

## A NEW 10N DEADWEIGHT FORCE STANDARD MACHINE

*Gang Hu<sup>1</sup>, Jile Jiang<sup>1</sup>, Tao Li<sup>2</sup>, Zhimin Zhang<sup>1</sup>, Honglei Ji<sup>2</sup> and Lijun Zhuang<sup>2</sup>*

<sup>1</sup>National Institute of Metrology(NIM), Beijing, P.R. China, [hugang@nim.ac.cn](mailto:hugang@nim.ac.cn)

<sup>2</sup>Shanghai Marin Equipment Research Institute (SMERI), Shanghai, P.R. China

**Abstract:** A new 10N deadweight force standard machine is developed by NIM. The force range of this machine is from 1mN to 10N. There are 10 groups of weights, 10 pieces deadweights in each group. This machine is composed of deadweights, automatic loading and unloading system, load frame and deadweight hanging system, balance mechanism and so on. Air bearing technique is applied to the balance mechanism. The structure of the deadweight force standard and its main components are introduced in detail. The performance test results of the air bearing are demonstrated in this paper.

**Keywords:** force, deadweight force standard machine, air bearing

### 1. INTRODUCTION

Over the past ten years, force measurements in the range below 10N have been more and more widely applied in many fields such as advanced materials, hardness metrology, biology, precision manufacturing, aviation and aerospace and so on. For example, in reliability test and research on MEMS materials and components, special experimental devices are used to test tension, compression, relaxation, creep, fatigue, torsion and other mechanical properties of the MEMS specimen. The force transducers in the range of 1mN-10N are applied to force measurement and control in these devices. These transducers should be traced to force standard machines with high accuracy. In instrumented indentation test for hardness and materials parameters, small test force from milli-Newton to Newton range should be calibrated [1]. However, the minimum force of the national force standard machines is 10N in China at present. Traceable force standard machines and approaches below 10N were lacking.

Several National Metrology Institutes (NMIs) in the world established small force standard machines for fulfilling the demand of small force measurements. The Physikalisch-Technische Bundesanstalt (PTB) in Germany has developed a 200N deadweight force standard machine and extended force range down to 0.5N[2]. The Korea Research Institute of Standards and Science (KRISS) in Korea established a 22N deadweight force standard machine and its force range down to 0.5N[3].

NIM launched a project of developing a 10N deadweight force standard machine in 2015. The force range of this machine is from 1mN to 10N. It extends measuring range of NIM's deadweight force standard machines down to 1mN and meets the demands of force dissemination in the range of 1mN-10N. The structure of the deadweight force standard and its main components are described in detail in the following section.

### 2. THE STRUCTURE OF THE DEADWEIGHT FORCE STANDARD AND ITS MAIN COMPONENTS

This machine is based on force realization principle of deadweights. It is composed of deadweights, automatic loading and unloading system, load frame and deadweight hanging system, balance mechanism and so on. Figure 1 is the schematic of 10N deadweight force standard machine developed by NIM.

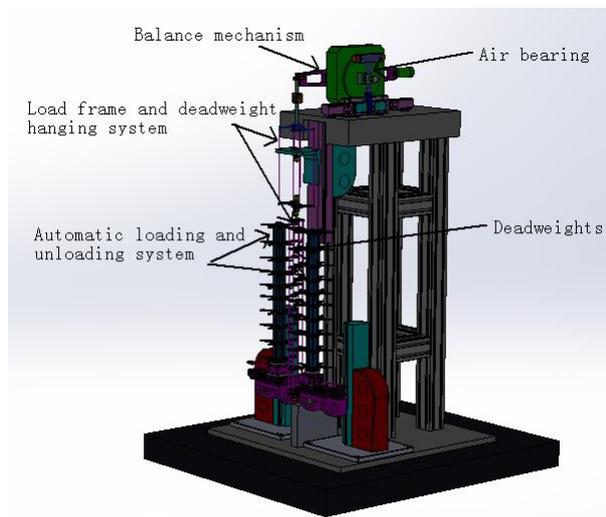


Figure 1 The schematic of 10N deadweight force standard machine

Most deadweight force standard machines realize initial force by using load frame and deadweight hanging system. Therefore, the magnitude of the initial force is limited by the mass of load frame and deadweight hanging system, smaller initial forces can't be realized. Differing from most deadweight force standard machines, this machine is equipped with a balance

mechanism. The balance mechanism uses a beam structure with a support. One side of the beam is suspended by a load frame and deadweight hanging system, the other side is a built-in counterweight balance component. The weight of load frame and deadweight hanging system is balanced and the forces generated by deadweights are applied to the force transducers to be calibrated. In this way, small initial force can be realized and force range of this machine is extended.

The friction caused by the support is a main uncertainty contribution. For minimising the friction, the support structure should be considered seriously. Knife edge and air bearing support techniques are widely used in force and torque standard machines. In small force and torque machines, air bearing support has smaller friction than knife edge support. Besides, precise positioning of deadweights should be taken into account. Because conical clearance fit with 0.1mm clearance is adopted in the positioning between deadweights and trays of deadweight hanging system, position change of the balance mechanism should be avoided during loading or unloading. If air bearing support is used, there is only a rotational degree of freedom. But in the case of knife edge support, there may be displacement degrees of freedom, it have adverse influence on precise positioning of deadweights. Therefore, a self-developed aerostatic bearing is used. The Figure2 shows its structure.

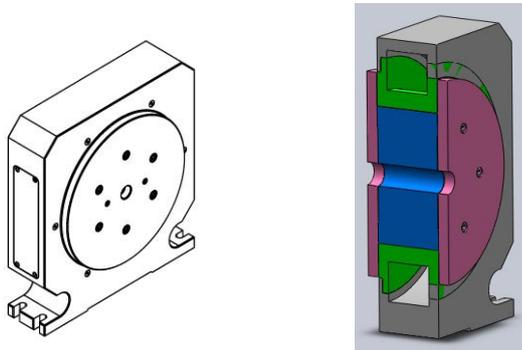


Figure2 A self-developed aerostatic bearing

This is the first application of aerostatic bearing technique for balance mechanism of deadweight force standard machine. The air bearing consists of a rotor and a stator. External gas source provides clean and dry gas with stable pressure to the bearing. The air flow is injected to the bearing surface through the throttle and forms a very thin pressure film. When the external impact force is applied on the rotor, the rotor is offset from center position, the gap in one side of impact force application increases, the pressure decreases. While the gap in the other side decreases, the pressure increases. As a result, the pressure difference between two sides reduces eccentricity of the rotor and makes it suspended in the center of the stator.

The structure of the balance mechanism with air bearing support is shown in Figure3. The original horizontal position of the beam is adjusted by the built-in counterweight balance component. The position of

the balance mechanism are fine adjusted by a fine adjustment mechanism until it is in a state of neutral equilibrium. The horizontal position of the beam is measured by a laser displacement sensor.

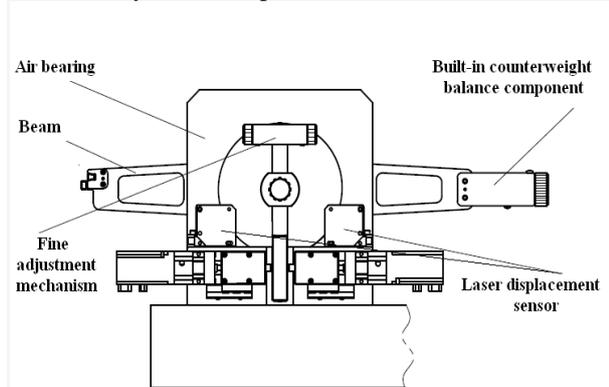


Figure3 The balance mechanism with air bearing support

For preventing beam and air bearing from excessive displacement caused by unexpected impact, a clearance clamping mechanism is applied. In this mechanism, two sets of motion module driven by servo motor constitute a beam limit protection unit and make the beam clamping at its horizontal state. When an unexpected impact applies to the beam, the beam only moves in minimal displacement and its displacement is restricted. Finally the impact is bore by beam limit protection unit, in this way the beam and air bearing are effectively protected.

A thin steel strip mechanism, which consists of two perpendicularly mounted steel strips, is adopted to suspend load frame and deadweight hanging system. The thickness of the steel strip must be as thin as possible to prevent friction, additional forces and moments and make load frame and deadweight hanging system suspending freely in vertical position. An ultra-thin the steel strip with the thickness of  $5 \mu\text{m}$  is used, and its material is 316L stainless steel.

A special designed load frame applicable to small force measurement is adopted. It consists of four-column with a base plate. The Figure4 shows the structure of the load frame. The base plate driven by a linear motion module is in the middle of the frame and can move vertically. Upper part of the frame is used for compression force transducer calibration, lower part is for tension calibration. For tension force calibration, a knife-edge universal joint structure is used to assure application of tension force axially. When the force is applied to the force transducer to be calibrated, the deformation of the transducer causes the deviation from horizontal position of the beam of balance mechanism. The laser displacement sensor monitors the change, makes the base plate move and beam back to the horizontal state.

There are 10 stacks in deadweight hanging system. A clearance clamping mechanism is in the bottom of the hanging system and prevents load frame shaking. When deadweights are put on or removed from the hanging

system, the clearance clamping mechanism clamps. As soon as force is applied to force transducer and outputs of the transducer are acquired, mechanism releases. In order to improve the sensitivity of this machine, Titanium alloy is used for load frame and deadweight hanging system.

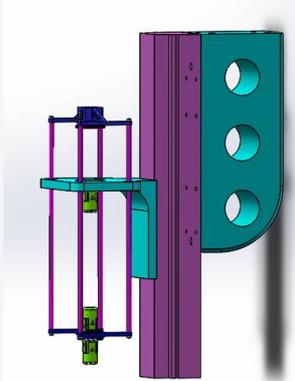


Figure4 Load frame with four-column

Two sets of automatic loading and unloading system with identical structure, which are in two sides of deadweight hanging system, realizes automatic loading and unloading of 10 sets of deadweights. It consists of weight support, rotating part, horizontal moving part, vertical moving part. There are 10 stacks in automatic loading and unloading system, 5 weight supports in each stack. Its schematic is shown in Figure5. The deadweights to be selected are rotated to the position immediately facing the hanging system by rotating part. Horizontal moving part carries the deadweights and moves directly above the trays in the hanging system. Then weight supports with deadweights driven by the vertical moving part moves downward. Therefore the deadweights are applied to the trays of the hanging system step by step. Unloading process is completed in a reverse mode. Conical clearance fit, in which the clearance is less than 0.1mm, is adopted in the positioning between deadweights and trays. This structure ensures the precise position of deadweights and reduces its swing.

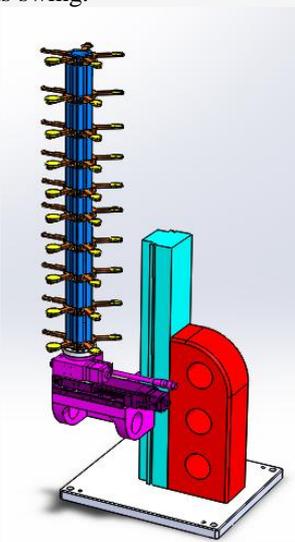


Figure5 Automatic loading and unloading system

There are 10 groups of weights, 10 pieces deadweights in each group. The combination of deadweights is as follows:

$1\text{mN} \times 10$ ,  $2\text{mN} \times 10$ ,  $5\text{mN} \times 10$ ,  $10\text{mN} \times 10$ ,  $20\text{mN} \times 10$ ,  $50\text{mN} \times 10$ ,  $100\text{mN} \times 10$ ,  $200\text{mN} \times 10$ ,  $500\text{mN} \times 10$ ,  $1\text{N} \times 10$ .

The deadweights of 0.01N~1N are made by stainless steel with density of  $8045 \text{ kg/cm}^3$ . Titanium alloy with density of  $4469 \text{ kg/cm}^3$  are used for deadweights of 0.001N ~0.005N. The maximum permissible error of the deadweights is within  $\pm 0.001\%$  of its nominal mass. The deadweights are applied to the hanging system step by step through an automatic loading and unloading system. As a result, 100 force steps are realized from 1mN to 10N.

This machine, composed of dozens of servo motors, switches and actuators, is a complex system. Signal acquisition, control and data processing are carried out by a computer control system. Whole operation process such as loading, unloading, beam balance adjustment is completed automatically.

### 3. PERFORMANCE TEST FOR AIR BEARING

The performance of the air bearing was tested before it is mounted on the balance mechanism. For test the performance, the air bearing was mounted on a test platform which is a solid steel structure, its carrying capacity were measured by applying weights at different positions. The rotor position of the air bearing is measured by a dial gauge. The experiments schematic is shown in Figure6. The experiment results are summarized in the Table1.

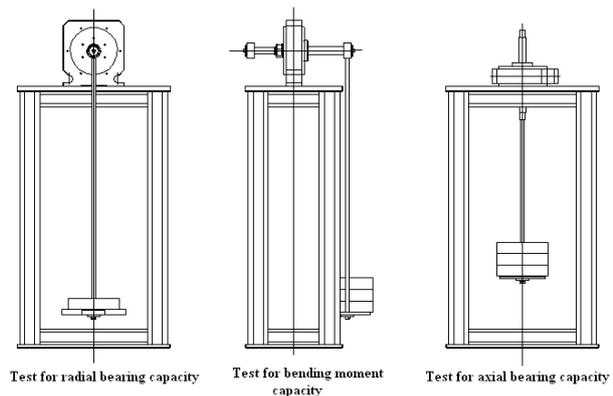


Figure6 The Schematic of the performance test of the air bearing

Table1 Carrying capacity of the air bearing

Parameters	
Radial bearing capacity (N)	750
Axial bearing capacity (N)	100
Bending moment capacity (Nm)	10

The friction torque is a main parameter of the air bearing. The test for friction torque was carried out by

applying small weight at the end of the test beam, the schematic is shown in Figure7. The position of the beam was observed through an infrared detector. If the position of the beam changes, it means that the torque which is generated by the small weight can be perceived by the air bearing. Before the test, the test beam was adjusted in a state of neutral equilibrium. During test, a stable environment without noise, vibration, air and any interference should be ensured. A series of small weights with diminished mass were applied in order until the position of the beam does not change. The experiment shows that the minimum weight  $m_{min}$  which breaks the balance was  $40 \mu\text{g}$ . The distance  $l$  between position for applying weight and axis of air bearing is 250 mm. Therefore, the friction torque of the air bearing is calculated as follows:

$$T_f = m_{min} g l = 40\mu\text{g} \times 9.8\text{m/s}^2 \times 250\text{mm} = 0.098\mu\text{Nm}$$

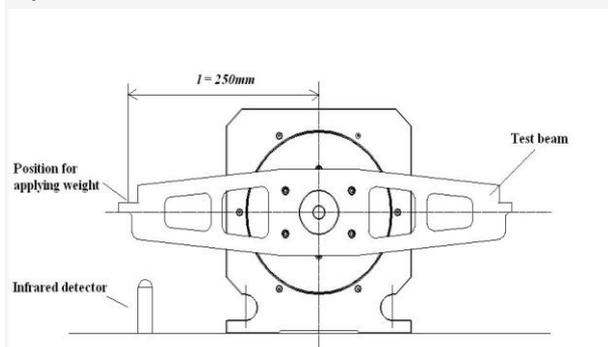


Figure7 The Schematic of friction torque test of the air bearing

#### 4. CONCLUSION AND FUTURE WORK

A new 10N deadweight force standard machine is developing by NIM. This machine is composed of deadweights, automatic loading and unloading system, load frame and deadweight hanging system, balance mechanism and so on. Air bearing technique is applied to the balance mechanism. The performance of the air bearing was tested.

The assembly of mechanical components has been completed, electrical and control components are adjusting and trial running. This machine will be built up in the second half of 2017. The sensitivity of the balance mechanism will be measured and uncertainty due to friction will be estimated. Besides, further investigation and experiments will be conducted.

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