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TRACEABILITY OF ROTATING TORQUE TRANSDUCERS CALIBRATED UNDER NON - ROTATING OPERATING CONDITIONS

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Abstract – In the strict sense, traceability of torque measurement with rotating torque transducers is given only for non-rotating operation. The presented study examines in how far such proof of traceability is valid also for rotating operation. The method of investigation is a comparison of simultaneous measurements of torque in a rotating shaft train. These consist of measurements with a rotating torque transducer on the one hand and measurements with a cradle-mounted absorption dynamometer on the other hand.

Keywords: rotating torque transducers, traceability

1 . INTRODUCTION

1.1. Torque measurement in automotive test stands

An important application for torque measurement are power test stands for testing of engines, transmissions, gearboxes etc. in the automotive industry, see fig. 1. There are two practical approaches for torque measurement in such test stands, [1].

Fig. 1. Engine test stand

The traditional way is to measure the reaction torque by applying what is known as a cradle-mounted dynamometer, see fig. 2. This means that the absorption dynamometer which is part of every test stand is mounted such that it can perform tilting motion about an axis parallel to the axis of rotation. It is prevented from tilting only by a lever arm which is connected to the foundation at its other end. The force in this connection is measured by a force transducer or load cell. Torque equals the product of this force and the lever arm length. In practice usually the step of determining a force first is omitted. Instead, the system is calibrated by applying known torque loads to the dynamometer housing so that the load cell can be adjusted to give torque readings. Unless a correction is done by means of a fast shaft torque calculator this torque measurement principle has a fundamental weakness when dynamic torque is to be measured.

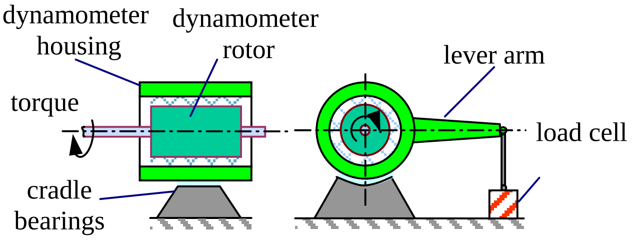

Fig. 2. Measuring reaction torque by means of a cradle mounted dynamometer

The second approach to torque measurement in test stands is what is known as in-line torque measurement. In this, a torque transducer is mounted as a part of the rotating shaft train. Electrical supply and measurement signals are transmitted either by sliprings or contactless.

1.2. Problem and approach for solution

Although the very purpose of in-line torque measurement is rotating operation, calibration of the rotating torque transducers is currently only possible as calibration under non-rotating conditions. The relevant national and international calibration standards and guidelines DIN 51309 and EA-10/14 are restricted to the case without rotation. Recent studies for further development of calibration procedures that are relevant for torque measurement in test stands deal with on-site calibration, [2], [3]. Another relevant topic is continuous or even dynamic calibration, [4]. Yet all these studies apply calibration only under non-rotating conditions.

In this context it needs to be emphasised that calibration during rotation must not be confused with dynamic calibration. In dynamic calibration the applied torque undergoes variations over time, which can also be achieved under non-rotating conditions.

Another effect that is related to the question under examination is the influence of rotation on the zero signal. This effect has been examined by manufacturers in the recent past. So what remains is what we might call the influence of rotation speed on the sensitivity of a rotating torque transducer.

In this study, a cradle-mounted dynamometer and a rotating torque transducer are implemented in the same shaft train of a test stand in order to determine the potential influence of rotation speed on torque measurement with a rotating torque transducer.

The cradle-mounted dynamometer is used as a reference for quasi-static torque during rotating operation. Thus potential influences of speed on the rotating torque transducer can be determined. The rotating torque transducer, on the other hand, provides traceability to national standards by a prior calibration in a calibration laboratory.

The influence of rotation speed on torque measurement is a point, where the principle of the cradle-mounted dynamometer has strong sides. Since the load cell itself is not moving at all, it will not undergo influences by rotation. The main influence that may affect this measurement principle is bearing friction. Yet it has to be considered in detail, whether such effects really pose a problem for the examination. The bearings enabling rotation do not affect the measurement, since both the outer and inner bearing race belong to the system which is on the cradle bearings. Only friction in the bearings enabling the tilting motion of the cradle-mounted machine housing may affect the torque measurements. Yet the tilting motion in these bearings is only minimal and therefore only small friction is to be expected. What is even more important in the context of this investigation is the fact that only the comparison between different rotation speeds is considered. And a considerable difference of the motions in these bearing (and thus also in friction) at different speeds is not to be expected.

2. EXPERIMENTAL INVESTIGATION

2.1 Experimental set-up

The experimental set-up is a test stand with one asynchronous electrical machine as drive and another one as the absorption dynamometer, see fig. 3 and fig. 4. Both machines are of type APA 202/10 by AVL / ELIN. In the speed range between 0 and 4000 min^{-1}, this type of machine can generate a torque of up to 478 N· m when used as a motor and up to 525 N· m when used as an absorption dynamometer. The machine is cradle-mounted with torque measurement via lever arm and load cell. The bearings enabling the tilting motion of the cradle type mounting are hydrostatic bearings. According to manufacturer's specification these bearings provide a friction level below measurability. Whereas the torque measurement signals of the dynamometer are fed into the control loop, the torque signal from the drive machine are available for the purpose of the investigation.

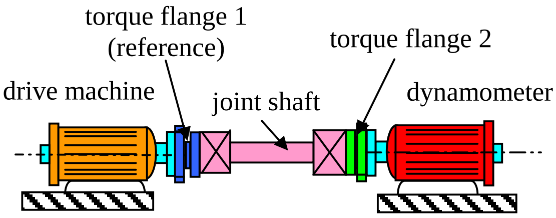

Fig. 3. Schematic of experimental set-up

The two machines are connected via a relatively simple straight shaft train without transmissions. Two rotating torque transducers, one adjacent to the drive machine and the other one adjacent to the dynamometer are included. The transducers are of type T10FS by HBM with a nominal range of 1 kN· m This type is an up-to-date torque flange style recommended for test stand applications with high accuracy requirements and does typically achieve class 0.05 acc. DIN 51309 and EA-10/14. The influence of rotation speed on the zero signal at 22000 min^{-1} is below 0.1 % of the nominal torque. For the presented study, rotation speeds were up to 6000 min^{-1}. The speed influence of the two torque transducers was recorded and was below 0.02 % at 7000 min^{-1}.

Like usual in test stand applications, several boundary conditions must considered in order to provide a minimisation of influences on the measurement uncertainty. The most important points are:

1. mechanical stresses due to the mounting,
2. cross talk from parasitic loads like bending moments resulting from misalignment, centering errors or unbalance,
3. residual magnetic forces in the electric machines that may cause a torque even at stand-still.

Points 1 and 2 were taken care of by use of the joint shaft (with the joint elements being lamella couplings), thorough mounting and centering. The influence of point 3 was eliminated by limiting the investigation to a comparison of transducers which all see the same torque. Therefore a reliable physical representation of torque zero was not needed.

Fig. 4: Experimental setup

2.2. Measurements at zero rotation speed

First, measurements were taken at zero rotation speed. The torque was increased in steps of 100 N· m from 0 N· m up to 400 N·m. The resulting torque is shown in fig. 5. In order to have equivalent conditions with the normal case of laboratory calibration, data acquisition was performed with a low pass filter with a low filter frequency, the setting was

0.25 Hz. The measured data was acquired with a data acquisition and processing software. For the evaluation, data from the time sections with nominally constant torque was averaged in order to equalise fluctuations.

A zero adjustment was made separately for each transducer based on the section with a torque of nominally zero. Although the physical zero torque (like constant torque for all the torque steps) is depending on the controller of the dynamometer, this zero adjustment is sufficient here, since it provides a common reference allowing the comparison of the influence on the sensitivities of the different transducer principles.

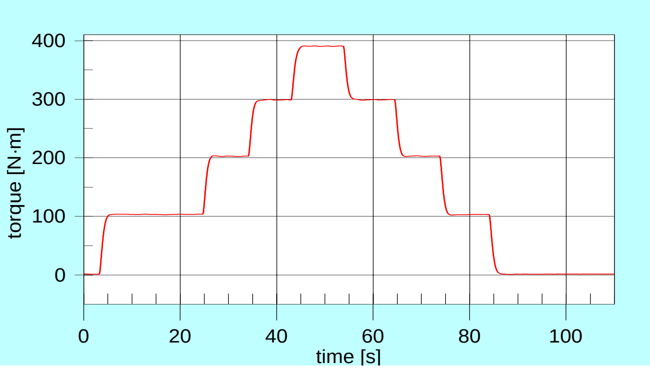

Fig. 5. Torque steps at zero rotation speed

The purpose of these measurements was to make sure that the two rotating torque flanges and the load cell of the cradle-mounted electrical drive machine indicate the same torque. Fig. 6 shows the relative deviation of the indication between the measuring devices.

Although the torque transducers have a nominal (rated) torque of 1 kN· m, all results presented here as percentages are related to 400 N·m, because this is the measurement range used in applications where the torque flanges are used together with the type of electrical machine used here.

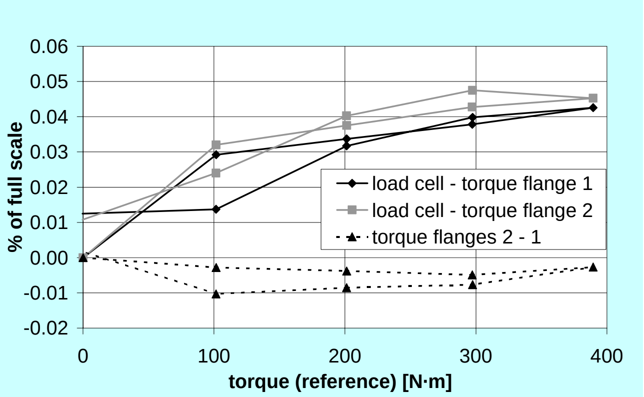

Fig. 6. Deviations of the torque measuring devices at zero rotation speed without sensitivity correction

Then, a sensitivity correction was performed to provide identical indication at zero torque and at full scale from all three instruments at full scale. Since the torque flanges had been measured in a traceable calibration laboratory, one of them was chosen as the reference for adapting the sensitivities of the two other transducers.

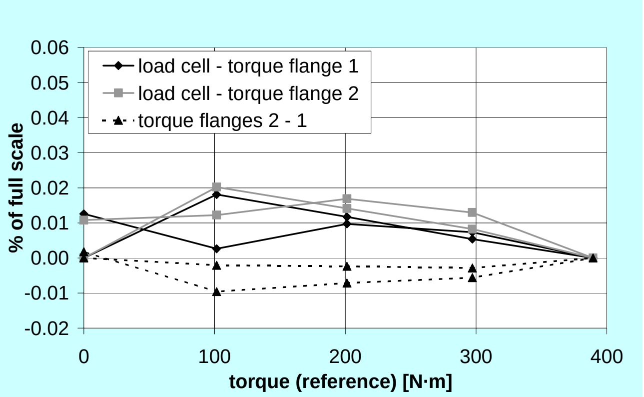

Fig. 7. Deviations of the torque measuring devices at zero rotation speed with sensitivity correction

The resulting curves are plotted in fig. 7. They show a maximum deviation of 0.02 % between one of the torque flanges and the load cell. It can be seen that the main sources for this deviation are a certain linearity deviation and hysteresis. Yet there must be other effects too, since the hysteresis curves seem to intersect with each other. The conclusion from this diagram is however, that this is a very small deviation in the context of torque measurement in automotive test stands. In such applications, accuracy requirements of 0.1 % and below (related to of the full range of the transducer!) usually are considered high precision. For the torque transducers used in this study, 0.02 % is the specified standard deviation of the reproducibility.

2.2. Measurements under rotation

For different rotational speeds, measurements were taken at constant speed and changing torque load. The pattern of torque steps was similar as for the test under non-rotating conditions. For technical reasons however the maximum torque was only 300 N· m

Averaging was done in the same way as for the measurements with rotation speed zero and also a separate zero adjustment was done for each measurement at zero torque at the respective rotation speed. This method gives optimum conditions for the comparison of the influence on the sensitivities of the different transducer principles.

The same measurements were taken with various filter settings for comparison. However the filtering chosen for the evaluations presented was 1 kHz low pass. This setting is typical for applications of torque measurements in power test stands because with typical applications it is important also to view the dynamic processes.

Fig. 8 shows the time history of torque from a test taken at a rotation speed of 2000 min^{-1}. In order to keep the graphics clearer the signals from torque flange 2 are omitted. The beginning of the graph shows different initial states: first, with the pump for supplying the oil bearings switched off, the load cell has a big offset due to prestress, the next section was with the oil bearing working, but rotation speed still zero. Finally the machine was set spinning. This transition is accompanied by another transient torque peak.

This is due to the torque required for acceleration. Another visible effect are the transient peaks whenever torque is switched to the next value. This overshoot is caused by the closed loop control incorporated in the electrical machines to control torque.

The graph also shows that the quasistatic torque is superimposed by fast dynamic disturbances. A zoom (fig. 9) reveals that these disturbances are not noise but rather very regular oscillations. These oscillations in the torque signal are most probably due to torsional vibrations in the shaft train.

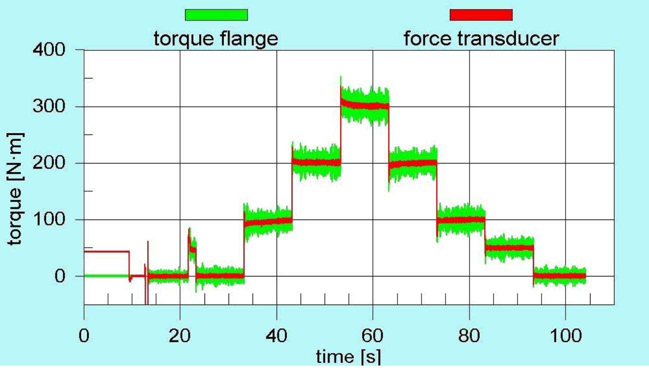

Fig. 8. Torque steps at rotation speed 2000 min^{-1}

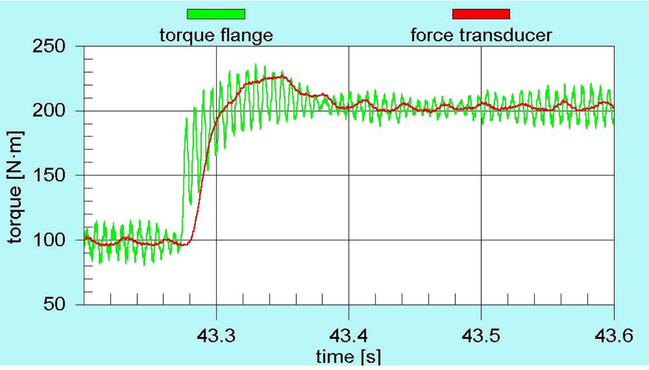

Fig. 9. Zoom of torque history at rotation speed 2000 min^{-1}

The zoom plot clearly shows which differences exist between the torque indicated by the rotating torque transducer and the load cell connected to the dynamometer via the lever arm. These differences do not only affect the frequency of the torque oscillations but also the reaction during the transition to the next torque step. The torque indicated by the rotating torque transducer increases faster. The overshoot (when the oscillations are not taken into consideration) is bigger with the load cell. These differences are reflecting true differences in torque at the respective positions of the two transducers. These differences are due to the fact that the inertia of the rotor of the electric machine needs a big amount of torque to be accelerated. This can be seen clearly from fig. 2. And whereas the load cell measures torque on the side of this inertia where the entire torque is introduced the rotating torque flange measures torque on the side of this inertia where only the portion of torque acts which remains after imposing the rotational acceleration on the inertia.

Fig. 10 shows the deviations of the indication of the measuring devices for a measurement at a rotation speed of 2000 min^{-1}, fig. 11 for 6000 min^{-1}. For ease of comparison the full scale value to which the percentages are related is again 400 N·m although only torque steps up to 300 N·m are included.

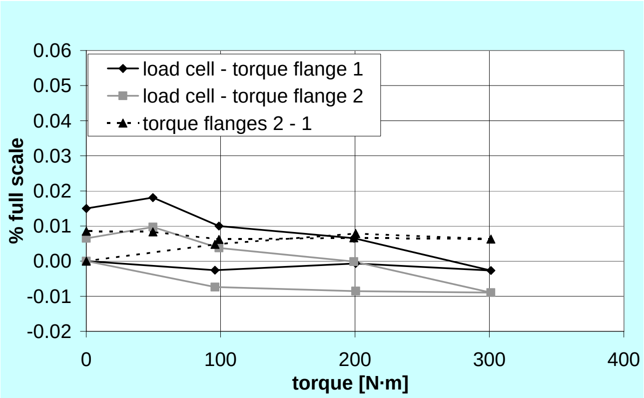

Fig. 10. Deviations of the torque measuring devices at rotation speed 2000 min^{-1}

Both figures show deviations between the different torque measuring principles which are even smaller than at zero rotation speed. There are two possible explanations for this: first, the oscillations and fluctuation caused by closed loop control of the dynamometer are bigger at zero rotation speed. If these oscillations do affect the measurements they might cause a bigger deviation at zero speed. Second, the main source of the deviations is hysteresis. However hysteresis in the measurements with rotation speeds of 2000 min^{-1} and 6000 min^{-1} is smaller because the torque step of 400 N·m was not included.

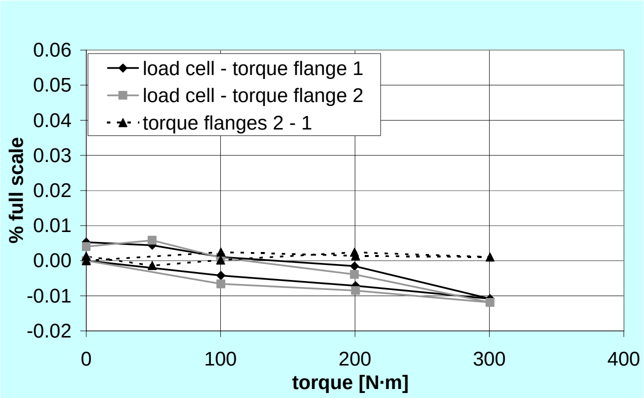

Fig. 11. Deviations of the torque measuring devices at rotation speed 6000 min^{-1}

3. CONCLUSION

The experiments close a gap in the chain of traceability of torque measurement by means of rotating torque transducers. For one type of such transducer it was shown that the influence of rotation speed on the sensitivity of the transducer is of the same order of magnitude as other contributions to the uncertainty of such transducers. The authors are aware that this study does not fulfil the requirements for a quantitative determination of measurement uncertainty, but due to the fact that the effect under consideration cannot be examined with the high precision calibration machines at hand in calibration laboratories the result is still quite useful.

Yet it must be mentioned that some conditions must be fulfilled in practical applications in order to take conclusions from the presented study to the practical application. Two of these conditions should be emphasised.

The first is that the influence of rotation speed on the zero signal can be much bigger than the influence on the sensitivity examined here. For this reason, all HBM torque flanges are tested for this influence.

The second condition is the possibility to create a state with a physical torque of zero to enable a reliable zero balancing.

A related question, which also needs to be answered for fully justifying the use of rotating torque transducers in automotive test stands is the question to what extent static calibration is valid for dynamic torque. This question is currently being examined by other authors.

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