Fast Torque Calibrations Using Continuous Procedures

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Abstract:
Unlike step procedures, continuous procedures permit calibrations to be carried out within a very short time. In continuous calibrations the fast change in torque and thus also in the signals give rise to specific problems. This paper gives advice on how to limit the influence of the most important effects on the measurement uncertainty. A simulation method is introduced, which allows the contribution of the reference creep to the measurement uncertainty to be calculated.

Introduction:
High-level calibrations of torque transducers are possible with overall relative measurement uncertainties of a few 10^{-5} in relation to the nominal value of the transducer. To achieve such results a well constructed deadweight torque standard and great expenditure of time and money are necessary.
For many transducers used for industrial applications, a measurement uncertainty in the range of 10^{-3} is sufficient. As in this field the laboratories often have to calibrate a great number of transducers, methods are needed which allow the time a calibration takes to be reduced as far as possible.
A comparison method can be used for fast torque calibrations in accordance with class 0,2 of the EA Guideline EA-10/14 [2]. This method which is based on the principle of torque generation by motor and gearbox allows a great variety of continuous loading processes. The time a load-unload sequence takes can be reduced by a factor of up to 100 compared to step loading process with deadweight machines.
In this paper, some of the most important effects of continuous methods are discussed. The effects of transducer creeping, which are important for the selection of a suitable reference transducer, the influence of the amplifiers, of the signal readout and of the data processing can considerably affect the measurement uncertainty. Most of the results are not only significant for continuous calibrations in the field of torque, but also for other work with strain-gauge transducers.

Transducer-creeping:
A matter to which a force or a torque is applied shows a time-dependent reaction which is known as creeping. In a transducer this applies not only to the measuring body itself but also to the strain gauge and the adhesive between them. A stable load therefore generates an output signal that can be described as a sum of exponential functions [1]:

$$S(t) = S_0\left(1+\sum_i A_i\left(1-e^{-\frac{t}{\tau_i}}\right)\right) \;,\; \frac{A_i}{S_0} = a_i \;, \qquad (1)$$

with the initial signal S_0 and the creep Amplitudes A_i .

The relative creep amplitudes a_i and the time constants τ_i are the creeping parameters of the transducer. In typical cases, the creeping behaviour can with sufficient precision be described by three exponential functions, where for our purposes the first function with a time constant τ_0 less than 2 s can be neglected because this contribution is too fast to be resolved in standard creep-tests. Regarding this fast creeping could be important only for methods performing much faster loading sequences, e.g. sinusoidal or impact loading.

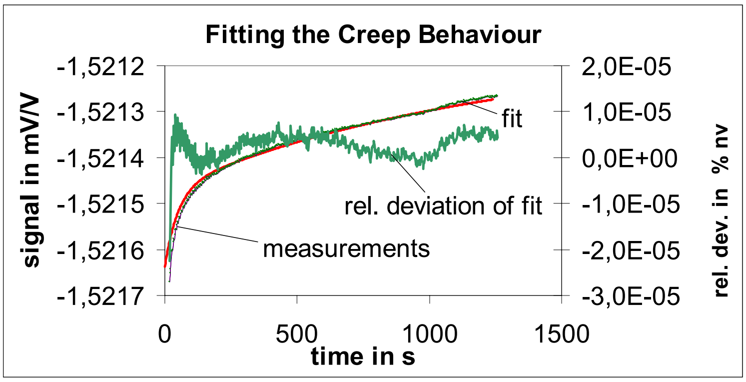

Fig. 1: Creeping of a torque transducer, fit with two exponential functions and relative deviation of the fit from the measurement referring to nominal value.

With direct mass loading, performing a rectangular load sequence, the creeping parameters of interest can be obtained. With two exponential functions (typical values of time constants: τ_1=50 s and τ_2=1000 s) it is possible to reproduce the creeping behaviour within $1 \cdot 10^{-5}$ (fig. 1).

The creep parameters, obtained by static loading, are also useful to describe the reaction of the transducer to continuously changing load. Depending on the torque M_{ext} the calibration facility impresses on the transducer, a recursive calculation furnishes for each time step t_m the creeping values $K(t_m)$, understanding the proceedings in the loaded matter of the transducer as a capability of creeping $C(t_m)$ which accumulates with increasing torque and is to be reduced in the same measure as the creep takes place (fig. 2):

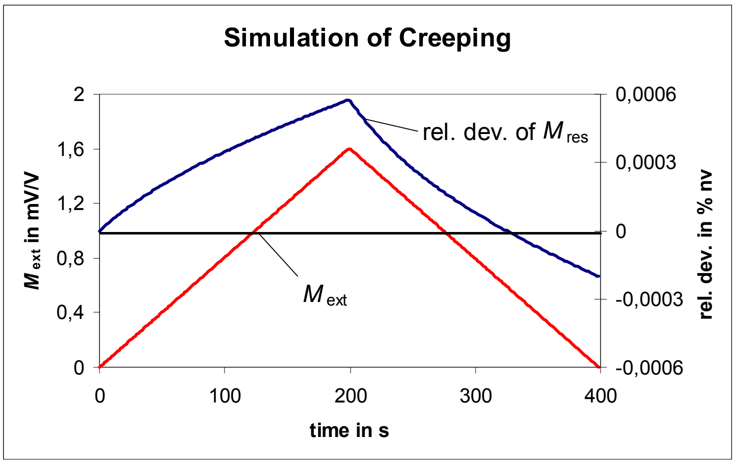

Fig. 2: M_{ext} as linear input with t_{Load}=200 s for simulation of creeping with the result given as relative deviation in % of the nominal value.
Parameters: a_1=a_2=0,0006 , t_1=50s and t_2=1000s

$$M_{res}(t_m) = M_{ext}(t_m) - \sum_i C_i(t_m) + \sum_i K_i(t_m) \qquad (2)$$

$$K_i(t_m) = C_i(t_m)\left(1 - e^{-\frac{(t_m - t_{m-1})}{\tau_i}}\right) \qquad (3)$$

$$C_i(t_m) = C_i(t_{m-1}) - K_i(t_{m-1}) - a_i\left(M_{ext}(t_m) - M_{ext}(t_{m-1})\right). \quad (4)$$

To simplify the calculations, the creeping for loading and unloading and for right-hand and left-hand torque is assumed to be equal. Although asymmetric creeping was observed here and there, for the great number of transducers and especially for principle investigations this assumption is sensible.

One requirement for the simulation of creep in the way described is the proportional dependence of $K(t_m)$ on the torque variation. Creeping tests with different loading torques M_{load} show that the relation between a and M_{load} is constant.

As a test for the simulation, the measurement results of a rectangular load, a multi-step load with 0%-50%-100%-50%-0% and a continuous load were compared with the corresponding calculated results. The qualitative agreement was very good, but because of difficulties in the determination of M_{ext}, a scaling factor was needed to achieve quantitative agreement (fig. 3 and fig. 4). M_{ext} is represented by the transducer signal without creeping, i.e. immediately after application of the torque. This value is accessible by extrapolation of the creeping function to t=0 for rectangular loading, but for continuous loading it can only be estimated by a measurement with very fast loading. It thus is important to eliminate the creep influence of the reference transducer and the calibration machine.

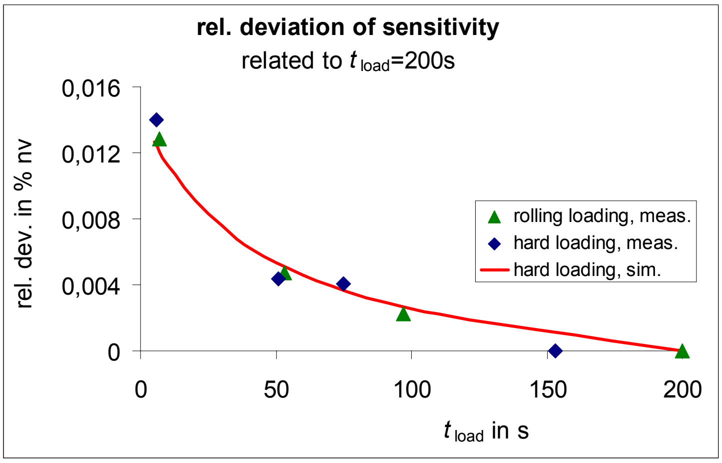

Fig. 3: Effect of creep on the sensitivity (100% loading value). Comparison of some measurements with the corresponding simulation. A scaling factor of 1,3 vertically shifts the simulation curve into the right position.

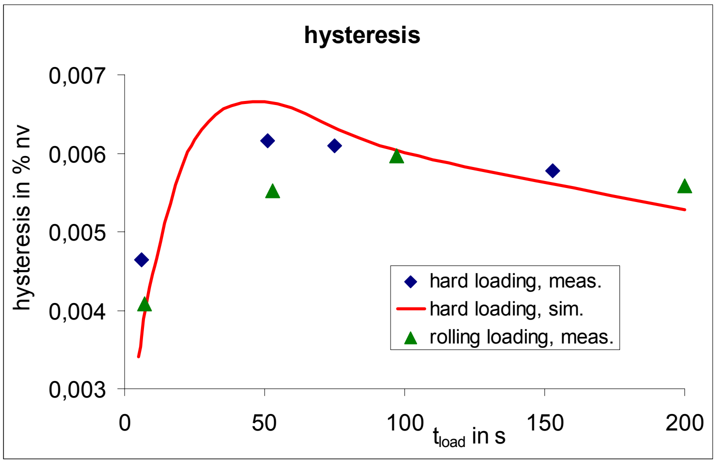

Fig. 4: Effect of creep on the hysteresis. Comparison of some measurements with the corresponding simulation. A scaling factor of 1,3 vertically shifts the simulation curve into the right position.

These difficulties affect the attempt to duplicate measurements by calculation. Nevertheless, the results justify the use of simulation for demonstrating the principal effect of creep. In addition, only the differences between two simulations (e.g. simulations with t_{Load}=200 s and t_{Load}=10 s, t_{Load} is the time for loading from 0% to 100% or vice versa) are examined here. For differences the problem calling for a scaling is eliminated.

For a number of combinations of creeping parameters, the differences mentioned above were calculated. It was found that for given time constants the values of relative deviations of sensitivity and hysteresis lay in a plane in the Cartesian co-ordinates of these relative deviations and a_1 and a_2. It thus is possible to scale the results found for a combination of a_1, a_2 and t_{Load} from a given range of creeping to another. In the figures 5 and 6, the results of such simulations are shown. For $a_1 = a_2 = 0{,}0001$, the dependence of sensitivity and hysteresis on t_{Load} are shown. The time constants are varied in three steps: typ.: τ_1=50 s, τ_2=1000 s, fast: τ_1=20 s, τ_2=500 s and slow: τ_1=100 s, τ_2=2000 s. While the sensitivity follows a monotone function such as an exponential function, the hysteresis has a maximum close to $t_{Load} = 2\tau_1$. In the example of these diagrams, scaling the results to another range of creeping as mentioned above means in order to fit a transducer with creeping parameters $a_1 = a_2 = x \cdot 0{,}0001$ the given curves should be multiplied by x.

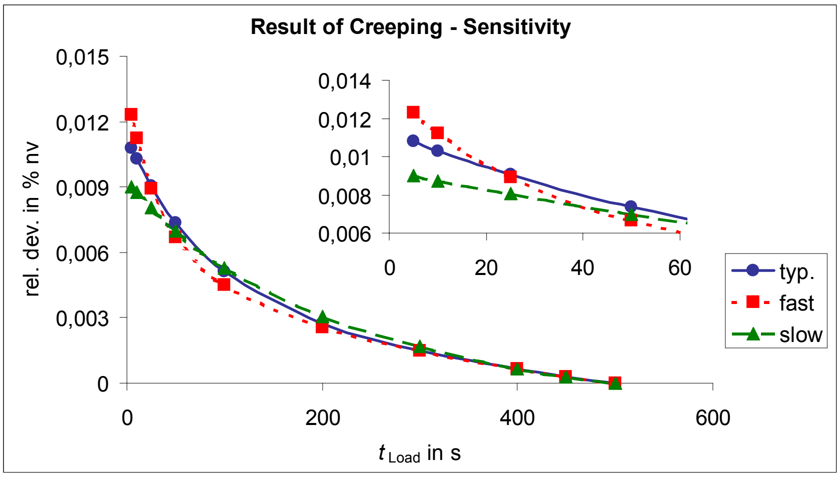

Fig. 5: Effect of simulated creeping to the measured sensitivity. Parameters given in the text.

Looking for a reference transducer according to the demands of the uncertainty budget, the required creep specification for this transducer can be found in the diagrams. For example, if we want to perform continuous calibrations with t_{Load} = 25 s and the deadweight calibration was done with t_{Load} = 200 s, we find in figure 5 that the sensitivity deviation amounts to (0,009-0,003)%=0,006% of the nominal value using a transducer with $a_1 = a_2 = 0{,}0001$. If a budget of up to 0,01% is available for this contribution, the reference transducer should be specified with $a_1 = a_2 < 0{,}00016$. The same applies by analogy to the hysteresis.

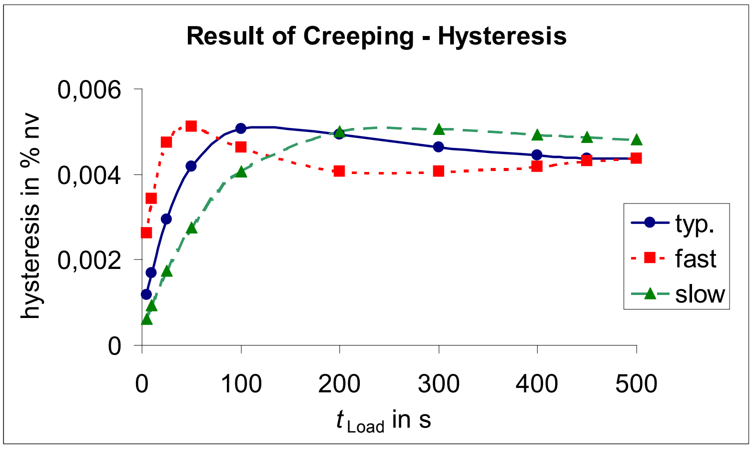

Fig. 6: Effect of simulated creeping to the measured hysteresis. Parameters given in the text.

Other parameters of interest for the selection of reference transducers are stability and transverse-force sensitivity. Laboratories without re-calibration capabilities need reference transducers with a good long term stability. As it is practical to change only the position of the test transducer during calibration, the rotation effect of the reference and thus its transverse-force sensitivity should be very small.

Even if the creep parameters are well known and it is possible to calculate the behaviour of the transducer under different time regimes, the question as to what result is the “right” one, is not answered. It depends on the circumstances whether the short-time result with low creep contributions or the long-time result with nearly complete creep is the better one.
In another investigation the effect of different loading sequences was tested. Linearly increasing and decreasing load with (a) or without (b) smoothed edges, linearly increased load with reduction of velocity at certain calibration points (c) and linearly increased load with stopping at certain calibration points (d) were compared. It was found that for sequences (c) and (d), the proposed aim of getting a greater number of values at the important points was reached but the change of the motor speed in short time produced a lot of mechanical disturbance. The optimum is a sequence (a) without starting ramp and a short stopping ramp, which avoids overloading at the point of reversal of the torque.

Amplifiers:

Amplifiers for continuous calibration should be capable of simultaneously performing the read-out for the two channels needed. Furthermore, the signal processing should in both channels be the same and the read-out rate should be high enough for fast measurements. For the interpolation of the measurements, a number of about 50 is needed. With t_{Load} = 5 s, the rate of the amplifier should be 10 Hz.
Small differences in the filter frequencies of identical amplifier channels are possible. By performing two measurements with crossed channels, the filter-difference Δf can be determined and taken into account in the uncertainty budget. Using the filter frequency f, the signal difference ΔS and the signal velocity $\dot{S}$ from the crossed channels experiment, Δf is given by:

$$\Delta f = \frac{f^2 \Delta t}{1 - f \cdot \Delta t}, \quad \Delta t = \frac{\Delta S}{\dot{S}} \quad . \qquad (5)$$

On a typical amplifier a filter difference of about $6 \cdot 10^{-3}$ Hz was measured. This leads to relative deviations of about $2 \cdot 10^{-5}$ of the nominal value.

Read-out:

As the signals of reference and test transducer change during measurement, it is necessary to read them out at the same time. In the case of a constant delay Δt between the trigger points of the channels, the response of the test transducer will be shifted by $\dot{S}\,\Delta t$ for increasing load and by $-\dot{S}\,\Delta t$ for decreasing load. In the characteristics diagram for the tested transducer the up and down branches are mismatched at the point of reverse by $2\dot{S}\,\Delta t$, therefore this problem is reflected in the calibration result.

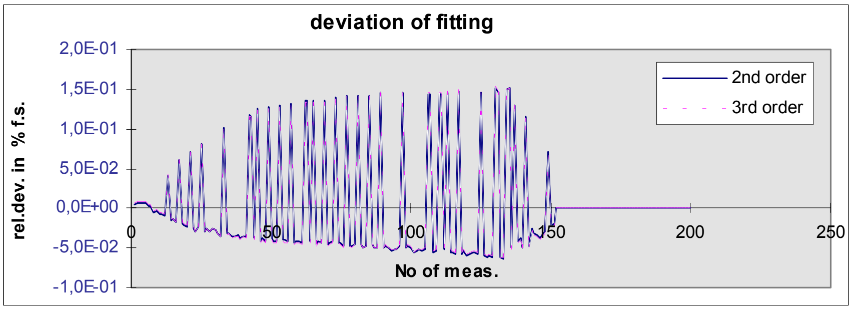

Fig. 7: Recognition of trigger instability in the deviations of the fit from the measurements.

Under instable triggering conditions, positive and negative delays are statistically distributed. In the calibration result no mismatch indicates the problem though the relative deviation can amount to several 10^{-4}. The dependence of the test transducer signal on the reference transducer signal is to be fitted in order to interpolate the signals at the points similar to a step calibration. The deviation of this fit from the measurements is very sensitive to instable signals. To detect trigger malfunction and single read-out errors (peaks) an optical check of the diagram as in figure 7 is necessary.

Data processing:

After a load-unload sequence the acquired data include pairs of output signals from reference and test transducer. Subsequent data processing is necessary to convert the reference signal into a torque value, whereas a third-degree polynomical should be used both for the increasing and for the decreasing part of the measurement. Furthermore, if the maximum torque does not reach the nominal value of the reference, a correction of the hysteresis is required.

The averaging effect of the interpolation yields smooth results. Therefore steady and well formed curves are not an indication of good calibrations and the check for mistakes has to be made in the raw data.

For example, constant parts at the beginning or end of a loading due to delay in the motor control should be truncated to avoid weighting by number in the fit.

Conclusions:

Continuous calibrations can be performed much faster than step calibrations. Due to the change of the signals during the measurement, compared to the step method, some new problems occur. This paper presents strategies to handle these problems with a view to limiting the influence of the most important sources of uncertainty connected with the continuous method. Following these strategies, continuous calibrations complying with class 0,2 of the EA Guideline EA-10/14 are possible.

References:

[1] Manfred Dietrich, Kriechkorrektur der Meßwerte von Kraftaufnehmern, Berlin 1996, internal report

[2] EA-10/14:2000-07, EA Guidelines on the Calibration of Static Torque Measuring Devices

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