NEW PROPOSALS FOR THE DYNAMIC TESTS OF TORQUE TRANSDUCERS

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ABSTRACT

There is a gap in the metrological traceability chain of the torque quantity. The dynamic use of this kind of sensor is based on traditional static calibration results. Two new systems are proposed in order to test the torque sensors dynamically. An inertial system provides the dynamic torque reference values through the acceleration of well known mass moments of inertia, while the brake torque system provides resistive torque during the application of constant or variable speed to the measuring transducer. The dynamic responses of the generated torque curves and some parameters can be analyzed, such as the peak torque errors, the high torque rates regions, the dynamic stiffness and angle displacement of coupling devices. A first approach of the uncertainty budget is carried out and results seemed satisfactory with an expanded uncertainty of 0.09 % in a 10 N m generated inertial torque.

Index Terms - Torque metrology, Torque transducer, Calibration.

1. INTRODUCTION

In the current international traceability chain of torque measurement, torque transducers that use the principle of dynamic measurement under rotational regimes, such as in engine test benches, turbines, power generators, brake testers, and electric/pneumatic fasteners, have traditionally tracked their calibration and verification methods to a series of standards, tools and equipment that are metrologically consolidated with a given uncertainty level. However, the state of the art for these calibrations is still based on the static working principle.

The dynamic behavior of torque sensors is not completely understood and there are no standard devices and procedures defined for the dynamic torque measurement and calibration. Also the fundamental scientific research interest in dynamic torque measurement is accompanied by a growing need of an enhanced knowledge in the industry.

Thus, BRÜGE in 1997 [1] published the first studies on the influence of dynamic rotation transducer calibrated statically, showing that there is a gap in the traceability of the quantity. ANDRAE [2] and BRUNS & WEGENER [3] published two articles on the key considerations for the transmission of torque in shaft power engine test benches, focusing primarily on the approach of how the measurand torque can be transferred to test benches, with an approach to this calibration.

From these first studies, PTB invested in researching a reference system for dynamic torque traceability and in 2003, BRUNS published the article "Sinusoidal Torque Calibration: A Design for Traceability in Dynamic Torque Calibration" [4] with a new concept system for generating dynamic sinusoidal reference torque. The assembly proposed consists of a rotational harmonic exciter mounted vertically on one side of a transducer (fixing side) and

structural elements with a well known moment of inertia coupled on the other side (measuring side). This reference moment of inertia is composed of the upper part of the transducer, some couplings and an alignment air bearing. Actually this system is under the development and "proof of concept" stage within the major project "Traceable Dynamic Measurement of Mechanical Quantities" of the European Metrology Research Programme (EMRP) [5]. The actual experimental set-up achieves a low torque amplitude of approximately 5 N m. A primary sine-torque facility with frequency range from 10 Hz to 1 kHz and increased amplitudes of up to 20 N m are under development.
This paper focus on the presentation of the two test benches under development aimed to do experimental work to cover a wide range of applications using different motion systems and different dynamic torque generating principles. Their measurement and load principles are presented here together with some details and descriptions of the main components of the respective assemblies.

2. DYNAMIC AND STATIC TORQUE MEASUREMENT

The static calibration of torque sensors is based on standard guidelines such as the DIN 51309 [6] which requires that the reference torque loads are applied and stabilized for a minimal time of 30 s before the data acquisition of the sensor's readings. This procedure guaranties for both mechanical and electric stabilizations of the equipment. Also the data acquisition unit is set commonly using a low pass Bessel filter with 0.2 Hz as the cutting frequency in order to maintain this stabilization. Based on this the acquisition rate is not an important parameter, once only one reading is enough for obtaining the corresponding calibration value. Figure 1.a shows as example a 10 N m step applied during a static calibration. There is depicted the 30 s stabilization time before the reading of the calibration torque value.
But, once this equipment is used for a dynamic application, the transducer response will be different and the digital set up parameters used during the static calibration will not work appropriately. As an example of that, figure 1.b shows the transducer response to a torque pulse load with the raw data (continuous line) shown together with its post process smoothed signal curve and an FFT 0.2 Hz Bessel filtered curve, simulating the static calibration adjustments.

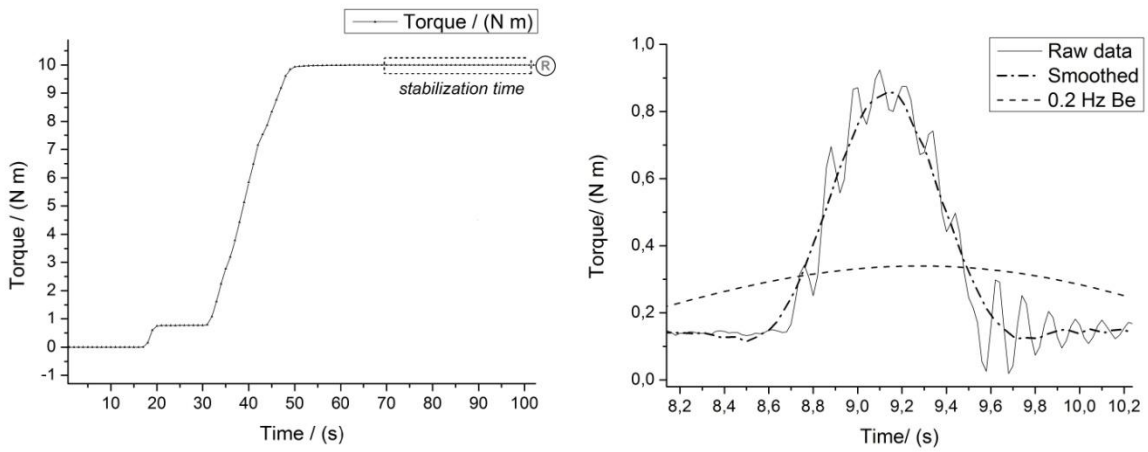

Fig. 1. (a) A measured 10 N m step during a static calibration according to DIN 51309; (b) Example of a measured 1 s pulse torque load with raw measured data and different post-processing.

According to the quality standard ISO 17025 [7], the conditions and adjustments applied during the calibration of an equipment must be repeated during its practical use. Then it is

clear that, beyond the different load conditions, if the digital's parameters used for the static calibration are maintained for this kind of dynamic application, there is a huge loss of data, including the peak of torque and time width of the curve.
These practical examples clarify the needs to test transducers under dynamic regimes, which should involve different calibration sequences, different mechanical loads, different electronic settings and different interpretations to the evaluated results.

3. INERTIAL TORQUE SYSTEM

This proposed system is based on the generation of torque by angular acceleration applied to known mass moments of inertia. The equation governing a generated reference torque is based on Newton's first law adapted to rotation, described by Eq. (1) as follows:

$$T = \theta \cdot \alpha = \theta \cdot \dot{\omega} \tag{1}$$

where:

T	Torque
θ	Mass moment of inertia
α	Angular acceleration
ω	Angular speed

In this method, the angular speed is the reference measured quantity and the acceleration is calculated by its numerical differentiation. The torque input is proportional to the acceleration input and is applied only during a step in angular speed.
The torque transducers are to be tested in the rotational regime and the comparable values of torque are extracted from the acceleration ramps applied to the measurement shaft. Figure 2.a shows a block diagram with the basic elements and measured data. Figure 2.b shows the acceleration and deceleration regimes during the application of one defined speed interval and the corresponding torque responses.

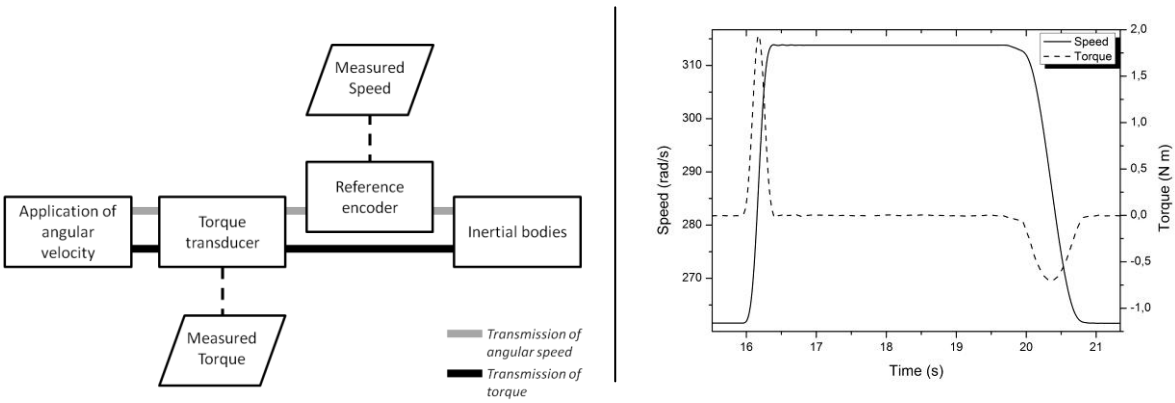

Fig. 2. (a) Block diagram of the basic elements; (b) Example of the proposed angular speed and torque regimes with acceleration and deceleration stages (ramps) depicted.

In the measurement axis of the assembly, two torque values are obtained and will be compared as the calibration result: the value measured by the transducer (T_M), which is the output signal based on the sensor's nominal sensitivity and interpolation curves obtained from its previous static calibration, and the reference inertial torque (T_R) evaluated from the acceleration of the reference inertial bodies (θ_R).
The axis' mass moments of inertia are composed not only by the θ_R, which can vary with the addition or removal of different mass pieces, but also by the initial mass moment of inertia

(θ_i), which corresponds to the permanently attached components (couplings, connection shafts, clamping). This inertia generates the so-called initial torque (T_{Mi}) under acceleration, but it is not metrologically traceable with no calibrated pieces, what makes it not adequately reliable to be used as a reference value.
Then, T_{Mi} will work only as a tare value and the reference net measured torque (T_{MR}) will be calculated from the difference between T_M and the T_{Mi}.
Thus, the estimated reference inertial torque (T_R) is compared to the transducer's net measured torque, T_{MR}. The curves shown in Fig. 3.a and the schema of Fig. 3.b clarify the method proposed.

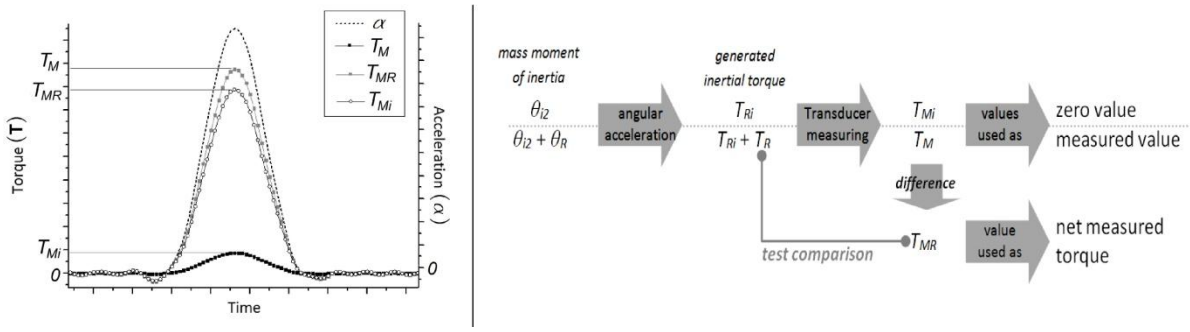

Fig. 3. (a) Proposed method for obtaining the acceleration and torque curves; (b) Diagram of the sequence to obtain the test comparable values.

Although the principle can be applied to any range of torque and angular speed, the design of the components to be used in the prototype is done for a range of 20 N m, within a range in angular speed of 10.47 rad s^{-1} (100 rpm) to 314.16 rad s^{-1} (3000 rpm). Both ranges of torque and speed offer a medium scale approach to apply a practical proof of concept for future work.
Once the principle and reading method were presented, some specification must be applied to each main components of the assembly proposed. The following are brief descriptions and considerations on the main characteristics of these elements, relating those to the functionality of the general system.

i. *Measurement axis drive* - The angular speed is applied to the axis by an electric AC motor and its variation is controlled by an AC driver control unit. According to the research done, this pair of equipment showed the best performance to speed and torque controls, where medium size motors can be used to reach the nominal torque of 20 N m. The speed curve showed in figure 2.b was induced by this kind of control, which the accuracy is about 0.01 % according to the manufacturers [8].
ii. *Reference encoder* - The incremental high quality reference encoder is of the hollow shaft type, with the measuring drum attached to the rotating axis. The encoder mounting allows the operator to have free access to this end of the axis, where the inertial discs are mounted, without interfering to the encoder itself. Beyond that, the measuring drum is fixed on a section such that the drum will not experience any deformation from potential transmission of torsion efforts during the application of torque.
iii. *Inertial reference* - The reference inertial bodies are simple shaped disc or ring mass pieces with equally distributed mass. The geometry and mass values must be measured in order to calculate the reference mass moments of inertia (θ_R) according to theoretical formulas. These pieces are provided with self-centering cone to cone mechanical interfaces, thus guarantying highly reproducible self-alignment to the rotary axis.

iv. *Assembly supports* - The torque transducer is supported by two bushings, which must be designed to minimum friction load and no stick-slip. Air bushing elements are the best solution for this support. The motor and the bushings are supported on the same table. The inertial bodies are cantilevered.

v. *Stiffness of the measurement axis* - Flexible couplings are commonly used to compensate for misalignments of shafts. Specifically for the proposed system, the transducer is connected by metal bellows couplings on both sides. As this kind of coupling can influence on the reading of the transmission of torque, the result of the calibration must be linked to the set of transducer and identification of these couplings used. As an alternative an flexible coupling can also be used between the motor and the bushing.

Figure 4 shows a sketch of the organization of these main elements in the assembly. There are the bushings supporting the transducer and the inertial bodies in a cantilever configuration, what allows the operator to have access to it.

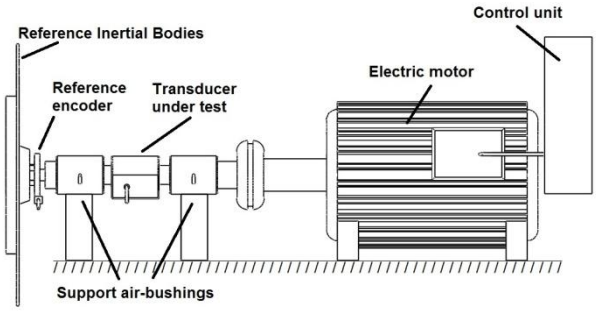

Fig. 4. Proposed assembly with main components identified.

The analysis of the torque responses of the transducer can be referred to the curves shown in Figure 5.The torque curves and torque rate curves for both measured and estimated values in a period of time during acceleration can be seen.

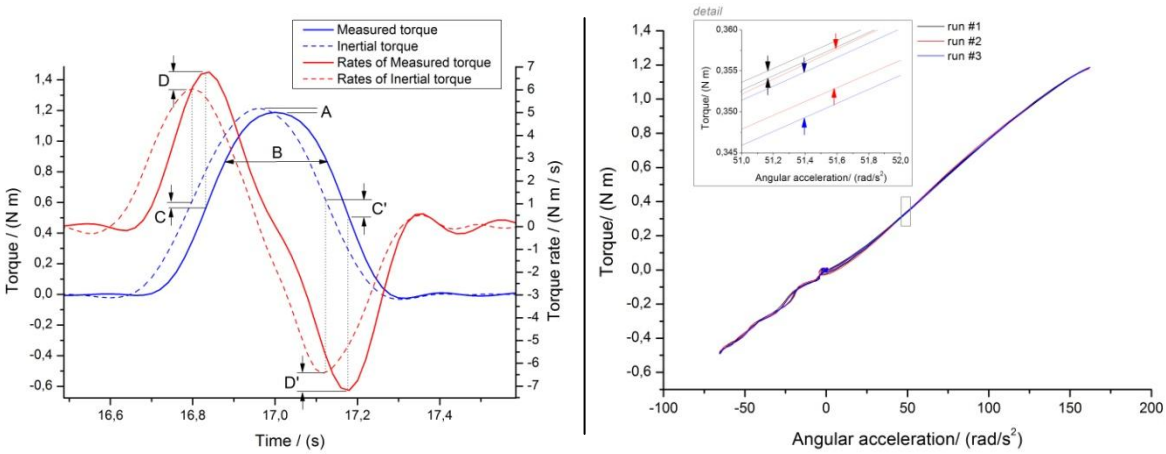

Fig. 5. (a) Torque curves and Torque rates curves for both measured and estimated inertial torque with main evaluation parameters identified (A) Torque peaks, (B) Time width, (C) Points of highest rates, (D) Torque rate peaks and valleys; (b) Measured torque versus calculated acceleration curve for three sequential axis driving in the same acceleration time and speed step (detail shows the hysteresis for the three runs).

There are some indentified parameters which will work as the characterization of the measurement results:

A. *Torque peaks* - The difference of peak values of torque is the most important parameter to be evaluated as the characterization of the set once it represents the maximum torque being applied to the shaft.
B. *Time width* - Different time widths can indicate a hysteresis behavior of the transducer and the dynamic sensitivity for this can be evaluated.
C. *Points of higher rates* - Inflection points of the torque ramps. Differences between time values and also torque values for the identification of the peak (and valley for C') torque rates. This is also a point of interest for the transducer if it is used for control of a driving shaft. That is also an indication of hysteresis of the transducer.
D. *Torque rate peaks and valleys (D')* - Difference between measured and inertial values of the maximum torque rates. Test of the capability of the transducer to read the highest torque changes during the axis driving. First studies indicate that a torque curve with 20 N m peak value can reach a 150 N m/s torque rate.

The graph in figure 5.b shows the relation between measured torque and calculated acceleration (derived by differentiation of the speed). According to Eq. (1) this relation should be linear and the inclination of the curve, or the rate between maximum acceleration and maximum torque, should represent the accelerated mass moment of inertia. But in the real situation, there is a non linearity in the acceleration process. Beyond that, three different runs with the same acceleration parameters (acceleration time and speed interval) generate three curves with different paths for increasing and decreasing acceleration, characterizing an hysteresis of the measurements.

4. BRAKE TORQUE SYSTEM

The second test bench is based on counter acting pneumatic motors. One of them acts as a motor and the other one as a brake. Torque and rotating speed are regulated by air pressure and air flow. This system reaches a maximum torque of about 10 N m and a maximum speed of 3000 rpm.
Two very precise angular encoders (identical model as used in the first test bench) are mounted to both ends of the transducer under test to measure the torsion of the torque transducer and the systems rotating speed (Figure 6).
To initiate peaks of torque or acceleration, a pneumatic boost system is installed in the drive motor side.

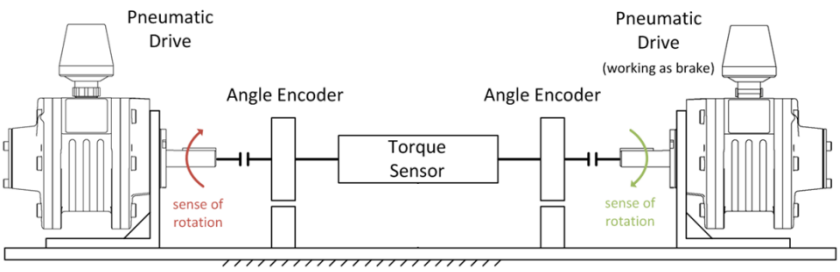

Fig. 6. Brake torque system

Comparing to the first test bench, this setup allows the variation of torque and rotating speed independently. Especially the applying of variable torque at constant speed is a major advantage in opposite to the other test bench. Also the influence of the torque ripple of the pneumatic motors and the electric motor to the dynamic measurement and calibration of torque is a subject of investigation.

Differently from the inertial torque system, there is no torque reference applied in the principle of this system, but a deeper analysis of some dynamic response can be done.
With the two precise measurements of angle and speed, it is possible to assess some parameters:

a) The time delay between speed measurements and torque measurements. The delay of the torque transducer is about 10^2 times the delay of the encoder reading. This delay is in the order of 500 µs and the data acquisition system needs to reach a resolution better than this. This parameter can be tested under constant speed stages or by the booster acceleration.

b) The dynamic stiffness of the device under test. The set of torque transducer and flexible couplings gives different stiffness to the assembly. The angle difference between both encoders is a measurement to quantify this stiffness.

c) Possibility to apply the brake torque at different constant speed stages.

d) Dynamic verification of built-in encoders is also possible with the set of high precision reference encoders.

5. UNCERTAINTY OF MEASUREMENT

The evaluation of the uncertainty of measurement for the systems proposed must include the influence and iteration of the quantities prescribed in the model, but also the contributions of the mathematical methods used to calculate derivative data and the time uncertainty contribution, once the dynamic description of the load curves will depend directly on the time values.
The uncertainty of measurement must cover some peculiar items of dynamic measurement beyond the traditional approach, where it can be highlighted:

- Obtain and compare the two curves of torque, with the possibility of having individual or equally distributed points to be analyzed in a measurement range (piecewise evaluation);
- The uncertainty of the method for differentiation of the speed signal to obtain acceleration values;
- Application of digital filters and smoothing proceedings and their contribution to the uncertainty of a value or range.

As a first approach to the uncertainty contributions analysis, some parameters can be highlighted in the example for the inertial torque system (figure 7). This estimation should be applied to the specific points of the torque curves, as the ones expressed in figure 5.a.
For the system with inertial torque, there are the Type B contributions to the reference inertial bodies, which are dimensional and mass quantities, and the contributions to the method of evaluating the torque values (algorithm). Type A contribution is the repeatability for the sequential driving of the acceleration ramps.
The mass moments of inertia of the discs are calculated through theoretical formulas, which use the values of the outside diameter, the thickness and the diameters of the inner conical surface, and also the mass of the pieces as an input.

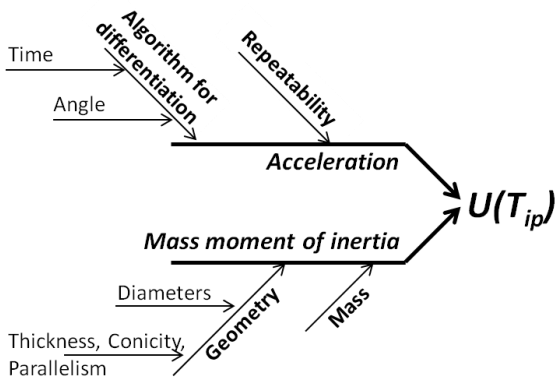

Fig. 7. Uncertainty budget for the reference inertial torque

As an example, the peak inertial torque is evaluated for an acceleration regime with a peak acceleration of 202 rad s^{-2} and a mass moment of inertia of about 0.05 kg m^2. Speed and torque data are simulated based on experimental measurements done in an auxiliary test bench with a torque transducer and integrated encoder. The mass moment of inertia is of the disc type with external and inner diameters. These data are shown in table 1.

Table 1. Characteristics of the mass moment of inertia

Quantity	**Nominal Values**
Ext. diameter	200 mm
Inner diameter	36 mm
Thickness	40 mm
Mass	9.615 kg
Material	Steel
θ	0.04959 kg m^2

Data is generated for three different acceleration ramps in the same speed interval between 209 rad s^{-1} and 261 rad s^{-1}, obtaining a repeatability indication of both inertial and measured torque. An acquisition rate of 50 Hz is used. The uncertainty contributions are identified in figure 7 and the estimated torque values for the standard uncertainties are shown in table 2. The final combined standard uncertainty is given for the inertial torque $u(T_{ip})$.

Table 2. Standard contributions for uncertainty of measurement of the inertial torque.

Quantity	**Standard Uncertainty (u)**
Algorithm	$2.70 \cdot 10^{-04}$ Nm
Repeatability	$4.50 \cdot 10^{-03}$ Nm
Geometry	$5.00 \cdot 10^{-05}$ Nm
Mass	$4.90 \cdot 10^{-04}$ Nm
T_{ip}	$4.53 \cdot 10^{-03}$ Nm

The derivation algorithm uncertainty considers the time interval accuracy of the digital reading unit and the angle accuracy of the encoder. Geometry considers the diameters, which are the main dimensional parameters for the estimation of the mass moment of inertia and the form errors. Mass error is based on OIML-R111 [9] class F1 weights.
The final uncertainty budget is represented in table 3 with the individual evaluated expanded values for each main parameter of the proposed comparison test, between estimated inertial torque and transducer measured torque.

The T_{mp} quantity is the torque indicated by the transducer. For this contribution, the main parameters are the repeatability of the measurements and the uncertainty obtained from the previous static calibration of the sensor.

Table 3. Relative expanded uncertainties of the individual parameters.

Quantity	Value	Expanded Uncertainty (U)	Coverage factor (k)
θ	0.049588 kgm^2	0.0098 %	2.00 (95%)
α_{peak}	202.34 rad/s^2	0.090 %	2.00 (95%)
T_{ip}	10.0338 Nm	0.090 %	2.00 (95%)
T_{mp}	9.353 Nm	0.62 %	2.00 (95%)

6. CONCLUSIONS

The proposed systems will cover a gap in the traceability chain of torque metrology. Complementary data will be generated for the traditional static calibration results. An inertial reference torque system is proposed with a methodology for data operation. The principle presented covers a wide range of parameters to be tested and compared in the torque load curves. The brake torque systems presents a different approach without a specific reference torque value, being a complementary system to evaluate the dynamic stiffness of transducers and couplings, along with the time response and angle shift measurements. An approach of the uncertainty budget contributions is applied and first estimated results are very satisfactory, reaching an expanded uncertainty of about 0,09 % for the inertial torque reference value.

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