Designation: E2428 – 15a

Standard Practice for Calibration and Verification of Torque Transducers[1]

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 (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 The purpose of this practice is to specify the procedure for the calibration of torque transducers.

NOTE 1—Verification by deadweight and a lever arm is an acceptable method of verifying the torque indication of a 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.[2]

1.2 The values stated in SI units are to be regarded as standard. Other metric and inch-pound values are regarded as equivalent when required.

1.3 This practice is intended for the calibration of static torque measuring instruments. The practice is not applicable for 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:*[3]

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 *ASME Standard:*

B46.1 Surface Texture[4]

2.3 *BIPM Standard*[5]

JCGM 200 International vocabulary of metrology–Basic and general concepts and associated terms (VIM)

3. Terminology

3.1 *Definitions:*

3.1.1 *primary torque standard*—a deadweight force applied through a lever arm or wheel, all displaying metrological traceability to the International System of Units (SI).

3.1.1.1 *Discussion*—for further definition of the term metrological traceability, refer to the latest revision of JCGM:200.

3.1.2 *secondary torque standard*—an instrument or mechanism, the calibration of which has been established by a comparison with a primary torque standard(s).

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *calibration equation*—a mathematical relationship between 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 8.5).

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

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

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

[4] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Two Park Ave., New York, NY 10016-5990, http://www.asme.org.

[5] BIPM, Pavillon de Breteuil, F-92312 Sèvres Cedex. http://www.bipm.org

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.

3.2.5.1 *Discussion*—The definition of deflection applies to output readings in electrical units as well as readings in units of torque.

3.2.6 *lower limit factor, LLF*—A statistical estimate of the limits of error 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 *specific torque device*—an alternative class of instruments not amenable to the use of a calibration equation.

3.2.7.1 *Discussion*—Such instruments, usually those in which the reading is taken from a dial indicator, are used only at the calibrated torque values. These instruments are also called limited-torque devices.

3.2.8 *loading range*—a range of torque values within which the lower limit factor is less than the limits of error specified for the instrument application.

3.2.9 *torque transducer*—a device or system consisting of an elastic member combined with a sensing device for measuring the strain or deflection of the elastic member under an applied torque.

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 metrologically traceable to the International System of Units (SI). Practice E2428 describes how these devices are to be calibrated. The procedures are useful to users of testing machines, manufacturers and providers of torque measuring instruments, calibration laboratories that provide calibration services and documents of metrological traceability, and service organizations using devices to verify testing machines.

5. Reference Standards

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

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

6. Requirements for Torque Standards

6.1 *Primary Torque Standard*—Torque, displaying metrological traceability to the International System of Units (SI) 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 surface (Roughness Average or Ra) of 3.2µm or less as specified in ASME B46.1.

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

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

where:

M = mass of the weight,
g = local acceleration due to gravity, m/s^2,
d = air density (approximately 1.2 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 metrologically traceable to the International System of Units (SI) for mass. The local value of the acceleration due to gravity, calculated within 0.0001 m/s^2 (10 milligals), may be obtained from the National Geodetic Information Center, National Oceanic and Atmospheric Administration.[6]

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

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

kilogram-force units (kgf). These customary force units are related to the newton (N), the SI unit of force, by the following relationships:

1 lbf = 4.44822 N
1 kgf = 9.80665 N (exact)

The newton (N) is defined as the force applied to a 1-kg mass that produces an acceleration of 1 m/s/s.
The pound-force (lbf) is defined as the force applied to a 1-lb mass that produces an acceleration of 9.80665 m/s/s.
The kilogram-force (kgf) is defined as the force applied to a 1-kg mass that produces an acceleration of 9.80665 m/s/s.

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

6.2 *Secondary Torque Standards*—Secondary torque standard is typically a torque transducer used with a machine for applying torque, or a mechanical or hydraulic mechanism to apply or multiply a 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 torque 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 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.

$$LLF_c = \sqrt{LLF_1^2 + LLF_2^2 + \ldots + LLF_n^2} \qquad (2)$$

where:

LLF_C = Lower limit factor of the combination, and
$LLF_{1,\,2,\,\ldots\,n}$ = Lower limit factor of the individual instruments

6.2.2 Torque transducers used as secondary torque standards shall be calibrated by primary torque standards and used only over the Class AA loading range (see 8.6.2.1).

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 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 continuously over the entire range of the instrument. This characteristic curve is a stable property of the instrument that is changed only by a severe overload or other similar cause.

7.1.1 Superposed on this curve are local variations of instrument readings introduced by imperfections in the torque transducer. Examples of imperfections include instabilities in excitation voltage, voltage measurement, or ratio-metric voltage measurement in a torque transducer. Some of these imperfections are less stable than the characteristic curve and may change significantly from one calibration to another.

7.1.2 *Curve Fitting*—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 torque transducer. A polynomial 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 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 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 with a probability of 95%. The LLF is, therefore, an estimate of one source of uncertainty contributed by the torque transducer when torque values measured in service are calculated by means of the calibration equation. Actual errors in service are likely to be different if torque values are applied under mechanical and environmental conditions differing from those of 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 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 specifies the procedure for obtaining the degree of the best fit calibration equation for these devices. Equations of greater than 5th degree shall not be used.

Note 4—For some torque transducers, use of a polynomial fit higher than the second degree may result in a lower LLF. Over-fitting should be avoided. Equations of greater than 5th degree cannot be justified due to the limited number of increments in the calibration protocol. Errors caused by round-off may occur if calculations are performed with insufficient precision. A torque transducer not subjected to repair, overloading, modifications, or other significant influence factors that alter its elastic properties or its sensing 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 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 torque transducer, providing, if possible, at least one calibration torque for every 10 % interval throughout the range. It is not necessary, however that these 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 8.6.1) is anticipated to be less than one tenth of the maximum torque applied during calibration, then torque values should be applied at or below this lower limit. The smallest torque applied 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 1667 × 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.

7.3.3 During the calibration, monitor and record the temperature as close to the torque transducer as possible. It is recommended that the test temperature not change more than ±1°C during calibration, but in no case shall it change more than ±2°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. An essential part of the manufacturing process for a torque transducer should be the application of a series of overloads to at least 10 % in excess of rated capacity. This should 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.

7.4.2 For any torque transducer, 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 transducers are usually used under increasing torque, but if a torque transducer is to be used under decreasing torque, it shall 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 transducer is calibrated with both increasing and decreasing torque, it is recommended that the same torque increments be applied, but required that separate calibration equations are developed.

7.4.3 The calibration 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 creep 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 torque transducer 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 potentially producing a better appraisal of the performance of the torque transducer. 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 transducer 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 6—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 7—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 *(c)* mounting in various orientations 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 8—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 transducer as the differences between the readings of the torque transducer under applied torque and the 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 the application of a torque or series of torque values. For method *(a)*, 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 applied torque values are applied before return-to-zero torque, a series of interpolated 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 × (Output 30 seconds after zero torque is achieved – Initial zero reading) /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 × (Initial zero reading – final zero reading 5 min. after the applied torque is removed) /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 ± 0.02% Class A Devices ± 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:

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

where:

τ = 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 transducer.

8.3.1 For high resolution devices (see 7.1.3), the procedure of Annex A1 may be used to obtain the best fit calibration equation. After determination of the best fit polynomial equation, fit the polynomial equation of that degree to the calibration data per 8.3, and proceed to analyze the data per 8.4 – 8.6.2.2.

8.4 *Standard Deviation*—Calculate a standard deviation from the differences between the individual values observed in the calibration and the corresponding values taken from the calibration equation. Calculate the standard deviation as follows:

$$\text{Standard Deviation } s_m = \sqrt{\frac{d_1{}^2 + d_2{}^2 + \ldots + d_n{}^2}{n - m - 1}} \tag{4}$$

where:

d_1, d_2, etc. = differences between the fitted curve and the n observed values from the calibration data,
n = number of deflection values, and
m = the degree of polynomial fit.

NOTE 9—The departures of the observed deflections from the calibration equation values are not random but arise partly from the localized non-linearities, discussed in 7.1.1. As a consequence, the distributions of the residuals from the least squares fit may not follow the normal curve of error and the customary estimates based on the statistics of random variables may not be strictly applicable.

8.5 *Determination of Lower Limit Factor, LLF*—LLF is calculated as 2.0 times the standard deviation. If the calculated LLF is less than the instrument resolution, the LLF is then defined as that value equal to the resolution. Express the LLF in torque units, using the average ratio of torque to deflection from the calibration data.

8.6 *Loading Range*—The range of torque values within which the LLF of a torque transducer does not exceed the maximum permissible error limit specified as a fraction or percentage of torque. Since the LLF for the torque transducer is of constant torque value throughout the entire range of the torque transducer, it will characteristically be less than the specified percentage of torque at the torque transducer capacity but will begin to exceed the specified percentage at some point in the lower range of the torque transducer. The loading range thus extends from the lower limit up to the instrument capacity. The loading range shall not include torque values outside the range of torque values applied during the calibration.

8.6.1 *Lower Limit of the Loading Range*—Calculate the lower end of the loading range for a specified percentage limit of error, P, as follows:

$$\text{Lower Limit} = \frac{100 \times LLF}{P} \tag{5}$$

8.6.2 *Standard Loading Ranges*—Two standard loading ranges are listed as follows, but others may be used where special needs exist:

8.6.2.1 *Class AA*—The lower limit of the instrument is 1667 times the LLF, in torque units, obtained from the calibration data.

NOTE 10—For example, an instrument calibrated using primary torque standards applied on a lever arm at a known distance had a calculated LLF of 0.338 N-m. The lower limit for use as a Class AA device is therefore 0.338 × 1667.0 = 563 N-m. The LLF will be less than the error limit of ±0.06 % of torque for torques greater than this lower limit to the capacity of the instrument. It is recommended that the lower limit be not less than 2 % (1/50) of the capacity of the torque transducer.

8.6.2.2 *Class A*—The lower torque limit of the instrument is 400 times the LLF, in torque units, obtained from the calibration data.

NOTE 11—In the example of Note 10, the lower limit for use as a Class A device is 0.338 × 400.0 = 136 Nm. The LLF will be less than the error limit of ±0.25 % of torque for torque values greater than this lower torque limit up to the capacity of the instrument. It is recommended that the lower limit be not less than 2 % (1/50) of the capacity of the torque transducer.

NOTE 12—The term "loading range" used in this practice is parallel in meaning to the same term in Practice E2624. It is the range of torque values over which it is permissible to use the instrument in a calibrating testing machine or other similar device. When a loading range other than the two standard ranges given in 8.6.1 is desirable, the appropriate error limit should be specified in the applicable method of test.

8.7 *Specific Torque Devices*—Any torque-measuring device may be calibrated as a specific torque device. These instruments shall be used only at the calibrated torque values and the curve-fitting and analytical procedures of 8.3 – 8.5 are replaced by the following procedures:

8.7.1 *Calculation of Nominal Torque Deflection*—From the calibration data, calculate the average value of the deflections corresponding to the nominal torque. If the calibration torque values applied differ from the nominal value of the torque values, as may occur in the case of a calibration by secondary torque standards, adjust the observed deflections to values corresponding to the nominal torque values by linear interpolation, provided that the torque differences do not exceed ±1 % of the torque capacity. The average value of the nominal torque deflection is the calibrated value for that torque.

8.7.2 *Standard Deviation for a Specific Torque Device*—Calculate the range of the nominal torque deflections for each calibration torque as the difference between the largest and smallest deflections for the torque value. Multiply the average value of the ranges for all the calibration torques by the appropriate factor from Table 1 to obtain the estimated standard deviation of an individual deflection about the mean value.

8.7.3 *Determination of LLF for Specific Torque Devices*—The LLF for a specific torque device is defined as 2.0 times the standard deviation, plus the resolution. Convert this quantity into torque units by means of a suitable factor and round to the number of significant figures appropriate to the resolution. The LLF is expressed as follows:

$$LLF = (2s + r)\tau_1 \tag{6}$$

where:

s = standard deviation,
r = resolution, and
τ_1 = average ratio of torque to deflection from the calibration data.

8.7.4 *Restrictions of Specific Torque Devices*—A specific torque device does not have a loading range as specified in 8.6, since it can be used only at the specific torque value(s) for which it was calibrated. The use is restricted, however, to those

TABLE 1 Estimates of Standard Deviation from the Range of Small Samples

Number of Observations at Each Torque	Multiplying Factor for Range
3	0.591
4	0.486
5	0.430
6	0.395

calibrated torque value(s) that would be included in a loading range calculated in 8.6 – 8.6.2.2.

9. Temperature Corrections for Torque Transducer During Use

9.1 *Temperature Effect on the Sensitivity of Temperature-Compensated Devices*—Torque transducers may have temperature compensation built in by the manufacturer. For devices with such compensation, the effect of temperature on the sensitivity of the device shall not exceed the following values:

9.1.1 *Class AA*—For devices used as Class AA standards, the error due to temperature on the sensitivity of the device shall not exceed 0.01%. (See Note 13).

9.1.2 *Class A*—For devices used as Class A standards, the error due to temperature on the sensitivity of the device shall not exceed 0.05%. (See Note 13).

9.1.3 If a torque transducer is used at temperatures other than the temperature at which it was calibrated, it is the users responsibility to insure that the performance of the device does not exceed the limits of paragraphs 9.1.1 or 9.1.2, or if such limits would be exceeded, that the device is calibrated at the expected temperature of use, or over a range of the expected temperatures of use and corrected accordingly.

NOTE 13—There is a negligible effect on the maximum values for Class AA, LLF (0.05% of applied torque) and Class A, LLF (0.25% of applied torque) when these values are added as root-sum-squares with the values for temperature error given in 9.1.1 and 9.1.2. Such a combination of error sources is valid in the case of independent error sources. It should be noted the temperature differences between conditions of calibration and use may result in significant errors. This error source should be evaluated by users to assure compliance with these requirements, when such usage occurs. Adequate stabilization times are required to insure that thermal gradients or transients in the torque transducers have equilibrated with the environment in which testing is to be performed. Otherwise, thermal gradients may cause significant errors in both temperature compensated devices and uncompensated devices.

It is recommended that the effect of temperature on the sensitivity of Class AA devices not exceed 0.0030% /°C and for Class A devices, that the effect of temperature on the sensitivity not exceed 0.010% /°C.

As an example, for the case of torque transducers that have temperature coefficients equal to the maximum recommended values, the error due to the temperature is negligible within ± 3°C for class AA devices and ± 5°C for class A devices referenced to the temperature at which those devices were calibrated.

10. Time Interval Between Calibration and Stability Criteria

10.1 All torque-measuring instruments and systems shall meet the range, accuracy, resolution, and stability requirements of this standard, and shall be suitable for their intended use.

10.2 Torque measuring instruments and systems used as secondary torque standards or for the verification of torque indication of testing machines shall be calibrated at intervals not exceeding two years after demonstration of stability supporting the adopted recalibration interval. New devices shall be calibrated at an interval not exceeding 1 year to determine stability per 10.2.1.

10.2.1 Torque transducers shall demonstrate changes in the calibration values over the range of use during the recalibration interval of less than 0.032 % of reading for torque transducers used over the Class AA loading range and less than 0.16 % of reading for those torque transducers used over the Class A loading range. See Note 14.

10.2.2 Devices not meeting the stability criteria of 10.2.1 shall be recalibrated at intervals that shall ensure the stability criteria are not exceeded during the recalibration interval. See Note 14.

NOTE 14—The above stability criteria provide minimum requirements for establishing calibration intervals for torque transducers. Users specifying percentage error limits other than Class AA or Class A should determine stability criteria appropriate to the instruments employed. For secondary torque standards, it is recommended that cross-checking be performed at periodic intervals using other standards to help ensure that standards are performing as expected.

10.3 *Calibration Following Repairs or Overloads*—A torque-measuring instrument or force multiplying system shall be calibrated whenever the calibration of the device might be suspect. Any instrument sustaining an overload that produces a permanent shift in the zero torque or force reading amounting to 1 % or more of the instrument capacity shall be calibrated before further use.

NOTE 15—A means of establishing a true zero reference is recommended in order to assure that the zero balance of calibration has not been shifted by an amount greater than 1 % of the transducer capacity.

11. Substitution of Electronic Torque Indicating Devices Used with Elastic Members

11.1 It may be desirable to treat the calibration of the torque transducer and the torque indicating device separately, thus allowing for the substitution or repair of the torque indicating device without the necessity for repeating a system calibration. When such substitution or repair is made, the user assumes the responsibility to assure that the accuracy of the torque measurement system is maintained. Substitution of the torque indication device shall not extend the system calibration/verification date. The following conditions shall be satisfied when substituting a metrologically significant element of the torque indicating measurement system.

11.2 The indicating device used in the initial calibration and the device to be substituted shall each have been calibrated and their measurement uncertainties determined. The indicator to be substituted shall be calibrated over the full range of its intended use including both positive and negative values if the system is used in clockwise and counter clockwise mode. The calibrated range shall include a point less than or equal to the output of the torque transducer at the lower torque limit and a point equal to or greater than the output of the torque transducer at the maximum applied torque. A minimum of five points shall be taken within this range. The measurement uncertainty of each device shall be less than or equal to one third of the uncertainty for the torque measurement system over the range from the lower torque limit to the maximum torque.

11.3 The measurement uncertainty of the torque indicating device shall be determined by one of the methods outlined in Appendix X1. It is recommended that a transducer simulator capable of providing a series of input mV/V steps over the range of measurement and with impedance characteristics similar to that of the torque transducer be employed as a check standard to verify calibration of the torque indicating device and in establishing the measurement uncertainty. The measurement uncertainty of the transducer simulator shall be less than or equal to one tenth of the uncertainty for the torque measurement system.

11.4 Excitation voltage amplitude, frequency, and waveform shall be maintained in the substitution within limits to assure that the effect on the calibration is negligible. It is a user responsibility to determine limits on these parameters through measurement uncertainty analysis and appropriate tests to assure that this requirement is met. Substitution of an interconnect cable can have a significant effect on calibration. If an interconnect cable is to be substituted, see Note 16.

11.5 A report of calibration for the original and substitute torque indicating devices shall be generated. The report shall include the identification of the item calibrated, date of calibration, calibration technician, test readings, the identification of the test equipment used to verify the performance of the torque indicating device, and the measurement uncertainty and metrological traceability. The report shall be available for reference as required.

NOTE 16—If an interconnect cable is substituted, care should be taken to assure that the new cable matches the original in all aspects significant to the measurement. (Such factors as the point of excitation voltage sensing and the impedance between the point of excitation voltage sensing and the elastic torque transducer may affect the sensitivity of the device to changes in applied torque.) It is recommended that the electronic torque indicator/cable performance be verified using a transducer simulator or other appropriate laboratory instruments.

11.6 Metrologically insignificant elements of torque measuring devices such as printers, computer monitors, etc., may be substituted following confirmation of proper function.

12. Report

12.1 The report issued by the standardizing laboratory on the calibration of a torque-measuring instrument shall be error-free and contain no alteration of dates, data, etc. The report shall contain the following information:

12.1.1 A statement that the calibration has been performed in accordance with Practice E2428. It is recommended that the calibration be performed in accordance with the latest published version of Practice E2428.

12.1.2 The manufacturer and identifying serial numbers of the instrument calibrated,

12.1.3 The name of the laboratory performing the calibration,

12.1.4 The date of the calibration,

12.1.5 The type of reference standard used in the calibration with a statement of the limiting errors or uncertainty,

12.1.6 The temperature at which the calibration was referenced,

12.1.7 A listing of the calibration torque values applied and the corresponding deflections, including the initial and return-to-zero torque values and measured deflections.

12.1.8 Treatment of zero in determining deflections (method *(a)* or *(b)* as described in 8.1). If method *(b)* is elected, also specify whether zero was determined by the average or interpolated method.

12.1.9 The coefficients for any fitted calibration equation and the deviations of the experimental data from the fitted curve,

12.1.10 The Lower Limit of the loading range expressed in this report applies only when the calibration equation is used to determine the torque value.

NOTE 17—For torque transducers in which deflections are displayed in engineering units (that is, N-m, lbf-in) users are cautioned that the lower limit expressed in the calibration report applies only when the calibration equation is used to determine the torque value, that is, the direct reading should be incorporated into the calibration equation to determine the applied torque.

12.1.11 The uncertainty associated with the calibration results and the limits of the loading range, and

12.1.12 The tabulation of values from the fitted calibration equation for each torque applied during calibration and, if available and suitable for comparison, a tabulation of the change in calibrated values since the last calibration for other than new instruments.

13. Keywords

13.1 torque transducer; torque standard; testing machine

ANNEX

(Mandatory Information)

A1. PROCEDURE FOR DETERMINING DEGREE OF BEST FITTING POLYNOMIAL

A1.1 This procedure may be used to determine the degree of best fitting polynomial for high resolution torque-measuring instruments (see 7.1.3).

A1.2 The procedure assumes that a torque-measuring instrument has been measured at *n* distinct, non-zero torques, and that the series of *n* measurements has been replicated *k* times at the same torques. At each torque, the mean of *k* measurements is computed. (The value *k* is not otherwise used here.) These *n* values are referred to as the mean data. The following analysis is to be applied only to the mean data, and is used only to determine the degree of best fitting polynomial.

A1.3 Fit separate polynomials of degree 1, 2, 3, 4, and 5 to the mean data. Denote the computed residual standard deviations by s_1, s_2, s_3, s_4, and s_5, respectively. The residual standard deviation from an m_1-degree fit is:

$$s_{m_1} = \sqrt{\frac{d_1^2 + d_2^2 + \ldots + d_n^2}{n_1 - m_1 - 1}} \qquad (A1.1)$$

where:

d_1, d_2, etc. = differences between the fitted curve and the *n* observed mean values from the calibration data,

n_1 = number of distinct non-zero torque increments, and

m_1 = degree of polynomial fit.

A1.4 These values for residual standard deviation are used in a sequential procedure to test whether the coefficient of the highest order term in the current fit is significant. Use will be made of the constants C(n_1, m_1) in Table A1.1. Quantities of the *F* distribution were used in computing these constants.

TABLE A1.1 Factors C(n_1, m_1) = (1 + [F.975 (1, $n_1 - m_1 - 1$) – 1]/($n_1 - m_1$))$^{1/2}$ for Determining the Best Degree of Polynomial Fit

n_1	$m_1 = 2$	$m_1 = 3$	$m_1 = 4$	$m_1 = 5$
10	1.373	1.455	1.582	1.801
11	1.315	1.373	1.455	1.582
12	1.273	1.315	1.373	1.455
15	1.195	1.215	1.241	1.273
20	1.131	1.141	1.151	1.163

A1.5 Compute s_4/s_5 and compare it to C(n_1 , 5). If $s_4/s_5 >$ C(n_1, 5) then the coefficient of the 5th-degree term is significant and the 5th-degree fit is determined to be best. Otherwise, compute s_3/s_4 and compare it to C(n_1, 4). Continue the procedure in the same manner until the coefficient of the highest-degree term in the current fit is determined to be significant. To state the rule generally, if $s_{m_{1-1}}/s_{m_1} >$ C(n_1, m_1) then the coefficient of the m_1th degree term is significant and the m_1 degree fit is determined to be best. Otherwise, reduce m_1 by one and repeat the test (m_1 = 5, 4, 3, 2).

A1.5.1 To illustrate the procedure, let $n_1 = 11$, $s_1 = 1.484$, $s_2 = 0.7544$, $s_3 = 0.2044$, $s_4 = 0.1460$, and $s_5 = 0.1020$ (see NIST Technical Note 1246, A New Statistical Model for Force Sensors). Compute $s_4/\ s_5 = 1.431 < 1.582 =$ C(11, 5). This indicates the 5th degree term is not significant, therefore compute $s_3/\ s_4 = 1.400 < 1.455 =$ C(11, 4). This indicates the 4th degree term is not significant, therefore compute $s_2/\ s_3 = 3.691 > 1.373 =$ C(11, 3). This indicates the 3rd degree term is significant, and the 3rd degree fit is determined to be the best degree of polynomial fit.

A1.6 After the determination of the degree of best fit, return to 8.3.1 of this practice and continue calculation and analysis of the calibration data.

APPENDIXES

(Nonmandatory Information)

SAMPLE PROCEDURES FOR DETERMINING TORQUE INDICATING INSTRUMENT UNCERTAINTY

X1. UNCERTAINTY ANALYSIS FOR AN ELECTRONIC TORQUE INDICATING INSTRUMENT FOR CLASS A LOAD RANGE USING A TRANSDUCER SIMULATOR AND THE METHOD OF MEASUREMENT UNCERTAINTY DETERMINATION IN ACCORDANCE WITH THE PROCEDURES OF ASTM E2428

X1.1 The torque transducer in the system for which it is desired to substitute the electronic torque indicator has a 2 mV/V output at full capacity. The torque measurement system is a Class A system with a lower limit equal to 10 % of the torque transducer's capacity. The expanded uncertainty of the system is 0.25 %. The standard uncertainty is 0.125 %.

X1.2 A transducer simulator with a measurement uncertainty equal to or less than one tenth of the allowable standard uncertainty for the torque measurement system is used to provide a series of discrete mV/V steps over the range of measurement (see 8.6.2.1 and 8.6.2.2 for allowable uncertainty). The instrument and transducer simulator should be connected and allowed to warm up according to manufacturer's recommendations. At least five readings taken three times for each polarity should be acquired over the calibrated range for the original torque indicating instrument and the device to be substituted. The readings should include a point less than or equal to the lower torque limit for the system, and another point equal to or greater than the maximum torque for the system. The transducer simulator settings should provide at least one point for every 20 % interval throughout this range. Care should be taken that environmental conditions do not significantly affect the accuracy of measurements taken.

NOTE X1.1—It is desirable to use the same transducer simulator for determining the readings of both indicators; however, different simulators may be used provided their outputs for a given input are identical within one tenth of the allowable standard uncertainty for the torque measurement system.

X1.3 The electronic torque indicator to be used as a substitute is evaluated to ensure that the electrical characteristics are the same, and that the interconnect cable is the same with respect to wiring, and wire types, sizes, and lengths.

X1.4 A transducer simulator capable of providing 0.2 mV/V steps is selected.

X1.5 The transducer simulator is connected to the original torque indicator and the reading at 0.2 mV/V and each 0.4 mV/V step between 0.4 and 2.0 mV/V are recorded. After the first run of readings, a second and third run are taken. This process is repeated for the opposite polarity. This process is repeated on the indicator to be used as a substitute. It is not required that the verification of the two indicators occur at the same time, provided the transducer simulator stability is evaluated over the relevant time period in the determination of its measurement uncertainty.

X1.6 A linear least squares curve fit is performed on the data set according to the procedure set forth in 8.1 – 8.5. The standard deviation is determined to be 0.00005 mV/V, and the uncertainty is 0.00010 mV/V (2.0 times the standard deviation). This value should be less than or equal to one third of the system uncertainty at the lower torque limit in electrical units, or less than:

$$(0.25\ \% \times 0.2\ \text{mV/V}) / 3 = 0.000167\ \text{mV/V}$$

X2. UNCERTAINTY ANALYSIS FOR AN ELECTRONIC TORQUE INDICATING INSTRUMENT FOR CLASS A LOAD RANGE USING A MEASUREMENT UNCERTAINTY DETERMINATION IN ACCORDANCE WITH THE METHOD OF NIST TECH NOTE 1297

X2.1 Using the same example from Appendix X1, the method of NIST TN 1297 is employed.

X2.2 The first step in a measurement uncertainty analysis of an electronic torque indicator is to identify the sources of error. The following are potential sources of measurement error in strain gage based torque transducer indicators:

Calibration Uncertainty (Gain Error)
Zero Offset
Temperature Effect on Sensitivity
Quantization Error
Normal Mode Voltage
Excitation Voltage Error
Power Line Voltage Variation
Non-linearity
Temperature Effect on Zero
Gain and Zero Stability
Common Mode Voltage
Noise
Electrical Loading
Error signals due to thermal EMF

X2.3 Each of these potential error sources, and any others of significance, should be evaluated for the conditions in which the indicator will operate. It is recommended that a transducer simulator or equivalent laboratory test instrumentation be used to verify indicator performance and assess errors. The same requirements for number and distribution of test points as given in the previous example apply.

X2.4 A typical analysis of the major error sources as determined for an indicator is given below:

Simulator Uncertainty	$u_c = 20$ ppm	Includes the ratio uncertainty.
Indicator Non-linearity	$u_{nl} = 116$ ppm	For 0.01 % non-linearity and an assumed rectangular probability distribution, $0.01/(3)^{0.5} \times 2.0$. Where a factor of 2 is specific to a particular indicator and should be determined by test to reflect the error over the full range of indicator use. Non-linearity is evaluated by test using a transducer simulator or other suitable instrument.
Temperature Effect on Gain	$u_t = 57$ ppm	For temperature coef. of 20 ppm/°C, ± 5°C; Assumed rectangular probability distribution.
Gain Stability	Negligible	Gain stability is not a factor if calibrated on a simulator at the time of substitution as the gain error is incorporated in the transducer simulator uncertainty.
Noise	Evaluated	Noise is already incorporated in the uncertainty that determines the lower limit. It is only necessary to adjust for noise if the noise exhibited by the substitute indicator exceeds that for the original indicator. The quantization error is often smaller than the noise and is included in the experimental determination of the noise. Noise for each indicator should be determined by test.

X2.5 Errors from the other potential sources are found to be negligible for this indicator (less than ⅕ of the largest error source). For DC indicators, the thermal emf error source can be significant and should be evaluated experimentally.

X2.6 The Combined Uncertainty based on the error sources evaluated is:

$$\text{Combined Uncertainty } u = (u_c^2 + u_{nl}^2 + u_t^2)^{0.5} = 131 \text{ ppm of Rdg.}$$

and the Expanded Uncertainty is:

$$\text{Expanded Uncertainty } U = \pm 0.026 \text{ \% of Reading in the range of } 0.2\text{–}2.0 \text{ mV/V}$$

X2.6.1 Expressed in mV/V units, the uncertainty is 0.000052 mV/V at the 0.2 mV/V level.

X2.6.2 The expanded uncertainty defines an interval within which the true value is expected to be contained with 95 % probability based on a coverage factor of 2.

X2.6.3 The allowable uncertainty for this Class A device, is 0.25 % of 0.2 mV/V, or expressed in electrical units, 0.0005 mV/V. Allowable uncertainty for the torque indicating instrument is equal to or less than one third of this limit, or 0.000167 mV/V. If the uncertainty is less than 0.000167 mV/V as in this example, the substitution is permitted.

X3. UNCERTAINTY ANALYSIS FOR AN ELECTRONIC TORQUE INDICATING INSTRUMENT FOR CLASS AA LOAD RANGE USING A MEASUREMENT UNCERTAINTY DETERMINATION IN ACCORDANCE WITH NIST TECH NOTE 1297

X3.1 Following the method in Appendix X2, an analysis is performed for a Class AA electronic torque indicator for a system with a 10 % lower torque limit and a 2 mV/V sensitivity at maximum torque.

Simulator Uncertainty	$u_c = 10$ ppm	Includes the ratio uncertainty.
Indicator Non-linearity	$u_{nl} = 58$ ppm	For 0.005 % non-linearity and an assumed rectangular probability distribution, $0.005/(3)^{0.5} \times 2.0$. Where a factor of 2 is specific to a particular indicator and should be determined by test to reflect the error over the full range of indicator use.
Temperature Effect on Gain	$u_t = 12$ ppm	For temperature coef. of 5 ppm/°C, ± 2°C; Assumed rectangular probability distribution.

X3.2 Errors from the other potential sources are found to be negligible for this indicator (less than ⅕ of the largest error source).

X3.3 The Combined Uncertainty based on the error sources evaluated is:

$$\text{Combined Uncertainty } u = (u_c^2 + u_{nl}^2 + u_t^2)^{0.5} = 60 \text{ ppm of Rdg.}$$

and the Expanded Uncertainty is:

$$\text{Expanded Uncertainty } U = \pm 0.012 \text{ \% of Reading in the range of } 0.2\text{–}2.0 \text{ mV/V}$$

X3.3.1 Expressed in mV/V units the uncertainty is 0.000024 mV/V at the 0.2 mV/V level.

X3.3.2 The expanded uncertainty defines an interval within which the true value is expected to be contained with 95 % probability based on a coverage factor of 2.

X3.3.3 The allowable uncertainty for this Class AA device is 0.05 % of 0.2 mV/V expressed in electrical units, or 0.0001 mV/V. Allowable uncertainty for the torque indicating instrument is one third of this limit, or 0.000033 mV/V. If the uncertainty is less than 0.000033 mV/V, as in this example, the substitution is permitted.

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