Measurement Techniques

GET 149-2023 state primary standard of the unit for torque

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Abstract
The article considers issues associated with the metrological support of high-precision instruments for measuring a torque of below 1.0 Nm. The areas of activity in which torque measurement is important are outlined. The authors describe the development history of the top-level standards base as an important element in the metrological support of torque measurement in the Russian Federation while providing brief information on the development level of the standards base in this measurement field abroad. Due to the increasing number of torque measuring instruments having an upper measurement limit of below 1.0 Nm, it became necessary to expand the measurement and calibration capabilities of the Russian Federation in this field, specifically within the range of 0.1–1.0 Nm. The composition of GET 149-2023 State primary standard of the unit for torque is given. The operating principles of four standard systems included in GET 149-2023 and the design of the standard are described. The created modern standard system EU-250-2 was included in GET 149-2023 for reproducing, maintaining, and disseminating the unit for torque within the range of 0.1–200 Nm. The results of studying the standard system EU-250-2 and the metrological characteristics of GET 149-2023 are presented.

Keywords State primary standard · Abstract · Metrological characteristics · Torque · Standard system

Introduction

As a physical quantity, torque characterizes a large number of processes, determining the operating modes of machines and units used in various sectors of industry and agriculture. Torque is measured when estimating power, efficiency, and specific fuel consumption in the design, study, production, and operation of such products as internal combustion engines, diesel engines, electric machines, compressors, hydraulic and pneumatic machines, reduction drives, etc. Torque should be measured when studying the strength of materials under static and dynamic loading, as well as when assessing the stiffness of structural elements that comprise machines and structures and the technical characteristics of such essential parts of various products as torque shafts, helical springs, spiral springs for clocks and electrical appliances, etc. Torque control is important in estimating the tightening force of threaded connections in automobile and tractor construction, in assembling metal structures of buildings, and in monitoring the operating modes of process equipment, for example, when operating rolling mills, drilling rigs, airplanes, helicopters, etc.

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Table 1 Measurement and calibration capabilities of foreign countries in measuring a torque of below 1.0 Nm

Country	Reproduction range, Nm	U (k = 2), %
Germany	0.01–1.00	0.020
Hong Kong	0.05–0.10	0.200
	0.10–1.00	0.100
Egypt	0.10–1.00	0.140
China	0.50–1.00	0.010
Korea	0.10–1.00	0.050
Colombia	0.10–1.00	0.100
Thailand	0.10–1.00	0.015
Japan	0.01–1.00	0.030

In the specified areas, torque is measured primarily within the range of 10^{-4}–10^6 Nm both in steady-state and rotation modes with frequencies of up to 10^5 min^{-1}.

The study aims to create a standard system realizing the unit for torque within the range of 0.1–1.0 Nm; to study the metrological characteristics of a standard system; to introduce the developed system into the composition of GET 149-2023 State primary standard of the unit for torque in order to measure torque within the specified range with high accuracy.

Development of a torque standards base

In 1985, GET 149-1985 State primary standard of the unit for torque was approved with a reproduction range of 20–2500 Nm and an error characterized by a relative standard deviation (SD) S of below $0.8 \cdot 10^{-4}$ and a residual systematic error (RSE) θ of below $2 \cdot 10^{-4}$. In 1986, a state hierarchy scheme (SHS) was approved.[1]

In 2006–2009, GET 149-1985 was improved. This resulted in the approval of GET 149-2010 State primary standard of the unit for torque[2] with a new composition and torque reproduction range of 1–20,000 Nm, with $S < 0.8 \cdot 10^{-4}$ and $\theta < 2 \cdot 10^{-4}$ within the range of $1–2.5 \cdot 10^3$ Nm and with $S < 1.5 \cdot 10^{-4}$ and $\theta < 4 \cdot 10^{-4}$ within the range of $2.5 \cdot 10^3–2 \cdot 10^4$ Nm. On January 1, 2013, the revised SHS was put into effect as a national standard.[3] The revised SHS is currently in effect.[4]

Torque measuring instruments, including standard instruments, are widely used and developed abroad. A significant number of countries have national standards of the unit for torque. Presently, the measurement and calibration capabilities (CMCs) of 18 countries (46 items) in the field of torque measurement, including the Russian Federation, are recorded in the database of the International Bureau of Weights and Measures (BIPM). In the BIPM database, torque CMC range of eight out of eighteen countries starts with values of below 1.0 Nm. The most advanced standard systems that have such reproduction ranges are those of Germany (PTB) [1] and China (NIM) [2]. The measurement and calibration capabilities of these countries within the given reproduction range are given in Table 1, where U is the relative expanded uncertainty (coverage factor of k = 2).

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[1] GOST 8.541-86. GSI. State Primary Standard and State Verification Schedule for Means Measuring Torque of Force.

[2] Rosstandart Order No. 1717 of May 12, 2010 "On Approval of the State Primary Standard of the Unit for Torque.".

[3] GOST R 8.752-2011. GSI. State Verification Schedule for Means Measuring the Torque of Force.

[4] Rosstandart Order No. 1794 of July 31, 2019 "On Approval of the State Hierarchy Scheme for Torque Measuring Instruments.".

The measurement of low torque values of 0.1–1.0 Nm is also in demand in the Russian Federation. According to the data of the Federal Information Fund for Ensuring the Uniformity of Measurements[5] for 2011–2021, about a quarter of newly registered torque measuring instruments have a measurement range including values of below 1 Nm.

This is accompanied by the development of a normative base for torque measurement in terms of standardizing technical requirements for measuring instruments and their metrological support.[6,7] These are international and national standards, e.g., ISO 6789-1:2017,[8] DIN 51309:2022-08,[9] BSI BS 7882-2017,[10] and Calibration Guide EURAMET cg-14[11].

Modern high-precision technical devices require appropriate metrological support when measuring a torque of below 1 Nm. Such devices also require constant maintenance, taking into account the specifics of their operation. These reproduction ranges can be attributed to the need to solve the problems associated with measuring low torque values with high accuracy.

GET 149-2010 improvement

The GET 149-2010 improvement was aimed at ensuring the uniformity of torque measurements, which involved improving the upper level of the SHS for instruments measuring torque within the low-value range. The measurement, calibration, and operating capabilities of GET 149-2010 were expanded with the development of the standard system EU-250-2. The introduction of an air bearing into the EU-250-2 composition provided a means to set the lower limit of the torque reproduction range equal to 0.1 Nm.

In order to ensure torque measurement uniformity in the Russian Federation, it became necessary to revise the SHS for torque measuring instruments, which involves its upper-level improvement within the small-value unit reproduction range.

GET 149-2023 composition

GET 149-2023 comprises the following elements:

- EU-250-2 standard system with a torque reproduction range of 0.1–200 Nm;
- EU-250 standard system with a torque reproduction range of 1–250 Nm;
- EU-2500 standard system with a torque reproduction range of 20–2500 Nm;
- EU-20000 standard system with a torque reproduction range of 200–20,000 Nm.

GET 149-2023 also includes the following comparators: Dm-TN standard transducer, 1 Nm, class VN (GTM Testing and Metrology GmbH, Germany), with the upper measurement limit of 1 Nm; TB2 standard transducers (Hottinger Baldwin Messtechnik GmbH, Germany), with the upper measurement limits of 100; 500; 3000; 10,000 Nm. The specified sensors are used to disseminate the unit for torque during comparisons.

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[5] Approved types of measuring instruments. available at: https://fgis.gost.ru/fundmetrology/registry/4 (accessed: December 19, 2023).

[6] GOST 33530-2015 (ISO 6789:2003) Assembly Tools for Standardized Tightening of Threaded Connections. Torque Wrenches. General Specifications.

[7] GOST R 8.796-2012. GSI. Torque Measuring Devices. Verification procedure.

[8] ISO 6789-1:2017. Assembly Tools for Screws and Nuts—Hand Torque Tools—Part 1.

[9] DIN 51309:2022-08. Materials Testing Machines—Calibration of Static Torque Measuring Devices.

[10] BSI BS 7882-2017. Method for Calibration and Classification of Torque Measuring Devices.

[11] Calibration Guide EURAMET cg-14. Version 2.0 (03/2011). Guidelines on the Calibration of Static Torque Measuring Devices.

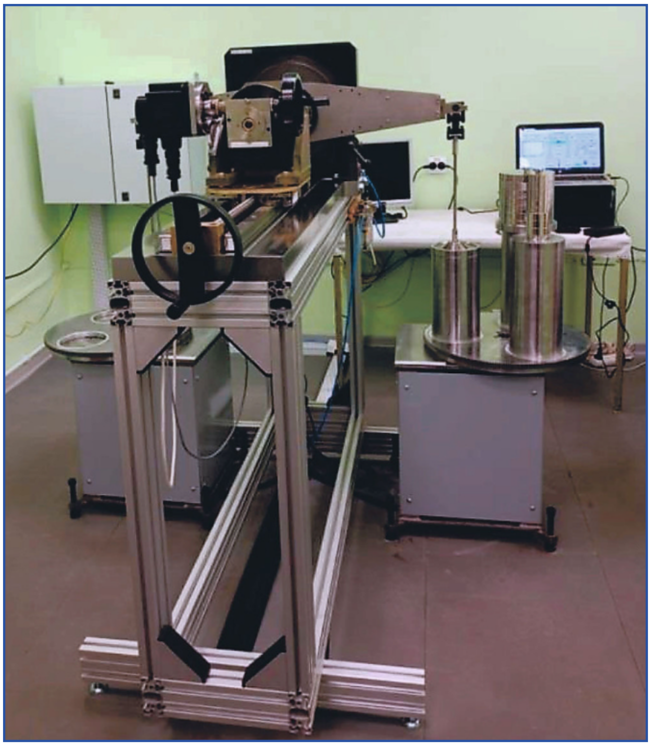

Fig. 1 Appearance of the EU-250-2 standard system

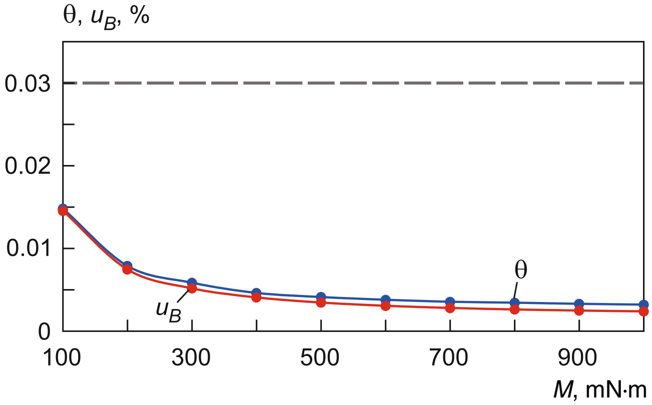

Fig. 2 Dependence of RSE θ and Type B standard uncertainty u_B on the reproducible value of torque M. (dashed line value specified in the design specification for EU-250-2 development)

Description of GET 149-2023 operating principle and design

Torque is a quantity resulting from the action of a force relative to an axis in space. Torque applied to an elastic body that cannot rotate freely due to the fixation of one end causes a torsional deformation of the body. Creating a state of equilibrium between the acting torque and the elastic response of the body forms the basis for the construction of systems for reproducing the unit for torque.

Each system used in GET 149-2023 consists of a supporting frame, a lever of a certain length mounted on the center support, a set of weights, and a drive for the torsion mechanism. Load knife-edges are positioned at the lever ends, with load-bearing bars placed on them. A certain number of weights required to reproduce a given torque value are placed on these bars by means of weight loading mechanisms. The rotation axis of the torsion mechanism drive runs through the pivot axis of the lever, which ensures that the measuring instrument to be verified produces torque with minimal distortions.

The EU-250, EU-2500, and EU-20000 standard systems use a base for the knife-edge fulcrum as the center support. In the created system EU-250-2, an air bearing is used as the center support. The measuring instrument to be verified (calibrated) is secured to the lever at one end and is attached to the torsion mechanism via an expansion coupling at the other end. The appearance of the standard system EU-250-2 is shown in Fig. 1.

Results of studying the standard system EU-250-2

Analysis of unit reproduction errors (uncertainties)

The equation of measurement in reproducing torque M is defined as follows

$$M = mgl\,(1 - \rho_{\mathrm{air}}/\rho_m)\cos\alpha \tag{1}$$

where m—mass of the weight(s) suspended on a lever; g—local gravitational acceleration; l—lever length; ρ_{air}—air density; ρ_m—material density of the weight; α—angle of lever deviation from the horizontal plane.

According to Eq. 1, the sources of uncertainty in torque reproduction include uncertainties associated with determining the mass of weights and the gravitational acceleration; measuring the lever arm length [3] (distance between the lever pivot axis and the top of the load knife-edge or the line of force action when using a thin metal strip for weight suspension [4]); non-horizontality of the lever; changes in air density ρ_{air}, which primarily depends on changes in atmospheric pressure and air composition (standard uncertainty can amount to $5.8 \cdot 10^{-6}$) [5]; friction in the lever support [6]. The uncertainty in reproducing the unit for torque can also be affected by other sources, such as parasitic loads whose characteristics are not directly included in the measurement equation [7].

Mass of weights

The systems use sets of weights of different masses. The weights are made of different materials: steel, stainless steel, and cast iron. For obtaining the corresponding value of force in newtons, the mass of weights is selected taking into account the gravitational acceleration, standard air density of $\rho_{\mathrm{air}} = 1.2\,\mathrm{kg}/m^3$, and experimentally determined material densities of weights ρ_m.

Gravitational acceleration

The gravitational acceleration is determined at the location of the standard systems. The contribution of gravitational acceleration is negligible and is not included in the overall uncertainty budget.

Lever length

Measurement of the lever length and estimation of its changes is one of the most difficult problems in reproducing torque with high accuracy [8, 9]. On the one hand, it is necessary to have accurate reference points on the lever for length measurements; on the other hand, the length changes due to temperature fluctuations and deformation of the lever under load. The lever length of the EU-250-2 system was determined using a Hexagon 8325-7 ABSOLUTE ARM coordinate measuring machine (France). The lever length of EU-250-2 is $l = (500.002 \pm 0.020)$ mm.

Angle of horizontal lever deviation

The deviation of the lever from the horizontal position was measured in a non-contact manner at a distance of approximately 300 mm from the lever pivot axis. This deviation was registered by the control system as a linear deviation; during the study, its value did not exceed 0.5 mm. This deviation corresponds to an angular deviation of 1.7 mrad, which is consistent with a standard uncertainty of 0.001 rad for the angle of lever deviation from the horizontal plane.

Table 2 Budget of uncertainty at the point 100 mN·m

Source	Value	$u(x)$	$c(x)$	$u(x)c(x)$	Contribution, %
Weight mass m, g	2,037,779	0.000011	4.91	0.000054	0.24
Weight density ρ_m, kg/m^3	7950.3	6.7	0.0000019	0.000013	0.06
Lever length l, m	0.500002	0.000010	200.0	0.002004	35.06
Air density ρ_{air}, kg/m^3	1.199	0.014	0.013	0.000176	0.77
Lever deviation from the horizontal position α, rad	0	0.0010	0.098	0.000096	0.42
Frictional torque M_{fr}, mN·m	0	0.0140	1	0.014434	63.23

Type B standard uncertainty u_B = 0.0146%,RSE of θ = 0.0148%

Table 3 Budget of uncertainty in torque reproduction

M_0, mN·m	M, mN·m	θ, %	u_B,%
100	99.9997	0.0148	0.0146
200	200.0008	0.0079	0.0075
300	300.0020	0.0059	0.0052
400	400.0022	0.0046	0.0041
500	500.0033	0.0041	0.0035
600	600.0044	0.0038	0.0031
700	700.0052	0.0036	0.0028
800	800.0066	0.0034	0.0026
900	900.0073	0.0033	0.0025
1000	1000.0082	0.0032	0.0024

In the study of the EU-250-2 standard system, the following characteristics were determined: SD of measurement results at $n = 20$ observations; RSE confidence limits; Type A and B standard uncertainties (u_A and u_B); combined standard uncertainty u_c.

With 20 observations at different torque reproduction points for different EU-250-2 load points within the range of 100–1000 mN·m, the SD of measurement results are as follows: the nominal values of reproducible torque $(x_i) = 100; 200; 300; 500; 1000$ correspond to the following type A relative standard uncertainties $u_A(x_i) = 0.0124; 0.0042; 0.0023; 0.0011; 0.0010$.

The relative SD (Type A relative standard uncertainty) decreases with increasing torque. At the lowest range point, the relative SD does not exceed 0.02%.

The budget of uncertainty in reproducing a torque of 100 mN·m is given in Table 2, where $u(x)$—standard uncertainty, $c(x)$—sensitivity coefficient, x—source of uncertainty.

Similarly, the budget of uncertainty in reproducing the torque was estimated within the range of 100–1000 mN·m. The results of studying the RSE θ and Type B standard uncertainty u_B are summarized in Table 3. A graph showing the dependence of the RSE θ and Type B standard uncertainty u_B on the reproducible torque value M is shown in Fig. 2. The obtained estimates of Type B standard uncertainty do not exceed 0.03%.

The metrological characteristics of GET 149-2023 are given in Table 4.

International comparisons

In 2004–2016, two international key comparisons were conducted in the field of torque measurements under the auspices of the BIPM. UNIIM—Affiliated Branch of the D. I. Mendeleev Institute for Metrology (UNIIM) participated in supplementary comparison with Physikalisch-Technische Bundesanstalt (PTB): COOMET 512/RU-

Table 4 Metrological characteristics of GET 149-2023

Characteristic	Value of the characteristic within torque reproduction ranges, N·m		
	0.1–1	1–2500	2500–20,000
SD (n = 20)%, not exceeding	0.02	0.008	0.015
RSE (p = 0.95), %, not exceeding	0.05	0.020	0.040
u_A (n = 20)%, not exceeding	0.02	0.008	0.015
u_B, %, not exceeding	0.03	0.010	0.020
U_C, %, not exceeding	0.04	0.013	0.025

Table 5 Results of Dm-TN transducer calibrations conducted by UNIIM and PTB

M, mN·m	UNIIM				PTB		E_{eq}
	U_{ave}, mV/V	u_A, mV/V	u_B, mV/V	U_C, mV/V	U_{ave}, mV/V	U_C, mV/V	
100	0.099774	0.000012	0.000020	0.000024	0.099728	0.000007	0.93
200	0.199389	0.000037	0.000040	0.000054	0.199484	0.000012	0.85
300	0.299152	0.000007	0.000060	0.000060	0.299253	0.000017	0.81
500	0.498675	0.000008	0.000100	0.000100	0.498825	0.000027	0.72
1000	0.997810	0.000008	0.000200	0.000200	0.997813	0.000055	0.01
–100	–0.099710	0.000012	0.000020	0.000024	–0.099719	–0.000008	0.18
–200	–0.199389	0.000037	0.000040	0.000054	–0.199473	–0.000012	0.75
–300	–0.299152	0.000007	0.000060	0.000060	–0.299238	–0.000017	0.69
–500	–0.498675	0.000000	0.000100	0.000100	–0.498799	–0.000027	0.60
–1000	–0.997810	0.000008	0.000200	0.000200	–0.997738	–0.000050	0.17

COOMET 512/RU-a/10 (COOMET.M.T-S1). The results of this comparison were published in 2017 [10]. As a result, the Russian Federation has the following torque calibration and measurement capabilities: torque reproduction range of 100–2500 N·m; relative expanded uncertainty of $2.0 \cdot 10^{-4}$.

The improvement of GET 149-2010 in 2022 involved comparing the results of the Dm-TN transducer calibration carried out using a PTB standard system with the calibration results obtained by UNIIM using the EU-250-2 standard system. The results of the Dm-TN transducer calibrations were compared at the following torque values: 100; 200; 300; 500; 1000 mN·m in both clockwise and counterclockwise torque directions.

Evaluation of comparison results

The results of measurements obtained during calibrations were used to estimate uncertainties and equivalence criteria E_{eq} at the loading stages, whose values helped to evaluate the comparison results. As the comparison reference value $\overline{x}_{i\ \mathrm{ref}}$ at the loading stage, transducer calibration results obtained by PTB were adopted.

The equivalence criteria are determined as follows

$$E_{eq} = \frac{|x_i - \overline{x}_{i\ \mathrm{ref}}|}{2\sqrt{u^2(x_i) + u^2(\overline{x}_{i\ \mathrm{ref}})}}$$

where x_i—result obtained at the loading stage of transducer calibration at UNIIM; $u^2(x_i)$—standard uncertainty of the result obtained at the loading stage of transducer calibration at UNIIM; $u^2(\overline{x}_{i\mathrm{ref}})$— standard uncertainty of the comparison reference value at the loading stage.

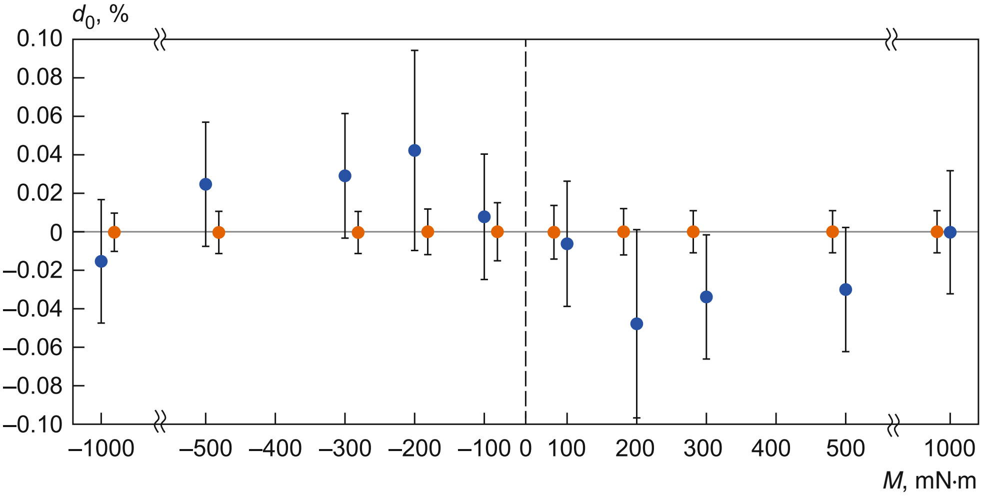

Fig. 3 Relative average deviations d_0 of the transducer output signal and relative expanded uncertainties in UNIIM (blue dots) and PTB (red dots) calibrations (for clockwise and counterclockwise torque directions)

The results of measuring the output signal of the Dm-TN transducer in the comparison process, as well as the results of estimating uncertainties and equivalence criteria, are shown in Table 5, where U_{ave}—average values of the transducer output signal. The relative average deviations d_0 of the transducer output signal and relative expanded uncertainties in UNIIM and PTB calibrations (for clockwise and counterclockwise torque directions) are shown in Fig. 3.

The maximum estimated equivalence criterion does not exceed the specified value equal to one. This fact confirms that in comparisons, UNIIM data can be recognized as confirming the stated uncertainty of the standard system EU-250-2 within the range of 0.1–1.0 N·m.

Conclusion

In this study, a standard system for reproducing and disseminating the unit for torque within an extended range was designed and manufactured. The developed system is included in GET 149-2023. The extended unit reproduction range of GET 149-2023 ensures torque measurement uniformity, which provides a means to solve relevant problems of measurement uniformity assurance when using a wider range of torque measuring instruments in various branches of the economy.

Conflict of interest B.A. Cherepanov, P.V. Migal and G.V. Horkov declare that they have no competing interests.

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