A novel design for a primary measurement standard for the quantity torque

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Abstract. Primary standards are established using a reference measurement procedure. Through the realization of the definition of a given quantity they provide traceability in the metrology chain. Most torque standards use calibrated weights linked to a lever arm to provide known torques in the rotational axis of the device. These standards do not succeed to provide continuous torque values because of limitation in weights combination and the intrinsic incremental steps of the technique. In automatic machines this can be overcome but it requires a complex mechanical system to operate. In designs that use movable weights along the lever arm the determination of the length of the lever arm is a large source of errors. Zeroing the torque standard also represents a major problem. An innovative and functional design that aims to solve the aforementioned disadvantages is presented.

1. Introduction

In the torque metrological chain, torque transducers are used to calibrate torque wrenches, and torque transducers are normally traceable to base quantities of mass and length, through torque standard machines. An example of SI traceability of torque is given in [1].

By definition, primary standards are established using reference measurement procedures [2]. The most widely solution for torque realization is the use of calibrated weights and a lever arm. Most National Metrology Institutes – NMI have such machines [3-6]. Complete metrological characterizations are performed [7-9] and also comparisons are made to assure metrological confidence [10]. Despite some variations, the main concept involves a known length levelled with a known mass in its end, applying a torque value in the main axis of the device [11]. The transducer to be calibrated is coupled to the machine. In order to change the applied torque the weights combinations are varied. Thus, the loading cycle achievable with deadweight machines usually follows a discrete pattern, due to limitations of the system [1, 12].

The Jockey-weight concept [13] works by sliding a movable weight along the lever arm. The weight can be gradually moved, and the torque can be linearly raised, but accuracy and repeatability of weight placement in a certain location requires complex mechanisms. As for any type of machine, a great deal of effort need to be done in order to know precisely the length of the lever arm, as this will affect directly the applied torque [14]. At the National Metrology Institute of Japan – NMIJ a detailed analysis of a 10 Nm dead weight torque standard machine was performed, with an emphasis on thermal expansion characteristics [15].
Designs should account for ease in automation, due to possible operator influences in hand operated machines. The need for automation of torque standard machines is investigated in the literature [16].

The bending of the arm and the thermal influences on its size are critical, as they cause undesirable changes in the applied torque. The reference line, where the weight is connected to the arm also plays an important role in torque metrology [14].

Especially in the case of the lower part of the working range, friction in the bearings affects negatively the torque standard. Some authors focus on the study of this specific matter, studying these effects and finding ways of determining the static friction torque [4, 17].

The industry is constantly pushing the development of more reliable torque standards [6-7, 10]. The construction of both small and large torque ranges face problems related to the realization of torque and reducing the uncertainty of the system.

The purpose of this paper is to introduce a new design for the realization of torque with potential to serve as a new primary torque standard machine [18].

2. Concept Description
The new design for torque standard is based on the angular variation of the position of a reaction arm. Current designs rely on the application of a known weight in the end of a lever arm of known length, which should be well aligned to the horizontal axis.

Since the torque will change according to the change of the length of the arm, rotating the arm will cause torque to change with the projection of the arm length.

The zero position of this new design is the vertical position, where no torque is applied to its main axis. By gradually rotating machine's angle, torque is applied with the sine of the angle with the vertical axis, measured by means of a precision level or encoder. Figure 1 explains the basic idea of this concept.

![Figure 1. Scheme of the new standard (Source: authors).](image)

A single calibrated weight can be applied in the construction of the torque standard. We propose a symmetric arm to act as a counter-torque. The design of the arm accounts for the machine to operate in two different modes, calibrating torque transducers in the clockwise and anticlockwise direction. Both calibrations can be performed in only one setup.

Two separate level indicators can be applied to redundancy, one in each side of the double arm. As the new design do not use weight stack as main operational principle, automation is easier to be done.
One of the main advantages of the proposed design is the possibility of application of continuous torque, without discrete ramp-up. The mechanism of applying gradually increasing or decreasing torque with discrete weights is much more complex, involving a drive mechanism and torque transducers or strain gauges to continuously measure the torque and compensate during weight stacking. Stabilization and control issues of the new system are perhaps not simple to achieve, and future prototypes will allow the validation of the standard for continuous torque application.

3. Operation

The torque can be modelled as $T (m, g, L, \theta)$, where $m$ is the applied mass, $g$ is the local gravity acceleration, $L$ is the length of the arm and $\theta$ is the angle between the arm and the vertical axis, as in Equation 1.

$$T = m \cdot g \cdot L \cdot \sin \theta$$ (1)

The maximum torque will be achieved when the angle is 90 degrees. A control loop for the operation of the standard can be seen in figure 2.

![Control Diagram](source: authors)

Figure 2. Control diagram (Source: authors).

Accounting for the exemption of weight changes, a simulation of the time involved in a torque transducer calibration (considering weights standardized by OIML, more commonly used by laboratories) shows that the new standard will be able to save time and therefore costs in calibration services (figure 3).
4. Uncertainty Estimation

Besides parasitic influences, such as bearing friction, bending moments and transversal forces, uncertainty of the new design, as in the case of any torque standard, is a matter of how well one knows the length of the arm and the weight being applied.

In the particular case of the new design being described, the length of the arm is measured by the inclination and length of the bar itself. The employed electronic level measuring system should be reliable and accurate, and have enough resolution. A detailed review about uncertainty evaluation for torque primary standards is done by Merlo [17]. The lower limit for the relative expanded uncertainty is referred to as $1 \times 10^{-5}$. Other interesting articles about this subject are the studies conducted by Park et al [4], Röske [7], Koji et al [8].

Equation 1 can be extended to include the influences of buoyancy acting on the dead-weight, unbalancing and inhomogeneities in the double reaction arm and friction on the rotating axis as follows in Equation 2:

$$T_{tot} = m \cdot g \cdot L \cdot \sin \theta \cdot (1 - \rho_d/\rho_w) - T_{bat} - T_{fri} \quad (2)$$

Uncertainty propagation law [19] to combine the effects of each component and related sensitivity coefficients can be easily deduced. Table 1 details the calculation of the expected total uncertainty of the proposed torque standard (simulating a 100 Nm applied torque).

The dimensions of the sensibility coefficients come from the partial derivatives of Equation 1. The probability distributions were assumed to be normal for all the sources of uncertainty except for Buoyancy, Unbalance and Friction (considered uniform), and the effective degrees-of-freedom were considered large enough to assume a coverage factor of two.

Components of Angle, Length and Mass are current Calibration and Measurement Capability – CMC of the Institute for Technological Research – IPT in São Paulo, Brazil and other Brazilian accredited laboratories. Local gravity uncertainty was obtained by measurements made by National Observatory – ON at IPT site. Buoyancy, Friction and thermal expansion of the reaction arm components are estimated by using reference values [4]. Arm flexure effects were adopted also according to literature [8]. Unbalance of the reaction arm may be corrected and the residual difference in mass between the arm and counter-arm parts (in this case 0.1 g was assumed) might generate a Torque and the uncertainty related to that effect would be equal to $(\Delta m \cdot g \cdot L \cdot \sin \theta)/\sqrt{3}$. 

![Figure 3. Comparison between times required to perform a calibration of a torque transducer (Source: authors)](image)
### Table 1. Uncertainty estimation (Source: authors).

| Description                | Estimate | c    | u    | c.u (Nm) |
|----------------------------|----------|------|------|----------|
| Angle (rad)                | 0.52359  | 173.206 | 2.18E-6 | 0.000378 |
| Length (m)                 | 1.02     | 98.040 | 2.04E-6 | 0.000200 |
| Arm Flexure (m)            | 0        | 98.040 | 1.77E-6 | 0.000174 |
| Thermal Growth (m)         | 0        | 98.040 | 1.77E-6 | 0.000174 |
| Mass (kg)                  | 20.039   | 4.990 | 1.65E-6 | 0.000082 |
| Gravity (m/s²)             | 9.78643  | 10.218 | 6.00E-6 | 6.13E-7  |
| Air density (kg/m³)        | 1.225    | -0.013 | 3.00E-2 | -0.00380 |
| Weight density             | 7906     | 1.96E-6 | 4.56E+1 | 0.000089 |
| Balancing (Nm)             | 0        | 1     | 2.88E-4 | 0.000288 |
| Friction (Nm)              | 0        | 1     | 1.73E-3 | 0.001730 |
| Torque Applied (Nm)        |          |       |       | 100.0007 |
| Combined Uncertainty – u (Nm) |       |       |       | 0.0019   |
| k                          |          |       |       | 2.00     |
| Expanded Uncertainty – U (Nm) |       |       |       | 0.0038   |

5. Conclusion

This work describes a new torque standard machine concept, intended to improve the current technique used to calibrate torque transducers. The state-of-the-art in terms of torque quantity is the use of weight stacks, despite the discrete application of torque and the difficulty in automation.

The concept of angular variation of the arm open up the possibility to expand the calibration procedure to a more realistic situation, where the transducer to be calibrated is used in continuous torque slope. Performance estimation has been done and a relative expanded uncertainty in the order of 4E-5 is expected. This uncertainty fulfills recommended CMC for torque primary standards and would allow the calibration of torque transducers to 0.05 class [20].

Future work may evaluate a full prototype of the new torque standard and calculate the CMC for the new primary torque standard, as well as intercomparison studies. A CMC in the order of the results found in this paper would be compatible with those found in the literature. For instance, NMI torque standards CMC range from 2E10-5 to 10E-5 [4, 7].

6. References

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