Journal of Measurement Science & Applications, JMSA. Vol (2) Issue (1)

Recent techniques in static and dynamic torque measurements

K.M. Khaled[1*]

[1] Force and Material Metrology laboratory, National Institute of Standards (NIS), Egypt
* khaled.abdelaziz@nis.sci.eg

Article Type: Review article

Abstract

The review article presents a historical scientific spot of light on the progress of torque measurements with focus on the traceability as a corner stone of NMIs daily work. An introduction to torque measurements including the background and the basic concepts of conventional static torque measurements with its traceability, as a derived mass unit, to force unit in Newton and the length unit in meter. Different methods of reaction torque measurements and its industrial applications are discussed. The advantages of the most common sensing part, the strain gauges, are deeply discussed. The construction of torque measuring body and how to transmit the signals in both static and rotary applications are viewed. The conceptual design of the primary and secondary torque standard machines and how their achieve traceability are briefly discussed. The static torque calibration machines from different leading NMIs are discussed to differentiate between the accuracy related designs; selection of bearing, selection of the measuring axis, design of the lever arm ends, and influences of connections and adapters. The NIS static torque standard machines are briefly discussed here. The dynamic torque measurements with its applications and impact to increasing industrial demand outside the research laboratories are discussed. The governor equations, assumptions, physical parameters and Modelling of the system are discussed as well. Pioneer European project with its results are presented. The NIS running research work in dynamic torque is presented. The most recent trend in torque and force measurements, the electromagnetic force/torque machines, is briefly discussed with focus on the pioneer researches and its outputs with future expectations.

Keywords: Torque, static, dynamic, electrostatic, traceability.

1 Introduction

Torque is defined as the applied force to a lever arm with known length therefore its simplest form is force multiply length. The realization of torque quantity and establishing the traceability through design of torque calibration machines with different accuracy levels is a fresh metrology field started in 1990^s [1]. Consequently, very few torque calibration machines at National Metrology Institutes (NMI) are frequently found. Such problems and associate uncertainties in both force and length measurements as they are two fields of metrology. And when they combine together to realize torque, new challenges will come in front.

In run-through, there are two main forms of applying torque; torque tools (wrenches commonly) or torque transducers. Torque tools are the daily use tools used to fasten screws and nuts such as wrenches, screwdrivers, multipliers, hydraulic, and pneumatic tools which are used in plants and workshops. They are mainly used to assemble different parts by generating appropriate amount of torque which produces internal tension between fastening bolts and nuts. Contrary, torque transducers are sensing and control element broadly used in various applications to measure, control, and adjusts the generated torque. Torque measuring devices mainly used in process quality control to check the performance and acceptance limits and calibration and tightening tools such as powered torque runners and drivers. In automotive industry the torque transducers are permanently fitted to monitor the fuel efficiency consumption, as well as for power assistance steering [2-13].

Particular applications of torque devices are studying the behavior of motors steering wheels. The alternating torque is generating as residual torque to the torque transducer such as curvilinear and straight linear travel. The torque application loading profile can’t be predicted, and excessive torque changes which generated by curvilinear and straight linear travel or parking-in are superposed by small torque changes the road profile and obstacles. The alternating torque applications calibration procedure is user to calibrate the torque transducers used in such applications to simulate the practice application. Polynomial equations are generated to fit the calibration measurements to cover the transducer’s full range [3].

2 Static torque standards machines

The accuracy level should depend on each country needs and situations. Such case studies are presented here for different design concepts from different countries; Germany, Finland, Italy, and Egypt to build their torque calibration machines. The principle of the component system presented by D. Peschel [1] and applied in the PTBs’ machines is also applied in many other NMIs such as KRISS, NMIJ, UME, CENAM. Therefore, this article presents particular designs where concepts are different.

2.1 Primary standard torque calibration machines

Starting from the metrological traceability in field of force measurements, similar standard machines were developed for realization of torque quantity at the PTB. It has four primary standard torque calibration machines established to realize torque unit are tabulated in Table (1) [14]. The design principle for their design is a force application to the end of a lever system buoyed on a low friction aerostatic bearing [13]. The radial bearing offers the ability of rotation of its axis, the crosswise forces substitute on the lever arm produces tilting moments then this tilting moment converted to a torque vector. Therefore, pure torque can be used to calibrate torque measuring devices. The lever –mass system is supported in an aerostatic bearing. The torque is generated by the motor driver system and measured by the supporting force on a pay compensation weighing device. A freely suspension of mass piece, possible oscillations in the weighing device is damped to reach system stabilization. A data acquisition system for both the signal of the calibrated torque transducer and of the mass stack device permits martial drift to minimize the error of mass handling repetitions and consequence calibration and measurement uncertainty (CMC).

The 1 kN·m torque calibration machine set up is showed in Figure (2). A detailed explanation is given in [15-23]. The machine has unique mass selection mechanism ranges, torque steps of 2 N·m are used in the range from 2 N·m to 1 kN·m. This is because of selecting different masses for right-hand side torques and left hand side torques in a combination to increase the ability of choosing small torque steps of 2 N·m.

Table 1: Primary torque calibration machines (PTB) [15]

Description	Measurement range 1 Min max	Measurement range 2 Min max	Expanded Uncertainty range 1 (k = 2)	Expanded Uncertainty range 2 (k = 2)
20 kN·m	100 N·m to 20 kN·m	10 N·m to 1000 N·m	2×10^{-5}	1×10^{-4}
1 kN·m	2 N·m to 1000 N·m	0.2 N·m to 5 N·m	2×10^{-5}	1×10^{-4}
20 N·m	0.1N·m to 20 N·m	-	2×10^{-5}	-
1 N·m	0.05 N·m to 1N·m	0.0005 N·m to 0.1 N·m	1×10^{-4}	1×10^{-3}

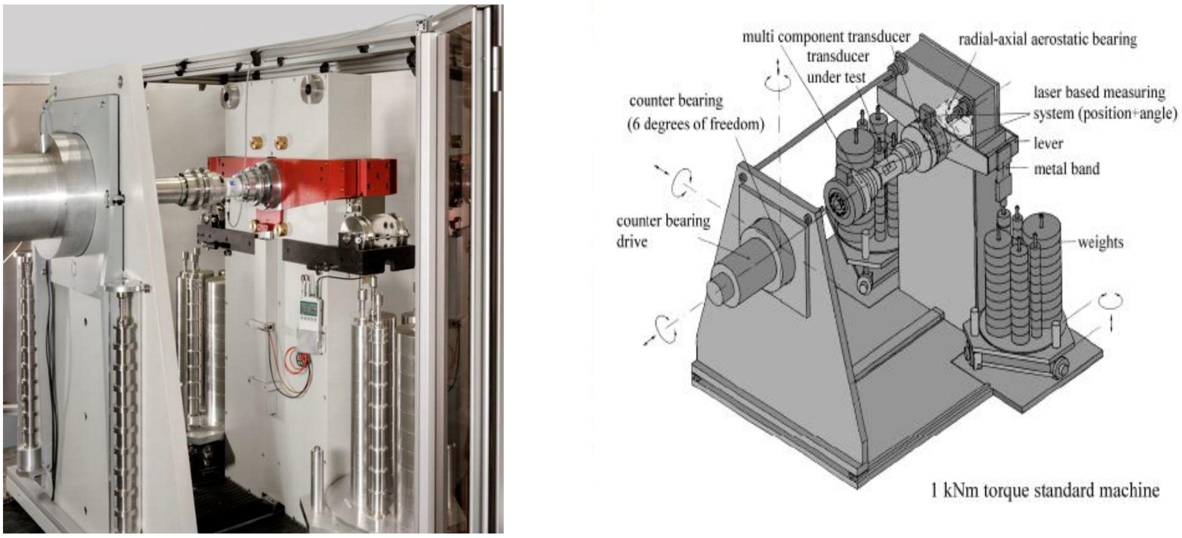
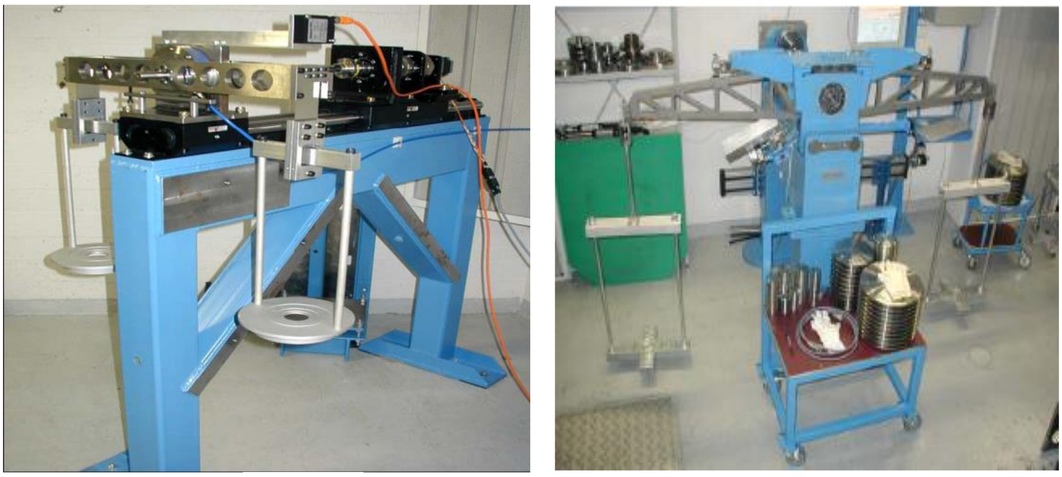


Figure 2: Photograph of 1 kN·m torque calibration machine on the left (PTB) and its main components on the right.

The 20 N·m torque calibration machine has a very similar design and concept of operation, it has 3 stacks to cover the range from 100 mN·m up to 20 N·m in both clockwise and anticlockwise directions with relative expanded uncertainty of 5×10^{-5} [15].

At the NMI of Finland (MIKES), they have two primary torque standard machines. A lever-weight system is developed for calibrating torque transducers, where the weights are loaded manually. Figure 3a and 3b shows the 20 N·m and 2 kN·m MIKES torque standard machine.



a) **b)**

Figure 3: **a)** 20 N·m and **b)** 2 kN·m, primary torque calibration machines (MIKES)

As shown in Figure 3, the machines are using aerostatic bearings to reduce the friction to the minimum to be able of achieving relative expanded measurement uncertainty of 2×10^{-4}.

The ball bearings are used to establish the mechanism called counter rotating bearings. This mechanism is consisting of two ball bearing rows in series radially. The inner ring of the smaller bearing row is assembled to the machine shaft while its outer ring is the inner ring of the bigger one. This mechanism could be used in secondary standard torque calibrations or the primary torque calibrations. The bigger outer bearings are fixed to the machine. Standard ball bearing is used in this counter rotating mechanism. A rotation drive system is used to rotate these bushes [24-26]. MIKES uses a toothed belt derived by a motor drive with reduction gear train to rotate these bushes. Figure 4 shows a schematic view of the 2 kN·m dead weight machine counter rotating bearings.

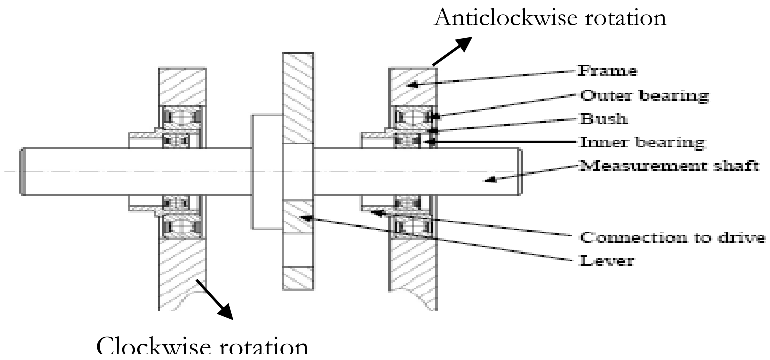


Figure 4: Counter rotating bearings in 2 kN·m torque calibration machine (MIKES)

The NMI of Italy (IMGC) 2 kN·m torque calibration machine [27] and NIS 1 kN·m machines [28-38] introduced a modified shape of the lever arm end to be able to have the same lever arm length even if the lever arm is rotated within limits. This idea was established by interrupting a sphere shape between the lever arm end and the machine loading frame. This principle has a disadvantage which is determining the accurate length of the lever arm, primarily because of dependency between the position of the force acting line and the local tension along the contact lines between the sphere connected to the lever arm and the machine loading frame. A schematic front view of the lever arm with the spherical ends is shown in Figure 5. Both lever arm ends are coaxial cylindrically with the machine axis.

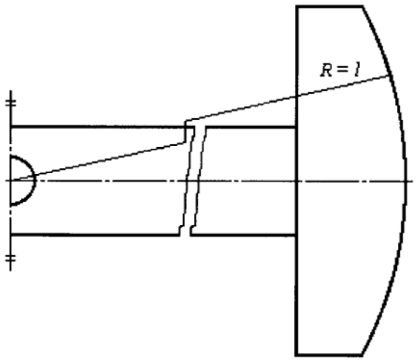


Figure 5: Front view of the 2 kN·m torque standard machine (IMGC)

This design principle offers possibility to evade controlling the lever arm horizontal position accurately. The machine uses counter rotating bearings as fulcrum as shown in Figure 6 [24]. The measuring range of this machine is from (0.005- 2) kN·m with expanded uncertainty of 5x10^{-4}. Figure (6a) and (6b) shows a photograph of the IMGC and NIS machines, respectively.

(a) (b)

Figure 6: (a) 2 kN·m torque standard machine at IMGC, (b) 1 kN·m primary torque standard machine at NIS.

2.2 Secondary Standard Torque Calibration Machines

The torque calibration machines with their lever-mass systems offers accurate measurements but considered a time-consuming measurements. Nevertheless, various torque measuring devices are used for continuous or quasi-static torque measurements in the field. The principle of the secondary machines is to use a high accuracy torque transducer as reference value connects the torque transducer under calibration in series, then use a torque generation drive to apply the required torque values. There are four secondary torque machines at PTB for automated continued measurements. Figure (7) shows the 20 N·m machine. Interchangeable reference torque transducers are mounted to the motor/gear driving unit through a flexible coupling and hydraulic clamps.

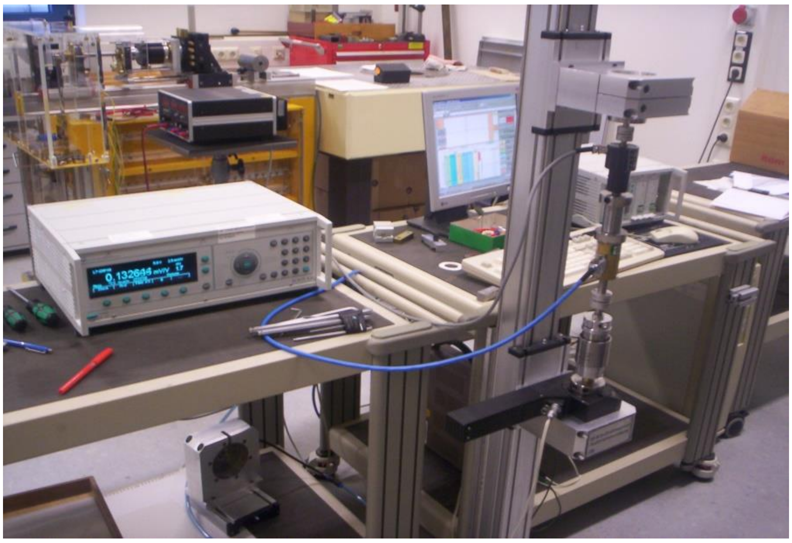


Figure 7: 20 N·m torque standard machine at (PTB)

Another technique used to realize the torque quantity through the measuring double-side lever arm is located at the opposite end of the machine frame. Two multi-components strain control hinges are used to convert the generated torque steps to coupled forces, there force are measured by reference force transducers traceable to force unit. The double-side lever arm is supported by a movable crosshead can be move vertically to adjust the height of measuring space up to 4 m length.

3 Dynamic torque measurements

The reason for research on the traceability of dynamic torque transducer calibration comes mainly from two applications with dynamic torque signals [39-43].

3.1 Principle of Dynamic Torque Calibration

Authors At the moment, commonly accepted calibration machines as well as calibration procedures for a dynamic torque transducers calibration, do not exist. Entirely torque transducers which used in the dynamic applications or even rotary applications are calibrated statically only.

The Newton’s second law is the governance law in the primary dynamic. The applied dynamic torque T(t) equivalents the mass moment of inertia J multiply the rotational acceleration $\ddot{\varphi}$(t).

$$T(t) = J \cdot \ddot{\varphi}(t)\,. \qquad (1)$$

The first dynamic torque machine applying this principle was established and performance evaluated at PTB [42, 44, 47-49]. PTB was leading the European Metrology Research Programme Joint Research Project IND09 to realize dynamic traceability for mechanical quantities; pressure, force, and torque. PTB through the project improved their dynamic torque machine by replacement of the exciter and the larger aerostatic bearing.

Figure (8) shows the principle in design and the main parts of the dynamic torque device at PTB. The device is oriented vertically while all machine parts are assembled in series to rotate freely. The torque is generated by a rotational exciter located at the bottom. The exciter is able to move vertically by three guided vertical screws to be adjustable to meet the length and assembly requirements. The calibrated torque transducer is assembled to machine above the rotational exciter.

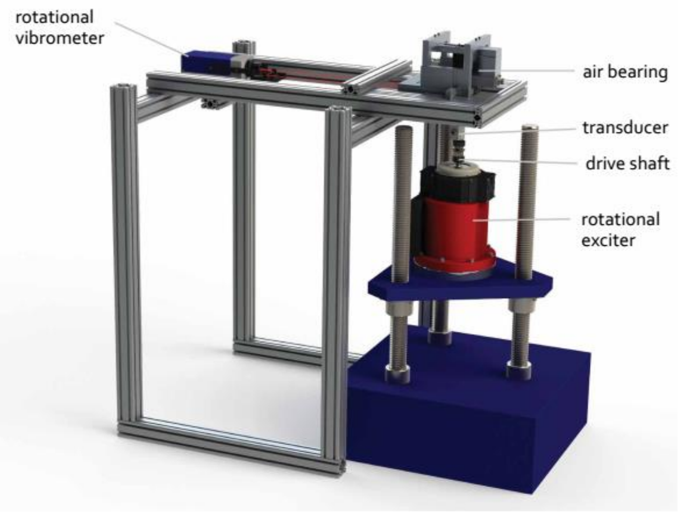


Figure 8: Schematic drawing of the PTB’s dynamic torque machine

3.2 Physical Model

Torque transducers are commonly coupled from both sides to different types of connections to measure the applied torque. The mechanical connections with its mass moment of inertia have effect to the transducer’s dynamic behavior. In order to realize these influences, the model calculations are used to represent the whole mechanical system of both torque transducer under test and measuring device. The proposed model uses a system be made up of two main mass moment of inertia elements J_H, J_B joined by a torsion spring c_T and in parallel with damper d_T, that describe the device under test (DUT), and at the top of the model, an extra mass moment of inertia J_0. The dynamic behavior is represented by the amplitude response which represents the ratio of the angular accelerations’ amplitudes $\ddot{\varphi}_0$ and $\ddot{\varphi}_B$ at both the top and the bottom of the dynamic torque machine, respectively. Figure (9) shows the proposed model and the amplitude response.

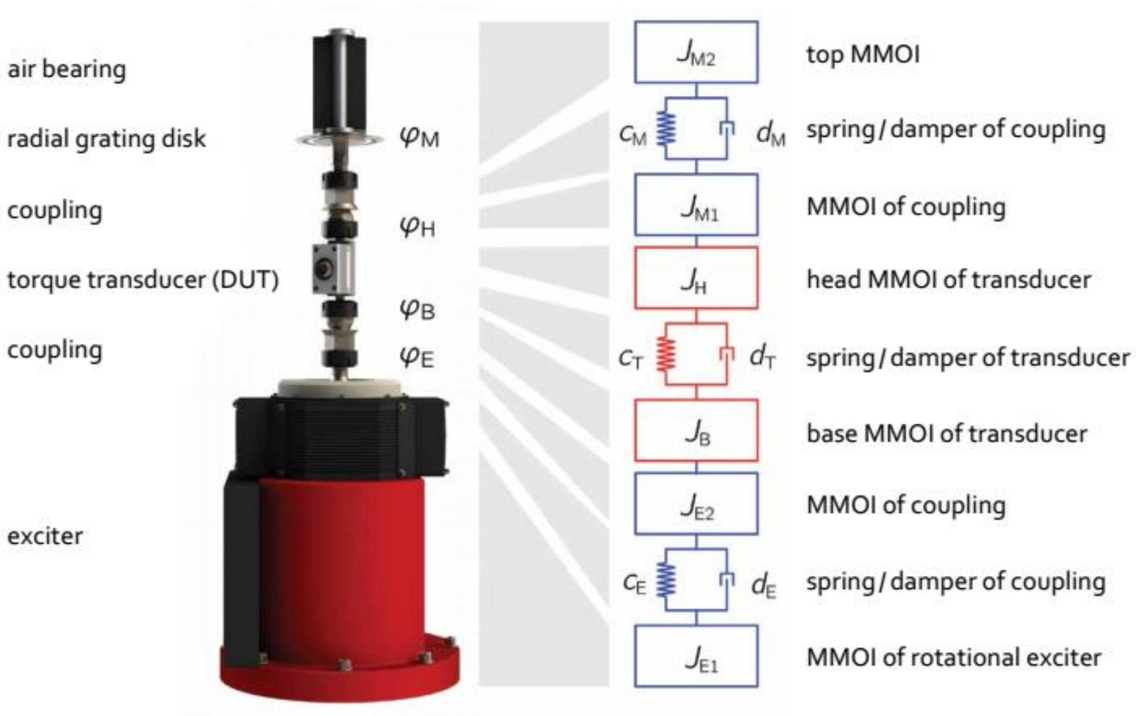


Figure 9: Modelling of the dynamic torque calibration machine

The identification of the torque measurement instrument's model parameters is required. Therefore, three devoted supplementary measurement set-ups were established to define system mass moment of inertia, stiffness coefficient [43], and damping coefficient [44]. Since the three coefficients are now known by three auxiliary measurements, the model parameters can be specified [44-48].

Two years ago, the NMI of Egypt (NIS) started to work in realization of dynamic torque. The proposed design is a horizontal axis, which consists of a motor drive connected to a dynamic torque transducer mounted between two flexible couplings. The free side of the dynamic torque transducer is coupled to a shaft passes through an air bearing and the other side of this shaft is connected to a disc with a changeable mass coupled to its outer distance. The rotation of the motor drive cause sinusoidal torque application. The torque amplitude is controlled by the changeable masses coupled to the rotary disc and the frequency could be controlled by the drive motor rotational speed [50].

4 Electromagnetic torque machines

As mentioned in the introduction part the dead weight torque standard machines produces torque by means of distance from traceable mass to the international prototype kilogram (IPK) and gravitational acceleration. This generated standard torque, on the other hand can calibrate only the static torque value. Dynamic torque applications have recently been increasing. So far, there is no traceability to the dynamic torque measurements. Research on the traceability of dynamic torque has been initiated within the European Research Project IND09, and some outputs have already been presented [51–56]. Recently, the field of mass standard has been studying the Kibble balance to overcome the limits to the IPK artifact [57–62]. As a result of these researches, the mass definition has been redefined as Planck's constant beginning in 2019. This opens the door to the derived units, force and torque, to be changed as well to be defined using the Kibble balance principle [63], [64].

In the beginning of 2021, Myeong Hyeon Kim from KRISS introduced his pioneer research showing the design principle of generating standard torque using the principle and basics of the Kibble balance. Furthermore, as this machine uses the electromagnetic force in consistence with the Kibble balance idea, it has the advantage of being able to realize both static and dynamic torque in the same machine [63].

The weighing mode and the moving mode are two modes applied for redefining the kilogram on the basis of Planck's constant. The weighing mode is an experiment that maintains gravity-electromagnetic force equilibrium. The moving mode is a test to measure induced voltage and coil velocity.

Figure 10 shows the shape of the coil of the proposed new dead weight torque standard machine (DMTSM). Magnetic fields are distributed in opposite directions on both sides of the coil as shown in the figure. Therefore, a coupled force is generated in a direction perpendicular to the linear coil when a current is applied to this coil. This generated force produces torque based on the entire center; the coupled force and produced torque are formulated as:

$$F = B\,Il \qquad (2)$$

$$T = r \times F = r \times B\,Il \qquad (3)$$

$$T = U\,I/\omega \qquad (4)$$

where F is the Lorentz force, B is the magnetic field, I is the current, l is the effective length of the coil, T is the produced torque, and r is the radius from the entire center, U is the induced voltage, and ω is the angular velocity of the coil. Meanwhile, using the second mode, such as the principle of the Kibble balance, the magnetic field and the radius can be omitted. The second mode in principle, in which the coil rotates under the magnetic field, is the rotating mode. When the coil moves under a uniform magnetic field an induced voltage is produced.

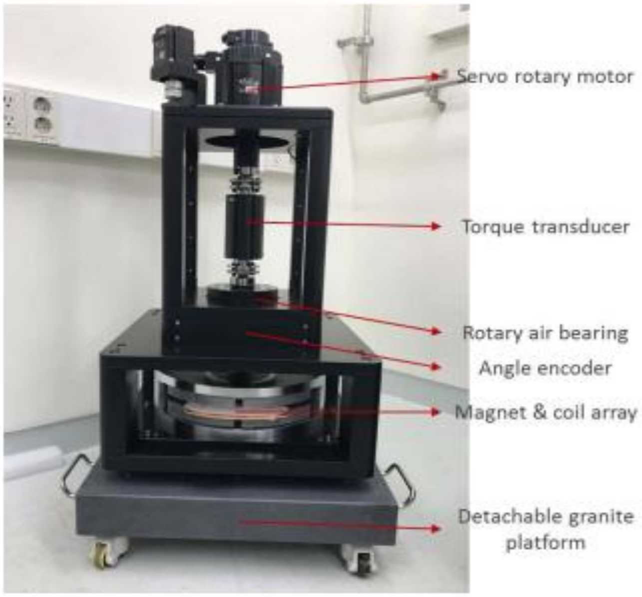


Figure 10: Dual-Mode torque standard machine (KRISS) [65].

The manufacturing process of the proposed machine and experiments were conducted. The machine capacity is 10 N·m in static torque mode with relative expanded uncertainty less than 10^{-4}. The target dynamic torque frequency range is up to 100 Hz. The results of the performance evaluation for the static or the dynamic measurements as torque standard machine are not published yet.

The other trial was at NMIJ Japan by applying the Equation (4) [66-67] to cover the range from 0.27 μN·m to 100 mN·m. The measurements relative expanded uncertainty is 0.17 %. The performance evaluation of this machine was done by comparing its results with the 10 N·m primary static torque calibration machine. The comparison points were from 0.01 N·m to 0.1 N·m with 10 increments in both clockwise and anticlockwise directions. This Machine has an angular measurement system to calibrate the rotational speed. Figure (11) shows the NMIJ machine.

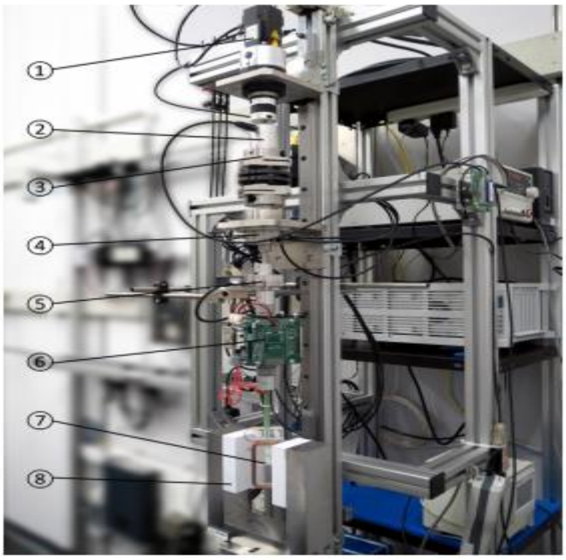


Figure 11. Electromagnetic force torque standard machine (NMIJ). Key: (1) motor driver with gear box, (2)

torque transducer, (3) adapters, (4) air bearing, (5) photosensitive encoder, (6) electrical volt and current millimeter, (7) rectangle-cross section coil, and (8) two neodymium magnets [67]

Overall, using the features of the watt balance in the force and torque measurements and the fact that *I* is not affected by gravity, allow installing the machine itself in arbitrary locations to calibrate measuring devices.

5 Conclusions

A historical review starting from the concepts and basics to the recent techniques of static and dynamic torque measurements is presented. The conceptual design of static torque standard machines and the requirements to have a standard machine with a certain level of uncertainty are discussed with focus on the influencing components. The dynamic torque measurements with its applications and impact to increasing industrial demand outside the research laboratories; such as impulse wrenched and calibration of rotary test rigs are discussed. The governor equations, assumptions, physical parameters and Modelling of the system are discussed as well. Pioneer European project with its results are presented. The NIS calibration machines which cover the range up to 100 kN·m for static measurements and the running research work in dynamic torque are presented. The dramatic impact of the redefinition of the kilogram on the future of torque measurements is discussed. The principle of the Kibble balance and its governor formulas are now used to re-shape the SI traceability of torque measurements in both static and dynamic applications. Author expect in the few upcoming years to see the principle of electrostatic force torque machines will grow rapidly to cover the small and intermediate torque range because it is a quite easy for both static and dynamic. More improvements and more simple designs may be introduced to widen the application scope

6 Declarations

6.1 Study Limitations

None.

6.2 Acknowledgements

None.

6.3 Funding source

None.

6.4 Competing Interests

None.

7 Human and Animal Related Study

None.

7.1 Ethical Approval

None.

7.2 Informed Consent

None.

References

[1] D. Peschel, “Torque – not simply <<Force X Length>>”, *PTB news*, 2.1997.

[2] N. Whitehead., A. Cheshmehdoost, A. Verrall, B. Jones, “Torque Measurement by Employing a Mechanical Resonator”, *International Conference on Force and Mass Measurements*, Tampere-Finland- Sept. 1997.

[3] D. Roeske, D. Peschel, “Investigations into the Alternating Torque Calibration of Torque Transducers”, *International Conference on Force and Mass Measurements*, Tampere-Finland- Sept. 1997.

[4] R. Schicker, G. Wegener, “Measuring Torque Correctly”, *HBM publish*, Germany – 2002, ISBN 3-00-008945-4.

[5] Assembly tools for screws and nuts – Hand torque tools – Requirements and test method for design conformance testing, quality conformance testing and recalibration procedure”, ISO 6789:2017, parts 1 and 2.

[6] El-Anwar Mohamed Ibrahim Mohamed, “Construction, Performance Evaluation and Proposal For Upgrading NIS Torque Standard Machine”, Master Thesis, Faculty of Engineering, Cairo University, January 2000.

[7] Data sheet of Torque Transfer Wrench (TTS), HBM – Germany.

[8] Static Calibration of Torque Wrench Calibration Devices, DKD R-3-8, 1995.

[9] Assembly tools for screws and nuts – hand torque tools – requirements and test methods, ISO 6789, 2003.

[10] Calibration of Static Torque Measuring Devices, DIN 51309, 2005.

[11] Method for calibration and classification of torque measuring devices BS 7882, British standard, 2017.

[12] EA Guidelines on the Calibration of Static Torque Measuring Devices, EA-10/14, European co-operation for Accreditation, 2000.

[13] D. Peschel, D. Mauersberger, “Determination of the Friction of Aerostatic Radial Bearings for the Lever- Mass System of Torque Standard Machines”, *Proceedings of the XIIIth IMEKO World Congress*, Torino, Italy, Sept., 1994.

[14] D. Peschel, “The State of the Art and Future Development of Metrology in the Field of Torque measurement in Germany”, *Proceedings of the 15th IMEKO TC3 Conference*, Tamper, Finland, Mar. 1997.

[15] C Schlegel, D Röske, D Mauersberger, Paul Hohmann, “Metrological Characterization of a 20 N·m Torque Calibration Standard Machine at PTB, Germany”, *J. Phys.: Conf. Ser*. 1065 042026, 2018.

[16] Adolf K., Mauersberger D., Peschel D., “Specifications and Uncertainty of Measurement of the PTB's 1 kN·m Torque Standard Machine”, *Proceedings of the 14th IMEKO TC3 Conference*, Warsaw, Poland, Sept., 1995.

[17] Röske D., Adolf K., “On the Problem of Lever Arm Lengths in the Realization of the Torque – Finite Element Calculations on Lever Models”, *Proceedings of the 14th IMEKO TC3 Conference*, Warsaw, Poland, Sept., 1995.

[18] D. Röske, “Realization of the Unit of Torque - Determination of the Force-Acting Line Position in Thin Metal Belts”. *Proceedings of the 15th IMEKO TC3 Conference*, Madrid, Spain, Oct. , 1996.

[19] A. Brüge, “Influence of Eccentric Mounting on the Calibration of Torque Measuring Devices”, *Proceedings of the 15th IMEKO TC3 Conference*, Madrid, Spain , Oct. , 1996.

[20] D. Peschel, K. Adolf, „Projekt einer 20-kN·m-Drehmoment-Normalmeßeinrichtung“. Published in PTB-Mitteilungen 101 6/91, pp. 413-414. (in German)

[21] D. Peschel, “Proposal for the Design of Torque Calibration Machines Using the Principle of a Component System”, *Proceedings of the 15th IMEKO TC3 Conference*, Madrid, Spain, Oct., 1996.

[22] PTB web site, www.ptb.de, PTB > Structure > Division 1 > Department 1.2 > Working group 1.22, accessed in Aug., 2021.

[23] D. Peschel, D. Mauersberger, D. Schwind, K. Kolwinski, “The New 1.1 MN·m Torque Standard Machine of The PTB Braunschweig/Germany”, *Proceedings of the 19th IMEKO TC3 Conference*, Cairo, Egypt, Feb., 2005.

[24] A. Pusa, “Torque Calibration in Finland”, *Proceedings of the 15th IMEKO TC3 Conference*, Madrid, Spain, Oct., 1996.

[25] A. Pusa, M. Sachs, “Influence of Counter rotating Bearing in Torque Calibration”, *Proceedings of the 19th IMEKO TC3 Conference*, Cairo, Egypt, Feb., 2005.

[26] A. Pusa, D. Roeske, M. Sachs, “Comparison Measurement of MIKES_RAUTE 20 kN·m Torque Reference Device with PTB”, *Proceedings of the 19th IMEKO TC3 Conference*, Cairo, Egypt, Feb., 2005.

[27] S. Merlo, C. Ferero, C. Marinari, E. Martino, ‘Metrology of Torque: New Developments at CNR-IMGC”, *Proceedings of the XV IMEKO TC3 Conference*, Osaka, Japan, June 1999.

[28] H.M. Abdel Hakem, A.A. El-Sayed, A.E. AboEl-Ezz, “Design, Construction and Performance Tests of Torque Meters”, NIS-Egypt, 1992.

[29] D. Peschel, "Proposal for the Design of Torque Calibration Machines Using the Principle of a Component System", *International Conference on Force and Mass Measurement*, Madrid-Spain- Sept. 1996.

[30] Khaled Abdelaziz Mohamed, “DESIGN, DEVELOPMENT AND CALIBRATION OF TORQUE STANDARD MACHINE”, Ph.D. Thesis, Faculty of Engineering, Cairo University, 2016

[31] K.M. Khaled , D. Röske, A.E. Abuelezz, M.G. Elsherbiny, "Humidity and temperature effects on torque transducers, bridge calibration unit and amplifiers", *Measurement*, Volume 74, October 2015, Pages 31–42.

[32] K.M. Khaled , D. Röske, A.E. Abuelezz, M.G. Elsherbiny, "The influence of temperature and humidity on the sensitivity of torque transducers", *Measurement* 94 (2016) 186–200.

[33] K.M. Khaled, D. Röske, "The influence of temperature and humidity on the creep of torque transducers", *IMEKO TC3, TC5 and TC22 International Conferences,* May 30, 2017 – June 1, 2017,Helsinki, Finland.

[34] Khaled Abdelaziz Mohamed, "Design, Construction and Performance Evaluation of Torque Standard Machine", Master Thesis, Faculty of Engineering, Cairo University, July 2010.

[35] K.M. Khaled, G. Aggag, A.E. Abuelezz, M.G. Elsherbiny "The influence of misaligN·ment on the uncertainty of vertical torque calibration machine" MAPAN-*Journal of Metrology Society of India* 06/2011; 26(2):153-157. DOI:10.1007/s12647-011-0015-4.

[36] K.M. Khaled, G. Aggag, A.E. Abuelezz, and M.G. Elsherbiny, "Mechanical design of NIS new reference torque standard machine", *21st Conference on Measurement of Force, Mass and Torque Together with HARDMEKO 2010 and 2nd Meeting on Vibration Measurement, IMEKO TC3, TC5 and TC22 Conferences,* 2010., pp 109-114.

[37] K.M. Khaled, G. Aggag, A.E. Abuelezz, and M.G. Elsherbiny, "Performance evaluation of nis new reference torque standard machine", *21st Conference on Measurement of Force, Mass and Torque Together with HARDMEKO 2010 and 2nd Meeting on Vibration Measurement, IMEKO TC3, TC5 and TC22 Conferences*, 2010., pp 269-272.

[38] Min-seok Kim and K.M. Khaled, "Torque Key Comparison CCM.T-K1.3. Measurand Torque: 0 N m, 500 N m, 1000 N m", *Metrologia*, Volume 52, Issue 1A, article id. 07007 (2015).

[39] R.S. Oliveira et al, "New proposal for the dynamic test of torque transducers", *58th ILMENAU SCIENTIFIC COLLOQUIUM*, Technische Universitat Ilmenau, 2014.

[40] D. Röske, Torque Measurement: From a Screw to a Turbine, *PTB-Mitteilungen* 118 (2, 3), pp. 48–55, 2008.

[41] T. Bruns, "Sinusoidal Torque Calibration: A Design for Traceability in Dynamic Torque Calibration", *XVII IMEKO World Congress*. Dubrovnik, Croatia, 2003.

[42] Ming Xia *et al*, "Research and application of dynamic torqie calibration for torque test bench of electric actuator in nuclear power plant", J. *Phys.: Conf. Ser*. 1634 012154 (2020).

[43] L. Klaus, T. Bruns and M. Kobusch, "Determination of Model Parameters for a Dynamic Torque Calibration Device", *XX IMEKO World Congress,* Busan, Republic of Korea, 2012.

[44] Andre Schafer, "Dynamic Measurements as an Emerging Field in Industerial Metrology", *PTB Mitteilungen:Amts – und Mitteilungsblatt der Physikalisch – Technischen Bundesanstalt Braunschweig* – Berlin – January 2015.

[45] Andre Schafer and sascha Eichstadt, "Evaluation of dynamic measurement uncertainty for industrial applications", *IMEKO 23rd TC3, 13th TC5 and 4th TC 22 International Conference*, Helsinki, Finland, 2017.

[46] M. Kobusch *et al*, "European Research project for the Dynamic Measurements of Mechanical Quantities", *Simposio de Metrologia*, Querataro, Mexico, 2014.

[47] L. Klaus, "Dynamic torque calibration", *PTB-Mitteilungen* 25(2015), No. 2.

[48] L. Klaus and M. Kobusch, “Experimental Method for the Non Contact Measurement of Rotational Damping”, *IMEKO International TC3, TC5 and TC 22 Conference,* Cape Town, South Africa, 2014.

[49] L. Klaus, B. Arendacká, M. Kobusch and T. Bruns, “Dynamic Torque Calibration by Means of Model Parameter Identification”, *ACTA IMEKO*, 4 (2), pp. 39–44, 2015.

[50] K.M. Khaled, Ehab Elashkar, “ Design of a dynamic torque calibration machine”, Research proposal for a Master degree, National Institute of Standards (NIS), Force and Material Metrology Laboratory, 2019.

[51] C. Bartoli et al., “Traceable dynamic measurement of mechanical quantities: Objectives and first results of this European project,” *Int. J. Metrology Qual. Eng.*, vol. 3, no. , pp. 127–135, 2012.

[52] T. Bruns, “Sinusoidal torque calibration: A design for traceability in dynamic torque calibration”, *Proc. of 17th IMEKO World Congr*ess, 2003, pp. 282–285.

[53] L. Klaus, T. Bruns, and M. Kobusch, “Determination of model parameters of a dynamic torque calibration device”, *Proc. of 20th IMEKO World Congress,* Sep. 2012, pp. 1–4.

[54] L. Klaus, B. Arendacká, M. Kobusch, and T. Bruns, “Model parameter identification from measurement data for dynamic torque calibration”, *Proc. of Joint IMEKO Int. TC3, TC5 TC22 Conf.*, Cape Town, South Africa, Jan. 2014, pp. 1–4.

[55] L. Klaus, B. Arendacká, M. Kobusch, and T. Bruns, “Dynamic torque calibration by means of model parameter identification,” *Acta Imeko*, vol. 4, pp. 39–44, Jun. 2015.

[56] L. Klaus and S. Eichstädt, “Monte-Carlo-based uncertainty propagation with hierarchical models—A case study in dynamic torque,” *Metrologia*, vol. 55, pp. S70–S85, Feb. 2018.

[57] D. Haddad et al., “Invited article: A precise instrument to determine the planck constant, and the future kilogram”, *Rev. Sci. Instrum.*, vol. 87, no. 6, 2016, Art. no. 061301.

[58] C. A. Sanchez, B. M. Wood, R. G. Green, J. O. Liard, and D. Inglis, “A determination of Planck’s constant using the NRC watt balance,” *Metrologia*, vol. 51, no. 2, p. S5, 2014.

[59] H. Baumann et al., “Design of the new METAS watt balance experiment Mark II,” *Metrologia*, vol. 50, pp. 235–242, May 2013.

[60] C. M. Sutton, M. P. Fitzgerald, and D. G. Jack, “The concept of a pressure balance based watt balance”, *Proc. CPEM*, Jun. 2010, pp. 131–132.

[61] D. Kim et al., “Design of the KRISS watt balance”, *Metrologia*, vol. 51, no. 2, p. S96, 2014.

[62] M. Kim et al., “Establishment of KRISS watt balance system to have high uniformity performance”, *Int. J. Precis. Eng. Manuf.*, vol. 18, no. 7, pp. 945–953, 2017.

[63] A. Nishino, K. Ueda, and K. Fujii, “Design of a new torque standard machine based on a torque generation method using electromagnetic force”, *Meas. Sci. Technol.*, vol. 28, no. 2, Dec. 2016, Art. no. 025005.

[64] M. Kim, “Design of a new dual-mode torque standard machine that operates on the principle of the Kibble balance”, *2020 Conference on Precision Electromagnetic Measurements (CPEM),* Aug. 2020, pp. 1–2.

[65] MyeongHyeon Kim, "Design of a new dual-mode torque standard machine using the principle of the Kibble balance", *IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT*, VOL. 70, (2021), 1005207

[66] A. Nishino, K. Ueda, K. Fujii, "Design of a new torque standard machine based on a torque generation method using electromagnetic force", *Meas. Sci. Technol*. 28 (2017), 025005 (11 pp)

[67] A. Nishino, K. Fujii, "Calibration of a torque measuring device using an electromagnetic force torque standard machine", *Measurement*, Volume 147, (2019) 106821.