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A NEW TECHNOLOGY FOR DYNAMIC TORQUE MEASURING BASED ON A DIFFERENTIAL MECHANISM

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Abstract: A new technology demonstrated by an innovative measuring instrument is presented. This instrument is conceived to measure the dynamic torque in shafts and rotating mechanical elements. The present paper describes the instrument layout, a laboratory prototype recently developed and the results of the first tests performed on the prototype in order to study its capabilities.

Keywords: Torque Sensor, Torque Transducer, Dynamic Torque, Torque Measurement.

Introduction

Power transmitted by a shaft or by any other rotating element (e.g. gear, turbine, cloches, etc.) can be determined from its angular velocity and torque. While the angular velocity may be measured directly, the magnitude of the torque is very difficult to obtain.

Torque can be divided into two categories, either static or dynamic. The difference between them lies in the produced effect. If the torque produces a reactive force, the torque is considered a static torque. On the other hand, the torque is a dynamic torque if it produces a rotation. The first torque does not supply power whereas the second one does. Consequently, the dynamic torque is the quantity related to the power on a mechanism that is rotating.

The difficulty of the measurement of the dynamic torque is that the shaft rotation cannot be stopped when measuring the torque because the dynamic torque would disappear. Therefore, the measurement shall be done with the shaft rotating. On the other hand, the measurement of the Dynamic Torque will allow a direct measure of the shaft's power. Knowing this data will make possible the control of the power source of the kinematic chain and this will allow improving the operation of the mechanism. A control of the power usually improves the application of cyclic loads over mechanical elements, since fatigue failures would be able to be controlled and even avoided.

The control over the power source is mandatory on many applications of the industry: agro alimentary, naval, aeronautics, energy, etc. Generally, this control is required in every process containing power sources (e.g. engines or motors) that produce mechanical works and that require a control over the supplied power in order to adapt it to variable loads coming from the process.

Current Technologies applied to the Dynamic Torque Measurement

The measurement of the Dynamic Torque is basically carried out by means of two quantities [1]: Force F, and either Stress τ_m, Strain γ_m, or Twist Angle ϕ. The magnitudes of these quantities are obtained by means of electrical signals generated by transducers. The Dynamic Torque is finally obtained by processing these signals. The expressions that relate the Dynamic Torque with the previous quantities are:

$$\tau_m = \frac{16 \cdot T}{\pi \cdot d^3} \quad (1)$$

$$\gamma_m = \frac{16 \cdot T}{\pi \cdot d^3 \cdot G} \quad (2)$$

$$\phi = \frac{32 \cdot L \cdot T}{\pi \cdot d^4 \cdot G} \quad (3)$$

$$T = F \cdot l \quad (4)$$

where d is the shaft's diameter, G is the torsional stiffness of the material, L is the span of the shaft between cross sections and l is the force arm's length.

The measurement of the shaft's Strain γ_m is made using four gauges connected in a Wheatstone bridge arrangement (see figure 1).

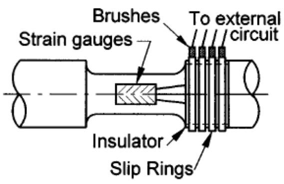

Figure 1. Arrangement for the Strain γ_m measure.

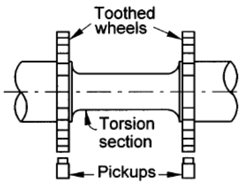

Figure 2. Arrangement for the Twist Angle ϕ measure.

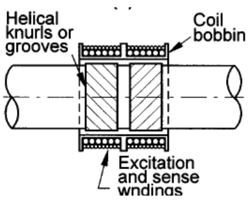

Figure 3. Arrangement for the Stress τ_m measure.

Twist angle ϕ can be measured as shown in figure 2. The presented configuration allows measuring the torsion angle between two parallel cross sections of the shaft loaded with torque. The stress τ_m is obtained by detecting the permeability change between two grooved regions that induce different output voltages at their windings, as shown in figure 3. The force *F* that induces the Dynamic Torque *T* could be obtained by using a load cell loaded with an arm of length *l* that is joined to a motor housing. This motor housing is free to spin. From among all these measuring technologies, the one related to the Strain γ_m is the most extended. It is not common to find commercial devices based on the other technologies. Figure 4 shows several commercial devices for measuring dynamic torque that use the extensiometric gauges technology.

Figure 4. Commercial devices with Strain γ_m technology based on extensiometric gauges.

Nowadays, around 20 companies manufacture worldwide these devices. Their catalogs offer from a few number of different measuring products to more than 500 models (HIMMELSTEIN, S. AND COMPANY supplier). Commercial full scales range from 1 N·m and up to several thousand, tens of thousands and even hundreds of thousands of N·m. The provided precision ranges start at 0.050 % full scale, although the most common precision is about 0.100 %.

Almost every manufacturer provides error data related to nonlinearity (≤ ±0.100 %), hysteresis (≤ ±0.100 %) and non-repeatability (≤ ±0.100 %). These errors are associated with the transducer element, which consists of a metallic thin film adhered to the torsionally loaded shaft. During operation, the continuous stretching and shrinking of the film may cause the material stiffness to vary as the number of cycles increases. The interface between the film and shaft may also be affected with this fatigue phenomenon. These variations on the initial properties deteriorate the measurements.

Errors in measurements may also be produced by the rotating movement of the gauge, since the gauge rotates with the shaft, or by the effect of the temperature, since this produces thermal expansions.

An important aspect of these instruments is the calibration procedure. Reference [2] explains that calibrations shall be made accordingly the procedures of the standards ISO 6789:1992, DIN 51309 y BS 7882:2008. These standards build up their calibration procedures based on static torques. Standard BS 7882:2008 is described step by step in reference [3].

Dynamic Torque Meter (DTM): New Technology for Torque Measurement

The physical concept of this new instrument is the comparison against a Reference Torque which is created by the instrument itself. The equation that governs this Torque is:

$$N = I \cdot \dot{\theta} \cdot \dot{\psi} \cdot \cos(\theta) \qquad (5)$$

where *N* is the torque (Reference Torque), *I*, the inertia of the rotating masses, $\dot{\theta}$ the nutation speed, $\dot{\psi}$ the spin speed and θ the nutation angle. Expression (5) indicates the value of the torque *N* generated in a gyroscopic mechanism, which consists of several masses that move in spin and nutation rotation in a controlled way [4]. The torque *N* varies proportionally with the nutation rotation experimented by the masses.

The functional diagram of this new instrument, called Dynamic Torque Meter (DTM), is shown in figure 5. The DTM consists of several components: Torque Supply (TS), Mechanical Comparator (MC) and Brake (B).

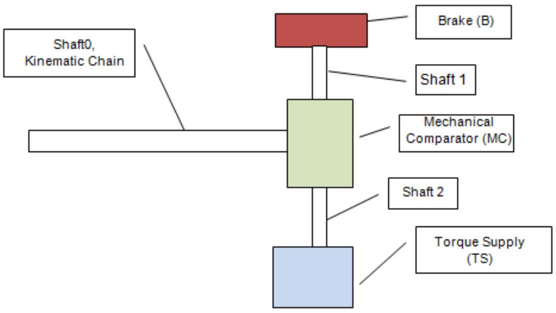

Figure 5. Functional Diagram of the Dynamic Torque Meter (DTM).

The TS is a device that generates torques based on the conservation of linear momentum principle.

$$N = \frac{dL}{dt} \qquad (6)$$

In order to produce a torque of magnitude and direction previously known, the DTM has rotating masses that rotates in counter-spin and counter-nutation. The four coordinated movements produce a Torque on the Shaft 2 (figure 5) that follows a sinusoidal law. B device poses a progressive impedance, emulating system's work, in order to absorb the power which is supplied in the kinematic chain by Shaft 0.

MC device is a differential mechanism with one input shaft and two output shafts. The dynamic torque, which is the object of the measurement, is applied to the input shaft (Shaft 0). The two output shafts, Shaft 1 and Shaft 2, are connected to B device and TS device, respectively.

Figure 5 shows the arrangement of the DTM instrument in order to perform a test. There is a power source connected at the free end of Shaft 0 in such a way that the rotation experimented by this shaft is directly dependent on the dynamic torque generated by the power source. Shafts 1 and 2 tend to rotate in the same direction and at equal velocity. However, Shaft 2, which is connected to TS, has a restriction applied to its end that does not allow it to rotate in the direction induced by the input shaft but does allow it to rotate in the opposite direction. On the other hand, Shaft 1 does not have any restriction and it can rotate freely. In this shaft, B device generates a braking torque that absorbs the transmitted power that the test setup requires.

Thus, at this moment, a torque of value P_0 is applied to Shaft 0, and two torques, P_1 and P_2, are produced in Shafts 1 and 2, respectively. Since there is no internal gear ratio at MC device, both P_1 and P_2 have the same magnitude, so being

$$P_1 = P_2 \qquad (7)$$

it results in

$$P_0 = P_1 + P_2 = 2 \cdot P_2 \qquad (8)$$

Hence, torques produced in Shafts 1 and 2 are half the input torque applied to shaft 0. From this situation, TS starts to work and generates an increasing torque P_g of sinusoidal form and opposite direction to the torque produced in Shaft 2. Note that, as mentioned previously, this shaft cannot rotate in the same direction as P_2 although rotation in the opposite direction is not restricted. Therefore, as soon as magnitude P_g becomes greater than magnitude P_2, Shaft 2 starts to rotate in the same direction as P_g. It is when P_g equals to P_2, knowing the gyroscopic masses values, and registering velocity and angle values, that the value of P_2 can be assessed. Knowing P_2 and using equation (8), the value of P_0 is finally obtained.

In case of a variable dynamic torque applied to Shaft 0, the measurement operation previously described is repeated over time with an adequate frequency to detect its evolution. TS device can supply a variable torque P_g by means of a pair of rotating elements. These elements develop controlled rotations in spin and in nutation. The expression that gives the torque generated by these rotating elements is:

$$P_g = I \cdot \dot{\Psi} \cdot \dot{\theta} \cdot \cos(\theta) \qquad (9)$$

that coincides with equation (5), above mentioned.

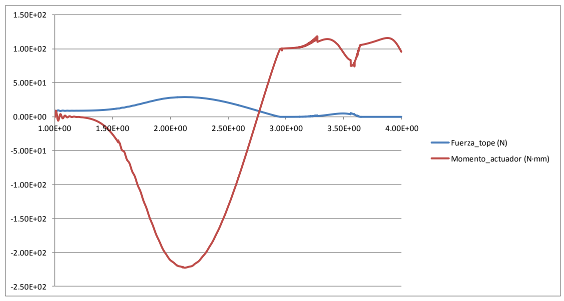

Figure 6. A DTM measurement operation simulation.

Several kinematic simulation tests have been done in order to validate the operation of the DTM when it measures the Dynamic Torque from a motor connected to Shaft 0 (see figure 5). As an example, figure 6 shows two curves resulting from the simulations. One of the curves represents the reaction force at the restriction that prevents Shaft 2 from rotating in the same direction as the required by Shaft 0. The other curve represents the torque produced by TS device.

It can be seen in figure 6 that there is initially a constant reaction force at Shaft 2 restriction derived from the input action applied at Shaft 0. Then, TS device starts to generate a sinusoidal torque and the reaction force at the restriction increases, since the first half cycle of the TS torque coincides in sign with the input torque at Shaft 0. Once the minimum value of TS torque is exceeded, the reaction force starts to decrease until a zero value is reached. At this moment, the restriction stops restraining Shaft 2 because TS torque makes Shaft 2 begin to rotate in the opposite direction.

All variables of expression (9), with the exception of the inertia, can be obtained directly by registering time and angle measurements. The electronic measuring instruments provide high precision that even does not depend on any material property nor have any problem related with linearity or hysteresis. By contrast, traditional instruments based on gauges have these problems.

At present, the DTM device is being developed at laboratory level. It has capacity for measuring dynamic torques ranged from 0.100 N·m to 30 N·m. Several tests are being performed at the moment in order to determine its degree of precision.

Figures 6, 7 and 8 show the current status of the development of the DPM instrument.

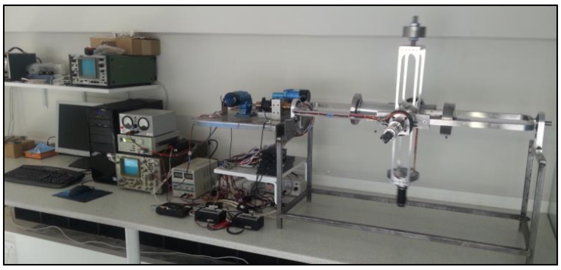

Figure 6. Laboratory facility for the Dynamic Torque Meter (DTM).

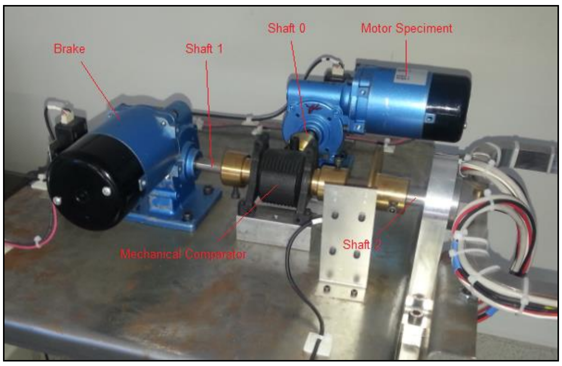

Figure 7. Partial view of the DTM over the MC device.

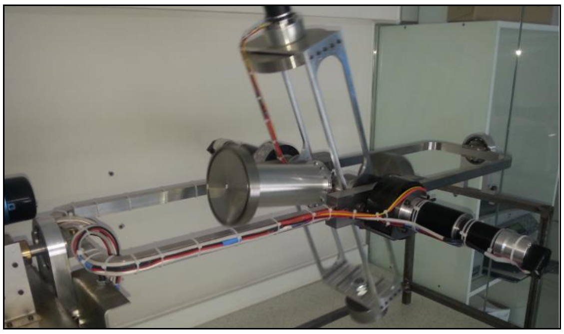

Figure 8. Partial view of the DTM over the Torque Supply (TS).

MPD Laboratory Prototype

As it is shown in figures 6, 7 and 8, a demonstration prototype has been built in order to validate the concept developed by this new technology. This concept test is supported by a mechanical assembly that implements the scheme proposed in figure 5, with the additional structure support and electronic control elements, which are necessary for performing the various movements of the assembly and achieving the measurement process.

The prototype has been built with precision mechanical elements for the TS device, which has also been equipped with position encoders for nutation and spin movements, and also with the counters required for closing the feedback loops of the servo controllers, by this, achieving the angular velocity and position measurements on the masses that provide the output reference torque. The MC device has been built on a classical differential gear, it has not been instrumented itself as magnitudes on three shafts are already monitored. Also, the B device has been built featuring a DC motor, acting as generator, and connected to an electronic load that is capable of setting desired levels of power load at the generator output. This B device has also been equipped with the corresponding position encoder and control counter. Finally, a DC motor has been used as torque supply, it is the Device under Test or DuT. A programmable power supply has been used to control it, and it has been equipped with an encoder/counter pair to check for the correct assigned voltage/angular speed values. All the subsystems have been connected to a computer that implements the control functions and also register monitored data, and performs the effective torque measurement computations.

In order to come to the final setup and correct configuration of the DTM, a series of subsystem unit tests was carried out. These tests began with the adjustment of the nutation and spin movements of the TS, and were followed by unit tests for adjusting the B device and controlling parameters of the DuT. The spin adjustment was achieved by characterizing its control elements, motors and gyroscopic masses, getting the correspondence between assigned control values and the angular velocities $\dot{\psi}$ effectively measured. The same procedure was followed for the characterization of nutation control elements, adding the effective angular positions θ measurements to the angular velocity $\dot{\theta}$ measurements of the nutation masses. To control B device, an encoder was attached to the generator's shaft, it measured the rotational magnitudes in relation to the assigned electronic load values. As well, an additional encoder was attached to the DuT shaft, getting the correspondence between its angular velocity and its electrical supply magnitudes, i.e. applied voltage and supplied current, at each time step during the unit tests. By this way we have obtained a DTM prototype with a measurement resolution limit of 36 ppm over the considered range of 20 N·m, which is better figure than those offered by competitive solutions.

Measurement Campaign and Instrument Performance Tests Results

Once the TS device elements were characterized, we proceeded with an initial test campaign in order to characterize the MC device and determine the performance of the new measurement technology. The objective was to gather data of enough quality for contrasting the results against cutting edge torque measurement technologies.

The test campaign consisted of a series of torque measurement tests carried out on a DuT. The tested DuT was a DC brushed motor, 45 W, 314.159 rad/s (3000 rpm), 48 V, mounted with a 25:3 reduction factor gearbox, capable of developing an 1.200 N·m torque. This DuT was set to run under different supply and mechanical load conditions. Inherent to the DC motor used, the assigned voltage value set its angular velocity, while the mechanical load was set by means of setting the generator/electronic load pair parameters at the B device. The ability of the electronic load for working either as a constant power load or as a constant current load has allowed for easy testing procedures for obtaining the required values for building the graphical parameterized torque curves of the DuT, adding on the inherent relationship between torque and supply current on the kind of DuT used. With this work, it has become possible to program the unit tests sequences for obtaining the detailed torque curves.

For these curves, primary parametric sweeps of unit tests were performed, where the angular velocity of the DuT was stepped at 5.236 rad/s (50 rpm) intervals. Also at each interval, second level sweeps were performed were the mechanical load/sink was stepped at regular intervals (5 W steps). At each unit test the torque measurement was carried out by direct comparison against the reference torque produced by the TS device. The TS device was configured to produce a maximum output torque greater than the expected torque value of the DuT, in order trigger the trip point detector.

This DuT motor was selected on first hand for the purpose of initiating the assessment and verification of the capabilities of the new technology, and for this reason the work has been focused on analyzing and determining the effects of the constitutive MC elements on the quality of the measurement.

This way, the first torque curves have been obtained on the available DuT at no load regime. This procedure has served to characterize the constitutive elements of the MC device, as the differential mechanism poses loses on the kinematic chain that must be measured and compensated for in the general measuring procedure of a dynamic torque value. The work is now at the stage of achieving the full characterization of these constitutive elements in order to assess the capabilities of the new differential dynamic torque measuring technology.

Although the early research stage, and pending on new testing campaigns to gather more information and measurement data for improving the accuracy and resolution that the new differential DTM is firstly offering, it has been possible to identify the elements of the system that require additional work for their characterization. By means of these customized characterizations for each element it will possible to determine the dynamic torque produced by a torque supply and to assign the corresponding contributions to the measurement introduced by the elements in the kinematic chain of the DTM assembly, with special focus on the mechanical comparator.

As well, it has been intended to carry out the construction of the demonstrating prototype with the greatest fidelity to the design and with optimal processes and materials in order to minimize the technical effects on the measurement accuracy. Nevertheless, during the next research activities it will be necessary to improve the efficiency and performance of the MC in order to reduce the uncertainty on the assignment of the measured torque value to the DuT.

Differential DTM Technology versus traditional technologies

Among all the traditional technologies above-described, that are designed for measuring dynamic torques, the technology based on the Strain γ_m measuring is the most developed. Instruments based on this technology are known to have several disadvantages that affect to measuring quality. These are nonlinearity, hysteresis and non-repeatability, among others coming from these ones: errors of interpolation, errors in zero balance and errors in repeatability. Such disadvantages come up to measurements performed with this kind of instruments to be quite unreliable. This reality has propitiated new research in order to achieve improvements on the precision and uncertainty of instruments [3]. In this sense, the DPM achieve a technologic change due to the procedure to obtain the Dynamic Torque with the equation (9). With the new device, the inconveniences due to the employ of strain gauges can be avoided.

Conclusions

A new measurement instrument has been introduced, this instrument performs the measurement of a torque in dynamic conditions by comparing it to a high precision reference torque, which is generated under controlled conditions with highly accurate and stable assignment parameters, i.e. time, angles and mass inertia.

Besides, with this new instrument, it is expected to reach higher accuracy levels than those achieved by technologies based on extensiometric gauges.

It is necessary to continue working on the characterization of the whole set of elements that take part in the measurement process, as their estimations must be fully characterized and correctly accounted for, with special focus on the mechanical comparator.

At present, the accuracy and resolution capabilities of a laboratory prototype are being evaluated. It is expected to continue testing during additional testing campaigns in order to deepen knowledge on the behavior of the DTM and to compare higher quality results against competitive technologies.

During the following months, the development of the first industrial products will be started. These developments will be aimed at different application where accuracy on the torque measurement is an important issue, covering a wide measuring range according to the industry demands.

References

[1] Ivan J. Garshelis, Measurement, Instrumentation, and Sensors Handbook, CRCnetBase, Section IV, Ch. 24 Torque and Power Mesurement, 1999.

[2] Luca G. Bochese. Measurement uncertainty in torque calibration, ASQ CQE, CRE (Milano-ITALY).

[3] Harish Kumar, Anir Kumar & Sanjiv Gupta, Design studies and testing of a torque transducer. National Physical Laboratory, New Delhi, India, August 2011.

[4] Jesús Gómez, Actuador Giroscópico Avanzado para Control de Actitud de Satélites, Tesis Doctoral, Escuela Politécnica Superior del Ejército, Madrid 2010.