Metrological Characterization of a 20 N·m Torque Calibration Standard Machine at PTB, Germany

C Schlegel¹, D Röske¹, D Mauersberger¹ and Paul Hohmann²
¹Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig, Germany
²CEH Calibration Engineering Hohmann, Am Schlaggraben 9, D-63853 Mömlingen

E-mail: Christian.Schlegel@ptb.de

Abstract. This article describes a new deadweight torque calibration machine for the range of 100 mN·m to 20 N·m at PTB. Construction details as well as a description of the main operation principle will be given. The uncertainty of the provided torque steps will be calculated according to the conventional error propagation according to the GUM. The obtained uncertainty will be verified by comparison measurements with the PTB 1 kN·m deadweight torque standard machine.

1. Introduction
The machine presented in this article is a torque standard machine, which means that the torque is traced back to the units of kg, m and s of the International Systems of Units (SI). Several similar machines are in operation in the Physikalisch-Technische Bundesanstalt (PTB) [1,2] as well as in other National Metrology Institutes [3,4]. For PTB, the machine became necessary to close the gap between the 1 kN·m and the 1 N·m standard machines. So far, the torque in the range of 1 N·m to 20 N·m was calibrated mainly with a reference torque calibration machine, where the transducer under test has relied on the precision of the reference transducer. In the last few years, more and more accredited calibration laboratories in Germany have come into operation. These laboratories demand the highest possible accuracy for their transfer transducers. This is only possible with the use of so-called “dead weight” calibration machines, where the force is initiated by weights in the Earth’s gravitational field.

2. Construction and operating principle of the machine
The main task of machine described is a traceable calibration of torque transducers. The traceability will thereby be realized by the length of a lever arm and the weights of several masses which can be arranged in such a way that their force acts exactly perpendicularly to the lever arm. To obtain a very precise contact point of the force on the lever, very thin metal bands serve as connection in the force flow between the lever and the mass stack, see Figure 1 d. The lever is a double-arm design, so that both clockwise and anticlockwise torque can be generated. In Figure 1 one can see an overview of the 20 N·m standard torque calibration machine. Each side of the machine has a mass chain of 22 mass pieces, which are arranged in 3 mass blocks, see Figure 3. The distribution of the mass pieces can be seen in Table 1. If the machine is not being in operation, the rod of the mass chain is clamped by a clamping mechanism. If a torque applied, the supporting arm (Figure 1, e) is positioned under the lever in such a way that only a gap of 15 µm between the lever arm and support arm will remain.
The masses will be deposited on their own support points on the main mass rod and the clamping will be opened. The lever then moves to the supporting arm and comes to rest. Therefore, the force transducer connected with the support arm indicates a specific weight force. The force can then be reduced relatively quickly with the counter drive motor. If the force is zero, a fine adjustment will be made by controlling the horizontal lever arm position. After that, the supporting arm is lowered and the lever arm with the masses is free. The measurement value can then be taken for this torque step.

| Mass Stack  | Subset 1          | Subset 2          | Subset 3          | Subset 4          | Σ Mass |
|-------------|-------------------|-------------------|-------------------|-------------------|--------|
| Stack 1     | 3 x 100 mN·m      | 3 x 100 mN·m      | 3 x 200 mN·m      | 1 x 300 mN·m      | 1.5 N  |
|             | 1 x 100 mN·m      |                   |                   |                   |        |
| Stack 2     | 1 x 400 mN·m      | 1 x 400 mN·m      | 2 x 500 mN·m      |                   | 1.5 N  |
| Stack 3     | 3 x 1 N·m         | 3 x 2 N·m         | 1 x 4 N·m         | 1 x 4 N·m         | 17.0 N |

3. Uncertainty determination

The uncertainty of the provided torque of the machine can be derived from the definition of torque, $\tilde{M}$, which is defined as the vector product between position vector, $\tilde{r}$ (the vector from the reference point of the torque axis to the point where the deadweight force acts) and the force vector $\tilde{F}$: $\tilde{M} = \tilde{r} \times \tilde{F}$. This equation leads to the model equation for the torque determination using the deadweight force, $m \cdot g$, with the acting mass, $m$ and the local gravitational acceleration, $g$ as well as the lever length, $l$.

$$M = m \cdot g \cdot l \left(1 - \frac{\rho_L}{\rho_m}\right) \cos(\alpha) + \sum_{i=1}^{n} \Delta M_i \quad (1)$$

To correct the air buoyancy of the mass pieces, the air density, $\rho_L$ and the density of the mass, $\rho_m$ must be considered. The angle $\alpha$ is the angle of inclination of the lever against the horizontal. The $\Delta M_i$ are additional influencing quantities which are in the actual case the friction moment of the air bearing, $M_{f}$ a small additional moment $M_D$, due to the air flowing through the nozzle into the air gap of the air bearing and moments $M_F$ induced through other undesired force effects (for example air flows onto the masses and the lever, magnetic and electrostatic forces etc.). In [1], a more detailed explanation and an
estimate of their uncertainties can be found. The model equation (1) can now be treated with the error propagation formalism according the GUM, which leads, for example, to the uncertainty budget in Table 2. $\times 10^{-6}$ for the 20 N·m torque step.

Table 2. Uncertainty balance for the 20 N·m step (22 weights)

| Quantity $X_i$ | Estimate $x_i$ | Standard uncertainty $w(x_i)$ | Distribution function | Sensitivity coefficient $c_i$ | Contribution to relative measurement uncertainty $w(x_i)$ |
|----------------|----------------|--------------------------------|-----------------------|-------------------------------|----------------------------------------------------------|
| $m$ 8.1541055 kg | 13.8592 mg | normal | 2.45 N·m kg$^{-1}$ | 1.70$\times 10^{-6}$ |
| $g$ 9.812524 m s$^{-2}$ | 5 μm s$^{-2}$ | normal | 2.038 N·s$^{-2}$ | 5.10$\times 10^{-6}$ |
| $l$ 0.25000 m | 2 μm | normal | 80 N | 8.00$\times 10^{-6}$ |
| $\rho_c$ 1.20 kg m$^{-3}$ | 0.0462 kg m$^{-3}$ | rectangular | -2.5 $\times 10^{-3}$ N·m·kg$^{-1}$ | -5.79$\times 10^{-6}$ |
| $\rho_w$ 7975 kg m$^{-3}$ | 6.09 kg m$^{-3}$ | rectangular | 3.8 $\times 10^{-3}$ N·m·kg$^{-1}$ | 1.15$\times 10^{-7}$ |
| $a$ 0 rad | 0.714 mrad | normal | -1.4 $\times 10^{-2}$ N·m·rad$^{-2}$ | -5.10$\times 10^{-7}$ |
| $\delta M_e$ 1.36$\times 10^{-6}$ N·m | 4.0$\times 10^{-4}$ mN·m | rectangular | 1 | 2.00$\times 10^{-8}$ |
| $\delta M_D$ 0 N·m | 2.9$\times 10^{-4}$ mN·m | rectangular | 1 | 1.45$\times 10^{-8}$ |
| $\delta M_F$ 0 N·m | 2.9$\times 10^{-4}$ mN·m | rectangular | 1 | 1.45$\times 10^{-8}$ |

$M$ 20.0000 (1 $\pm$ 2.01 $\times 10^{-5}$) N·m ($k = 2$)

Figure 2. Some details of the machine are shown. There are three groups of mass blocks which are supported by the platforms p1-p3. The platforms are joined with a lifting frame, e), which can be driven by a stepper motor, f). Other details are the lever position control, which is realized by a laser sensor, a) and a pointer, b), connected with the lever. As indicated, the laser beam of the sensor touches the pointer.

Figure 3. Sectional view of the mass blocks is shown. The masses are interlaced to reduce the length of the mass chain. Altogether 22 individual mass pieces are arranged in such a way. The support points of the mass disks along the main rod are also shown. The shape of the 10th mass block differs significantly from the other ones. This block serves as a support of the overlying nine mass blocks.

Figure 4. Depiction of the support arm, a) to support the lever, to realize a very smooth torque application and to avoid oscillations of the lever arm. During the support of the lever, the force can be measured by a force transducer, b). The whole arm can be moved by an excentre drive, c).
4. Comparison with the 1 kN∙m Standard machine
The obtained uncertainty can be verified through several comparisons with the 1 kN∙m [2] standard machine which are shown in Table 3. The comparisons are undertaken for clockwise and anticlockwise torque and were repeated on different days with slightly different environment parameters.

| Step in N·m | 1 kN·m machine mean value in mV/V | T in °C | H in % | 20 N·m machine mean value in mV/V | T in °C | H in % | relative deviation | $E_n$ |
|-------------|----------------------------------|--------|--------|---------------------------------|--------|--------|--------------------|------|
| +10         | 1.334543                         | 21.52  | 40.3   | 1.334529                        | 21.52  | 43.0   | -1.112 × 10^{-6}   | 0.39 |
| +10         | 1.336974                         | 21.23  | 40.5   | 1.336976                        | 21.23  | 43.2   | 1.473 × 10^{-6}    | 0.05 |
| +10         | 1.336974                         | 21.23  | 39.8   | 1.336958                        | 21.23  | 44.8   | -1.148 × 10^{-6}   | 0.41 |
| -10         | -1.336968                        | 21.25  | 39.8   | -1.336974                      | 21.25  | 42.6   | 3.967 × 10^{-6}    | 0.14 |
| -10         | -1.336968                        | 21.29  | 41.6   | -1.336954                      | 21.29  | 46.6   | -1.076 × 10^{-6}   | 0.38 |
| +20         | 1.324040                         | 21.37  | 41.6   | 1.324053                        | 21.37  | 43.0   | 1.014 × 10^{-6}    | 0.36 |
| +20         | -1.324140                        | 21.33  | 40.8   | -1.324139                      | 21.33  | 43.7   | -1.218 × 10^{-6}   | 0.04 |
| +10         | 1.336976                         | 21.16  | 41.7   | 1.336974                        | 21.16  | 42.5   | -1.532 × 10^{-6}   | 0.05 |
| -10         | -1.336965                        | 21.13  | 41.1   | -1.336973                      | 21.13  | 42.4   | 6.195 × 10^{-6}    | 0.22 |

The relative deviation of the mean values (related to the 1 kN·m machine) is, in all cases, smaller than $2.0 \times 10^{-5}$ which verifies the obtained measurement uncertainty according to Table 2. Using this difference and the relative uncertainties of both machines of $2.0 \times 10^{-5}$ ($k = 2$) leads to the normalized error, $E_n$ given in the last column of Table 3.

5. Conclusion
The new 20 N·m torque standard machine of PTB has a measuring range of 100 mN·m to 20 N·m. The machine can be operated fully automatically for clockwise and anticlockwise torque. With the aid of an air bearing for the main axis of the lever, a low-friction movement of the lever arm can be guaranteed. One feature is the possibility to have a climate chamber around the transducer under test. Comparison measurements with the 1 kN·m standard machine verify a relative uncertainty of $2.0 \times 10^{-5}$ ($k = 2$).

6. References
[1] Röske D 2014 Metrologia 51 87
[2] Adolf K, Mauersberger D, Peschel D 1995 Proc. of the 14th IMEKO TC3 Conference, 5-8 September, 1995, Warsaw, pp 174-76
[3] Gang H, Jiang J, Li T, Zhang Z, Ji H and Zhuang L 2017 Proc. of the 23rd IMEKO TC3 Conference, 30 May to 1 June 2017, Helsinki, http://www.imeko.org/publications/tc3-2017/IMEKO-TC3-2017-009.pdf
[4] Zhang Z, Yue Z, Feng M, Jile J, Gang H and Wei Z L 2017 Proc. of the 23rd IMEKO TC3 Conference, 30 May to 1 June 2017, Helsinki, http://www.imeko.org/publications/tc3-2017/IMEKO-TC3-2017-026.pdf

Acknowledgments
The authors wish thank Holger Kahmann (PTB) for his helpful discussion concerning the mechanical layout.