.cfm

¹⁶ The validity of this equation depends on the use of appropriate units for the variables, W , S and V_{Ex} .

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- Temperature Effect on Zero

If the load cell is tested or calibrated using a weight standard, then any error associated with the weight should also be included.

Equation (4) needs to be modified to account for these error sources. Unfortunately, given the assortment of specification units, the error terms cannot simply be added at the end of the equation. The appropriate load cell output equation is expressed in equation (5).

$$LC_{out} = \left[(W_s + TE_{out} \times TR_{\circ F}) \times S + NL + Hys + NS + ZO + TE_{zero} \times TR_{\circ F} \right] \times V_{Ex} \quad (5)$$

where

$$W_s = W_n + W_e \quad (6)$$

$$V_{Ex} = V_n + V_e \quad (7)$$

and

W_n	=	Nominal or stated value of weight standard
W_e	=	Bias of weight standard
V_n	=	Nominal excitation voltage
V_e	=	Excitation voltage error
TE_{out}	=	Temperature effect on output
$TR_{\circ F}$	=	Temperature range in °F
NL	=	Nonlinearity
Hys	=	Hysteresis
NS	=	Noise and ripple
ZO	=	Zero offset
TE_{zero}	=	Temperature effect on zero

Equations (5) through (7) constitute an error model for the load cell output. Given some knowledge about the error distributions, then the variance addition rule can be applied to estimate the uncertainty in the load cell output voltage for a given applied load. This procedure involves some additional concepts and methods that are not covered in this paper.

A list of transfer functions for selected MTE is provided in Table 10 for illustrative purposes. While these transfer functions include basic error terms, they are not considered to be definitive. The actual form of the equations will vary depending on the MTE specifications, as demonstrated in equation (5).

Table 10 Generalized Transfer Functions for Selected MTE

Transfer Function	Error Sources
Sensor or Transducer (No Excitation) $Y_{out} = X_{in} \times S + Y_{os} + Y_e$ Y_{out} = electrical output X_{in} = physical input quantity S = sensitivity Y_{os} = zero offset Y_e = sensor or transducer error	<ul style="list-style-type: none"> • Reference junction • Nonlinearity • Hysteresis • Noise • Resolution • Repeatability • Offset error • Temperature effects • Long-term stability

Transfer Function	Error Sources
<p>Sensor or Transducer (Excitation)</p> $Y_{out} = X_{in} \times S \times E + Y_{os} + Y_e$ <p> Y_{out} = electrical output X_{in} = physical input quantity S = sensitivity E = excitation voltage or current Y_{os} = zero offset Y_e = sensor or transducer error </p>	<ul style="list-style-type: none"> • Nonlinearity • Hysteresis • Noise • Resolution • Repeatability • Offset error • Temperature effects • Long-term stability
<p>Excitation or External Power Source</p> $E = E_n + E_e$ <p> E = excitation voltage or current E_n = nominal excitation voltage or current E_e = excitation error </p>	<ul style="list-style-type: none"> • Accuracy • Drift • Stability
<p>Precision Input or Reference Standard</p> $RS = RS_n + RS_e$ <p> RS = reference standard value RS_n = nominal or indicated value RS_e = reference standard error </p>	<ul style="list-style-type: none"> • Bias • Drift • Stability • Environmental
<p>Simulator or Calibrator</p> $Y_{out} = Y_n + Y_{os} + Y_e$ <p> Y_{out} = indicated output value Y_n = simulator or calibrator output Y_{os} = zero offset Y_e = simulator or calibrator error </p>	<ul style="list-style-type: none"> • Hysteresis • Noise • Resolution • Repeatability • Offset error • Temperature effects • Stability
<p>Analog or Digital Multiplexer</p> $Y_{out} = X_{in} + Y_e$ <p> Y_{out} = electrical output X_{in} = analog or digital input Y_e = multiplexer error </p>	<ul style="list-style-type: none"> • Cross-talk • Thermal-induced Voltages
<p>Amplifier</p> $Y_{out} = X_{in} \times G + Y_e$ <p> Y_{out} = output X_{in} = input G = gain Y_e = amplifier error </p>	<ul style="list-style-type: none"> • Gain accuracy • Gain stability • CMMR • Noise • Nonlinearity • Offset error • Settling Time • Slew Rate • Overshoot • Temperature effects
<p>Charge Amplifier</p> $Y_{out} = -Q_{in} / C_r + Y_e$ <p> Y_{out} = voltage output Q_{in} = current input C_r = range capacitor Y_e = electrical input </p>	<ul style="list-style-type: none"> • Drift due to leakage current • Drift due to offset voltage

Transfer Function	Error Sources
<p>Filter</p> $Y_{out} = X_{in} \times A + Y_e$ <p> Y_{out} = output X_{in} = input A = attenuation Y_e = filtering error </p>	<ul style="list-style-type: none"> • Linearity • Offset error • Thermal effects • Stability • Passband Ripple & Flatness • Stopband Ripple & Flatness • Stopband Attenuation
<p>AD and DA Converters</p> $Y_{out} = X_{in} + Y_e$ <p> Y_{out} = digital or analog output X_{in} = analog or digital input Y_e = ADC or DAC error </p>	<ul style="list-style-type: none"> • Aperture error • Sampling distortion • Stabilization • Quantization • Nonlinearity • Offset error • Supply rejection • Temperature effects • Long-term drift
<p>Cables and Connectors</p> $Y_{out} = X_{in} \times A + Y_e$ <p> Y_{out} = electrical output X_{in} = electrical input A = attenuation Y_e = cabling or connector error </p>	<ul style="list-style-type: none"> • Attenuation • Loading • Interface Errors
<p>Data Acquisition</p> $Y_{out} = Y_{in} + Y_e$ <p> Y_{in} = input Y_{out} = output Y_e = DAQ error </p>	<ul style="list-style-type: none"> • Time Code Error • Signal Conditioning Error
<p>Data Processors</p> $Y_{out} = Y_{in} + Y_e$ <p> Y_{in} = input Y_{out} = output Y_e = processor error </p>	<ul style="list-style-type: none"> • Regression Error • Round-off/Truncation Error
<p>Output Displays</p> $Y_{out} = Y_{in} + Y_e$ <p> Y_{out} = output Y_{in} = input Y_e = resolution error </p>	<ul style="list-style-type: none"> • Resolution

7 Conclusions

Measurements are an important aspect of decision making, communicating technical information, establishing scientific facts, monitoring manufacturing processes and maintaining human and environmental health and safety. Consequently, industries and governments spend billions of dollars annually to acquire, install and maintain MTE.

Manufacturer specifications are an important element of cost and quality control for testing, calibration and other measurement processes. They are used for equipment selection or establishing equipment substitutions for a given measurement application. In addition, specifications are used to estimate MTE bias uncertainties essential for measurement uncertainty analysis and decision risk analysis. Therefore, it is important that manufacturer specifications are properly interpreted and applied to assess MTE performance and reliability.

This paper has presented detailed discussions and important issues about obtaining, interpreting and applying manufacturer specifications. Recommended practices have been presented and illustrative examples given for combining specifications. However, additional efforts are needed to address existing inconsistencies and incomplete reporting of MTE specifications.

Note: Subsequent to the presentation of this paper in Washington, DC, the NCSLI Board of Directors approved the creation of a new subcommittee to identify and publish recommended practices for developing, reporting, obtaining, interpreting, validating and applying MTE specifications. The document will be titled NCSLI RP-5 “Measuring and Testing Equipment Specifications.”

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