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A New Spin on Kibble: A Self Calibrating Torque Realization Device at NIST

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Abstract
After the 2019 redefinition of the International System of Units (SI), torque no longer needs to be traceable to a calibrated weight suspended from a known lever arm. Specifically, a modification of the Kibble principle used for realizing the kilogram allows for direct realization of torque via electrical measurements traceable to the revised SI. A recent National Institute of Standards and Technology/US Air Force collaborative effort to design, construct and characterize a self-calibrating electromechanical instrument mainly consisting of a tabletop-sized permanent magnet-electromagnet system aimed at generating 1 mN·m to 1 N·m with 0.1 % accuracy for directly calibrating torque tools is underway. This instrument, the Electronic NIST Torque Realizer, is intended to replace the current torque standards of mass and length, and put primary torque realization standards in the hands of calibration facilities.

Keywords: metrology, torque, instrument design, Kibble principle

1. Introduction

After the 2019 redefinition of the International System of Units (SI), torque no longer needs to be traceable to a calibrated weight suspended from a known lever arm. Specifically, a modification of the Kibble principle used for realizing the kilogram allows for direct realization of torque via electrical measurements traceable to the revised SI [1]-[3].

Nishino *et al.* [2] demonstrated that SI-traceable torques on the scale of mN·m or less can be generated without the use of traditional torque generation methods utilizing gravity and lever-arms.

For small torque lower than 1 cN·m, the process of balancing small mass artifacts required to calibrate fragile transducers is difficult, burdensome, and often irreproducible. A recent National Institute of Standards and Technology (NIST)/US Air Force collaborative effort to design, construct and characterize a self-calibrating electromechanical instrument mainly consisting of a tabletop sized rotating electromagnet aimed at generating 1 mN·m to 1 N·m with 0.1 % accuracy for directly calibrating torque tools is currently underway.

This instrument, the Electronic NIST Torque Realizer (ENTR), is intended to re-route the SI standards dissemination chain from mechanical standards to electrical standards, empowering calibration facilities ranging from military to research and industry to directly realize torque for themselves.

This paper seeks to analyze performance of the ENTR prototype as it stands in its current stage of development with regards to uncertainty in the value of torque produced via the modified Kibble principle.

This paper will outline the current state of the ENTR project, beginning with a description of the modified Kibble principle at the core of operation. The mechanical construction is outlined, as are the electronic components. A brief outline of operational processes are also described. Finally, the current state of the ENTR project is discussed through analysis of prototype testing results, including the current uncertainty budget, followed by planned future work.

2. Operational Theory

The realization of torque is achieved via a conversion of the traditionally linear Kibble principle to a rotational frame. In the linear version, a round coil is translated vertically through a fixed magnet system. In the rotational version, a set of permanent magnets spin with respect to a fixed D-shaped coil. The process of realizing torque requires two modes of operation: spin mode (eq. 1) and torque mode (eq. 2)

$$V = B(\varphi)Lr\,\dot{\varphi} \quad (1)\,, \qquad \tau = B(\varphi)LrI \quad (2)$$

where V is the induced voltage in the coil caused by rotation of the permanent magnet system, B is the magnetic flux density of the magnet through the coil, L is the total length of the radial wire segments of the coil, r is the distance between the axis of rotation and the center of each wire segment, $\dot{\varphi}$ is the angular velocity, τ is the torque, and I is the electrical current. Strictly speaking, V, τ and B are all functions of the angle φ of the magnet ranging from 0° to 360° and to simplify the notation, we set:

$$\beta(\varphi) = B(\varphi)Lr \quad (3)$$

Thus, a condensed way to depict eqs. 1 and 2 would be:

$$V(\varphi) = \beta(\varphi)\,\dot{\varphi} \quad (4)\,, \quad \tau(\varphi) = \beta(\varphi)I \quad (5)$$

In spin mode, $\beta(\varphi)$ is calculated by measuring the induced voltage in the coil $V(\varphi)$ while simultaneously sampling the instantaneous angular velocity of the permanent magnet $\dot{\varphi}$ every time a voltage measurement is taken. A plot is then generated for $\beta(\varphi)$ in the domain [0°,360°).

In torque mode, the magnet is servoed to a desired angle φ_1 by injecting a current I into the coil controlled by a Proportional-Integral-Derivative (PID) feedback loop. The torque $\tau(\varphi_1)$ can then be calculated by multiplying the measured current with the $\beta(\varphi)$ imported from spin mode, explicitly:

$$\tau\left(\varphi_1\right) = I\,\frac{V\left(\varphi_1\right)}{\dot{\varphi}} \qquad (6)$$

Where $\frac{V\left(\varphi_1\right)}{\dot{\varphi}}$ is a unique but constant value for any given φ, assuming constant temperature.

3. Mechanical Design

At the heart of ENTR is a set of two ring magnets capable of rotation. A pair of commercial NdFeB axially magnetized rings are each sliced in half using a waterjet cutter. Half the semi circular rings are flipped upside down, paired back with the original half, and placed onto mild steel yokes for guiding the magnetic flux. The yokes are fixed to a rigid shaft such that the two magnet sets are oriented in attraction and the slits between the top and bottom magnets were aligned, see Fig. 1. Two ZrO_2 radial ball bearings constrain the rotation of the shaft. A previous study was conducted comparing the internal friction of multiple commercial bearings and ZrO_2 was chosen for its lowest friction properties within the study group. The lower bearing is set into a base plate for the rotary shaft to rest on, and the upper bearing is held in place by a bracket which attaches to the base plate, see Fig. 2.

A precision machined tapered ring built into the bottom yoke provides a surface for mounting a Renishaw RESM[1] optical rotary encoder.

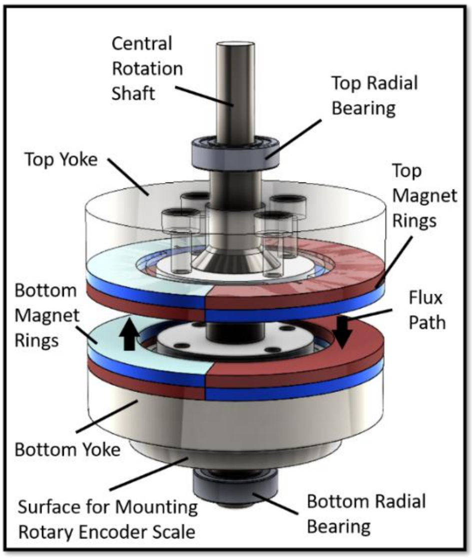

Figure 1. 3D CAD model of rotational components. Top magnetic yoke made transparent for easier visibility and magnet polarities shaded red/blue for clarity. A stainless steel stepped shaft is constrained by the inner racers of two ZrO_2 ceramic bearings. Two mild steel yokes are mounted onto flanges on the shaft and four half ring magnets are attached to the yokes. Each pair has opposite polarity per yoke and the two magnet assemblies are oriented in attraction. The bottom yoke is machined with a tapered ring for centering the encoder scale.

4. Coil Design

To generate a torque, the straight segments of a D-shaped coil interact with the magnetic field generated inside the gap between the two magnet pairs. Due to the irregular geometry, the coil is fabricated on a printed circuit board (PCB) as opposed to the traditional method of wire winding. This method of constructing coils has proven advantageous due to ease of manufacturing, low cost, and thus mass producible in the future.

Every 0.8 mm thick PCB is double sided, each containing 33 turns. The cross sectional dimensions of each trace are 0.36 mm by 0.71 mm and each trace is separated by 0.125 mm. A stack of 8 PCBs results in a total of 528 turns and rests on plastic hex standoffs such that the stack sits vertically centered between the magnets. The total coil resistance measured is approximately 120 Ω, see Fig. 3

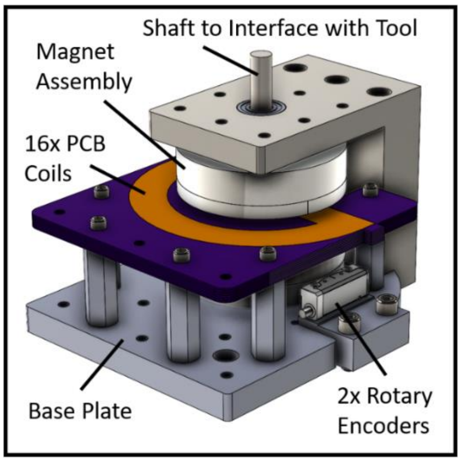

Figure 2. CAD model of full ENTR assembly.

Figure 3. CAD model of the top side of a single 0.8 mm thick PCB. A total of 33 turns are printed on each side. At the top of the PCB are two bare solder pads, allowing for stacking and soldering in series. A stack of 8 PCBs with 528 turns has a total resistance of about 120 Ω.

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[1] Certain commercial equipment, instruments, and materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

5. Operation

In order to switch between spin mode and torque mode, a system of physical relays controlled through LabVIEW are used.

Both voltage and current measurements are performed using a Keysight 34465A Digital Multimeter. Current is generated using a Keithley 2401 source measure unit.

The torque applied to the system is calculated and displayed in real time for the user to observe. A user can attach a torque tool such as a dial-face torque watch to the shaft, and compare the torque reading on the dial to the torque produced by ENTR.

5.1. Spin Mode

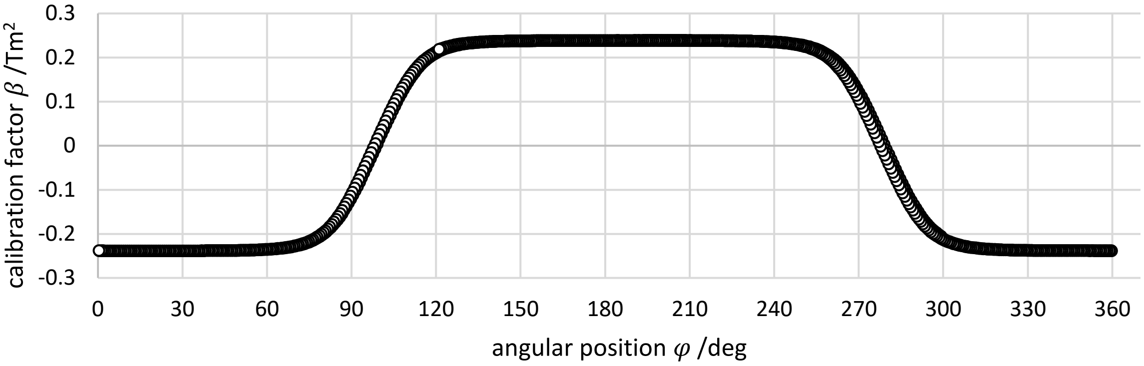

Figure 4. An example of a calibration factor profile created in spin mode over approximately three revolutions.

In spin mode, the LabVIEW program monitors angular position, angular velocity, and induced voltage within the coil. ENTR is driven to some chosen angular velocity by injecting a current defined by position through the D-shaped coil. Once the rotating magnet assembly reaches the desired maximum angular velocity, the system takes simultaneous measurements of the angular velocity and induced voltage until some defined minimum angular velocity is reached. A profile of β vs φ is created using these voltage and velocity values as shown in fig. 4. The program then fits a 4th degree polynomial function to each of the domains of relative flatness, and records the maximum or minimum of the fit function within that domain. These values are taken and recorded as β_{max} and β_{min}.

Once these values of maximum and minimum are recorded, the system switches the relays back to the current source, and ENTR is again driven to the desired max velocity, and the process repeats.

As the system runs, the recorded values of β_{max} are averaged, as are the values of β_{min}. The system will run in this way indefinitely until the user switches the system to torque mode.

5.2 Torque Mode

In the torque mode, the program switches the relays such that the current source is part of the coil circuit, and sends a command to the digital multimeter to measure current produced by the source unit and driven through the coil.

While any angular position with a non-zero value of Beta could theoretically be used for torque mode application, the chosen position for torque mode operation is defined as the angular position $\varphi + 90$ degrees from where $\beta(\varphi) = 0$ and $d\beta(\varphi)/d\varphi > 0$. This location corresponds to the averaged value of β_{max} found in spin mode.

The program uses PID feedback control to rotate the magnet assembly of ENTR to the desired position. Once the system has reached the desired angular position, torque applied to the central shaft is opposed by a torque created by current driven through the coil controlled by the PID feedback loop. From equation (5), the torque applied to the system can be determined by using the averaged value of β_{max} taken from spin mode.

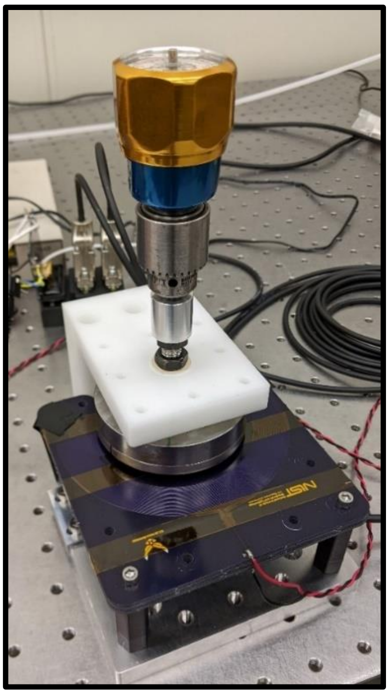

Figure 5. ENTR in the lab with a dial-face torque watch attached to top of rotary shaft. The chuck of the torque watch is coupled to the rotational shaft with a custom made adapter.

6. Experimental Methodology

In order to evaluate the performance of the ENTR prototype, we use a hanging mass/lever arm system including a 2.54 cm (1.00 in) Mountz calibration wheel as shown in fig. 6. ENTR is oriented such that the rotational axis is perpendicular to the direction of gravity while a mass is placed on a hanger on one side of the calibration wheel, creating a net torque. A similar hanger is suspended from the other side of the calibration wheel to act as a counterweight. The theoretical value of the torque produced by this hanging mass/lever arm system is then compared to the reported torque produced by ENTR.

Masses and hangers are weighed using an analytical balance and the masses used for testing are placed on one hanger. Mass is added in 5 g increments from 0 g to 100 g, testing a range of torques from -2.49 cN·m to +2.49 cN·m (±3.53 in·ozf). Theoretical torque, τ_{appl}, is determined by the equation:

$$\tau_{appl} = mgr \qquad (7)$$

where m is the net mass of one hanger/mass set minus the other, g is the local acceleration of gravity, and r is the radius of the calibration wheel. We assume that the axial orientation of the rotary shaft is perpendicular to the direction of gravity.

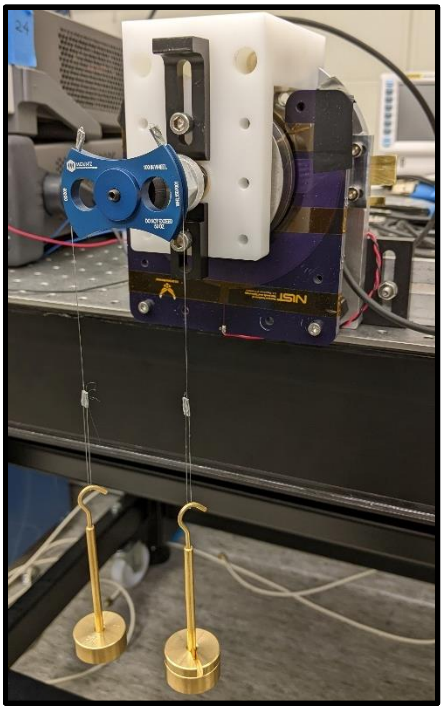

Figure 6. ENTR in its horizontal orientation with test masses suspended from a Mountz 2.54cm (1.00in) calibration wheel.

7. Results and Discussion

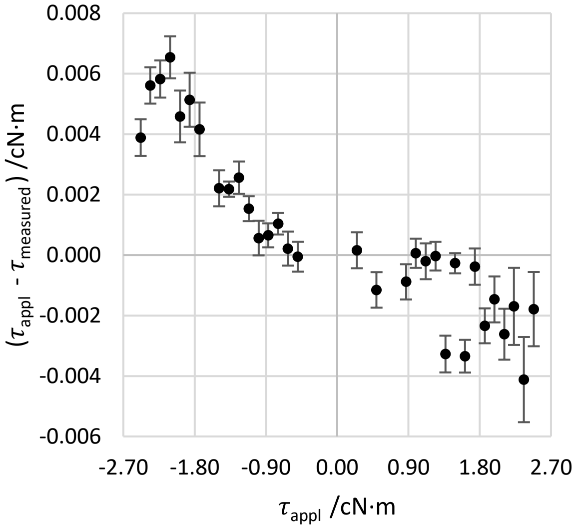

Figure 7. Plot of absolute difference of averaged torque values measured by ENTR vs torque values applied by the hanging masses. Error bars represent the statistical uncertainty of the measured torque values.

Fig.7, depicting the difference between τ_{appl} and $\tau_{measured}$, indicate promising initial results with room for improvement. The Mountz calibration wheel has a length uncertainty of ± .025 mm (0.001 in) which may account for some of the percent difference in fig. 7. Standard deviation of the percent difference values is 0.24 % and the 11 points outside one standard deviation are omitted in the plot. Other sources of error may include friction of the bearings constraining the rotary shaft, and misalignment of the rotary shaft assembly in relation to gravity.

Error bars are calculated as the standard deviation of 270 torque measurements made in torque mode at 20 samples/second. Sources of error include nature of the control loop, friction of the ceramic bearings holding the rotor, air currents disturbing the hanging masses, and uncertainty of the encoder system.

8. Summary

We show a working prototype of the self-calibrating ENTR system that can measure torques with 0.3 % or better agreement with conventional methods for the operational ranges tested. Further development is needed in order to improve accuracy and operational range.

9. Conclusions and Future Work

Our work has shown significant progress on the development of a new device for calibration of torque tools. Future work includes determining a full uncertainty budget as well as design and construction of a revised ENTR prototype. Alternate designs of several components of the mechanical construction are planned, including incorporation of aerostatic bearings to further lower operational ranges. These revisions of mechanical design will also aid in ease of prototype testing and (dis)assembly. An alternate encoder system is to be investigated with the dual goals of improving performance and reducing costs of production down the development line.

10. Acknowledgements

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