Evaluation of small-capacity force transducers using a developed 2 N dead-weight type force standard machine

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ABSTRACT
A 2 N dead-weight type force standard machine (DWM) had been developed at the National Metrology Institute of Japan (NMIJ). Modifications of the force transducers and weight receivers of the DWM improved measurement reproducibility with rotational position change. Two modified small-capacity force transducers with rated capacities of 1 and 2 N could be precisely calibrated according to International Organization for Standardization (ISO) 376. The results showed quite smaller uncertainties in the calibration ranges of 100 μN to 1 N and 200 μN to 2 N than the catalogue accuracies of commercial transducers. The validity of the calibration capability of the 2 N DWM was confirmed by comparing it with a 50 N DWM. The results obtained by two DWMs coincided within the uncertainties of calibration.

1. Introduction
Measurements of small forces in the sub-Newton and milli-Newton ranges have been applied for the evaluation of material mechanical properties and quality control of products in various fields such as medical treatment, food, and biology. Therefore, to ensure the reliability of these small-force measurements, their traceability to small-force standards is essential. However, currently, the lower end of disseminated force standards in Japan is realized by a 50 N dead-weight type force standard machine (DWM), which can realize force in 1 N steps in the range of 1–50 N [1]. Thus, the National Metrology Institute of Japan (NMIJ), in the National Institute of Advanced Industrial Science and Technology, developed a small DWM that has a rated capacity of 2 N and is called the 2 N DWM [2]. Figure 1 shows (a) an overview and (b) photograph of the developed 2 N DWM. The machine has features such as a balancing mechanism to compensate for the gravitational force acting on the loading frame and the loading stage with receivers in a comb shape for loading and unloading the International Organization of Legal Metrology (OIML) type weights individually. The force transducer lifting mechanism is adopted to maintain the contact point between the loading frame and the force transducer under calibration during calibration irrespective of the height and stiffness of the transducer. The force-holding mechanism is adopted to hold the force applied to the force transducer during the weight exchange. The anti-swing mechanism is adopted to reduce the swinging and twisting of the weight receivers and maintain the position of the loading stage during loading and unloading of the weights. With this 2 N DWM, the lower end of the disseminated force standard in Japan can be extended from 1 N to 10 mN.

In addition to NMIJ, several national metrology institutes have developed various force standard machines to establish small-force standards. The Korea Research Institute of Standards and Science (KRISS), Republic of Korea, developed a 20 N DWM whose small-force range is extended down to 500 mN [3]. The National Institute of Metrology, China, developed a 10 N DWM whose small-force range is extended down to 1 mN [4,5]. Furthermore, Centro Español de Metrología, Spain, developed a DWM that provides measurement capabilities from 100 N down to 100 mN [6]. Moreover, unlike these dead-weight force standard machines, force standard machines using an electronic balance as a kind of converter have also been developed. The Physikalisch-Technische Bundesanstalt, Germany, developed a force standard machine for the range of 100 μN–200 mN [7]. KRISS developed a force standard machine with a small-force range of 50 mN–5 N [8]. These force standard machines based on the electronic balances still refer to the mass standard for the traceability in those force ranges.

To the best of our knowledge, here, no calibration results have been reported for small-capacity force transducers using these force standard machines in the sub-Newton to milli-Newton ranges. That means the calibration capabilities of force standard machines have
not been investigated. The authors presume that the reason is that any high-accurate and appropriate force transducers are not able to be manufactured in the world. Then, we had previously attempted to calibrate two commercially available small-capacity force transducers using the NMIJ 2 N DWM [9]. The poor reproducibility of the results, however, suggested incomplete symmetry in the force transducers, the 2 N DWM, or both. Some modifications to the force transducers, the 2 N DWM, or both, were necessary to improve the reproducibility.

The following experiments were carried out in this study in order to strengthen the reliability of small-force measurements. First, before the experiments, the force transducers to be calibrated and the 2 N DWM were modified. Second, to declare the calibration and measurement capability (CMC) of the 2 N DWM for small-capacity force transducer calibration in the future, as a challenging study, we conducted calibrations of the modified 1 and 2 N capacity force transducers by compressive forces according to the loading timetable described in International Organization for Standardization (ISO) 376, which is the standard document for calibrations of force measuring instruments used for the verification of uniaxial testing machines [10]. Finally, to validate the calibration capability of the 2 N DWM, we compared it with the developed 50 N DWM of NMIJ using the modified 2 N capacity force transducer as a transfer standard.

Here, the CMC is explained as a calibration and measurement capability of an accredited laboratory available to customers under normal conditions, according to the policy of International Laboratory Accreditation Cooperation (ILAC) [11]. The authors regard including the uncertainty ascribable to the best existing device in the CMC as important, respecting to the policy of ILAC.

2. Methods and experimental conditions

2.1. Modifications of force transducers

Two small-capacity force transducers with the strain-gauge principle were used in the experiments, Tr. 1 (DBJ-1N) and Tr. 2 (DBJ-2N), both manufactured by Showa Measuring Instruments Co., Ltd., Japan. The rated capacities of Tr. 1 and Tr. 2 are 1 and 2 N, respectively. The nominal deflections of both force transducers are approximately 2 mV/V. A precise indicator with a digital resolution of 0.000001 mV/V was used (ML38B in MGPlus, manufactured by Hottinger Baldwin Messtechnik GmbH).

In the previous study [9], it was found that the shape of the loading rods of these force transducers were not suitable for the evaluation of the 2 N DWM. The upper ends of the rods were initially threaded for connecting with objects of measurement, and additional loading buttons equipped with spherical surfaces could not be adopted because of interference between the long rods and insufficient height of the calibration room of the 2 N DWM. These conditions caused unpredictable distributions of contact points between the rods of the force transducers and the loading frame of the 2 N DWM. The rods of the transducers were replaced to solve this problem. The length of the new rods was shortened to fit the calibration room, and their top ends were machined spherically (1.5 mm radius of curvature) instead of adopting additional loading buttons. Both modified transducers are shown in Figure 2.

2.2. Modifications of the 2 N DWM

The loading stage of the 2 N DWM includes comb-shaped weight receivers to adopt OIML-type cylindrical standard weights for the convenience of mass calibration. However, we found that the centre of gravity of the comb-shaped receivers slightly shifted from the geometric centre. Even such a slight shift brought undesirable moment and inclination of the loading frame. We improved the horizontal levelness of the loading
frame and loading stage much precisely by the following way. The weight receivers were modified to move the centre of gravity close to the geometric centre by machining the opposite side of the weight receivers from the combs. Additionally, a universal joint was inserted between the loading frame and loading stage as a linkage, as shown in Figure 3. These modifications successfully reduced the moment around the top centre of the loading frame.

2.3. Evaluation of small-capacity force transducers according to ISO 376

We had previously attempted to calibrate the two small-capacity force transducers of Tr. 1 and Tr. 2 using the 2N DWM; however, calibration results showed poor reproducibility with the rotating mounting position of both force transducers [9]. After the modifications of the force transducers and the 2N DWM to improve the path of force transmission as described in Sections 2.1 and 2.2, the capabilities of these force transducers were reevaluated using the 2N DWM.

Tr. 1 and Tr. 2 were calibrated according to the prescription of ISO 376, in the same manner as in the previous study before the modifications [9]. The calibration procedure is shown in Figure 4. The maximum calibration force was applied to the force transducer for three iterations as preloading at the 0° position before two series of calibration cycles. In each calibration cycle, the calibration force was applied to the force transducer, by increasing and decreasing in eight steps (10 %, 20 %, 30 %, 40 %, 50 %, 60 %, 80 %, and 100 % of the maximum force). Here, even though the calibration at decreasing force steps is not essential in the prescription of ISO 376, we adopted the evaluation of reversibility into the calibration procedure to obtain further information about the force transducer. Then, a preloading and a series of calibration cycles were applied at the 120° and 240° positions, individually.

The setup of Tr. 1 at the 0° position is shown in Figure 5 as an example of installation after modification. Standard weights are removable and were picked following the calibration force range. For Tr. 1, one 100 mN, two 200 mN (No. 1 and No. 2), and one 500 mN weight were chosen as the standard weights. The calibration force steps and corresponding standard weights are shown in Table 1 for Tr. 1 and Tr. 2. Here, e.g. “100 mN weight” means a weight upon which the gravitational force of 100 mN acts under the environment of NMIJ in this study.

2.4. Comparison of the 2N and 50N DWMs

An internal comparison with the 50N DWM was carried out to confirm the validity of the 2N DWM. Because there are only two force steps of 1N and 2N overlapping between the two DWMs, both steps were selected for the comparison. For the 2N DWM, the force step of 1N was realized by the combination of one 100 mN, two 200 mN, and one 500 mN weight, and the force step of 2N was realized by the combination of the same four weights for 1N and an additional 1N weight. For the 50N DWM, the force step of 1N was realized by just the 1N loading frame as the first weight, and the force step of 2N was realized by adding a 1N linkage.
Table 1. Calibration force steps and corresponding standard weights.

| Combination of weights | Force steps 100 mN | 200 mN (No. 1) | 200 mN (No. 2) | 500 mN | 1 N |
|------------------------|---------------------|----------------|---------------|--------|-----|
| Tr.1                   | -                   | -              |               | -      | -   |
|                        | 100 mN              |                |               |        |     |
|                        | 200 mN              |                |               |        |     |
|                        | 300 mN              |                |               |        |     |
|                        | 400 mN              |                |               |        |     |
|                        | 500 mN              |                |               |        |     |
|                        | 600 mN              |                |               |        |     |
|                        | 800 mN              |                |               |        |     |
|                        | 1 N                 | -              |               |        |     |
| Tr.2                   | -                   | -              |               | -      | -   |
|                        | 200 mN              |                |               |        |     |
|                        | 400 mN              |                |               |        |     |
|                        | 600 mN              |                |               |        |     |
|                        | 800 mN              |                |               |        |     |
|                        | 1 N                 | -              |               |        |     |
|                        | 1.2 N               |                |               |        |     |
|                        | 1.6 N               |                |               |        |     |
|                        | 2 N                 | -              |               |        |     |

Note: - indicates weights corresponding to force steps.

Figure 5. Calibration setup using the modified 2 N DWM.

Figure 6. States of Tr. 2 installed in the (a) 2 N DWM and (b) 50 N DWM during measuring.

Figure 7. Loading procedure adopted for the comparison.

weight to the loading frame as the second weight. Tr. 2 was selected for the comparison because both force steps could be applied to the force transducer of 2 N capacity.

In Figure 6, the states of Tr. 2 installed in the two DWMs during measuring are shown. The loading procedure adopted for the comparison is shown in Figure 7. Three iterations of preloading were applied before two series of measurement cycles at the 0° position. The force was maintained at 2 N for 60 s for each preloading. After preloading, measurements were conducted with increasing and decreasing forces at the force steps of 1 N and 2 N in the order of 0, 1 N, 2 N, 1 N, and 0 return. The time interval between successive cycles was 3 min. After measurement at the 0° position, a preloading and series of measurement cycles were applied at both the 120° and 240° positions.

3. Results and discussions

3.1. Evaluation of the uncertainty source arising from the eccentric moment

The modifications successfully reduced the eccentric moment caused by the misalignment between the centre of gravity and the geometric centre in the weight receivers, as mentioned in Section 2.2. The authors, however, still suspected that a slight misalignment remained between the centre of gravity on the loading
frame and the measurement axis of the force transducer. This misalignment might cause the inclination of the loading frame and another eccentric moment. The eccentric moment possibly transmits to the balancing arm through a thin metal band that is used for hanging the loading frame from the balancing arm [2].

If the foregoing hypothesis were correct, the horizontal position of the force transducer under calibration would affect the balance around the fulcrum of the arm. When we purposely shifted the measurement axis of the horizontal position in the force transducer from the centre of the loading frame approximately ±2 mm and imparted a nominal force of 2 N into the force transducer, the applied force observed by the transducer changed proportionally by approximately ±2 mN. The change was also proportional to the applied force. At the present state, we cannot improve the accuracy of the alignment between the force transducer and the loading frame by less than ±0.3 mm because of visual inspection. Therefore, the maximum change from the nominal force was estimated as ±0.3 mN against the applied force of 2 N, and relative standard uncertainty associated with the remaining misalignment $w_{ma}$ was evaluated as $8.7 \times 10^{-5}$ by assuming a rectangular distribution at all force steps. It is expected that this source of uncertainty can be reduced by the improvement of the thin metal band, the accuracy of alignment, or both. However, this will be the subject of future work.

This uncertainty source does not affect the evaluation of simple repeatability because the contact point between the force transducer and the loading frame is maintained without a rotational position change of the force transducer. However, when performing calibration with a rotational position change, $w_{ma}$ must be taken into account.

### 3.2. Evaluation of small-capacity force transducers according to ISO 376

The relative nonlinearity curves of Tr. 1 and Tr. 2, shown in Figures 8 and 9, respectively, were obtained by using the 2 N DWM. The horizontal and vertical axes indicate calibration force steps and relative nonlinearity, respectively. Square, diamond, triangle, and circle symbols indicate the 0°-1st, 0°-2nd, 120°, and 240° calibration cycles, respectively. Solid and broken lines indicate the relative nonlinearity curves of increasing and decreasing force steps, respectively. The relative nonlinearity was obtained by dividing the average deflection at the maximum force step of the calibration cycles of the 0°-1st, 120°, and 240° positions. The calibration results after modification are shown in Figures 8(a) and 9(a). To compare the results from before and after modification, the calibration results before the modification are shown in Figures 8(b) and 9(b) [9]. It was found that the calibration results significantly improved with the modification, especially in the reproducibility results. The following discussion is based on the calibration results of Tr. 1 and Tr. 2 after modification, as shown in Figures 8(a) and 9(a).

The relative nonlinearity curves of the calibration cycles at three rotational positions agreed closely with each other, indicating small reproducibility with rotation. Those of the two calibration cycles at the 0° position agreed closely with each other, too, indicating small repeatability without rotation.

The relative expanded uncertainty of the calibration results was calculated based on Annex C in ISO 376 by Equation (3), as shown in Table 2. In the table, $w_{repr}$, $w_{repe}$, and $w_{reso}$ represent the relative standard uncertainties associated with the reproducibility and repeatability of the measurement results, and the resolution of the force transducer connected to the indicator, respectively. Here, the uncertainty source associated with temperature fluctuation was omitted because of its negligible contribution at the stable calibration condition (23.0°C ± 0.2°C). Even though hysteresis and zero return were evaluated following the daily calibration.
procedure, uncertainty sources associated with hysteresis and zero return were excluded from the calculation in this study because they had no connection with the calibration capability of the DWM. Relative expanded uncertainties $W$ were twice the fitted curves of the relative combined uncertainties against force steps by using the inverse proportionality function. The values of $W$ were $1.9 \times 10^{-4}$ for Tr. 1 and $1.8 \times 10^{-4}$ for Tr. 2 at the force step of each rated capacity. Even in the whole calibration ranges, quite small uncertainties could be obtained; the maximum values of $W$ were $8.2 \times 10^{-4}$ for the range from 100 mN to 1 N, and $3.5 \times 10^{-4}$ for the range from 200 mN to 2 N. The catalog accuracies (mostly expressed by the simple relative nonlinearity for the full scale, the simple relative hysteresis for the full scale, the simple relative nonlinearity for the full scale, the simple relative hysteresis for the full scale, and the misalignment between the loading frame and force transducer axes).

3.3. Comparison of the 2 N and 50 N DWMs
As mentioned in Section 2.4, two measurements were performed using the 2 N and the 50 N DWMs at the force steps of 1 N and 2 N. The deviation of the two measurements and their uncertainties were evaluated. Because the interval between the two measurements was short enough, sensitivity drift between measurements was not considered. The uncertainty components considered are listed in Table 3.

For the 50 N DWM, the relative combined standard uncertainty arising from the realized force acting on the standard weights $w_{fsm}$ was evaluated to be $5.4 \times 10^{-6}$ irrespective of force steps [1]. The relative expanded uncertainty of measurement $W_{50N}$ can be expressed as follows:

$$W_{50N} = k\sqrt{w_{fsm}^2 + w_{repr}^2 + w_{repe}^2 + w_{reso}^2} \quad (1)$$

The values of relative reproducibility error $b$ of the measurement results were $1.9 \times 10^{-4}$ at the force step of 1 N and $2.2 \times 10^{-5}$ at the force step of 2 N. We also confirmed the relative repeatability error $b'$ of the measurement results; the values were $3.1 \times 10^{-5}$ at the force step of 1 N and $1.7 \times 10^{-5}$ at the force step of 2 N, which are almost consistent with previously reported results: $3.4 \times 10^{-5}$ at the 1 N step and $2.2 \times 10^{-5}$ at the 2 N step [2]. The definition of $b$ and $b'$ are prescribed in ISO 376. Because oscillation of the balancing arm comparable to the sensitivity limit affected the deflections of the force transducers, these peak-to-peak fluctuations were approximately 10 digits ($0.000010$ mV/V) at zero force and were taken into account as $w_{reso}$. The relative deviation at the 1 N and 2 N force steps between the 2 N DWM and the 50 N DWM, respectively, is shown in Figure 10. The horizontal axis...
Table 2. Uncertainty budget at each calibration force step of Tr. 1 and Tr. 2.

| Force steps | w_{fsm} | w_{repr} | w_{repe} | w_{reso} | w_{ma} | w (%) | W (%) |
|-------------|---------|----------|----------|----------|--------|-------|-------|
| Tr.1        |         |          |          |          |        |       |       |
| 100 mN      | 0.0029  | 0.062    | 0.0038   | 0.0010   | 0.0087 | 0.063 | 0.082 |
| 200 mN      | 0.0015  | 0.0026   | 0.017    | 0.00051  | 0.0087 | 0.019 | 0.047 |
| 300 mN      | 0.0010  | 0.0094   | 0.0044   | 0.00034  | 0.0087 | 0.014 | 0.035 |
| 400 mN      | 0.00079 | 0.0081   | 0.0090   | 0.00026  | 0.0087 | 0.015 | 0.030 |
| 500 mN      | 0.00071 | 0.0031   | 0.0020   | 0.00020  | 0.0087 | 0.0094| 0.026 |
| 600 mN      | 0.00058 | 0.0060   | 0.0024   | 0.00017  | 0.0087 | 0.011 | 0.024 |
| 800 mN      | 0.00052 | 0.0050   | 0.0042   | 0.00013  | 0.0087 | 0.011 | 0.021 |
| 1 N         | 0.00051 | 0.0068   | 0.0034   | 0.00010  | 0.0087 | 0.012 | 0.019 |
| Tr.2        |         |          |          |          |        |       |       |
| 200 mN      | 0.0015  | 0.017    | 0.0023   | 0.0010   | 0.0087 | 0.020 | 0.035 |
| 400 mN      | 0.00079 | 0.0041   | 0.0086   | 0.00034  | 0.0087 | 0.0096| 0.022 |
| 600 mN      | 0.00058 | 0.0024   | 0.0031   | 0.00026  | 0.0087 | 0.0095| 0.021 |
| 800 mN      | 0.00052 | 0.00040  | 0.0049   | 0.00020  | 0.0087 | 0.011 | 0.020 |
| 1.2 N       | 0.00038 | 0.0013   | 0.0025   | 0.00017  | 0.0087 | 0.0091| 0.019 |
| 1.6 N       | 0.00039 | 0.0012   | 0.0018   | 0.00013  | 0.0087 | 0.0089| 0.021 |
| 2 N         | 0.00045 | 0.0016   | 0.0022   | 0.00010  | 0.0087 | 0.0091| 0.018 |

Table 3. Uncertainty budget of the comparison between the 2 N and 50 N DWMs.

| Relative uncertainty | Machine | Uncertainty component | 1 N       | 2 N       |
|----------------------|---------|-----------------------|-----------|-----------|
|                      | 50 N DWM| Realizing force        | 5.4 × 10^{-6} | 5.4 × 10^{-6} |
|                      |         | Reproducibility        | 3.7 × 10^{-6} | 3.1 × 10^{-6} |
|                      |         | Repeatability          | 1.0 × 10^{-6} | 1.4 × 10^{-6} |
|                      |         | Resolution             | 2.0 × 10^{-6} | 1.0 × 10^{-6} |
|                      |         | Expanded uncertainty    | W_{50N}   | W_{2N}    |
|                      | 2 N DWM | Realizing force        | 5.1 × 10^{-6} | 4.5 × 10^{-6} |
|                      |         | Reproducibility        | 5.5 × 10^{-5} | 6.3 × 10^{-5} |
|                      |         | Repeatability          | 1.8 × 10^{-5} | 9.8 × 10^{-6} |
|                      |         | Resolution             | 2.0 × 10^{-5} | 1.0 × 10^{-6} |
|                      |         | Misalignment           | W_{ma}    |           |
|                      |         | Expanded uncertainty    | W_{2N}    |           |

Figure 10. Relative deviation of the 2 N DWM compared with the 50 N DWM.

refers to the force step; the vertical axis indicates the relative deviation. The mean deflection was calculated using the first measurement cycle at the 0°, 120°, and 240° positions for each DWM, and the relative deviation was expressed as the mean deflection obtained using the 50 N DWM being equal to zero. The relative deviation values were −4.5 × 10^{-5} at the force step of 1 N and 1.5 × 10^{-4} at the force step of 2 N. The error bar shows the relative expanded uncertainty of measurement by using the two DWMs. The expanded uncertainty values were 2.1 × 10^{-4} at the force step of 1 N and 1.8 × 10^{-4} at the force step of 2 N for the 2 N DWM, and 1.4 × 10^{-5} and 1.3 × 10^{-5}, respectively, for the 50 N DWM. The comparison demonstrated that the deviation between the two DWMs was within the comparison uncertainty obtained by the root sum square of the expanded uncertainties. From this comparison, we confirmed the validity of the 2 N DWM and considered that for the evaluation of small-capacity force transducers, the relative deviation is acceptable at the present stage. Consequently, by these calibration experiments, we confirmed that high-precision calibration for small-capacity force transducers could be performed with the 2 N DWM at NMIJ.

4. Conclusion

In this study, we evaluated the uncertainty of calibration (calibration capability) of small-capacity force transducers using the 2 N DWM developed at NMIJ. Modifications of the force transducers and the 2 N DWM were conducted to improve the ability of high-precision calibration for the small-capacity force transducers by using the 2 N DWM. The uncertainty arising from misalignment between the force transducer and the loading frame was evaluated experimentally. As a challenging
study, two small-capacity force transducers with rated capacities of 1 N and 2 N were precisely calibrated using the 2 N DWM according to the prescription of the ISO 376. The calibration results were reliable and significantly improved after modifications. The relative expanded uncertainties of the calibration results were $1.9 \times 10^{-4}$ for Tr. 1 and $1.8 \times 10^{-4}$ for Tr. 2 at each rated capacity. The validity of the 2 N DWM was confirmed by comparing it with the 50 N DWM using a small-capacity force transducer with a rated capacity of 2 N. The relative deviation values were $-4.5 \times 10^{-5}$ at the force step of 1 N and $1.5 \times 10^{-4}$ at the force step of 2 N. Improvements in the structure and the reproducibility of the installation position of the force transducer are necessary, in the future, to obtain a more reliable and highly accurate calibration capability.

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**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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