XX IMEKO World Congress
Metrology for Green Growth
September 9−14, 2012, Busan, Republic of Korea

RENOVATION OF NMIJ′S 54 kN DEAD-WEIGHT FORCE STANDARD MACHINE INTO 100 kN MACHINE

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Abstract: NMIJ's 54 kN dead-weight force standard machine (DWM) has been upgraded to a 100 kN DWM by replacing the old weights with newly designed ones. There are four major improvements: extending the capacity from 54 kN to 100 kN, realizing calibration forces in Newtons, enabling 8- or 10-step calibrations for 50 kN and 100 kN ranges, and reducing maintenance work by motorizing the weight lifting mechanism. The calibration capability of the renovated DWM was confirmed to be better than 2.0×10^{-5} in terms of relative expanded uncertainty when calibrating some of the best force transducers available on the market.

Keywords: Force standard, SI unit of force, subdivision of force steps, motorization, DWM

1. INTRODUCTION

Recently, the demands for accurate calibration of force transducers have increased with the growing need for saving energy and resources. Dead-weight force standard machines (DWMs) are the most accurate machines among those presently used. The National Metrology Institute of Japan (NMIJ) had five DWMs with rated capacities of 500 N, 3 kN, 20 kN, 54 kN, and 540 kN. However, the latter two DWMs were inconvenient for calibrating force measuring instruments in accordance with the present international standards because they were designed and manufactured in the early 1960s and had the following disadvantages:

(a) Force calibration in the old unit: kilogram force
(b) Insufficient number of force steps for 8- or 10-step calibration with force measuring instruments of certain capacities
(c) Inconvenience of periodical maintenance on the hydraulic actuator

The first disadvantage concerns the fact that the masses of the dead-weights are adjusted to realize integer values of kilogram-force. To modify the weights to generate forces in Newtons, the SI unit of force, the masses should be increased by approximately 2 %. This requires not only mass readjustment but also a design change of the weights. Alternatively, extrapolation is required for conversion of the calibration results in kilogram-force to Newtons, and an additional uncertainty source arising from the extrapolation has to be considered due to the nonlinearity of force measuring instruments. Even though the uncertainty due to the extrapolation is not as large as other ones when calibrating a high-grade force measuring instrument, realizing forces in SI units completely eliminates this uncertainty source.

As for the second disadvantage, there is a conflict in the design of the loading frame in terms of the strength required to support all of the weights, the room size required for installing a compressive force measuring instrument, and the low weight required to realize a first calibration force step as small as possible. The first calibration force steps were 1 tf (approximately 9.8 kN) in the previous 54 kN DWM and 3 tf (approximately 29.4 kN) in the existing 540 kN DWM. These values are too large as they correspond to

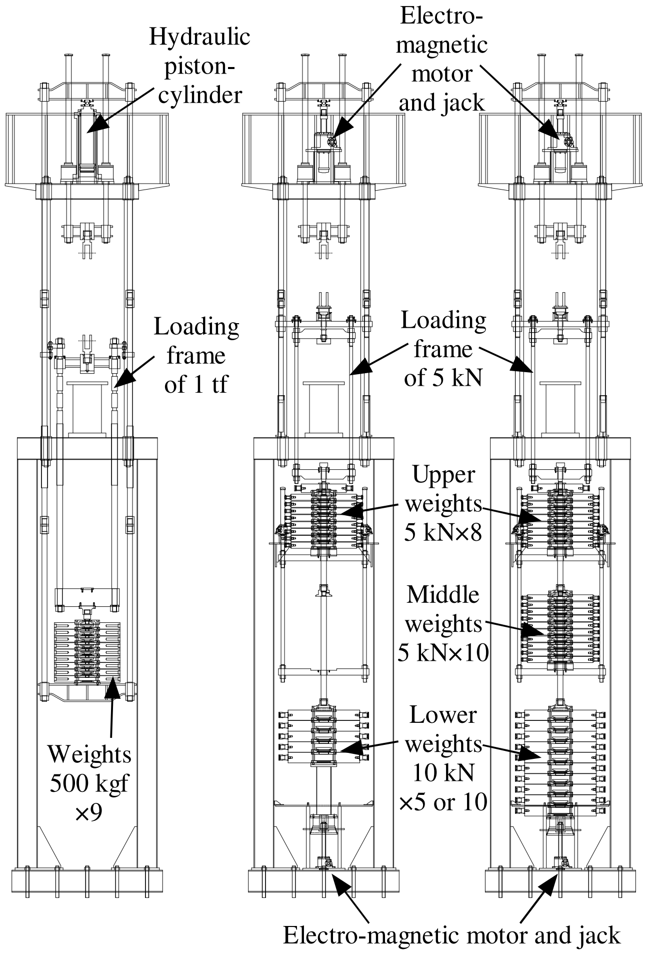

Fig. 1. Structural modification from (a) the 54 kN DWM to (b) the 100 kN DWM. (c) A planned 200 kN DWM is also illustrated.

approximately 20 % of the 50 kN calibration force range, approximately 30 % of the 100 kN range, and approximately 15 % of the 200 kN range, respectively. In order to carry out the calibration procedure described in the current international standard [1], they should be 10 % or less of the capacity of the force measuring instrument to be calibrated while maintaining sufficient strength and sufficient dimensions of the calibration room.

The third disadvantage concerns the need for periodic replacement of fluid in the hydraulic actuator to prevent mechanical trouble due to contamination of the fluid. This disturbs the effective operation of the DWM.

Therefore, we planned to upgrade the 54 kN DWM. There are four major improvements: extending the capacity from 54 kN to 100 kN, realizing calibration forces in Newtons, enabling 8- or 10-step calibration for 50 kN and 100 kN ranges, and reducing maintenance work by motorizing the weight lifting mechanism. This paper describes the design and calibration capability of the new 100 kN DWM.

2. DESIGN AND STRUCTURE

Fig. 1 shows drawings of (a) the previous 54 kN DWM, (b) the renovated 100 kN DWM, and (c) a planned 200 kN DWM. However, there are some financial issues to be resolved to realize the planned 200 kN DWM.

2.1 Loading frame and weights

The old weights were manufactured using cast iron in the early 1960′s, and their masses were adjusted so as to realize calibration forces in units of kgf. Because they consisted of the loading frame of 1 tf (approximately 9.8 kN) and a series of nine linkage weights of 500 kgf

Fig. 2. Space for additional middle weights between upper and lower weights.

(approximately 4.9 kN), force measuring instruments of 50 kN rated capacity cannot be calibrated in 10 % force steps with this 54 kN DWM. Additionally, because the minimum force step realized by the other 540 kN DWM is 3 tf (approximately 29.4 kN), force measuring instruments of 100 kN rated capacity also cannot be calibrated in 10 % force steps.

The new weights were produced using stainless steel, and their masses were adjusted so as to realize forces in units of N. They consist of a 5 kN loading frame, a 5 kN rod, and two series of linkage weights, an upper series consisting of eight 5 kN linkage weights and a lower series consisting of five 10 kN ones. Therefore, the rated capacity of the DWM has been extended from 54 kN to 100 kN, and 8- or 10-step calibrations have been enabled for the 50 kN and 100 kN ranges. In calibration of a 50 kN force transducer, the lower linkage-weight series is never loaded.

The DWM has space reserved for integrating additional weights up to a total of 100 kN, as shown in Fig. 2, that is, another series of ten 5 kN linkage weights in the middle and five 10 kN linkage weights to be added to the lower series. The loading frame and the rod were designed to have sufficient strength for suspending weights of 200 kN in total. The renovation plan shown in Fig. 1(c) will also enable 8- or 10-step calibration from the first step of 10 % or less for a calibration force range of 200 kN. Separation of the linkage weights into three series will make it possible to realize force steps with almost even time intervals, when calibrating force transducers of 50 kN, 100 kN, and 200 kN rated capacities, which are very common among commercially available force transducers.

2.2 Lifting mechanism

The old lifting mechanism was driven by a hydraulic piston-cylinder and required periodic maintenance work, such as replacement of the hydraulic fluid. The new lifting mechanisms are driven by electromagnetic motors and jacks and have four parts for the loading frame and the three linkage-weight series. For now, however, only three parts are used in accordance with the present configuration of the weights. Motorization has reduced the maintenance work considerably.

The capacities of the electromagnetic motors and jacks for lifting the linkage-weight series were determined from the gravitational force acting on each linkage-weight series and assuming a safety factor of 2. In the final plan shown in Fig. 1(c), the total gravitational force acting on each series is 45 kN for the upper series (including the rod), 50 kN for the middle series, and 100 kN for the lower series. Consequently, the capacities of the motors and jacks were chosen to be 100 kN for the upper and the middle series and 200 kN for the lower series. On the other hand, the motor and jack for lifting the loading frame should be able to lift the total weight of 200 kN, because preloading and creep tests require quick loading and unloading of multiple weights corresponding to the rated capacity of the force transducer in order to obtain limited information about the viscoelasticity of the force transducer. Therefore, these capacities were chosen to be 400 kN.

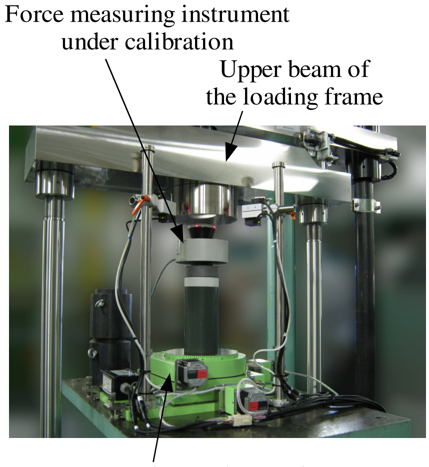

Fig. 3. Automatic rotation equipment incorporated into the 100 kN DWM.

2.3 Control system

A personal computer (PC)-based automatic control system had been employed for the 54 kN DWM [2]. Although it was an economical system, advances in the PC field were so fast that the input/output board introduced at the previous automation stage [2] was not supported by the present version of the PC's operating system, and the older parallel bus architecture was also in a precarious position, at risk of no longer being supported. Therefore, a programmable logic controller (PLC)-based system was newly developed for the 100 kN DWM instead of the previous PC-based system. The control system of the automatic rotation equipment for the compressive force transducer [3] was also incorporated into the new system. The equipment set-up is shown in Fig. 3.

Each electromagnetic motor, a kind of induction motor, was connected with the PLC through an inverter. The weight moving speed in up and down directions can be varied from 0.4 mm/s to 1.6 mm/s by the inverter. Instead of setting a load cell onto each of the weight supporting beams below the weight stacks, a rotary potentiometer was attached to each of the supporting beams, and a non-contact gap sensor was installed on the supporting frame of the loading frame for detecting contact and release between the supporting frame and the loading frame. Then the PLC calculates the positions at which to stop the weight motion and to change the weight moving speed.

The new PLC-based control system is equipped with a touchscreen as a user interface. It is possible to select between autonomous calibration operation without a PC and cooperative operation with a PC via serial communication, to suit the interface of the force measuring instrument.

3. CALIBRATION CAPABILITY

The calibration capability was confirmed once after completion of the DWM upgrade. However, after The Great East Japan Earthquake on 11th March, 2011, checks were carried out once again after cleaning and readjusting the DWM components to recover from the damage caused.

Table 1. Uncertainty budget sheet of calibration force realized by the 100 kN DWM.

Uncertainty source X_i	Evaluation	$u(X_i)$ / 10^{-6}	$\nu(X_i)$
Mass of dead-weight	Type B	5.0	∞
Gravitational acceleration	Type B	0.5	∞
Air buoyancy compensation	Type B	2.0	∞
Inclination of force introduction	Type B	0.3	∞
Combined relative standard uncertainty of the calibration force		5.4	∞

Symbols: $u(X_i)$ and $\nu(X_i)$ are the relative standard uncertainty and the degree of freedom associated with uncertainty source X_i.

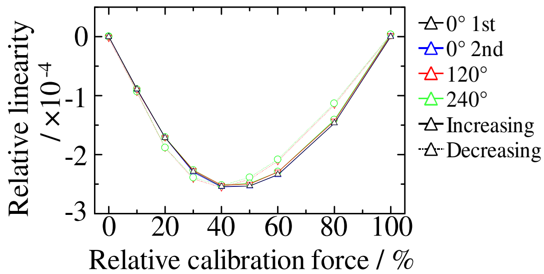

Fig. 4. Force-linearity plot of the calibration results.

3.1 Uncertainty budget

The uncertainty budget of the calibration force realized by the DWM is shown in Table 1. All of the uncertainty sources influencing the calibration force were considered as rectangular distributions. The masses of the newly manufactured dead-weights were calibrated so as to establish traceability to the national mass standard, and the loading table was verified to be horizontal after the recovery work. Common values for gravitational acceleration and air buoyancy compensation are adopted among all of the NMIJ's DWMs.

3.2 Calibration results of a force measuring instrument

ISO 376:2011 suggests a method of evaluating the uncertainty of calibration results of force measuring instruments [1]. The calibration capability was estimated in accordance with this standard. Because the contribution of the drift in the zero output is crucial to the calibration uncertainty, the force measuring instrument used for the calibration capability evaluation was chosen from commercially available devices from the viewpoint of small zero drift. Fig. 4 shows the force-linearity plot of the calibration results. Table 2 gives evaluated uncertainties of the calibration results. Since the Calibration and Measurement Capability (CMC) was evaluated for the best case of calibrating a force proving instrument classified for specific forces only, the uncertainty associated with interpolation was not taken into account.

The relative standard uncertainty associated with the applied calibration force had already been evaluated as mentioned above and given in Table 1. That associated with reproducibility of the calibration results was the standard

Table 2. Uncertainty budget sheet of the calibration result for the 100 kN DWM.

Uncertainty source X_i	Distribution	Relative calibration force / %								$\nu(X_i)$
		10	20	30	40	50	60	80	100	
		$u(X_i)$ / 10^{-6}								
Applied calibration force	Type B	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	∞
Reproducibility of the calibration results	Type A	4.0	1.1	2.4	1.8	2.6	2.5	2.0	1.1	2
Repeatability of the calibration results	Type B	3.8	0.9	2.5	1.4	0.4	0.6	0.0	0.4	∞
Resolution of the indicator	Type B	6.7	3.3	2.2	1.7	1.3	1.1	0.8	0.7	∞
Creep of the instrument	Type B	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	∞
Drift in the zero output	Type B	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	∞
Temperature of the instrument	Type B	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	∞
Interpolation	N/A	—	—	—	—	—	—	—	—	—
Combined relative standard uncertainty of the calibration result		12	9.3	9.5	9.0	9.0	9.0	8.8	8.6	>>50
Relative expanded uncertainty given by equation whose coefficients are twice those of the best fit equation / 10^{-6}		23	20	19	19	18	18	18	18	

Symbols: $u(X_i)$ and $\nu(X_i)$ are the relative standard uncertainty and the degree of freedom associated with uncertainty source X_i.

deviation calculated from three incremental deflections obtained in three different rotational positions, and its effective degree of freedom was 2. That associated with the creep of the instrument was alternatively evaluated by the second method described in the standard; that is, dividing the hysteresis by a factor of 3, because the calibration was carried out with both incremental and decremental forces. The hysteresis can be calculated individually at each force step, while creep was evaluated uniquely. Therefore, the maximum value of relative hysteresis was taken into account. If the creep of the instrument, instead of the hysteresis, could be adopted for evaluating this uncertainty source, the relative standard uncertainty would be reduced to 3.9×10^{-6}. The relative standard uncertainty associated with the temperature of the instrument was evaluated by considering a temperature fluctuation of 0.3 K during calibration and a relative temperature coefficient of sensitivity of 3×10^{-5} K^{-1}. Actual values of the effective degrees of freedom of the combined relative standard uncertainty at each force step were different; however, all of these values were over 50.

Finally, the best-fit least-squares equation was determined using all of the combined relative standard uncertainties against force. The relative expanded uncertainty was calculated by multiplying the value given by the best-fit equation and the coverage factor of 2, and was found to be 2.0×10^{-5} in the best case. The calibration capability of this upgraded 100 kN DWM is of the same level as those of other DWMs.

3.3 Intra-laboratory comparisons with other DWMs

To verify the calibration capability, intra-laboratory comparisons were also carried out between the 20 kN and 100 kN DWMs and between the 100 kN and 540 kN DWMs.

Two compressive force transducers with rated capacities of 20 kN and 100 kN were prepared for the comparisons. Three measurements were carried out in a comparison: the first measurement on a smaller DWM, the second measurement on a larger one, and the final measurement on the smaller one again. Then the second measurement result was compared with the mean of the first and the final ones. Each measurement was carried out in accordance with the procedure described in ISO 376 [1]; however, only a limited number of force steps, instead of the usual eight, were employed in the comparisons. Force steps of 5 kN, 10 kN, 15 kN, and 20 kN were used for the comparison between the 20 kN and 100 kN DWMs, and force steps of 50 kN, 80 kN, and 100 kN were used for the comparison between the 100 kN and 540 kN DWMs. The relative expanded uncertainty of the comparison was evaluated taking into account uncertainties of applied calibration forces by both DWMs, reproducibility of the calibration results, resolution of the indicator, drift in the zero output, difference in hysteresis measured by the smaller and larger DWMs, and

Table 3. Results of the intra-laboratory comparisons.

DWM compared	20 kN DWM				540 kN DWM		
Force step	5 kN	10 kN	15 kN	20 kN	50 kN	80 kN	100 kN
Relative deviation / 10^{-6}	4.0	−2.5	−1.0	−0.3	14	−3.6	−4.7
Relative expanded uncertainty of the comparison at a level of confidence of approximately 95 % / 10^{-6}	24	19	18	17	22	22	24

drift in sensitivity between the first and the final measurements. The minimum value of the effective degrees of freedom of the combined relative standard uncertainty at each force step was 28. As shown in Table 3, at all of the force steps, the deviations were smaller than the comparison uncertainties. Therefore, it can be concluded that the equivalence of these DWMs was confirmed.

4. SUMMARY

NMIJ's 100 kN DWM has been successfully upgraded from the previous 54 kN DWM by replacing the old weights with newly designed ones. The calibration capability of the renovated DWM was confirmed to be better than 2.0×10^{-5} in terms of relative expanded uncertainty at a level of confidence of approximately 95 % when calibrating some of the best force transducers available on the market.

5. ACKNOWLEDGEMENT

The authors would like to thank Dr. Jianxin Sun of the NMIJ/AIST for calibrating the masses of the newly manufactured dead-weights.

6. REFERENCES

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