Dynamic Torque Calibration – Necessity and Outline of a Model-Based Approach

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The demand for traceable dynamic measurements of mechanical quantities has increased over the last few years. In this context, methods for the dynamic calibration of torque transducers are under development. A measuring device for dynamic torque calibration is presented in this paper, and methods to model the dynamic behaviour of torque transducers as well as the measuring device are described.

1 Introduction

In industry various applications with dynamic torque excitations exist. Yet, there are no documentary standards or even methods for dynamic calibration. The joint research project IND09 of the European Metrology Research Programme (EMRP) is concerned with the traceability of the dynamic measurement of mechanical quantities [1]. The research of nine European National Metrology Institutes in the field of the related measurands force, torque and pressure aims at developing methods for dynamic calibration and at enabling the dissemination of the units.

At present, a strong demand for the traceability of dynamic torque measurement exists in two important fields:

1) In the manufacturing process of high quality industrial products, screw connections – especially those of safety relevant connections – need to be fastened quickly and to a well-known torque. For this application, impulse wrenches are often used. These tools fasten screw connections by applying a sequence of short impulses (with a duration in the range of milliseconds) as illustrated in Figure 1a. These impulses are generated by releasing a pre-tensioned hydraulic fluid. Impulse wrenches offer short fastening times and good reproducibility. However, there is no possibility of dynamic calibration yet.

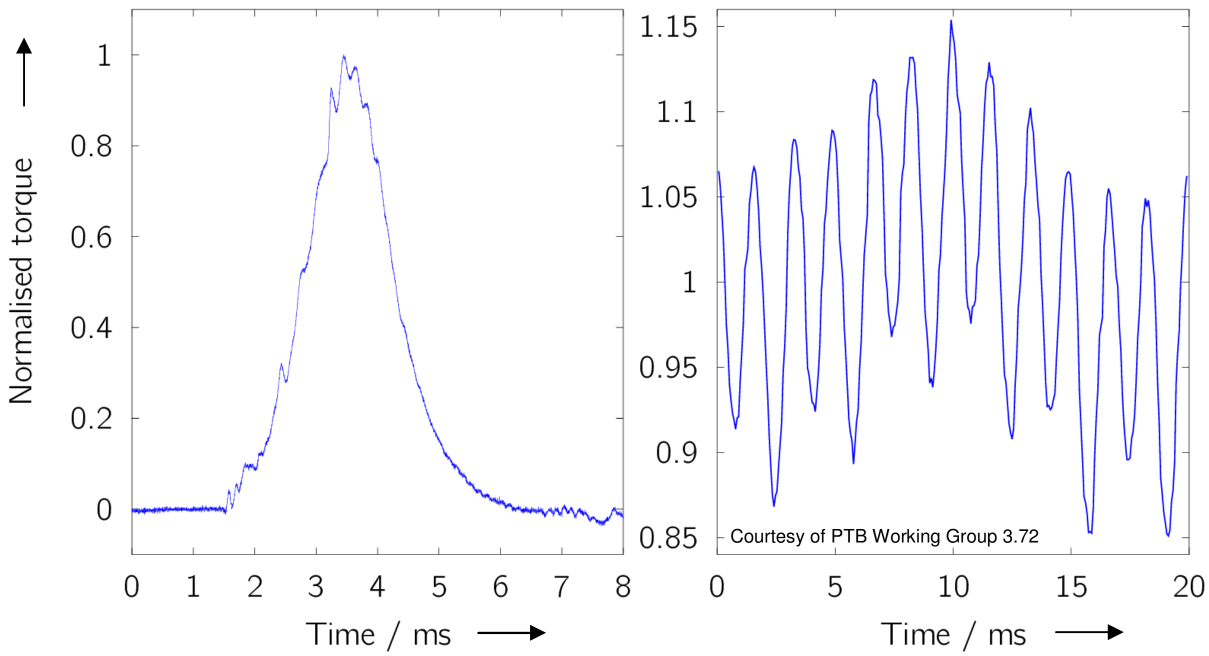

Figure 1a: Fastening cycle of an impulse wrench (left).
Figure 1b: Dynamic torque output of an electric asynchronous machine (right).

2) The mechanical output power of combustion engines and electric drives is usually measured by means of the angular velocity (revolutions per minute) and the torque. These measurements are carried out for the determination of the mechanical output power ratings

and – far more critical in terms of demand for low measurement uncertainties – for power efficiency measurements. This application has gained importance due to the efforts to further improve the fuel efficiency of vehicles. The torque output of these machines can be highly dynamic in comparison to the mean torque (see Figure 1b) and the frequency content extends up to the kilohertz range.

2 Torque transducers

At present, the calibration of torque transducers used for the above-mentioned applications can be carried out statically, only. A static calibration of torque transducers is possible over a wide range of torque levels and with low uncertainties. However, the use of a statically calibrated torque transducer for dynamic torque measurements may lead to incorrect results. From experience with force transducers which are related in mechanical design, measuring technology and mounting situation, there may be measurement deviations due to frequency-dependent sensitivity. Because of the fact that torque transducers are always coupled on both sides to their mechanical environment (which is the same with force transducers), their dynamic behaviour may vary depending on the coupled components. Figure 2 shows the influence of different (assumed to be rigidly coupled) mass moments of inertia (MMOI) J_0 on the sensitivity of a transducer modelled as a single degree-of-freedom (SDOF) system (see the transducer's model in Figure 3). This kind of variation may occur when using a transducer in different mechanical set-ups.

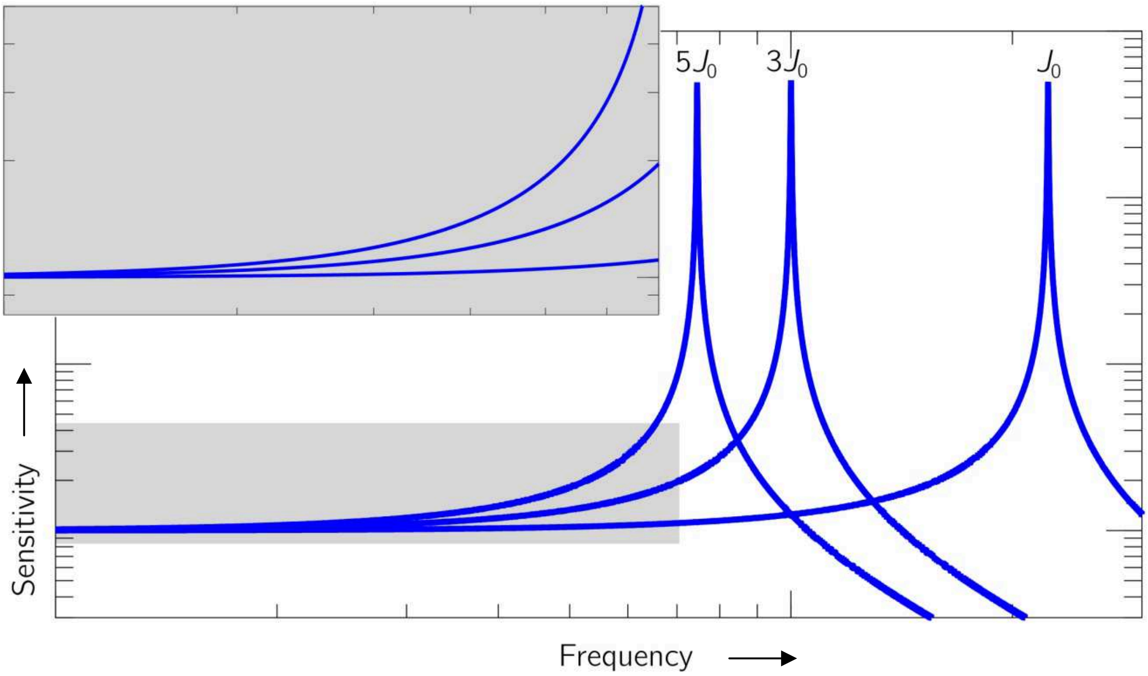

Figure 2: Frequency response of a transducer modelled as a SDOF system with different coupled MMOI resulting in a change of the frequency-dependent sensitivity.

The measurement principle of the majority of torque transducers is based on the measurement of torsion, which is typically carried out by means of strain gauges, but other principles are used as well. This results in a characteristic mechanical design. In general, transducers are designed to have a high torsional stiffness, but the structural components on which the strain gauges are applied have to exhibit a sufficiently high compliance. To be able to characterise the dynamic behaviour of a torque transducer, the transducer is described by an appropriate model and the model parameters are identified during the calibration process. From experience with force transducers, it is known that a linear and time-invariant model (LTI) describes the behaviour well [2]. The proposed model of the transducer consists of two MMOI elements J_{H}, J_{B} both at the top and at the bottom (representing the rigid components on each side), connected by a torsional spring c_{T} (which represents the measuring element of the transducer) and a damper d_{T} in parallel (see Figure 3).

3 Measuring device

The calibration itself is to be carried out by applying periodic torque excitations in a broad range of frequencies. For this purpose, a method for a primary realisation of dynamic torque was proposed [3] and a measuring device was developed. The measurement principle is based on Newton's second law; the acting torque $M(t)$ is measured by means of a mass moment of inertia J and the angular acceleration $\ddot{\varphi}(t)$, giving

$$M(t) = J \cdot \ddot{\varphi}(t). \tag{1}$$

The components of the dynamic torque calibration device are arranged along one vertical axis. Using an air bearing, this transmission train can rotate with negligible friction. At the bottom, a rotational exciter generates sinusoidal torque. Above the exciter, the device under test (DUT) is mounted between two coupling elements with high torsional stiffness but low stiffness to transmit bending moments and axial force. This mechanical characteristic is realised by means of a laser-welded steel diaphragm, which is stiff for torsional load but flexible for bending and axial loads. The couplings feature interchangeable collet chucks to be able to adapt to different diameters of the DUT's rod ends. Above the DUT, the angular acceleration measurement components are arranged. All components above the DUT contribute to the acting mass moment of inertia of Equation (1).

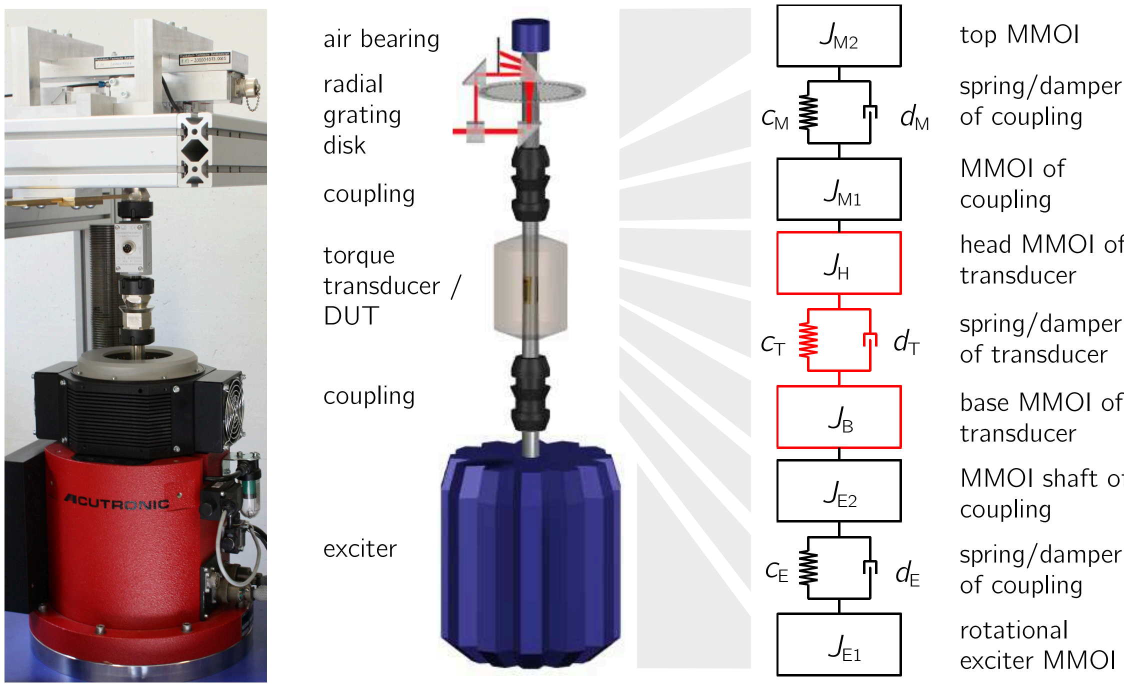

Figure 3: Dynamic torque calibration device (left), schematic image of corresponding components (middle) and model of the dynamic torque calibration device (right, black) including the model of the transducer (right, red).

The measurement of the angular acceleration is carried out by means of a laser Doppler interferometer for the measurement of rotational vibrations and a radial grating disk. The radial grating disk is rigidly mounted on the shaft axis of the measuring device. The interferometer's two laser beams pass through the grating disk. At the grating, the laser beams are diffracted and the first order of the diffracted beams is coupled back into the interferometer. The advantage of the two-beam measurement through the grating disk is the high robustness against parasitic oscillations which are not measured at all (in the vertical direction and horizontally in the grating line's direction), or are eliminated due to subtraction (horizontal orthogonal to the grating line).

An improved rotational exciter (see Figure 3 on the left) enables oscillations up to 1 kHz and torque levels up to 20 N·m.

4 Model of measuring device

As mentioned above, the dynamic behaviour of torque transducers may be dependent on the coupled mechanical environment. Because of the fact that the properties of the transducer, i.e. the model parameters of the proposed model, need to be determined independently of the measuring device, it is necessary to distinguish between the properties of the measuring device and the transducer. This distinction can be carried out by modelling the measuring device including the transducer under test. The model of the measuring device is again assumed to be linear and time-invariant [4].

The physical model representations are based on the components of the measuring device as illustrated in Figure 3 on the right. The coupling's torsional stiffness is represented as the spring-damper element (c_{M}, d_{M}; c_{E}, d_{E}), while the MMOI is summed up with other rigidly coupled components as MMOI J_{M2} and J_{E1}. Only the half of the couplings opposite the spring-damper elements connected to the DUT are modelled as discrete MMOIs J_{M1}, J_{E2} to be able to distinguish between the DUT's and the measuring device's properties.

To be able to identify the dynamic properties of the transducer under test, it is not only necessary to model the measuring device, but also to know about the measuring device's properties prior to the identification of the DUT's properties. For this purpose, procedures were developed and auxiliary measuring set-ups were designed, manufactured and commissioned. These measurement set-ups enable the determination of the MMOI and the torsional stiffness [4]. An auxiliary measurement set-up for the determination of damping properties is currently under development.

Conclusions

This paper describes the necessity of research in dynamic torque calibration. A device for dynamic torque measurement is presented and the corresponding model of the measuring device, including the transducer under test, is described. This model description is a prerequisite to be able to identify the parameters of a transducer from measurement data. The future goal is to be able to describe the dynamic behaviour of transducers based on the identified parameters in any (known) measurement application.

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