# Investigation of a deadweight force standard machine with a 1 mN – 10 N range

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ABSTRACT
A 10 N small force standard machine with air-bearing support has been developed by NIM. Differing from traditional deadweight force standard machines, this machine is equipped with a balance beam supported by air bearing. The weights of the load frame and deadweight hanging system are balanced, and the initial force is extended to 1 mN. Furthermore, there are innovative designs in the load frame and tension force joint. Performance experiments such as sensitivity, repeatability, and rotation effect are carried out. The uncertainty of this machine is evaluated as $1.0 \times 10^{-4}$ ($k = 2$) in the range of 1 mN – 0.5 N, $4.0 \times 10^{-5}$ ($k = 2$) in the range of 0.5 N – 10 N. The structure of this force standard machine and its key components are introduced in detail. The performance experimental results and uncertainty evaluation are demonstrated in this paper.

## 1. INTRODUCTION

In recent years, the demands of force measurements beyond common ranges are growing. For small force measurements in the range of millinewtons to newtons, there are more and more applications in biology, pharmaceutics, advanced materials, hardness metrology, precision manufacturing, and more. For example, small force transducers in the pharmaceutical industry and small force testing machines for solder in integrated circuit package industry should be measured and calibrated. Small forces from millinewton to newton are required to be traced in instrumented indentation test for hardness and materials parameters [1].

For realising small force, some National Metrology Institutes (NMIs) have developed small force standard machines, with minimum forces at newton or sub-newton range. For instance, a 200 N deadweight force standard machine was established by The Physikalisch-Technische Bundesanstalt (PTB) in Germany. The force range of this machine is from 0.5 N to 200 N [2]. The Korea Research Institute of Standards and Science (KRISS) developed a 22 N deadweight force standard machine, whose minimum force is 0.5 N [3].

However, the minimum force value of China's Calibration and Measurement Capabilities (CMCs) published in the BIPM key comparison database is 10 N at present [2]. Traceable force standard machines below 10 N with high accuracy were found to be lacking. As a result, higher accuracy force measurements in this range cannot be achieved. This issue has an adverse influence on relative fields and industries.

Concerning the structure and design of deadweight force and torque standard machines [4]-[6], a new 10 N deadweight force standard machine has been developed by NIM [7],[8]. Its minimum force is extended to 1 mN. This machine consists of deadweights; an automatic loading and unloading system; a load frame; a deadweight hanging system; a balance beam; and a control system. The structure and special design of the mechanical system and electronic control system are described in the next two sections. In section 4, the performance experiments and results are demonstrated. Uncertainty evaluation is introduced in section 5. Finally, in the concluding section, the major features and characteristics of this machine are summarised.
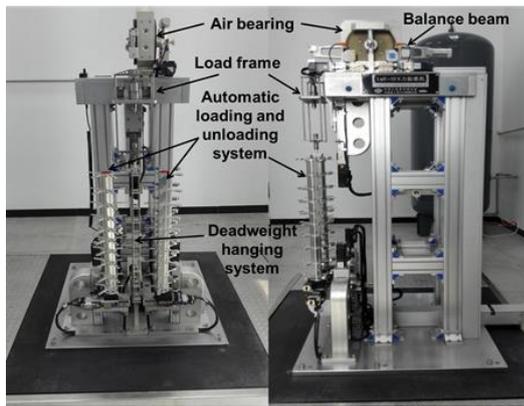
Figure 1. A 10 N deadweight force standard machine.



Figure 2. Balance beam with aerostatic bearing support.

## 2. THE STRUCTURE AND MAIN COMPONENTS OF THE MECHANICAL SYSTEM

Figure 1 shows the structure of the 10 N deadweight force standard machine. Differing from traditional deadweight force standard machines, the aerostatic bearing technique is applied to support the balance beam, and innovative designs and special structures in the load frame and tension force joint are used.

### 2.1. Balance beam with aerostatic bearing support

For mitigating the weights of load frame and deadweight hanging system, a balance beam made by Titanium alloy is used in this machine. Its structure is shown in Figure 2. The end of the beam is a built-in counterweight balance mechanism. By adjusting the position of the counterweights, the weights of the load frame and deadweight hanging system are balanced. There is a fine adjustment mechanism in the middle of the beam. It is used for the fine-adjusting centroid of the balance beam. The position of the beam is measured by two laser displacement sensors, which are placed on two sides of the beam symmetrically. Finally, the beam is adjusted in a state of neutral equilibrium.

A self-developed aerostatic bearing is used for the support of the beam. Compared to knife-edge support, air bearing support has smaller friction and only a rotational degree of freedom. Therefore, standard uncertainty caused by support is minimised. Furthermore, it has the advantage of the measurement and control of the position of the balance beam and the accurate positioning of deadweights.

An air supply system includes an oil-injected air compressor, air dryer, filters, and an air tank. Clean and dry gas with stable pressure is provided by the air supply system and is injected into the bearing surface through the throttle. The gap between the rotor and stator is no larger than 0.01 mm. When it works, there is a very thin pressure film between the rotor and stator. The pressure film can resist the external impact force and make the rotor suspend in the centre of the stator.

A clamping mechanism is composed of two sets of motion module, driven by servo-motors on both sides of the balance beam. As soon as the mechanism clamps the beam, the displacement of the beam is restricted within $\pm$ 0.2 mm. As a result, the beam and air bearing support are protected from unexpected impact or force.

There is a suspending mechanism for the load frame and deadweight hanging system at the end of the balance beam. It has two perpe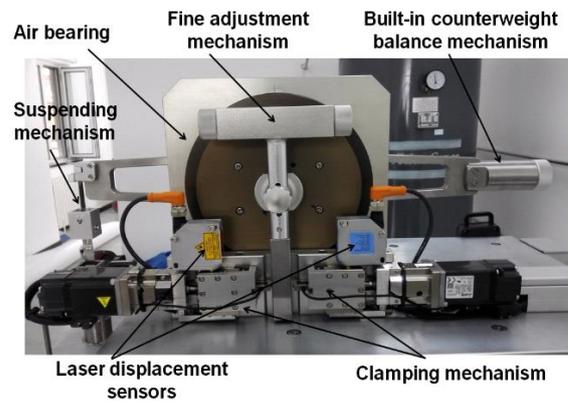ndicularly mounted thin steel strips. This mechanism makes the load frame and deadweight hanging system suspend freely and prevents the influence of additional forces and moments.

### 2.2. Load frame

A compact four-column structure is used as the load frame. Figure 3 shows its structure. It consists of four hollow pillars made by Titanium alloy; upper and lower beams; and a base plate. I-type beams are used for reducing the weights. There is a base plate in the middle of load frame. The upper space of the load frame is applied to the compression force measurement, and the lower space is used for tension force measurement. The position of the base plate can be adjusted through a linear motion module. The motion module driven by a servo-motor can move vertically along the linear guide. In this way, the positioning accuracy of the base plate is 0.02 mm.

### 2.3. A knife-edge universal joint for tension force measurement

In contrast to the traditional tension force joint, a knife-edge universal joint is used. Figure 4 shows its structure. It is composed of a cross head, two knife edges, a universal joint seat, and a universal joint head. The universal joint seat is connected to one knife edge, and the universal joint head is connected to the other knife edge. The two knife edges are set up perpendicularly. As a result, there is only line contact between two edges, and the friction is very small. In addition, this universal joint reduces the standard uncertainty due to the non-coaxiality of the tension force application.

### 2.4. Other components and units

Two automatic loading and unloading systems, which are composed of weight supports and three-dimensional movement
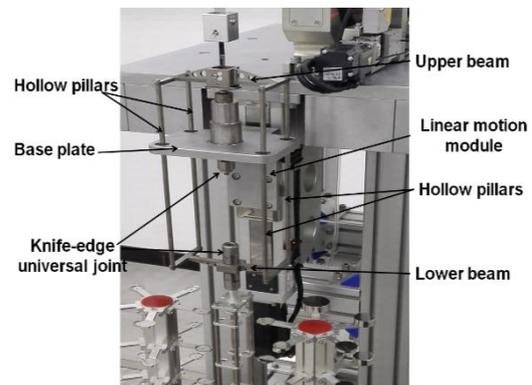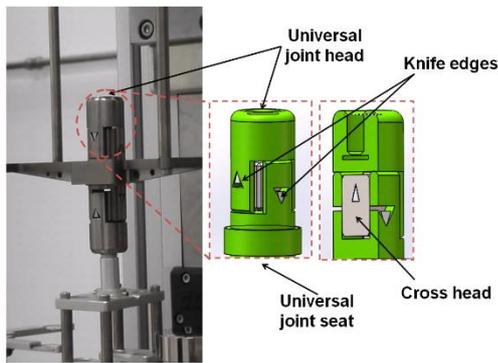


Figure 3. Load frame.

Figure 4. A knife-edge universal joint for tension force measurement.

units, are adopted for loading and unloading deadweights. There are ten layers and five weight supports distributed evenly on each layer. Deadweights are placed on the weight supports. Three-dimensional movement units include rotating, horizontal moving, and vertical moving mechanisms.

There are ten layers in the deadweight hanging system. To prevent it from shaking, a clamping mechanism clamps the hanging system during the loading and unloading processes. As soon as the deadweights are placed on the hanging system, the clamping mechanism releases. Therefore, forces are applied to force the transducer freely in a vertical direction.

Deadweights are divided into ten groups, with the following combinations: $1\,mN \times 10$, $2\,mN \times 10$, $5\,mN \times 10$, $10\,mN \times 10$, $20\,mN \times 10$, $50\,mN \times 10$, $100\,mN \times 10$, $200\,mN \times 10$, $500\,mN \times 10$, and $1\,N \times 10$.

The deadweights of 10 mN - 1 N are made of stainless steel, deadweights of 1 mN - 5 mN are made of Titanium alloy.

This machine is mounted on a marble platform, which is placed on a concrete base block isolated from the floor of the laboratory. There is a plexiglass cover outside of this machine for protecting airflow disturbance and dust.

## 3. THE ELECTRONIC AND CONTROL SYSTEM

The electronic and control system consists of a PC, a Programmable Logical Controller (PLC) and self-developed software. Figure 5 shows the electronic and control system.



Figure 5. The electronic and control system.

There are three control modules: deadweight automatic loading and unloading; balance beam position control; and measurement process control.

Because the fit clearance of the positioning between deadweights and the racks of the hanging system is less than 0.1 mm, the precise positioning of the deadweights is crucial in the loading and unloading process. In the control module of deadweight automatic loading and unloading, absolute coordinate positioning control technology is adopted to ensure the accurate positioning of the deadweights. When starting origin restoration, the positions of the deadweights, which are put on weight supports, are initialised. The deadweights that are to be selected are rotated to the position immediately facing the hanging system by the rotating mechanism. The horizontal moving mechanism transfers the deadweights into the hanging system. While the vertical moving mechanism moves downward, the deadweights are applied to the racks of the hanging system step by step. Unloading is completed in a reverse process. As long as the deadweights are unloaded, they can be restored to their initial positions without any deviation.

The balance beam mechanism balances the weights of the load frame and deadweight hanging system and is in a state of neutral equilibrium. During the force measurement process, the deformation of the force transducer that is to be calibrated causes the balance beam to deviate from its original position. Displacement feedback control is realised by the control module of the balance beam position. According to the design requirements of the control system, the horizontality of the balance beam should not be larger than ±0.1 mm/m and overshoot should be prevented. As soon as the balance beam deviates from its equilibrium position, the change of position is measured by the laser displacement sensors, and the position of base plate is adjusted by the linear motion module. As a result, the balance beam is restored to a position of equilibrium. Under these conditions, the weights of the load frame and deadweight hanging system are compensated entirely, and there are no lateral forces applied to the force transducer that require calibration.

In the measurement process control module, there are three operation modes: standard mode (fully automatic operation), single point mode (semi-automatic operation), and manual operation mode. In standard mode, the measurement parameters, such as measurement range; force points; preload numbers; measurement cycle numbers; and waiting and reading times are set by the user interface. The whole measurement process: loading; unloading; and data acquisition and processing are completed automatically. In single point mode, one-time loading or unloading operation can be realised. This mode is applied in a one-step operation or by commissioning the machine. There are four operation programs in the manual operation mode: origin restoration; range replacement; selection and deadweight groups adjustment; and clamp and release adjustment. They are used for the adjustment and setting of the main components of the machine.

A self-developed software is applied in the electronic and control system. The software of the PC receives a user's instructions through the interface; sends corresponding commands to the PLC system; and realises specific operation functions. The PLC software implements positioning, speed, and timing controls for the servo-motors, sensors, and actuators. The output of the force transducer that requires calibration are acquired by the PC, restored, and analysed by database software.
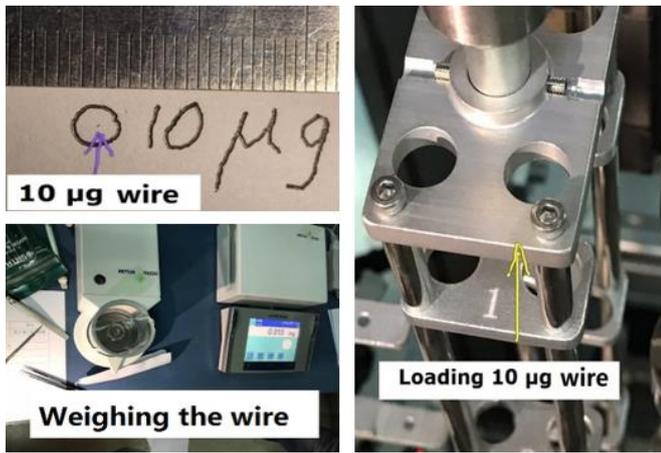
Figure 6. Sensitivity experiment without loading.



Figure 7. The results of repeatability experiments.

## 4. PEFORMANCE EXPERIMENTS

Performance experiments for the 10 N deadweight force standard machine were carried out. The force transducers used in the experiments were calibrated and found to comply with the requirements of ISO 376: 2011(E) for class 00.

### 4.1. Sensitivity experiments

Sensitivity is a main parameter for evaluating the magnitude of friction of the balance beam. When the beam was adjusted in a state of neutral equilibrium, a sensitivity experiment without loading was carried out. This experiment is shown in Figure 6. In the case of an unloading condition, a wire with very small mass was applied on one side of the balance beam. The position change of the balance beam was observed at the same time. It was found that the minimum mass of the wire, which caused a significant position change, was only 10 µg. The arm length of the balance beam is 250 mm. Therefore, the friction torque of the balance beam was found to be less than 0.03 µN·m.

A sensitivity experiment with a load was carried out when a force was applied to a force transducer. As soon as the output of the transducer was stable, a small standard weight was loaded on the end of the beam. The output of the transducer was monitored. Sensitivity is calculated as follows:

$$S_1 = \frac{\Delta m_1}{m_1} \times 100\% \tag{1}$$

where $\Delta m_1$ is the minimum mass of the standard weight, which caused a significant change of output of the transducer, and $m_1$ is the nominal mass corresponding to the applied force.

The sensitivity experiment results with different forces are summarised in Table 1.

### 4.2. Repeatability experiments

The repeatability experiments were conducted in force ranges of 1 N – 10 N, 0.5 N – 5 N, and 0.2 N – 2 N. For 1 N – 10 N, a GTM KTN-Z/D 10 N force transducer was used. For

0.5 N – 5 N and 0.2 N – 2 N, a GTM KTN-Z/D 5 N force transducer was used. The experiment procedure was as follows:

Preload three times. The first two times preload the maximum force directly. In last one, preload step by step.

Then, load from 10% to 100% of the nominal force step by step, three times.

A 60-second interval between different force steps was used. The repeatability is calculated as:

$$R = \frac{X_{max} - X_{min}}{\overline{X}} \tag{2}$$

where $X_{max}$, $X_{min}$, and $\overline{X}$ are the maximum, minimum, and average values of the outputs of the transducer respectively.

The results of the repeatability experiments are shown in Figure 7. It is clear that the repeatability is less than $4.0 \times 10^{-5}$.

### 4.3. Rotation effect experiments

Rotation effect experiments were carried out as follows: pre-loadings and measurement series are taken four times and three times respectively at 0° position. Then, preload once and measure once at other positions. The measurement sequence is given in Figure 8. The force steps in this experiment are 5 N and 10 N. The readings should be taken four minutes after a change in every force step. GTM KTN-Z/D 10 N and HBM S2M 10 N force transducers were used.

The rotation effect is characterised by reproducibility. It is given as

$$R_{repro} = \frac{\sqrt{\frac{\sum_{i=1}^{9}(x_i - \bar{x}_i)^2}{9 \times (9-1)}}}{\bar{x}_i} \tag{3}$$

where $x_i$ is a deflection of the force transducer at 0°, 90°, 180°, 270°, … $\bar{x}_i$ is mean deflection.
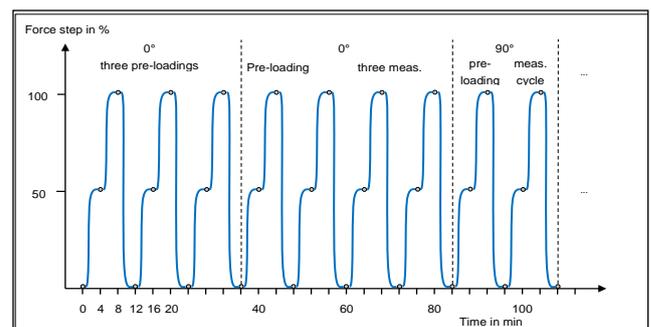


Figure 8. The measurement sequence.

Table 1. Sensitivity experiment results with different forces.

| Force (N) | Nominal mass of standard deadweight (g) | Minimum mass of weight (mg) | Sensitivity |
|---|---|---|---|
| 10 | 1020.42916 | 5 | $4.90 \times 10^{-6}$ |
| 1 | 102.042916 | 2 | $1.96 \times 10^{-5}$ |
| 0.5 | 51.021458 | 1 | $1.96 \times 10^{-5}$ |

Table 2. Rotation effect experiment results.

| Degrees | GTM KTN-Z/D 10 N | | HBM S2M 10 N | |
|---|---|---|---|---|
| | 5 N | 10 N | 5 N | 10 N |
| | Deflections (mV/V) | | Deflections (mV/V) | |
| 0 | 1.001652 | 2.002996 | 1.000316 | 2.000226 |
| 90 | 1.001716 | 2.003168 | 1.000316 | 2.000252 |
| 180 | 1.001699 | 2.003182 | 1.000304 | 2.000216 |
| 270 | 1.001682 | 2.003088 | 1.000356 | 2.000228 |
| 360 | 1.001677 | 2.003059 | 1.000303 | 2.000215 |
| 450 | 1.001707 | 2.003160 | 1.000305 | 2.000248 |
| 540 | 1.001694 | 2.003184 | 1.000302 | 2.000222 |
| 630 | 1.001704 | 2.003128 | 1.000353 | 2.000241 |
| 720 | 1.001649 | 2.002991 | 1.000317 | 2.000235 |
| Mean deflection (mV/V) | 1.001687 | 2.003106 | 1.000319 | 2.000231 |
| Reproducibility | $8.0 \times 10^{-6}$ | $1.3 \times 10^{-5}$ | $7.0 \times 10^{-6}$ | $2.3 \times 10^{-6}$ |

The experiment results are shown in Table 2. The results demonstrate that the reproducibility is less than $4.0 \times 10^{-5}$.

## 5. UNCERTAINTY EVALUATION

The force realised by the deadweight force standard machine can be calculated as:

$$F = mg\left(1 - \frac{\rho_a}{\rho_w}\right) \tag{4}$$

where $m$ is the mass of the deadweights, $g$ is the local gravitational acceleration, $\rho_a$ is the density of air, and $\rho_w$ is the density of the deadweights.

From the mathematical model, the following standard uncertainty components should be considered:

1) Mass calibration of the deadweight
2) Local gravitational acceleration
3) The density of air
4) The density of the deadweights

Furthermore, the structure and mounting factors of this machine are also uncertainty contributions. They include the following components:

5) The friction in the balance beam
6) The swing of the deadweights
7) Plate inclination (for compression force only)
8) Non-coaxiality (for tension force only)

### 5.1. Standard uncertainty of mass calibration of deadweight

The nominal mass of the deadweights are calculated according to equation (4). The maximum permissible errors of the deadweights are in the range of $\pm 1 \times 10^{-5}$ of its nominal value. The deadweights were calibrated by the mass laboratory of NIM. The deadweights, the measured mass of which are within permissible errors, are selected and put on the machine. The nominal mass and measurement uncertainties of the deadweights are demonstrated in Table 3.

Table 3. The nominal mass and measurement uncertainties of the deadweights.

| Force in N | Nominal mass in g | Relative standard uncertainty | Material of deadweights |
|---|---|---|---|
| 1 | 102.042916 | $8.82 \times 10^{-8}$ | Stainless steel |
| 0.5 | 51.021458 | $9.80 \times 10^{-8}$ | |
| 0.2 | 20.408583 | $1.96 \times 10^{-7}$ | |
| 0.1 | 10.2042916 | $2.94 \times 10^{-7}$ | |
| 0.05 | 5.1021458 | $4.90 \times 10^{-7}$ | |
| 0.02 | 2.0408583 | $9.80 \times 10^{-7}$ | |
| 0.01 | 1.0204292 | $1.47 \times 10^{-6}$ | |
| 0.005 | 0.5102755 | $2.74 \times 10^{-6}$ | Titanium alloy |
| 0.002 | 0.2041102 | $5.88 \times 10^{-6}$ | |
| 0.001 | 0.1020551 | $7.84 \times 10^{-6}$ | |

### 5.2. Standard uncertainty of local gravitational acceleration

The gravitational acceleration at the location where this machine is built up was measured as 9.80126037 m/s² by the gravity laboratory of NIM. Considering the influence of the earth tide, the standard uncertainty of the measurement result $u_g$ is $3.00 \times 10^{-7}$.

### 5.3. Standard uncertainty of the density of air

Through observations and statistics for many years, the average value of the density of air is 1.2 kg/m³ in our laboratory, and its variation does not exceed 0.04 kg/m³. Assuming a uniform probability distribution, the standard uncertainty of the density of air $u_{\rho_a}$ can be given as:

$$u_{\rho_a} = \frac{0.04}{\sqrt{3} \times 1.2} = 1.92 \times 10^{-2} \tag{5}$$

### 5.4. Standard uncertainty of the density of the deadweights

The density of the deadweights was measured by the mass laboratory of NIM. For deadweights made of stainless steel, the density is 8,045 kg/m³ with an expanded uncertainty of 140 kg/m³($k$=2). For the deadweights made of Titanium alloy, the density is 4469 kg/m³, with an expanded uncertainty of 140 kg/m³($k$=2).

Therefore, the standard uncertainties of density of the deadweights $u_{\rho_w}$ are $8.70 \times 10^{-3}$ and $1.57 \times 10^{-2}$ for deadweights made of stainless steel and Titanium alloy respectively.

### 5.5. Standard uncertainty of friction in the balance beam

The friction of the air bearing support in the balance beam is the primary uncertainty contribution of this machine. For evaluating this uncertainty budget, the sensitivity of the balance beam was tested. The sensitivity experiment results are demonstrated in the final section of this article.

According to conservative estimates, the standard uncertainties caused by friction in the balance beam $u_{fr}$ are $1.96 \times 10^{-5}$ in the range of 0.5 N – 10 N and $4.90 \times 10^{-5}$ in the range of 1 mN – 0.5 N respectively.

### 5.6. Standard uncertainty of the swing of deadweights

During the loading process, the swing of the deadweights may slightly influence the direction of the applied force. For this machine, there is almost no swing of the deadweights due to the use of the clamping mechanism in the deadweight

Table 4. Standard uncertainty budgets.

| Sources of standard uncertainty | Distribution | Coverage factor | Relative uncertainty |
|---|---|---|---|
| Mass calibration of deadweights $u_{m,s}$ / $u_{m,T}$ | Uniform | $\sqrt{3}$ | $1.47 \times 10^{-6}$ (for stainless steel) |
| | | | $7.84 \times 10^{-6}$ (for Titanium alloy) |
| Gravity acceleration $u_g$ | / | / | $3.00 \times 10^{-7}$ |
| Density of air $u_{\rho_a}$ | Uniform | $\sqrt{3}$ | $1.92 \times 10^{-2}$ |
| Density of the deadweights $u_{\rho_w}$ | / | 2 | $8.70 \times 10^{-3}$ (for stainless steel) |
| | | | $1.57 \times 10^{-2}$ (for Titanium alloy) |
| Friction in balance beam $u_{fr}$ | / | / | $4.90 \times 10^{-5}$ (in 1 mN - 0.5 N) |
| | | | $1.96 \times 10^{-5}$ (in 0.5 N - 10 N) |
| Swing of deadweights $u_s$ | / | / | $1.00 \times 10^{-6}$ |
| Plate inclination (for compression force) $u_i$ | / | / | $2.00 \times 10^{-10}$ |
| Non-coaxiality (for tension force) $u_a$ | / | / | $1.37 \times 10^{-7}$ |

hanging system. The standard uncertainty of the swing of the deadweights $u_s$ is estimated as less than $1.00 \times 10^{-6}$.

### 5.7. Standard uncertainty of plate inclination (for compression force only)

Due to limitations of manufacturing and assembly techniques, the base plate is slightly inclined. This results in the disalignment of the axis between the applied force and force transducer that require calibration. The level degree of the machine was adjusted and measured within 0.02 mm/m. As a result, the standard uncertainty of the plate inclination $u_i$ can be estimated as:

$$u_i = 1 - \cos\alpha = 1 - \cos\left(\arctan\left(\frac{0.02}{1000}\right)\right) = 2.00 \times 10^{-10} . \quad (6)$$

### 5.8. Standard uncertainty of non-coaxiality (for tension force only)

Due to limitations in manufacturing and assembly techniques, there is a slight misalignment of the axis between the upper and lower tension force joints. The misalignment angle $\beta$ was estimated less than $0.03°$. Therefore, the standard uncertainty of the non-coaxiality for the tension force $u_a$ can be given as:

$$u_a = 1 - \cos\beta = 1 - \cos(0.03°) = 1.37 \times 10^{-7} . \quad (7)$$

The standard uncertainty budgets of this machine are summarised in Table 4.

### 5.9. Combined standard uncertainty and expanded uncertainty

The relative combined standard uncertainties are calculated for compression or tension forces as Equation (8) or Equation (9) respectively:

$$u_{rc} = \sqrt{u_m^2 + u_g^2 + (u_{\rho_a}^2 + u_{\rho_w}^2)\,\rho_a^2/(\rho_w - \rho_a)^2 + u_{fr}^2 + u_s^2 + u_i^2} \quad (8)$$

Table 5. The combined standard uncertainty and expanded uncertainty of 10 N deadweight force standard machine.

| Force ranges | The combined standard uncertainty | The expanded uncertainty (k = 2) |
|---|---|---|
| 1 mN - 0.5 N | $5.0 \times 10^{-5}$ | $1.0 \times 10^{-4}$ |
| 0.5 N - 10 N | $2.0 \times 10^{-5}$ | $4.0 \times 10^{-5}$ |

Note: The uncertainty evaluation results are available for compression force and tension force.

$$u_{rt} = \sqrt{u_m^2 + u_g^2 + (u_{\rho_a}^2 + u_{\rho_w}^2)\,\rho_a^2/(\rho_w - \rho_a)^2 + u_{fr}^2 + u_s^2 + u_a^2} \quad (9)$$

The relative expanded uncertainties for compression or tension forces are given as:

$$U_{rc} = 2 \times u_{rc} \quad (10)$$

$$U_{rt} = 2 \times u_{rt} \quad (11)$$

The combined standard uncertainty and expanded uncertainty of the 10 N deadweight force standard machine are calculated according to Equations (8) to (11), and their results are summarised in Table 5.

## 6. CONCLUSIONS

A 10 N deadweight force standard machine with air bearing support has been developed by NIM. Its force range is from 1 mN to 10 N. In contrast to traditional deadweight force standard machines, a balance beam is applied to compensate the weights of load frame and a deadweight hanging system. The aerostatic bearing technique is applied to support the balance beam, and innovative structures in load frame and tension force joint are used.

Performance experiments for this machine were carried out. The friction torque of the balance beam was evaluated as being less than 0.03 μN·m. Concerning 0.5 N to 10 N, the sensitivity is no larger than $1.96 \times 10^{-5}$, and repeatability is less than $4.0 \times 10^{-5}$. The reproducibility, which is caused by the rotation effect, is less than $4.0 \times 10^{-5}$ at 5 N and 10 N.

The standard uncertainties of the main influence factors are analysed, and the expanded uncertainty is estimated as $1.0 \times 10^{-4}$ (k = 2) in 1 mN – 0.5 N, $4.0 \times 10^{-5}$ (k = 2) in 0.5 N – 10 N, respectively.

Further investigation and experiments will be conducted. Comparisons with other deadweight force standard machines will be carried out.

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