NIM’s 100 kN Deadweight Force Standard Machine

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Abstract. A set of 100 kN deadweight force standard machine was developed at National Institute of Metrology (NIM). This machine is capable of realizing force from 1 kN to 110 kN with 1 kN force step both in compression and tension. The machine employs 31 pieces of weights which may be selected optionally to supply force, as a result, there does not exist counter-force during loading process while the machine calibrates the force transducers with different rated capacities. The loading time for each force step is same. The machine is suitable for the type test of load cell in accordance with the international recommendation of OIML R60. This paper introduces the mechanical structure and working principle, the uncertainty evaluation, comparison results with NIM’s other deadweight machines.

1. Introduction
The deadweight force standard machines are widely used in national metrology institutes for realizing national force standards with the smallest uncertainty. NIM force laboratory maintains six deadweight force standard machines with capacities of 1 MN, 300 kN, 10 kN, 6 kN, 1 kN and 300 N. Among series of deadweight force standard machines, there is still a lack of 100 kN deadweight force standard machine, there are large demands of high precision measurements of force transducers and type tests of load cells in accordance with OIML R60 in the range of 1 kN~100 kN. In order to meet the requirements, a set of 100 kN deadweight force standard machine was developed at NIM. The forces range of the machine is from 1 kN to 110 kN, the uncertainty is smaller than $2 \times 10^{-5}$ ($k=3$).

2. The Construction and Work Principle
The machine consists mainly of weights, loading frame (including the reverser and suspension rod), weights supporting frame, weights lifting frame, lifting cylinder and piston assembly and platforms. The constructions of the upper part and lower part of the machine are shown in Figure 1 and Figure 2 respectively. Generally, for the deadweight force standard machines, the loading frame is made as a whole part, the smallest force is generated by the weight of the loading frame, due to restriction by the weight of loading frame, the smallest force realized is larger than minimum force desired. In order to realize the wide force range from 1 kN to 110 kN, simultaneously to ensure the strength of the loading frame, the loading frame of the machine is divided into two parts: reverser and suspension rod which weight is 1 kN respectively. The machine employs 31 pieces of weights: 10 pieces of 1 kN weight, 10 pieces of 2 kN weight, 1 pieces of 3 kN, 5 pieces of 5 kN weight , and 5 pieces of 10 kN weight. The reverser, suspension rod generates first and second force step separately, 31 pieces of weights may be combined optionally to generate force, when the force transducers with different rated capacities are calibrated, there need not exchange weights, as a result there is no counter-force during loading, thus
the high precision force measurement is realized. The mass stack configuration of the machine is shown in Table 1.

The traveling beam together with reverser constitute the compression space which can be adjusted by controlling the movement of the traveling beam via motor, the reverser and medium beam constitute the tensile space which is adjusted by the turbine and worm device. The selected weights are transported from the shifting pawls connected to the supporting columns to the weight suspension rod or vice-versa by the lifting frame, so that the load is supplied to the calibrated force transducer. The lift cylinder-piston assembly is placed on the upper beam, which is used to supply force to rating force or reduce force to zero rapidly. During calibration 31 pieces of weights could be selected to load optionally, the loading time for each force steps is same. The machine can meet the requirement of type test of load cell in accordance with OIML R60.

Table 1: The mass stack configuration of 100 kN force standard machine

| Weight No.       | Weight pieces | Force generated by weight F (kN) | Nominal mass of weight m (kg) | MPE of weight mass (g) |
|------------------|---------------|----------------------------------|------------------------------|------------------------|
| Reverser         | 1             | 1                                | 102.0433                     | ±0.51                  |
| Suspension rod   | 1             | 1                                | 102.0433                     | ±0.51                  |
| 1kN weight       | 10            | 1                                | 102.0433                     | ±0.51                  |
| 2kN weight       | 10            | 2                                | 204.0866                     | ±1.02                  |
| 3kN weight       | 1             | 3                                | 306.1299                     | ±1.53                  |
| 5kN weight       | 5             | 5                                | 510.2165                     | ±2.55                  |
| 10kN weight      | 5             | 10                               | 1020.4330                    | ±5.10                  |

Figure 1: Upper part of 100 kN machine

Figure 2: Lower part of 100 kN machine
3. Evaluation of uncertainty

For the deadweight force standard machine, the force generated is given by

\[ F = mg \left(1 - \frac{\rho_a}{\rho_w}\right) \]  

(1)

Where, \( m \) is the mass of deadweights as well as reverser and suspension rod, \( g \) is the local acceleration due to the gravity, \( \rho_a \) and \( \rho_w \) are the density of the air and the weight material respectively.

According to the function error theory, the relative combined standard uncertainty \( u_{c,r} \) is obtained by

\[ u_{c,r} = \left( \frac{u_m}{m} \right)^2 + \left( \frac{u_g}{g} \right)^2 + \left( \frac{u_{\rho_a}}{\rho_a} \right)^2 + \left( \frac{u_{\rho_w}}{\rho_w} \right)^2 \frac{\rho_a - \rho_w}{\rho_a} \]  

(2)

Where, \( u_m \) from the mass measurement of weights, \( u_g \) from the gravitational acceleration measurement, \( u_{\rho_a} \) from the variety of air density, \( u_{\rho_w} \) from the density measurement of weight material.

Besides the above uncertainties caused by the physics factors, there are some additional uncertainties, such as the uncertainty \( u_{5,r} \) caused by the swing of weights stack, the uncertainty \( u_{6,r} \) by non-level of upper and lower compression plates or the uncertainty \( u_{7,r} \) by the non-coaxality of the tensile fittings. The source of uncertainty, probability distribution, coverage factor and relative standard uncertainty are listed in table 2.

Table 2: The table of uncertainty budget

| Source of uncertainty                                      | \( u_{i,r} \) | Probability distribution | Coverag factor | Relative standard uncertainty |
|------------------------------------------------------------|---------------|--------------------------|----------------|-----------------------------|
| The mass measurement of weights                            | \( u_{1,r} \) | Normal                   | 3              | \( 1.7 \times 10^{-6} \)   |
| The gravitational acceleration measurement                  | \( u_{2,r} \) | Normal                   | 3              | \( 6.6 \times 10^{-8} \)   |
| The variety of air density                                  | \( u_{3,r} \) | Rectangular              | \( \sqrt{3} \) | \( 3.0 \times 10^{-6} \)   |
| The density measurement of the weights material             | \( u_{4,r} \) | Normal                   | 3              | \( 6.6 \times 10^{-7} \)   |
| The influence by swing of weights stack                     | \( u_{5,r} \) | Triangle                 | \( \sqrt{6} \) | \( 1.0 \times 10^{-6} \)   |
| The influence by non-level of compression plates            | \( u_{6,r} \) | projective               | 10/3           | \( 2.0 \times 10^{-8} \)   |
| The influence by non-coaxality of tensile fittings         | \( u_{7,r} \) | projective               | 10/3           | \( 4.5 \times 10^{-8} \)   |

Note: \( u_m = \frac{m}{m}, \ u_g = \frac{g}{g}, \ u_{\rho_a} = (u_{\rho_a}/\rho_a)(\rho_a/(\rho_a - \rho_0)), \ u_{\rho_w} = (u_{\rho_w}/\rho_w)(\rho_a/(\rho_a - \rho_0)) \)

For compression force, the relative standard uncertainty \( u_{c,r} \) is calculated by

\[ u_{c,r} = \sqrt{\sum_{i=1}^{5} u_{i,r}^2 + u_{6,r}^2} = 3.7 \times 10^{-6} \]  

(3)

For tension force, the relative standard uncertainty \( u_{c,r} \) is calculated by

\[ u_{c,r} = \sqrt{\sum_{i=1}^{5} u_{i,r}^2 + u_{7,r}^2} = 3.7 \times 10^{-6} \]  

(4)
Considering the confident level $p=99.73\%$ and the coverage factor $k=3$, the relative expanded uncertainty $U_{c,r}$ is calculated by

$$U_{c,r} = 3u_{c,r} = 1.2 \times 10^{-5}$$

(5)

4. Result of comparison with NIM’s other deadweight machines

The comparisons have been carried out to verify the validity of the declared uncertainty of the machine. 100 kN force machine was compared with 6 kN, 10 kN and 300 kN deadweight force machine at NIM. 300 kN, 6 kN deadweight force machine participated in CCM force key comparisons, so that a link to these comparison is available. The comparison measurements were carried out in the force range of 1 kN~110 kN. The comparison results of the 100 kN machine with the other machines show a good agreement and consistency with the declared uncertainties. Figure 3 shows comparison results with NIM’S 6 kN, 10 kN and 300 kN machines.

![Figure 3: Result of comparison with NIM’S 6 kN, 10 kN and 300 kN machine](image)

5. Summary

By adopting the construction of separate reverser and suspension rod and employing 31 pieces of weights, 100 kN force machine realizes wide force range from 1 kN to 110 kN. The weights of the machine may be combined optionally to supply force, therefore while calibrating the force transducers with different rated capacities, there need no weights exchange, so that there does not exist counter-force during loading process. The loading time for each force step is same. The lift cylinder-piston assembly is used to supply force to rating force or reduce force to zero rapidly. The machine can meet the requirement of type test of load cell in accordance with OIML R60. The comparison results of the 100 kN force machine with the other deadweight force machines show a good agreement and consistency with the declared uncertainties.

6. References

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