The New 1 kN·m Torque Standard Machine in National Institute of Metrology, China

Jile Jiang*, Kun Wu, Bin Guo, Shi Wu and Zhimin Zhang
Laboratory of Force and Torque, Division of Mechanics and Acoustics, National Institute of Metrology, China

*Corresponding author email: jiangjl@nim.ac.cn

Abstract. A 1 kN·m deadweight torque standard machine is established in National Institute of Metrology, China. The torque range is 5N·m-1200 N·m. The deadweights utilized in the machine can generate the torque of 1200 N·m, 600N·m, 360N·m, 240N·m, 120N·m and 60 N·m, respectively. The torque can be applied both in clock-wise and counter clock-wise direction in sequential loading process. The aerostatic bearing is introduced to the torque standard machine in order to eliminate the influence of friction. The symmetric V type rotor and stator are used to provide the reliable support both in axial and radial direction. The material of the lever arm is invar alloy, performing with the minimum deformation with the change of the ambient temperature. The counter torque part will make the precise adjustment to make a horizontal alignment of the lever arm. The relative standard uncertainty of the torque generated by the machine is less than 1e-5.

Keywords: Deadweight; Torque; Aerostatic bearing.

1. Introduction
Torque is very essential quantity which needs to be traceably measured precisely in industrial. During the test of the performance of the engine, the reliability of the power transmission system and the process of the assembly, the torque meters need to be calibrated before use. In order to realize the the high precision torque value the national metrology institutes around the world have established series of the torque standard machine based on deadweight mass and the advanced lever supporting techniques[1-4]. In recent years NIM, China has developed 1 N·m, 100 N·m, 20 kN·m deadweight torque standard machine to replace the old torque standard machines which are equipped with knife-edge supporting system. The new founded 1 kN·m deadweight torque standard machine is studied in this research. Generally, many techniques in 1kN·m deadweight torque standard machine are very similar to those in 100 N·m and 20 kN·m deadweight torque standard machine. This paper will focus on structure and the performance tests and the uncertainty analysis.[5,6]

2. Structure of the Torque Standard Machine
The whole structure of the 1kN·m deadweight torque standard machine is shown in figure 1. According to the finite analysis the stiffness characteristics of unilateral lever arm under full load require that the deflection and deformation of full load should be less than 0.05 mm. Standard arm lever system equipment determines the accuracy of the length value, which is the standard value of the length size. The structure of the arm lever was stiff enough with less weight, so as to obtain a high sensitivity of the arm lever.
In case that the failure of the linkage between the torque transducer and the machine, the arm lever protection can prevent the impact to the aero-bearing, the lever arm and the deadweight mass.
Unlike the structure used in 20 kN·m torque standard machine, the suspension of weight is built based on the thin metal plate. The weight suspension with complex structure

In order to realize the torque of 50 N·m, 100 N·m, 200 N·m, 300 N·m, 500 N·m and 1000 N·m, with the consideration of arm lever length, the force of the deadweight is 6.25 N, 12.5 N, 25 N, 37.5 N, 62.5 N and 125 N, respectively. For each type of the deadweight, there are 12 pieces of the mass in each side of the stack, so as to generate 120% of the rated standard torque. There are totally 144 pieces of the deadweight so as to generate the torque in clockwise and counter-clockwise. The structure of the deadweight is shown in figure 2.

The relative most permissible error of the weight is ±2e-6. According to the description in the previous paragraph, there are six types of the weight that will be loaded on the side of the arm. Due to the limitation space of the lift platform of the mass stack, five types of the weight will be assembled on the platform. The 6.25 N deadweight will shear the same position of 12.5 N deadweight if the small torque is about to realized. The deadweight will be loaded in sequence. The maximum loading speed of a single mass will be 1 mm/min. The loading capacity of the platform will be over 600 kg. The structure of the loading platform is shown in Fig.3. Besides, together with the mass stack, the whole loading system will be protected by transparent box, preventing any disturbance due to the air turbulence, vibration, and adhesion of the small matters. Before the assembly of the loading platform the base will also modified with the vibration isolation.

Figure 1. 1 kN·m deadweight torque standard machine.

Figure 2. The structure of the deadweight.

Figure 3. The loading platform.

3. Performance Test

The performance test was carried out by the laboratory since the torque standard machine was finished. The torque sensors, TT1 series, were used to collect the data measured on national torque primary standard machine under well controlled temperature and humidity. The indicator is the amplifier DMP41 (Serial Number: 161920061).

3.1. Repeatability and Reproducibility

Since the new founded 1 kN·m torque standard machine covers torque range of 50 N·m, 100 N·m, 200 N·m, 300 N·m, 500 N·m and 1000 N·m, respectively, the repeatability and reproducibility test results are shown in Fig.4. In repeatability test each load was measured three times in position of 0. In
reproducibility test the torque value was the average value when the torque meter was loaded in position of 0, 120, 240, respectively.

![Figure 4. Repeatability (4a, counterclockwise; 4b, clockwise) and reproducibility (4c, counterclockwise; 4d, clockwise) of 1 kN·m torque standard machine.](image)

Figure 4. Repeatability (4a, counterclockwise; 4b, clockwise) and reproducibility (4c, counterclockwise; 4d, clockwise) of 1 kN·m torque standard machine.

As shown in figure 4, the repeatability is less than 0.002%, except for the value of 10% of 300 N·m in counter clockwise mode. Considering the rotational effect the reproducibility of 1 kN·m torque standard machine is less than 0.003%.

### 3.2. Sensitivity

The indicator would show the difference of the output of the torque meter before and after the small mass was loaded on the end of the lever arm. The obvious and stable change of the output distinguished by the indicator represented the sensitivity of the torque standard machine at a certain range. Here the sensitivity results in the torque range of 50 N·m and 1000 N·m are shown in Table 1.

**Table 1. Sensitivity test.**

| Sensitivity in the torque range of 1000 N·m | Nominal torque (N·m) | Output of torque meter (mV/V) | Relative change of indicator |
|-------------------------------------------|----------------------|-------------------------------|-----------------------------|
| Nominal weight of single mass: 12755580.3 mg | 0                    | 0.000000                      |                             |
|                                            | 100                  | 0.134990                      | 0.00047%                    |
|                                            | 100                  | 0.135009                      |                             |
|                                            | 1000                 | 1.350083                      | 0.00047%                    |
| After placing a mass of 60mg               | 100                  | 0.134990                      |                             |
|                                            | 100                  | 0.135009                      |                             |
|                                            | 1000                 | 1.350083                      |                             |
| After placing a mass of 600mg              | 1000                 | 1.350085                      |                             |

| Sensitivity in the torque range of 50 N·m  | Nominal torque (N·m) | Output of torque meter (mV/V) | Relative change of indicator |
|-------------------------------------------|----------------------|-------------------------------|-----------------------------|
| Nominal weight of single mass: 637779.0 mg | 0                    | 0.000000                      |                             |
|                                            | 5                    | 0.133990                      | 0.00047%                    |
|                                            | 10                   | -0.134007                     |                             |
|                                            | 50                   | -1.338127                     | 0.00047%                    |
| After placing a mass of 3mg                | 5                    | 0.133990                      |                             |
|                                            | 50                   | -1.338131                     |                             |
| After placing a mass of 30mg               | 50                   | -1.338131                     |                             |
As shown in Table 1, 0.00047% of the single mass caused a stable and distinguishable change of the readout.

4. Uncertainty Budget
As shown in Table 2, relative standard uncertainties associated in the new founded torque standard machine was listed.

**Table 2. Uncertainty budget.**

| Source of uncertainty                              | Source of uncertainty | k   | u   |
|---------------------------------------------------|-----------------------|-----|-----|
| Repeatability                                     | 6.2×10^-6             |     |     |
| Reproducibility                                   | 5.3×10^-6             |     |     |
| The mass measurement of weights                   | 3.9×10^-7             |     |     |
| The gravitational acceleration measurement         | 2.0×10^-7             |     |     |
| The variety of air density                         | 3×10^-6               |     |     |
| The density measurement of the weights material    | 8.6×10^-7             |     |     |
| Arm length 3,1                                     | 1.9×10^-6             |     |     |
| Temperature influence                              | 6.9×10^-7             |     |     |
| Loading deformation                                | 2.5×10^-9             |     |     |
| Lever inclination                                  | 0.6×10^-9             |     |     |
| The influence by weight swing                      | 2.449×10^-6           |     |     |
| The influence by non-coaxality of rotation axis and counter axis | 1.732×10^-6           |     |     |
| The influence by friction                          | 2×10^-10              |     |     |
| The relative combined standard uncertainty         | 9.2×10^-6             |     |     |
| The relative combined expanded uncertainty (k=2)   | 1.9×10^-5             |     |     |

5. Comparison to Other Torque Standard Machine
Besides the measurements of the torque sensors, the comparison tests between the new founded 1 kN·m torque standard machine, 100 N·m, torque standard machine and 20 kN·m torque standard machine were also carried out so as to verify the accuracy. The uncertainties of the other tow torque standard machines are listed in Table 3. As shown in Table 3, the principle of the torque generation and the way of lever support of these torque standard machines are same to the 1 kN·m torque standard machine. In the comparisons the torque meters were tested in the position of 0°, 120°, 240°, respectively. The averaged value was used and the load-unloading time was 4 minutes before the reading. The other technical details were referred to CCM.T key comparison protocol. The indicator was also DMP 41.

**Table 3. Uncertainty of the torque standard machine.**

| Torque standard machine | Way of lever support | Way of force generation | Uncertainty (k=2) |
|-------------------------|----------------------|-------------------------|-------------------|
| 100 N·m                 | Aerostatic bearing   | deadweight              | 2e-5              |
| 20 kN·m                 | Aerostatic bearing   | deadweight              | 2e-5              |

The En numbers were calculated as following equation:

\[
E_n = \frac{|x_i - x_j|}{\sqrt{U_i^2 + U_j^2}}
\]

\(x_i\) is the measuring results of the torque meter under a certain torque load. \(U_i\) is the expanded uncertainty of the measuring results, \(x_i\). \(U_i\) can be calculated as following equation:
\[ U_i = k \sqrt{(u_{i,m})^2 + (u_{i,ta})^2 + (u_{i,td})^2} \]  

(2)

\( u_{i,m} \) is the standard relative uncertainty of the torque standard machine; \( u_{i,ta} \) is the standard relative uncertainty of the torque measurement regarding to the repeatability and the positions; \( u_{i,td} \) is the standard relative uncertainty of the torque meter regarding to the drift during the time. Here the value of \( u_{i,td} \) can be omitted because of the time of the comparison is much smaller than one year.

The comparison results are shown in Table 4-7.

**Table 4.** Comparison results.

| Torque (N·m, clockwise) | Measuring results of torque machine (mV/V) | En |
|-------------------------|--------------------------------------------|----|
|                         | 100 N·m                                   | 1000 N·m |    |
| 10                      | 0.132608                                  | 0.132641  | 0.79 |
| 20                      | 0.265222                                  | 0.265230  | 0.10 |
| 30                      | 0.397835                                  | 0.397859  | 0.19 |
| 40                      | 0.530463                                  | 0.530490  | 0.16 |
| 50                      | 0.663089                                  | 0.663124  | 0.17 |
| 60                      | 0.795721                                  | 0.795772  | 0.20 |
| 70                      | 0.928354                                  | 0.928417  | 0.21 |
| 80                      | 1.060998                                  | 1.061072  | 0.22 |
| 90                      | 1.193649                                  | 1.193726  | 0.20 |
| 100                     | 1.326297                                  | 1.326358  | 0.15 |

**Table 5.** Comparison results.

| Torque (N·m, counter-clockwise) | Measuring results of torque machine (mV/V) | En |
|---------------------------------|--------------------------------------------|----|
|                                 | 100 N·m                                   | 1000 N·m |    |
| 10                              | -0.132587                                 | -0.132594  | 0.18 |
| 20                              | -0.265193                                 | -0.265208  | 0.18 |
| 30                              | -0.397814                                 | -0.397834  | 0.16 |
| 40                              | -0.530427                                 | -0.530466  | 0.23 |
| 50                              | -0.663048                                 | -0.663097  | 0.24 |
| 60                              | -0.795679                                 | -0.795720  | 0.16 |
| 70                              | -0.928315                                 | -0.928361  | 0.16 |
| 80                              | -1.060951                                 | -1.061003  | 0.15 |
| 90                              | -1.193598                                 | -1.193655  | 0.15 |
| 100                             | -1.326232                                 | -1.326303  | 0.17 |

**Table 6.** Comparison results.

| Torque (kN·m, clockwise) | Measuring results of torque machine (mV/V) | En |
|--------------------------|--------------------------------------------|----|
|                         | 20 kN·m                                    | 1000 N·m |    |
| 0.50                     | 0.674955                                  | 0.674985   | 0.03 |
| 1.00                     | 1.350050                                  | 1.350088   | 0.01 |
Table 7. Comparison results.

| Torque (kN·m, counterclockwise) | Measuring results of torque machine (mV/V) | En |
|----------------------------------|------------------------------------------|----|
|                                  | 20 kN·m                                | 1000 N·m |    |
| 0.50                             | -0.674999                              | -0.674992 | 0.14 |
| 1.00                             | -1.350091                              | -1.350097 | 0.09 |

Because of the mass stack of 20 kN·m torque standard machine in range of 5 kN·m was loaded in step of 500 N·m, there were only two points compared. According to the comparison results shown in Table 4-7, the torque realized by these three torque standard machine agreed with each other. En=0.79 under 10 N·m in clockwise test can be found in Table 4, which shows the unstable performance of both small torque meter and the torque machine.

6. Conclusions

A 1 kN·m deadweight torque standard machine is established in National Institute of Metrology, China. The torque range can be realized in 5N·m-1200 N·m. With the uncertainty analysis and the comparison to the other torque standard machine, the relative standard uncertainty of the torque generated by the machine is 1e-5. This new founded torque standard machine will be applied for the high precision torque calibration in industry.

Acknowledgments

This research is sponsored by National Key R&D Program of China No. 2017YFF0204905.

References

[1] BIPM key comparison database, Internet: https://www.bipm.org/kcdb/comparison/quick-search?keywords=torque&displayResults=true, accessed in September, 2021.
[2] OHGUSHI Koji, OTA Takashi, KATASE Yoshihisa and TOJO Takuro, “Estimation of the Best Measurement Capability in the 1 kN·m Deadweight Torque Standard Machine,” Proceedings of the 17th IMEKO TC-3 International Conference, 326-332, 2001.
[3] Zhimin Zhang, Yue Zhang, Feng Meng, et al. “Design of 20 kN·m torque standard machine at NIM”, XXI IMEKO World Congress “Measurement in Research and Industry”, Prague, Czech Republic, 2015
[4] D. Röske, “Investigation of the influence of disturbing components on the torque measurement”, 16th IMEKO TC3 conf., pp. 280-285, Taejon, Korea, 1998
[5] Zhang Zhimin, Zhang Yue and etc., “The development of 100 N·m torque standard machine at NIM”, XIX IMEKO World Congress, Lisbon, Portugal, 2009
[6] Averlant P, Lacipiere P, David J M. DEVELOPMENT OF THE NEW LNE 5 kN.m DEADWEIGHT TORQUE STANDARD MACHINE. IMEKO 22nd TC3, 12th TC5 and 3rd TC22 International Conferences 3 to 5 February, 2014, Cape Town, Republic of South Africa