XVIII IMEKO WORLD CONGRESS
Metrology for a Sustainable Development
September 17 – 22, 2006, Rio de Janeiro, Brazil

25 kN·m TORQUE CALIBRATION MACHINE REACHES U_{bmc} = 0.008 % USING NEW DESIGN FEATURES

Hans W. Werner [1], Daniel Schwind [2]

[1] Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany, Hans-Werner.Werner@hbm.com
[2] GTM Gassmann Testing and Metrology GmbH, Bickenbach, Germany, Daniel.Schwind@gtm-gmbh.com

Abstract: Due to the need to calibrate high-precision torque transducers also for production purposes, a suitable torque reference standard had to be built up. Using new design features and qualifying the calibration machine by self-contained measurements and advanced measurement uncertainty calculations, resulted in a best measurement capability of U_{bmc} = 0.008 %.

Keywords: torque, machine, uncertainty.

1. INTRODUCTION

For about 15 years, HBM’s 20 kN·m torque reference standard was state-of-the-art for providing precision torque transducers and calibration service. It is one of HBM's torque calibration machines accredited in the DKD (Deutscher Kalibrierdienst) and represented the national torque standard for some years up to 1995. Due to its age, its U_{bmc} deteriorated to 0.02 %, respectively 0.04 %. However, today this isn’t sufficient anymore, as more and more users ask for increasingly accurate torque transducers. So, HBM has been looking for a partner who could provide a suitable calibration machine.

GTM offered a technologically outstanding solution using both strain-controlled hinges and an active control to eliminate all parasitic bearing moments. In order to significantly extend the calibration capability, a range of 100 N·m to 25 kN·m in 100 N·m steps had to be covered. So, a machine with a measuring range five times larger than those already existing had to be built up. Application for DKD accreditation was based on self-contained measurements with torque transducers selected from HBM’s series production and a self-developed measurement uncertainty model. Comparison calibrations at PTB provided the necessary reference data for this purpose.

Finally a best measurement capability of U_{bmc} = 0.008 % in the range from 100 N·m to 20 kN·m could be reached. In the range up to 25 kN·m, a more theoretical evaluation was required and resulted in U_{bmc} = 0.01 %.

2. TRACEABILITY OF TORQUE IN GERMANY

Since 1990, PTB has been committed to intensive research and development tasks in the field of the measurand torque. At PTB, torque can meanwhile be traced over nine powers of ten in the range from 10^{-3} N·m to 10^{6} N·m at best possible measurement capability from a current perspective. Among others, a 20 kN·m torque standard machine based on the dead weight principle with a best measurement capability of 0.002 % is available.

This creates favorable conditions in Germany for developing torque machines that also use other technologies and principles of function. Before the start of the project, HBM and GTM - in agreement with PTB - have defined the goal which was not only to reach the best possible measurement capability but also to confirm the absolute value of torque in Germany. So, the calibration of the lever length, of the local gravity and of the masses helped to create another primary standard in the torque range of up to 25 kN·m.

Principally, there are two options for the traceability of torque machines used for industrial purposes within the DKD: The simpler method uses transfer transducers exclusively for determining torque and the measurement uncertainty. With the more elaborate method that can only be applied using dead weight machines, the lever-mass system is first calibrated with fractions of the measurement uncertainty in the magnitude of 10^{-6}. Calibration of the fully operational measuring equipment then follows in a second step using transfer transducers.

3. TECHNICAL DETAILS OF THE DESIGN

3.1 Principal design

The principal design of the measuring equipment using a two-arm lever with strain-controlled hinges, binary stacked masses and a spring-controlled dummy load with electro-mechanical stops has been described in detail in [1]. The most important feature of the machine is that it measures all moments affecting the lever system and then eliminates all parasitic bearing moments by an active control.

The calibration object and the torque machine with all its components is to be considered a closed system that is not affected by external moment. Torque exerted by the torque machine completely acts on the calibration object. However, this only applies, if no other moments or forces can come to act on the transmission path from the torque generation with the lever-mass system to the calibration object. Based on this requirement, lever and masses must be constructed accordingly and an appropriate adjustment mechanism must be allowed for. The key elements therefore are the introduction of the mass forces into the lever and the mounting of the lever to the machine frame.

For years, GTM has consistently advanced the concept of strain-controlled hinges; the hinges were used in over 15 measuring machines. The largest torque machine realized so far was a 5 kN·m machine; the experiences gained with the smaller machines now needed to be utilized for the largest torque machine worldwide based on the dead weight principle with direct load at HBM.

To introduce the mass forces, the strain-controlled hinges offer the advantage of fatigue resistance and stability and at the same time a precise definition of the lever length.

For mounting the lever on the machine frame, the strain-controlled hinges represent an effective means to save costs already during procurement and, because of their service friendliness, especially also in the long-term comparison with other mounting types.

However, the main advantage of the strain-controlled hinges compared with alternative methods is the information on the active bending moments allowing a complete description of the closed system. Since no moments act externally, the sum of the moments is made up of the lever-mass system, the moments in the strain-controlled hinges M_{Hinges} and the torque M_{Torque} acting on the calibration object, see formula (1).

$$\Sigma M = 0$$
$$= m \cdot g_{\text{loc}} \cdot l + M_{\text{Hinges}} + M_{\text{Torque}} \quad (1)$$

The measured moment of the strain-controlled hinges is added as input variable to the control loop for the counter torque drive; target value of the control is 0 N·m. This renders the moment of the hinges as zero and the moment of the calibration object corresponds to the moment of the lever-mass system, see formula (2) and (3).

$$M_{\text{Hinges}} = 0 \quad (2)$$
$$M_{\text{Torque}} = -m \cdot g_{\text{loc}} \cdot l \quad (3)$$

Fig. 1. View of one set of masses, lever and operation platform

The two 1.6-m-lever-arms are made of the material invar. They each have to carry up to 8 masses of non-magnetizable stainless steel for direct loading, so that a torque range from 100 N·m to 25 kN·m in 100 N·m steps is covered (see figure 1 and figure 2).

The total length of the lever between the two couplings of the masses has been precisely adjusted and then calibrated. See description of the method in [2].

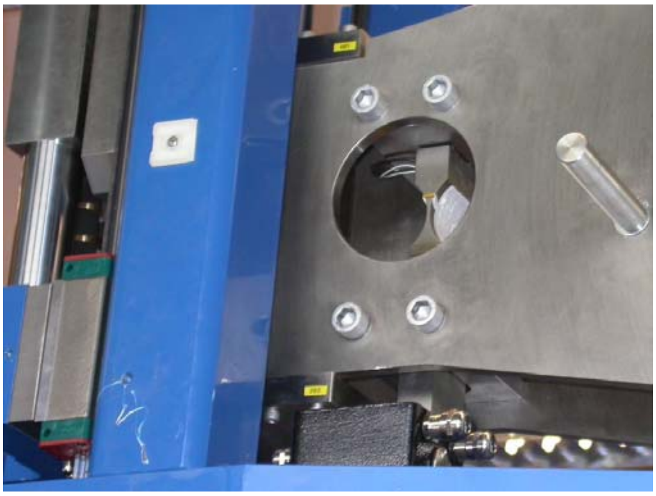

Fig. 2. Strain-controlled mass hinge

3.2 Line of force application using bending beams

Adjustment and calibration are performed with unloaded hinges. It is intended that during operation the force application axis will be exactly in the middle of the hinge beam. This only applies for purely axial load without bending the hinge beams, but for induced bending moments the line of force application will be shifted by *e* (see figure 3).

The question arises as to how great the expected shift of the force application axis will be. After all, at their narrowest point the hinge springs of the mass coupling have a width *b* of 52 mm and a thickness *s* of 2 mm (see figure 3).

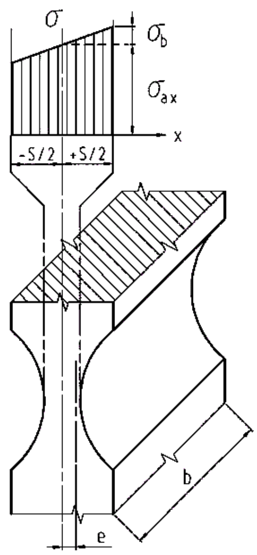

Fig. 3. Shift of force application axis

The shift e can be calculated as follows:

$$M = e \cdot F = b \cdot \int_{x=-\frac{s}{2}}^{x=+\frac{s}{2}} \sigma \cdot x \, dx \quad (4)$$

$$= b \cdot \int_{x=-\frac{s}{2}}^{x=+\frac{s}{2}} (\sigma_{ax} + \frac{2 \cdot \sigma_b}{s} \cdot x) x \, dx$$

$$= b \cdot \left[\frac{1}{2} \sigma_{ax} \cdot x^2 + \frac{2}{3} \frac{\sigma_b}{s} \cdot x^3 \right]_{x=-\frac{s}{2}}^{x=+\frac{s}{2}}$$

$$= \frac{1}{6} b s^2 \cdot \sigma_b$$

$$e = \frac{1}{6} \frac{b s^2}{F} \cdot \sigma_b \quad (5)$$

σ_b is a residual bending strain of approx. 0.002 N/mm² remaining as mounting moment during the control process.

In the worst case, the shift effect can be observed in the middle cross-hinge bearing as well as in the mass couplings.

$$\frac{\Delta l}{l_0} = \frac{2e}{l_0} \quad (6)$$

The result will be a lever arm change according to figure 4.

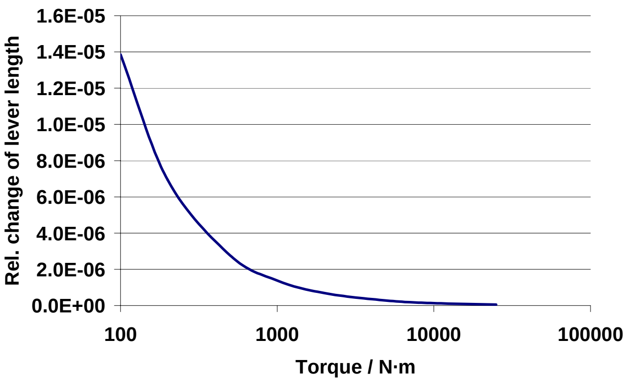

Fig. 4. Relative change of lever arm length

3.3 Lever material invar

The lever length will also be affected by the material choice. In order to minimize temperature effects, invar alloy was used with a thermal expansion coefficient of about (0.5 … 1) $\cdot 10^{-6}$ K^{-1}. The fact that invar's relative change of length is about $1 \cdot 10^{-5}$ per year is quite unknown [3]. Aged alloys from invar 36 have proved more time stable than alloys from superinvar which provides higher thermal stability.

So, HBM and GTM chose aged invar 36 for lever material. In order to verify the material's stability, a 500-mm-gage-block has been cut out of the raw material of the lever. It is stored under the same ambient conditions as the lever and is recalibrated each year.

4. DATA ACQUISITION METHOD

4.1 Traceability, transfer standards

It was agreed by PTB that all measurements were to be taken by HBM. In order to provide reference data, the torque transducers used as transfer standards at first should be calibrated at PTB.

So HBM selected from their series production a set of transducers covering the measuring range of the machine. One major requirement was that the transducers' measuring ranges should be widespread and overlap each other if possible (see table 1). Especially the lower end of the machine's range should be examined very intensively. Finally, 10 measurements for clockwise and anti-clockwise torque with different transducers were used for proving traceability.

N·m	Tra. A	Tra. B	Tra. C	Tra. D	Tra. E
100	X				
200	X	X			
300	X	X			
400	X	X	X		
500	X	X			
600		X	X		
800		X	X		
1000		X		X	
1200			X		
1500				X	
1600			X		
2000			X	X	X
2500				X	
3000				X	
4000				X	X
5000				X	
8000					X
12 000					X
16 000					X
20 000					X

Table 1. Torque steps used with the transfer standards

4.2 Tests for determining uncertainty effects

GTM as the designer of the machine knows best which uncertainty effects might influence the intended high-precision measurements. So they performed a lot of tests to find out the actual size of the uncertainty components caused by the different mechanical characteristics of the machine. They provided data for:

- Symmetry of the lever arms,
- Sensitivity to interfering moments like eccentric coupling of masses,
- Control deviation,
- Resolution (as a function of the lever's stability),
- Zero return, affected by the energy stored in the strain-controlled hinges,
- Bearing remanence,
- Zero drift caused by temperature.

See underlined letters as reference for formula (7).

5. MEASUREMENT UNCERTAINTY

After determining the uncertainty effects caused by the machine's mechanical behavior, an uncertainty model had to be set up. It has been based on [4] and [5]. Due to the particularities of both the quantity torque and the design features of the machine, some additional factors had to be taken into account.

Formula (7) represents the calculation of the actual torque applied by the calibration machine including all uncertainty effects. Estimates of the parasitic moments are zero.

The uncertainty calculation carried out in a self-developed evaluation sheet (see figure 4) has been based on these data.

$$M_{\mathrm{TCM}} = \left(m \cdot g_{\mathrm{loc}} \cdot \left(1 - \frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{m}}} \right) \cdot (l + \Delta_{\mathrm{Symm}}) \cdot (1 - \delta x_{\mathrm{Ecc}}) \cdot (1 - \delta x_{\mathrm{Cont}}) + \delta x_{\mathrm{Res}} + \delta x_{\mathrm{Zero}} + \delta x_{\mathrm{Rem}} + \delta x_{\mathrm{Drift}} \right) \cdot (1 - \Delta_{\mathrm{Trace}})$$

with $$(1 - \Delta_{\mathrm{Trace}}) = 2 - \frac{\overline{M_{\mathrm{TCM}}} \cdot (1 - \Delta_{\mathrm{RelDev}}) \cdot (1 - \Delta_{\mathrm{HysTCM}})}{\overline{M_{\mathrm{TSM}}}} - \Delta_{\mathrm{Drift\_TraStd}} - \Delta_{\mathrm{Realisation}} \qquad (7)$$

where

- ρ_{L} : Density of ambient air
- ρ_{m} : Density of masses applied
- $\overline{M_{\mathrm{TCM}}}$: Mean value of torque indicated by the transfer standard in the torque calibration machine at HBM (TCM)
- $\overline{M_{\mathrm{TSM}}}$: Mean value of torque indicated by the transfer standard in the torque standard machine at PTB (TSM)
- δx : Parasitic moments; indices see section 4.2
- Δ_{Symm} : Lever arm length deviation caused by asymmetry
- Δ_{RelDev} : Relative deviation of the mean torque values between TCM and TSM
- Δ_{HysTCM} : Relative hysteresis of the TCM determined taking the hysteresis of the transfer standard in the TSM into account
- $\Delta_{\mathrm{Drift\_TraStd}}$: Relative long-term drift of the torque transfer standard
- $\Delta_{\mathrm{Realisation}}$: Relative standard uncertainty of torque realization at PTB

Evaluation of traceability measurements of a torque calibration machine TCM with direct load and cross hinge using torque transfer standards

Transfer standard: **Ref. A / 500 N·m (bridge 1)** — TCM: **25 kN·m (HBM)**
Serial no.: 44640034 — rel. drift: ± 0.003% — Load direction: ◉ clockwise torque ○ anticlockwise torque
Unit of the indication: mV/V — HBM Version Dm-k-03
Unit of the torque steps: N·m

Indication — TSM (=PTB reference): Reference lab: PTB 1.13; Amplifier: DMP40; Serial no.: ptb 962720026 — TCM (=calibration machine): Amplifier: DMP40; Serial no.: 65120010

Torque N·m	TSM 0°	TSM 120°	TSM 240°	U_{TSM} (k=2)	TCM 0°	TCM 120°	TCM 240°	Mass kg	Mass ± u
100	0.308 93	0.308 93	0.308 927	0.002%	0.308 923	0.308 917	0.308 918	6.371 885	0.0002%
200	0.617 908	0.617 906	0.617 9	0.002%	0.617 881	0.617 875	0.617 896	12.743 747	0.0002%
300	0.926 911	0.926 906	0.926 897	0.002%	0.926 858	0.926 879	0.926 884	19.115 632	0.0003%
400	1.235 923	1.235 918	1.235 904	0.002%	1.235 842	1.235 866	1.235 876	25.487 466	0.0002%
500	1.544 935	1.544 926	1.544 91	0.002%	1.544 829	1.544 852	1.544 873	31.859 351	0.0003%
400	1.236 009				1.235 89				
300	0.927 05				0.926 95				
200	0.618 054				0.617 989				
100	0.309 032				0.309 034				

Evaluation

N·m	TSM Hysteresis	TSM Mean value	TSM Reproducibility	u(TSM)	TCM Hysteresis	TCM Mean value	TCM Reproducibility	u(TCM)	Fixing and Result: Correction K	U_{bmc}
100	0.000 102	0.308 929	0.000 003	0.000 001	0.000 111	0.308 919	0.000 006	0.000 002		**0.007%**
200	0.000 146	0.617 905	0.000 008	0.000 002	0.000 108	0.617 884	0.000 021	0.000 006		**0.007%**
300	0.000 139	0.926 905	0.000 014	0.000 004	0.000 092	0.926 874	0.000 026	0.000 008		**0.007%**
400	0.000 086	1.235 915	0.000 019	0.000 006	0.000 048	1.235 861	0.000 034	0.000 01		**0.007%**
500	0.0	1.544 924	0.000 025	0.000 007	0.0	1.544 851	0.000 044	0.000 013		**0.007%**

N·m	*Rel. Deviations*	u(TSM)	Δ_{HysTCM}	Δ_{RelDev}	u(TCM)	U	E_n (U) →	E_n (U_{bmc})
100		0.000%	0.003%	-0.003%	0.001%	0.0056%	0.56	**0.45**
200		0.000%	-0.006%	-0.003%	0.001%	0.0064%	0.52	**0.48**
300		0.000%	-0.005%	-0.003%	0.001%	0.0060%	0.56	**0.48**
400		0.000%	-0.003%	-0.004%	0.001%	0.0056%	0.78	**0.62**
500		0.000%	0.000%	-0.005%	0.001%	0.0054%	0.87	**0.67**

------- *U(bmc) is ok.* -------

Fig. 5. Measurement evaluation

As we found out, the biggest fraction of the measurement uncertainty is caused by the drift of the transfer standards (see figure 6). And it is of a similar size for all five transducers and all their torque steps in both loading directions.

During the qualification phase of the new equipment we assumed a drift of 0.003%. That fitted very well with the results, when comparing the measurements of PTB and HBM. So, the transducers and their drifts are considered to be crucial when proving such an ambitious best measurement capability.

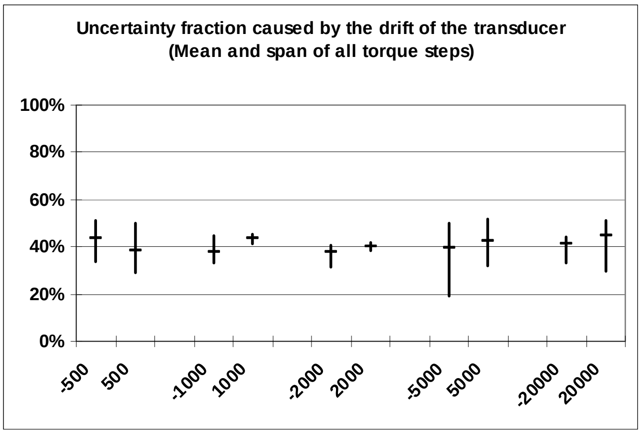

Fig. 6. Uncertainty caused by the drift of the transducer

6. CONCLUSION

The resulting values of the normalized error $E_n < 1$ confirmed the best measurement capability of U_{bmc} = 0.008 % up to 20 kN·m (see figure 7).

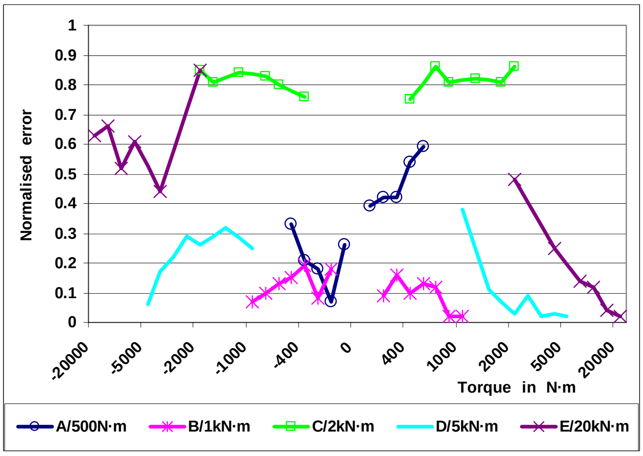

Fig. 7. Normalized error E_n of the reference transducers

In future, we will have to consider two important factors - transfer standards and invar length - as they both have a significant influence on maintaining the high level of accuracy of the new device.

REFERENCES

[1] H. Gassmann, T. Allgeier, and U. Kolwinski, „A new design of primary torque standard machines“, Proceedings of the 16th IMEKO World Congress, Vienna, 2000

[2] R. Oliveira, L. Cabral, U. Kolwinski and D. Schwind, „Performance of the new primary torque standard machine of INMETRO, Brazil“, Proceedings of the 19th IMEKO TC3 Conference, Cairo, 2005

[3] S.F. Jacobs, „Measuring Invar's Dimensional Stability“, The Invar Effect: A Centennial Symposium, edited by Jerry Wittenauer, TMS 1996, pp. 157-169

[4] A. Sawla, “Uncertainty scope of the force calibration machines”, Proceedings of the 16th IMEKO World Congress, Vienna, 2000

[5] "Guide to the Expression of Uncertainty in Measurement", International Organization for Standardization, ISBN 92-67-10188-9, First edition 1995