



Designation: **E2428—08 E2428 – 14**

## Standard Practice for Calibration of Torque-Measuring Instruments for Verifying the Torque Indication of Torque Testing Machines<sup>1</sup>

This standard is issued under the fixed designation E2428; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

### 1. Scope

1.1 This practice is to specify procedure for the calibration of elastic torque-measuring instruments.

NOTE 1—Verification by deadweight and a lever arm is an acceptable method of verifying the torque indication of a torque testing machine. Tolerances for weights used are tabulated in Practice E2624; methods for calibration of the weights are given in NIST Technical Note 577, Methods of Calibrating Weights for Piston Gages.<sup>2</sup>

1.2 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.3 This practice is intended for the calibration of static or quasi-static torque measuring instruments. The practice is not applicable for high-speed dynamic or high-speed torque calibrations or measurements, nor can the results of calibrations performed in accordance with this practice be assumed valid for dynamic or high speed torque measurements.

1.4 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

### 2. Referenced Documents

2.1 ASTM Standards:<sup>3</sup>

E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications

E2624 Practice for Torque Calibration of Testing Machines and Devices

2.2 American National Standard:

B46.1 Surface Texture<sup>4</sup>

<https://standards.iteh.ai/catalog/standards/sist/08f89c57/astm-e2428-14>

### 3. Terminology

3.1 Definitions:

3.1.1 *elastic torque-measuring device*—a device or system consisting of an elastic member combined with a device for indicating the measured values (or a quantity proportional to the measured value) of deformation of the member under an applied torque.

3.1.2 *primary torque standards*—a deadweight force applied through a lever arm or wheel, with a calibrated length or radius of a known uncertainty, that is traceable to national standards.

3.1.3 *secondary torque standard*—an instrument or mechanism, that has been calibrated by a comparison with a primary torque standard(s).

3.1.4 *torque*—a vector product of force and length, expressed in terms of N-m, lbf-in., etc.

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<sup>2</sup> Available from National Institute of Standards and Technology (NIST), 100 Bureau Dr., Stop 1070, Gaithersburg, MD 20899-1070, <http://www.nist.gov>.

<sup>3</sup> For referenced ASTM standards, visit the ASTM website, [www.astm.org](http://www.astm.org), or contact ASTM Customer Service at [service@astm.org](mailto:service@astm.org). For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

<sup>4</sup> Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, <http://www.ansi.org>.

### 3.2 Definitions of Terms Specific to This Standard:

3.2.1 calibration equation—a mathematical relationship between ~~output of the unit under test and the applied standard torque, sometimes referred to as deflection~~ and torque established from the calibration data for use with the torque transducer in service, sometimes called the calibration curve.

#### 3.2.1.1 Discussion—

Torque transducers have torque-to-deflection relationships that can be fitted to polynomial equations.

3.2.2 continuous-reading device—a class of instruments whose characteristics permit interpolation of torque values between calibrated torque values.

#### 3.2.2.1 Discussion—

Such instruments usually have torque-to-deflection relationships that can be fitted to polynomial equations. Departures from the fitted curve are reflected in the uncertainty (see [8.48.5](#)).

3.2.3 creep—The change in deflection of the torque transducer under constant applied torque.

#### 3.2.3.1 Discussion—

Creep is expressed as a percentage of the output change at a constant applied torque from an initial time following the achievement of mechanical and electrical stability and the time at which the test is concluded. Valid creep tests may require the use of primary torque standards to maintain adequate stability of the applied torque during the test time interval. Creep results from a time dependent, elastic deformation of the instrument mechanical element. In the case of torque transducers, creep is adjusted by strain gage design and process modifications to reduce the strain gage response to the inherent time-dependent elastic deflection.

3.2.4 creep recovery—The non-return to zero following a creep test.

#### 3.2.4.1 Discussion—

Creep Recovery is expressed as a percentage difference of the output change at zero torque following a creep test and the initial zero torque output at the initiation of the creep test divided by the output during the creep test. The zero-torque measurement is taken at a time following the achievement of mechanical and electrical stability and a time equal to the creep test time. For many torque transducers, the creep characteristic and the creep recovery characteristic are approximate mirror images.

3.2.5 deflection—the difference between the readings of an instrument under applied torque and the reading with no applied torque. The definition of deflection applies to output readings in electrical units as well as readings in units of torque.

3.2.6 torque range—lower limit factor, LLF—a range of torque values within which the uncertainty is less than the A statistical estimate of the limits of error specified for the instrument application of torque values computed from the calibration equation of the torque transducer when the torque transducer is calibrated in accordance with this practice.

#### 3.2.6.1 Discussion—

The lower limit factor is used as one factor that may establish the lower limit of the range of torque values over which the torque transducer can be used. Other factors evaluated in the establishment of the lower limit of the range of torque values are the resolution of the torque transducer and the lowest nonzero torque applied in the calibration load sequence.

#### 3.2.6.2 Discussion—

The lower limit factor was termed uncertainty in previous editions of E2428. While the lower limit factor is a component of uncertainty, other appropriate error sources should be considered in determining the measurement uncertainty of the torque transducer in service.

3.2.7 reading—a numerical value indicated on the scale, dial, electrical output or digital display of a torque-measuring instrument for a given torque.

3.2.8 resolution—the smallest change in reading or indication appropriate to the scale, dial, or display of the torque measuring instrument.

3.2.9 specific torque device—an alternative class of instruments not amenable to the use of a calibration equation.

### 3.2.9.1 Discussion—

Such instruments, usually those in which the reading is taken from a dial indicator, are used only at the calibrated torque values.

3.2.10 ~~uncertainty—torque range—a statistical estimate of the range of torque values within which the uncertainty is less than the limits of error in torque values computed from the calibration equation of a torque-measuring instrument when the instrument is calibrated in accordance with this practice specified for the instrument application.~~

## 4. Significance and Use

4.1 Testing machines that apply and indicate torque are in general use in many industries. Practice E2624 has been written to provide a practice for the torque verification of these machines. A necessary element in Practice E2624 is the use of devices whose torque characteristics are known to be traceable to national standards. Practice E2428 describes how these devices are to be calibrated. The procedures are useful to users of torque testing machines, manufacturers and providers of torque measuring instruments, calibration laboratories that provide calibration services and documents, and service organizations using devices to verify torque testing machines.

## 5. Reference Standards

5.1 Torque-measuring instruments used for the verification of the torque indication systems of torque testing machines may be calibrated by either primary or secondary standards.

5.2 Torque-measuring instruments used as secondary standards for the calibration of other torque-measuring instruments shall be calibrated by primary standards.

## 6. Requirements for Torque Standards

6.1 *Primary Standard*—Torque, with traceability derived from national standards of length and mass, and of specific measurement uncertainty, that can be applied to torque measuring devices. Weights used as primary mass standards shall be made of rolled, forged, or cast metal. Adjustment cavities shall be closed by threaded plugs or suitable seals. External surfaces of weights shall have a finish of 3.2m (Ra) or less as specified in ANSI B46.1.

6.1.1 The force exerted by a weight in air is calculated as follows:

$$\text{Force} = (Mg/9.80665) (1 - (d/D)) \quad (1)$$

where:

- $M$  = mass of the weight,
- $g$  = local acceleration due to gravity,  $\text{m/s}^2$ ,
- $d$  = air density (approximately  $1.2 \text{ kg/m}^3$ ),
- $D$  = density of the weight in the same units as  $d$ , and
- 9.80665 = the factor converting SI units of force into the customary units of force. For SI units, this factor is not used.

6.1.2 The masses of the weights shall be determined by comparison with reference standards traceable to the national standards of mass. The local value of the acceleration due to gravity, calculated within  $0.0001 \text{ m/s}^2$  (10 milligals), may be obtained from the National Geodetic Information Center, National Oceanic and Atmospheric Administration.<sup>5</sup>

NOTE 2—If  $M$ , the mass of the weight, is in pounds, the force will be in pound-force units (lbf). If  $M$  is in kilograms, the force will be in kilo gram-force units (kgf). These customary force units are related to the newton (N), the SI unit of force, by the following relationships:

$$\begin{aligned} 1 \text{ kgf} &= 9.80665 \text{ N (exact)} \\ 1 \text{ lbf} &= 4.44822 \text{ N} \end{aligned}$$

The pound-force (lbf) is defined as that force which, applied to a 1-lb mass, would produce an acceleration of  $32.1747 \text{ ft/s}^2$ .

6.1.3 The lever arm or wheel shall be calibrated to determine the length or radius with a known uncertainty, that is traceable to national standards of length. The expanded uncertainty with a confidence factor of 95 % ( $K=2$ ) for the torque calibrator shall not exceed 0.012 % .

6.2 *Secondary Standards*—Secondary torque standards may be either elastic torque-measuring instruments used with a machine for applying torque, or a mechanical or hydraulic mechanism to apply or multiply a deadweight force.

6.2.1 The multiplying ratio of a force multiplying system used as a secondary torque standard shall be measured at not less than ten points over its range with an accuracy of 0.06 % of ratio or better. Some systems may show a systematic change in ratio with increasing force. For these cases the ratio at intermediate points may be obtained by linear interpolation between measured values. Deadweights used with multiplying-type secondary standards shall meet the requirements of 6.1 and 6.1.2. The force exerted on the system shall be calculated from the relationships given in 6.1.1. The force multiplying system shall be checked annually by

<sup>5</sup> Available from National Oceanic and Atmospheric Administration (NOAA), 14th St. and Constitution Ave., NW, Room 6217, Washington, DC 20230, <http://www.noaa.gov>.

elastic force measuring instruments used within their class AA loading ranges to verify the forces applied by the system are within acceptable ranges defined by this standard. Changes exceeding 0.06 % of applied force shall be cause for re-verification of the force multiplying system.

$$LLF_c = \sqrt{LLF_1^2 + LLF_2^2 + \dots + LLF_n^2} \quad (2)$$

where:

$LLF^C$  = Lower limit factor of the combination, and  
 $LLF^{1, 2, \dots, n}$  = Lower limit factor of the individual instruments

6.2.2 Elastic torque-measuring instruments used as secondary standards shall be calibrated by primary standards and used only over the Class AA loading range (see 8.5.2.18.6.2.1).

6.2.3 Other types of torque standards may be used and shall be calibrated. The expanded uncertainty with a confidence factor of 95% (K=2) shall not exceed 0.06% of the applied torque.

## 7. Calibration

7.1 *Basic Principles*—The relationship between the applied torque and the deflection of an elastic torque-measuring instrument a torque transducer is, in general, not linear. As the torque is applied, the shape of the elastic element changes, progressively altering its resistance to deformation. The result is that the slope of the torque-deflection curve changes gradually and uniformly continuously over the entire range of the instrument. This characteristic of full-scale non-linearity curve is a stable property of the instrument that is changed only by a severe overload or other similar cause.

7.1.1 *Localized Non-linearities*—Superimposed Superposed on this curve are localized non-linearities—local variations of instrument readings introduced by the imperfections in the torque indicating system of the instrument. transducer. Examples of these imperfections include voltage and sensing instabilities. instabilities in excitation voltage, voltage measurement, or ratio-metric voltage measurement in a torque transducer. Some of these imperfections are less stable than the full-scale non-linearity characteristic curve and may change significantly from one calibration to another.

7.1.2 *Curve Fitting*—A second degree polynomial fitted to the observed calibration data using the method of least squares, predicts the deflection values for applied torque throughout the loading. To determine the torque-deflection curve of the torque transducer, known torque values are applied and the resulting deflections are measured throughout the range of the elastic torque measuring instrument (see torque transducer. A polynomial 8.4) equation is fitted to the calibration data by the least squares method to predict deflection values throughout the loading range. Such an equation compensates effectively for the full-scale non-linearity, allowing the localized non-linearities to appear as deviations. nonlinearity of the calibration curve. The standard deviation determined from the difference of each measured deflection value from the value derived from the polynomial curve at that torque provides a measure of the error of the data to the curve fit equation. A statistical estimate, called the uncertainty, is made of the Lower Limit Factor, LLF, is derived from the calculated standard deviation and represents the width of the band of these deviations about the basic curve. The uncertainty is curve with a probability of 95%. The LLF is, therefore, an estimate of the limits one source of error uncertainty contributed by the instrument torque transducer when torque values measured in service are calculated using by means of the calibration equation. Actual errors in service will vary for are likely to be different if torque values are applied under loading mechanical and environmental conditions differing from those of the calibration calibration. Other sources of uncertainty could increase the uncertainty of measurement of the torque transducer in service.

NOTE 3—While it is the responsibility of the calibration laboratory to calibrate the torque transducer in accordance with the requirements of this practice it is the responsibility of the user to determine the uncertainty of the torque transducer in service.

7.1.3 *Curve Fitting for High Resolution Devices—using polynomials of greater than 2nd degree*—The use of calibration equations of the 3rd, 4th, or 5th degree is restricted to devices having a resolution of 1 increment of count per 50000 or greater active counts at the maximum calibration torque. Annex A1 recommends as specifies the procedure for obtaining the degree of the best-fit best fit calibration curve for these devices. Equations of greater than 5th degree shall not be used.

NOTE 4—Experimental work by several calibration laboratories in fitting higher than second degree polynomials to the observed data indicated that, for some devices, For some torque transducers, use of a higher degree equation polynomial fit higher than the second degree may result in a lower uncertainty than derived from the second degree fit (ASTM-LLF, RR:E28-1009). Over-fitting should be avoided. Equations of greater than 5th degree should not cannot be used justified due to the limited number of torque increments in the calibration protocol. Numerical errors Errors caused by round-off may occur if calculations are performed with insufficient precision. A device used to measure torque torque transducer not subjected to repair, overloading, modifications, or other significant influence factors which that alter its elastic properties properties or its sensing characteristics characteristics will likely exhibit the same degree of best fit on each succeeding calibration as was determined during its initial calibration using this procedure. A device torque transducer not subjected to the influence factors outlined above which exhibits continued change of degree of best fit with several successive calibrations may not have sufficient performance stability to allow application of the curve fitting procedure of Annex A1.

7.2 *Selection of Calibration Torque Values*—A careful selection of the different torque values to be applied in a calibration is essential to provide an adequate and unbiased sample of the full range of the deviations discussed in 7.1 and 7.1.1. For this reason, the selection of the calibration torque values is made by the standardizing laboratory. An exception to this, and to the recommendations of 7.2.1 and 7.2.4, is made for specific torque measurement devices, where the selection of the torque values is dictated by the needs of the user.

**7.2.1 Distribution of Calibration Torque Values**—Distribute the calibration torque values over the full range of the instrument, torque transducer, providing, if possible, at least one calibration torque for every ~~10%~~ 10 % interval throughout the range. It is not necessary, however that these ~~torque values~~ torques be equally spaced. Calibration torque values at less than one tenth of capacity are permissible and tend to give added assurance to the fitting of the calibration equation. If the lower limit of the loading range of the device (see ~~8.5.18.6.1~~) is anticipated to be less than one tenth of the maximum torque applied during calibration, then ~~the torque values should be applied at or below this lower limit. In no case should the~~ The smallest torque applied be shall be equal to or below the theoretical lower limit of the instrument as defined by the values: 400 × resolution for Class A loading range and 20001667 × resolution for Class AA loading range. In torque transducer calibration with electrical instruments capable of linearizing the output signal, whenever possible, select calibration torques other than those at which the linearity corrections were made.

**7.2.2 Resolution Determination**—The resolution of a digital instrument is considered to be one increment of the last active number on the numerical indicator, provided that the reading does not fluctuate by more than plus or minus one increment when no torque is applied to the instrument. If the readings fluctuate by more than plus or minus one increment, the resolution will be equal to half the range of fluctuation.

**7.2.3 Number of Calibration Torque Values**—A total of at least 30 torque applications per mode, clockwise or counter clockwise, is required for a calibration and, of these, at least 10 must be at different torque values. Apply each torque value at least twice during the calibration in both the clockwise and counter clockwise direction, as applies.

**7.2.4 Specific Torque Devices (Limited Torque Devices)**—Because these devices are used only at the calibrated torque values, select those torque values which would be most useful in the service function of the instrument. Coordinate the selection of the calibration torque values with the submitting organization. Apply each calibration torque at least three times in order to provide sufficient data for the calculation of the standard deviation of the observed deflections about their average values.

### 7.3 Temperature Equalization:

**7.3.1** Allow the torque measurement system sufficient time to adjust to the ambient temperature in the calibration machine prior to calibration in order to assure stable instrument response.

**7.3.2** The recommended value for room temperature calibrations is 23°C (73.4°F) but other temperatures may be used.

**7.3.3** During the calibration, monitor and record the temperature as close to the elastic device as possible. It is recommended that the test temperature not change more than  $\pm 1^\circ\text{C}$  during calibration, but in no case shall it change more than  $\pm 2^\circ\text{C}$ .

**7.4 Procedural Order in Calibration**—Immediately before starting the calibration, pre-load the torque-measuring instrument to the maximum torque to be applied at least two times. Pre-loading is necessary to reestablish a stable minimum torque output value and to condition the transducer for stable performance. This is particularly necessary following a change in the mode of loading, as from clockwise to counter clockwise. Some instruments may require more than two pre-loads to achieve stability in zero-torque indication.

**NOTE 5**—Overload or proof load tests are not required by this practice. It must be emphasized that an essential part of the manufacturing process for a torque-measuring instrument should be the application of a series of overloads to at least 10 % in excess of rated capacity. This must be done before the instrument is released for calibration or service. For performance verification following overload within the safe overload range of the instrument, it is recommended that an overload test encompassing the anticipated range of overload be conducted.

**7.4.1** After pre-loading, apply the calibration torque value, approaching each torque value from a lesser value of torque. Torque values shall be applied and removed slowly and smoothly, without inducing shock or vibration to the torque-measuring instrument. The time interval between successive applications or removals of torque values, and in obtaining readings from the torque-measuring instrument, shall be as uniform as possible. If a calibration torque is to be followed by another calibration torque of lesser magnitude, reduce the applied torque on the instrument to zero before applying the second calibration torque.

**NOTE 6**—For any torque-measuring instrument, the errors observed at corresponding torque values taken first by increasing the torque to any given test torque and then by decreasing the torque to that test torque may not agree. Torque-measuring instruments are usually used under increasing torque, but if a torque-measuring instrument is to be used under decreasing torque, it should be calibrated under decreasing torque with decreasing torque values. Use the procedures for calibration and analysis of data given in Sections 7 and 8 except where otherwise noted. When a torque-measuring device is calibrated with both increasing and decreasing torque, it is recommended that the same torque increments be applied, but that separate calibration equations are developed.

**7.4.2** The standardizing laboratory shall decide whether or not a zero-torque reading is to be taken after each calibration torque value. Factors such as the stability of the zero-torque reading, the presence of noticeable non-return to zero following the application of torque loads, and the expected use are factors to be considered. It is pointed out, however, that a lengthy series of incremental torque values applied without returning to zero reduces the amount of sampling of the instrument performance. The operation of removing all torque from the instrument permits small readjustments at the torque reacting surfaces, increasing the amount of random sampling and thus producing a better appraisal of the performance of the instrument. It is recommended that not more than five incremental torque values be applied without return to zero. This is not necessary when the instrument is calibrated with decreasing torque; however, any return to zero prior to application of all the individual torque increments must be followed by application of the maximum torque before continuing the sequence.

**7.5 Randomization of Loading Conditions**—Shift the position of the instrument in the calibration machine before repeating any series of torque values. Rotate the torque cell in the mounting fixtures by amounts such as one-third, one quarter, or one-half turn,

and shift and realign any keyed connectors. If the calibration is done in both clockwise and counter clockwise directions, perform a part of the counter clockwise calibration, do the clockwise calibration, then finish the counter clockwise calibration afterward. Introduce variations in any other factors that normally are encountered in service, as for example, disconnecting and reconnecting electrical cables. Allow sufficient time for the instrument to reach temperature stability if power is removed or cabling is removed and then reconnected.

NOTE 7—A situation to be avoided is rotating the torque-measuring instrument from 0° to 180° to 0° during calibration, since the final position duplicates the first, and reduces the randomization of loading conditions.

NOTE 8—Depending on their design, torque transducers vary in sensitivity to mounting conditions, parasitic forces or moments due to misalignment. A measure of this sensitivity may be to simulate these factors such as (a) using fixtures of varying stiffness or hardness, (b) applying the appropriate torque for bolting fixtures with different torque ratings, or with angular or eccentric misalignment, and so forth. Such factors can sometimes be significant contributors to measurement uncertainty and should be reflected in comprehensive measurement uncertainty analyses.

NOTE 9—It is recommended that during the calibration of torque transducers that use a square drive, four rotations of the torque transducer should occur resulting in four calibration runs per mode.

## 8. Calculation and Analysis of Data

8.1 *Deflection*—Calculate the deflection values for the ~~torque-measuring instrument~~ torque transducer as the differences between the ~~measured~~ readings of the instrument torque transducer under applied torque and the ~~averages of the zero-torque reading with no applied torque.~~ The method selected for treatment of zero should reflect anticipated usage of the torque transducer. The deflection calculation shall (a) use the initial zero value only or (b) a value derived from readings taken before and after each ~~application of the application of a torque or series of torque values.~~ For method (a), ~~torque.~~ If the deflection is calculated as the difference between the deflection at the applied torque and the initial deflection at zero torque. For method (b), when it is elected to return-to-zero after each applied torque, the average of the two zero values shall be used to determine the deflection. For method (b) when a series of incremental force readings has been taken without return to zero, applied torque values are applied before ~~return-to-zero torque,~~ a series of interpolated zero torque zero-torque readings may be used for the calculations. In calculating the average zero-torque readings and deflections, express the values to the nearest unit in the same number of places as estimated in reading the instrument scale. Follow the instructions for the rounding method given in Practice E29. If method (a) is elected, a creep recovery test is required per the criteria of 8.2 to ensure that the zero return characteristic of the torque transducer does not result in excessive error.

8.2 *Determination of Creep Recovery*—Creep affects the deflection calculation. Excessive creep is indicated if large non-return to zero is observed following torque application during calibration. Perform a creep recovery test to ensure that the creep characteristic of the device does not have a significant effect on calculated deflections when method (a) is used to determine deflections. Perform the creep recovery test for new devices or existing devices that have not had a creep test performed, and for devices that have had major repairs, devices suspected of having been overloaded, or devices that show excessive non-return to zero following calibration. Creep and creep recovery are generally stable properties of a torque transducer unless the transducer is overloaded, has experienced moisture or other contaminant incursion, or is experiencing fatigue failure. If method (b) is used to determine deflections on a device both during calibration and subsequent use, the creep recovery test is not required. The creep recovery test is performed as follows:

8.2.1 Exercise the device to the maximum applied torque in calibration at least two times. Allow the zero reading to stabilize and record the value. Apply the maximum applied torque used in calibration of the device and hold as constant as possible for 5 min. Remove the applied torque as quickly as possible and record device output at 30 s and 5 min. Creep recovery error is calculated as follows:

8.2.1.1 Creep Recovery Error, % of Output at Maximum Applied Torque =  $100 \times (\text{Output 30 seconds after zero torque is achieved} - \text{Initial zero reading}) / \text{Output at Maximum Applied Torque}$

8.2.2 A zero return error shall be calculated as follows:

8.2.2.1 Zero Return Error, % of output at applied torque =  $100 \times (\text{Initial zero reading} - \text{final zero reading 5 min. after the applied torque is removed}) / \text{Output at applied torque}$ . The creep test shall be repeated if the zero return error exceeds 50% of the creep recovery error limits.

8.2.3 *Creep Recovery Error Limits*—Class AA Devices  $\pm 0.02\%$  Class A Devices  $\pm 0.05\%$ .

8.3 *Calibration Equation*—Fit a polynomial equation of the following form to the torque and deflection values obtained in the calibration using the method of least squares:

$$\text{Deflection} = A_0 + A_1\tau + A_2\tau^2 + \dots + A_5\tau^5 \quad (3)$$

where:

$\tau$  = torque, and  
 $A_0$  through  $A_5$  = coefficients.

A 2nd degree equation is recommended with coefficients  $A_3$ ,  $A_4$ , and  $A_5$ , equal to zero. Other degree equations may be used. For example the coefficients  $A_2$  through  $A_5$  would be set equal to zero for a linearized torque cell.