Design and Structure of new 1.5 kN and 5 kN deadweight force standard machine and result of comparison with 100 kN deadweight force standard machine

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ABSTRACT

1.5 kN and 5 kN deadweight type force standard machines (DWM) have been newly developed at the National Institute of Metrology, Thailand (NIMT). The preliminary characteristic of the new design in the range from 0.1 kN to 5 kN has an expanded uncertainty of 50 ppm. In order to verify the performance of these machines, the 1.5 kN DWM in the range of 0.1 kN – 1.5 kN has a loading frame with weight support, 11 deadweights of 0.1 kN and 2 deadweights of 0.2 kN. While the 5 kN DWM in the range of 0.2 kN – 5 kN has a loading frame with weight support, 4 deadweights of 0.1 kN, 8 deadweights of 0.2 kN and 6 deadweights of 0.5 kN.

The characteristic of both machines is carried out in the result of partially comparison using four force measuring devices (500 N, 1 kN, 2 kN and 5 kN) with a 100 kN DWM. These transfer standards are measured in two groups; the first group is measured between 1.5 kN DWM and 5 kN DWM using the reference data of measurement, and the second group is measured between 5 kN DWM and 100 kN DWM using the reference data of measurement.

For each of four force measuring devices, the measurement procedure is consisted of three initial preloading cycles with three measurement cycles at 0 degree orientation of the force transducer, and one preloading cycle with one measurement cycle at each of 90, 180 and 270 degree orientations. The comparison results of deadweight machine show the repeatability, reproducibility and deviations of the measurement results between the two newly deadweight force machines with 100 kN DWM.

Keywords: Deadweight force standard machine, DWM, force measuring device, uncertainty

1. INTRODUCTION

To meet the demands of Thai industry, the National Institute of Metrology, Thailand (NIMT) has already established a deadweight type force standard machine (DWM) of 100 kN rated capacity as a backbone of the national measurement standard of force. In last two years, NIMT has confirmed the performance of 100 kN DWM by bilateral comparison with NMJ. At present, the 1.5 kN DWM and 5 kN DWM have established in NIMT and were confirmed the performance by internal comparison.

The new DWM ensures the traceability of the basic quantities of mass, length, and time. The masses of the deadweights are traceable to the national mass standard of NIMT, and the gravitational acceleration at the location of the DWM is traceable to the national length and time standards of China through the absolute measurement of gravity on-site. In addition to securing traceability to national standards of basic quantities at the time of installation, it is necessary for any national metrology institute (NMI) to demonstrate the equivalence of its standards to those of other NMIs in foreign countries.

At the first time, the 1.5 kN DWM and 5 kN DWM were developed based on the rated capacity of 1.2 kN and 10 kN. The reason for modifying the 1.5 kN was to support the calibration of standard force transducer and to verify the hardness testing machine. For 5 kN DWM, NIMT already has 10 kN rated capacity inside 100 kN DWM, and it can be modified to calibrate the 2 kN and 5 kN rated capacities. With these two DWM, we can support the precision industrial having the small force down to 0.1 kN.

To this end, a internal comparison has been carried out between the newly implemented 1.5 kN DWM and 5 kN DWM with 100 kN DWM. This paper outlines the procedure and results of the internal comparison.
2. DESCRIPTION OF FORCE STANDARD MACHINES

1.5 kN DWM OF NIMT

The 1.5 kN force standard machine at NIMT, as shown in Fig. 1, consists of a main frame, a loading frame, a weight disk, a motor, and a control system.

The combination of sequential deadweight stack is as follows.
- 1 x 100 N (loading frame)
- 10 x 100 N (weight stack)
- 2 x 200 N

When the loading frame is at rest, it is supported by hanging on with the upper tensile jig, and its alignment is maintained by an automatic centering jig provided by hanging on with the upper tension jig. The force transducer or the test piece under calibration is set at the center of the tensile jig. The compression crossbeam moves as one and lift the force transducer and the loading frame together. Thus, the loading frame is separated from the centering jig, and the first load is applied to the force transducer. After stop moving the compression crossbeam, the lower crossbeam, which supports the other linkage weights to apply required forces one by one, is moved down.

![Figure 1: Photographs of NIMT’s 1.5 kN DWM.](image)

5 kN DWM OF NIMT

The 5 kN force standard machine of NIMT, as shown in Fig. 2, consists of a main frame, a loading frame, a weight disk, a motor, and a control system.

The combination sequential of deadweight disk is as follows.

1 x 200 N (loading frame)
4 x 100 N (weight stack)
7 x 200 N
6 x 500 N

The operating system is the same as the 1.5 kN deadweight force standard except only the loading frame is supported on a fixed slab, and its alignment is maintained by an automatic centering jig provided on the slab.
The 100 kN force standard machine in NIMT, as shown in Fig. 1, has a loading frame acting as a 1 kN weight and a series of linkage weights consisting of thirteen 1 kN weights, four 2 kN weights, a 3 kN weight, seven 5 kN weights, and five 10 kN weights. It can calibrate force transducers and test pieces of four rated capacities, namely, 10 kN, 20 kN, 50 kN, and 100 kN, each have ten force steps of equal increments. A 10 % overloading test can also be performed for these ranges; the maximum load of this DWM is 110 kN.

When the loading frame is at rest, it is supported on a fixed slab, and its alignment is maintained by an automatic centering jig provided on the slab. The force transducer or the test piece under calibration is set at the center of the compression table, or is hung at the center of the tensile fitting. The compression table and the tensile fitting move as one and lift the force transducer and the loading frame together. Thus, the loading frame is separated from the centering jig, and the first load is applied to the force transducer. After the compression table and the tensile fitting stop moving, the crossbeam, which supports the other linkage weights, moves down to apply the required forces one by one.
3. UNCERTAINTY EVALUATION OF 1.5 kN DWM AND 5 kN DWM

The force realization by using a deadweight force machine can be represented as follow:

\[ F = mg_{\text{loc}} \left( 1 - \frac{\rho_a}{\rho_w} \right) \prod_{i=1}^{n} (1 - \Delta_i) \]  

Where

- \( m \) is the mass of deadweight.
- \( g_{\text{loc}} \) is the local gravitational acceleration.
- \( \rho_a \) is the density of air.
- \( \rho_w \) is the density of deadweight.
- \( \Delta_i(i = 1, \ldots, n) \) is the relative error component caused by the structure of force standard machine, such as the error caused by an inclined compression table of machine or by oscillations of the deadweights.

3.1 Uncertainty of mass

The deadweights of the 1.5 kN and 5 kN force standard were calibrated by using the precision balance and standard masses that are traceable to the national mass standard of NIMT. The uncertainty of mass is not limited to the calibration uncertainty. In addition, we need to consider the deviations from the nominal mass values, because we can not adjust the masses of deadweights to exactly the nominal mass values. The maximum deviation is \( 3 \times 10^{-6} \), in this case. We also need to consider the long term stability of mass for years, which is equal to \( 4 \times 10^{-6} \).

Considering these the relative standard uncertainty of calibration of the calibration of deadweights, \( w_m \), was \( 2.45 \times 10^{-6} \).

\[ w_m = \sqrt{w_{\text{mass}}^2 + w_{\text{mass dev}}^2 + w_{\text{mass stabl}}^2} \]

\[ = 5.57 \times 10^{-6} \]

3.2 Uncertainty of gravitational acceleration

The gravitational acceleration at the site of the deadweight force standard machine was \( 9.78312431 \text{ m/s}^2 \). The maximum error in the acceleration due to time variation, height difference and acceleration measurement was \( 1.0 \times 10^{-5} \text{ m/s}^2 \). By assuming a uniform probability distribution of the error in the gravitational acceleration, the relative standard uncertainty due to the gravitational acceleration, \( w_g \), can be represented as follows:

\[ w_g = \frac{1}{\sqrt{3}} \frac{\Delta g}{g} = \frac{1}{\sqrt{3}} \frac{1.0 \times 10^{-5}}{9.78312431} = 5.9 \times 10^{-7} \]  

Where \( \Delta g \) is the error in the gravitational acceleration.
3.3 Uncertainty of air density

The density of air can be estimated by follow the CIPM formula for $\rho_a$ in kg/m$^3$:

$$\rho_a = \frac{0.34848 \cdot p - 0.009024 \cdot h_r \cdot e^{0.0612 t}}{273.15 + t}$$ (3)

Where, $p =$ the atmospheric pressure in hPa

$h_r =$ the relative humidity in %RH

$t =$ the temperature in °C

At the location of the 1.5 kN and 5 kN deadweight force machine, the atmospheric pressure carried from 985 hPa to 1020 hPa, the relative humidity varied from 30 %RH to 70 %RH, and the temperature varied from 21 °C to 24 °C over the period of a year. From this information and by using Eq.(3), the maximum variation of the air density can be estimated as 0.05 kg/m$^3$. By assuming a uniform probability distribution for the variation of the air density, the relative standard uncertainty due to the air density, $w_{\rho a}$, can be represented as follows:

$$w_{\rho a} = \frac{1}{\sqrt{3}} \frac{\Delta \rho_a}{\rho_a} = \frac{1}{\sqrt{3}} \frac{0.05}{1.20} = 2.58 \times 10^{-2}$$ (4)

Where $\Delta \rho_a$ is the variation of air density.

3.4 Uncertainty of density of deadweight

A relative error of 4 % for the density of deadweight and a uniform probability distribution of this error were assumed because, we sent 2 samples of DWM to the density lab of NIMT and the difference is not over than 4 %. The relative standard uncertainty due to the deadweights density $w_{pw}$, can be estimated as

$$w_{pw} = \frac{1}{\sqrt{3}} \times 0.04 = 23.1 \times 10^{-3}$$ (5)

3.5 Uncertainty of the compression crossbeam

To calibrate a force transducer, it is should be mounted on the compression crossbeam of a deadweight force machine. The compression crossbeam should be installed horizontally; however, it is usually slightly inclined due to the manufacturing limitation and the mounting techniques. We assumed that the inclination angle was 0.01 °. Because the inclination angle is constant, it is not necessary to consider the probability distribution in its value. Therefore, the relative standard uncertainty due to the compression crossbeam, $w_p$, can be represented as follows:

$$w_p = 1 - \cos(0.01 \,^\circ) = 1.52 \times 10^{-8}$$ (6)
3.6 Uncertainty of the oscillation of deadweight

The deadweight of a force machine often exhibits oscillatory motion that may slightly influence the applied force. By assuming the maximum swing angle of 0.03 ° with uniform probability distribution, the relative standard uncertainty, $w_{osc}$, can be estimated as follows:

$$ w_{osc} = \frac{1 - \cos(0.03 \, ^\circ)}{\sqrt{3}} = 7.91 \times 10^{-8} \quad (7) $$

From the mathematical model of force, Eq. (1), the relative combined uncertainty of the deadweight force machine can be represented as follow:

$$ w_c = \left\{ \sum \left( \frac{1}{F} \frac{\partial F}{\partial x_i} u_{x_i} \right)^2 \right\}^{1/2} \quad (8) $$

where $F$ is force generated by the force machine, and $u_{x_i}$ implies an absolute standard uncertainty component due to variation of $x_i$, which is one of the independence variables in Eq.(1), such as $m$, $g_{loc}$, etc. By substituting Eq. (1) into Eq. (8), the relative combined uncertainty can be represented as follows:

$$ w_c = \sqrt{\left( \frac{u_m}{m} \right)^2 + \left( \frac{u_g}{g} \right)^2 + \left( \frac{u_{\rho_{a}}}{\rho_{a}} \right)^2 + \left( \frac{u_{\rho_{w}}}{\rho_{w}} \right)^2 + \left( \frac{\rho_{a}}{\rho_{w} - \rho_{a}} \right)^2 + \sum_{i=1}^{n} w_{\Delta i}^2} $$

$$ = \sqrt{w_m^2 + w_g^2 + w_{\rho_{a}}^2 + w_{\rho_{w}}^2 + \left( \frac{\rho_{a}}{\rho_{w} - \rho_{a}} \right)^2} + w_p^2 + w_{osc}^2 \quad (9) $$

From Eq. (9), the relative combined uncertainty was calculated as $8.2 \times 10^{-6}$. By increasing the relative combined uncertainty with a factor of 2, the relative expanded uncertainty of the deadweight force standard machine was estimated as $16.4 \times 10^{-6}$.

There are additional uncertainty components that have not been considered in this uncertainty evaluation, such as the interaction between the force transducer and force machine. By considering these unknown uncertainty components, the relative expanded uncertainty of the 1.5 kN and 5 kN deadweight force standard machine was declared as $4 \times 10^{-3}$ with a confidence limit of approximately 95%. Because the homogeneity of density of weight is affect the uncertainty due to the density of weight as the detail in uncertainty of density of deadweight.
4. INTERNAL COMPARISON WITH 100 kN DWM

For this comparison, four force standard transducers were used with a high-precision amplifier (DMP-40). The initial and the final measurements were carried out with 1.5 kN DWM and 5 kN DWM, and the weighted mean of these results was compared with the reference measurements of 100 kN DWM. The same DMP-40 was used for all measurements. The reference temperature was chosen to be 23 °C.

For the comparison between 1.5 kN DWM and 5 kN DWM, the force steps were 200, 400 and 500 N for the 500 N force standard transducer; 500, 600, 800, and 1000 N, for the 5 kN DWM and 100 kN; 1 kN and 2 kN for the 2 kN force standard transducer; 2, 3, 4 and 5 kN for the 5 kN force standard transducer.

For each of the four force standard transducers, the measurement procedure consisted of three initial preloading cycles and three measurement cycles at 0 degree orientation of the force transducer, and one preloading cycle and one measurement cycle at each of 90, 180 and 270 degree orientations.

The time interval was decided as described in Fig. 5, with a view to minimizing the creep effect seen in the force transducer. Therefore, the time intervals between zero and the rated capacity and between zero and half of the rated capacity were extended to 360 seconds and 270 seconds, respectively, instead of the usual intervals of 180 seconds.

![Figure 5: Time interval of readings. Filled circles indicate readings.](image)

5. RESULTS AND DISCUSSION

As described in the previous section, the same measurement interval was adopted at both of them; even though, the time intervals were the same in the measurements at all machines.

Fig. 6, 7 and Table 1 show the relative deviations among 1.5 DWM, 5 kN DWM and 100 kN DWM. In Fig. 6, the horizontal axis indicates the comparison force steps, and the vertical axis indicates the relative deviation. The horizontal axis is divided into six parts corresponding to each force standard transducer. Zero on the vertical axis refers to the reference values at 5 kN DWM for comparison between 1.5 kN and 5 kN DWM; 100 kN as a reference values for comparison between 5 kN DWM and 100 kN DWM. Curves indicate relative the deviations of measurement results of 5 kN DWM and 100 kN DWM and with respect to the reference values in Fig 6, 7. Circular symbols on dotted lines, square symbols on dotted lines, and triangular symbols on solid lines indicate the relative deviations of the initial measurement the final measurement, and their weighted mean, respectively. Measurement uncertainties of the initial and final measurements were used as weights for calculating the weighted mean. Bars at each comparison step show the comparison uncertainty as described below.
Table 1: Comparison results between 1.5 kN DWM, 5 kN DWM and 100 kN.

<table>
<thead>
<tr>
<th>Deadweight force standard machine</th>
<th>Rated capacity of force standard transducer</th>
<th>Comparison force step</th>
<th>Weighted mean of relative deviation ($\times 10^{-6}$)</th>
<th>Relative comparison measurement uncertainty ($k = 2$) ($\times 10^{-6}$)</th>
<th>$E_n$ number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 DWM and 5 kN DWM</td>
<td>500 N</td>
<td>200 N</td>
<td>-1.1</td>
<td>62.8</td>
<td>-0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>400 N</td>
<td>13.0</td>
<td>63.4</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 N</td>
<td>16.0</td>
<td>64.9</td>
<td>0.26</td>
</tr>
<tr>
<td>1.5 DWM and 5 kN DWM</td>
<td>1000 N</td>
<td>500 N</td>
<td>-50.1</td>
<td>58.0</td>
<td>-0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>600 N</td>
<td>-49.0</td>
<td>73.9</td>
<td>-0.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>800 N</td>
<td>-48.3</td>
<td>88.2</td>
<td>-0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000 N</td>
<td>-43.2</td>
<td>58.0</td>
<td>-0.74</td>
</tr>
<tr>
<td>5 kN DWM and 100 kN DWM</td>
<td>2 kN</td>
<td>1 kN</td>
<td>8.4</td>
<td>45.6</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 kN</td>
<td>-10.0</td>
<td>48.1</td>
<td>-0.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 kN</td>
<td>21.0</td>
<td>61.3</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 kN</td>
<td>28.2</td>
<td>61.0</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 kN</td>
<td>30.8</td>
<td>63.7</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Averages of readings, repeatability, reproducibility, resolution, temperature fluctuation, sensitivity drift between the initial and final measurements of 1.5 kN DWM and 5 kN DWM were taken into account when estimating the uncertainty of the comparison measurements. Every ten readings at each force step were averaged and were regarded as a normal distribution to estimate the uncertainty. Repeatability and reproducibility were estimated as a type-A evaluation. Resolution, temperature fluctuation, and sensitivity drift were assumed to be rectangular distributions. $E_n$ numbers were calculated to evaluate the comparison results according to ISO/IEC Guide 43-1.
As shown in Fig. 6 and Table 1, the relative deviations between the results of 1.5 kN DWM and 5 kN by using the force standard transducer capacity a 500 N and 1000 N were small and satisfactory at all of the force steps and $E_n$ number is lower than 0.5 except for using 1000 N force standard transducer. These exceptions of the relative deviation were large and the $E_n$ number is over than 0.5.

In Fig. 7 and Table 1, the relative deviation between the result of 5 kN DWM and 100 kN DWM by using the force standard transducer capacity of 2 kN and 5 kN were satisfactory, the relative deviation is not over then $4 \times 10^{-5}$ and $E_n$ number is lower than 0.5. All of measurement, the $E_n$ numbers never exceeded the unity. Therefore, it can be concluded that the complete equivalence of both newly DWMs and 100 DWM was confirmed in the high and low force ranges and that a certain degree of equivalence was confirmed in the middle force range of the 1.5 kN DWM and 5 kN DWM.

5. SUMMARY

The internal comparison has been completed carried out between the newly installed 1.5 kN DWM, 50 kN and 100 kN using four force standard transducer of 500 N, 1000 N, 2 kN and 5 kN rated capacities as force standard transducer in order to verify the performance of this new machine.

In future, we will find the deviation to modify the machine for improving the relative deviation of the both deadweight force standard machines and plan to proceed the bilateral comparison to confirm the value with NMIJ.

REFERENCES


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