< Final report >

Report on the APMP.M.F-S2 supplementary comparison for 100 kN force

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1. Introduction

This supplementary comparison, named APMP.M.F-S2, was carried out at force range from 20 kN to 100 kN. It was based on an international cooperation scheme for verifying degree of equivalence between 100 kN dead-weight type force standard machine (DWM) of NIMT (Thailand) and 100 kN DWM of NMIJ (Japan). Although NMIJ and NIMT had already participated in the APMP.M.F-K2 key comparison, it was made only at 50 kN and 100 kN force steps. This supplementary comparison was planned to thoroughly compare the both DWMs in wider force steps than those of the key comparison, and thus it had no corresponding key-comparisons to be linked at that time. NMIJ organized the comparison as the pilot laboratory and NIMT participated in. This report describes scheme and results of the comparison.

2. Force standard machines participated in the comparison

2.1 General information

Force standard machines participated in this comparison are listed in Table 1.

Table 1. Force standard machines and participating laboratories.

Force standard machines			Institute
Capacity / kN	Type	Relative standard uncertainty of applied force	
100	Deadweight	5.4×10^{-6}	NMIJ (pilot lab)
100	Deadweight	5.1×10^{-6}	NIMT

2.2 Summary of the NMIJ's 100 kN DWM

The 100 kN DWM, as shown in Fig. 1, has a loading frame acting as a 5 kN weight and two series of linkage weights. The upper series consists of nine 5 kN weights and the lower one has five 10 kN weights. Both of the weight series are mounted on the supporting beams and the beams are driven independently by induction motors and screws. The loading table can be rotated by motors with a compressive force measuring device mounted on it, and one calibration sequence including rotational position change of the device can be conducted automatically not only in ordinary calibrations according to ISO 376 but also in special cases such as one according to this comparison protocol.

Fig. 1. The NMIJ's 100 kN DWM.

2.3 Summary of the NIMT's 100 kN DWM [1]

The 100 kN force standard machine in NIMT, as shown in Fig. 2, 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 having ten force steps of equal increments. A 10 % overloading test can also be performed for these ranges; that is, 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 required forces one by one.

Fig. 2. The NIMT's 100 kN DWM.

3. Traveling artifacts and measuring amplifiers

3.1 Traveling artifacts

The following equipment was prepared by NMIJ and was circulated as the traveling artifacts.

1) Force transducer

   Capacity: 20 kN (compressive force)

   Manufacturer: HBM GmbH

   Type: TOP-Z4A

   Serial number: 123930476

2) Force transducer

   Capacity: 50 kN (compressive force)

   Manufacturer: HBM GmbH

   Type: TOP-Z4A

   Serial number: 103630099

3) Force transducer

   Capacity: 100 kN (compressive force)

   Manufacturer: HBM GmbH

   Type: Z4A

   Serial number: 180530004

4) Bridge calibration unit

   Manufacturer: HBM GmbH

   Type: BN100A

Serial number: 010

5) Measuring amplifier

Manufacturer: HBM GmbH

Type: DMP40

Serial number: 024520004

However, the 20 kN force transducer was not actually used in the comparison as it was accidentally overloaded in the course of the comparison measurements, and the measurement data already obtained using this force transducer was discarded.

3.2 Measuring amplifiers

The measuring amplifier was included in traveling artifacts. The important settings applied for all measurements are the bridge excitation voltage of 5 V, the measuring range of 2.5 mV/V, the resolution of 0.000001 mV/V, and the cut-off frequency of low-pass filter of 0.1 Hz. The measuring amplifier was checked just before and after the measurement by referring to the bridge calibration unit mentioned above at the settings of +0.0, +0.2, +0.8, +1.0, +1.2, +1.4, +1.6, +1.8, +2.0, and +2.2 mV/V and also at the amplifier's internal calibration signal of 2.5 mV/V. Readings of the measuring amplifier connected with the force transducer were corrected based on the check results before calculating the deflections.

4. Comparison scheme and measurement procedures

The comparison scheme is based on other forgoing bilateral comparisons between force standard machines [1–4]. The first group of measurements was carried out at NMIJ, and the intermediate and last groups were performed by NIMT and by NMIJ, respectively. The first and last groups of measurements was carried out at NMIJ using its 100 kN DWM, and the intermediate measurements was performed by NIMT using its 100 kN DWM. The date and conditions of each measurement were listed in Table 2. The number after hyphen on identification codes in the table indicates capacity of the force transducer in kilonewton. The stability of sensitivity was estimated by difference between the first and last measurements executed by NMIJ.

Loading procedure is depicted as Fig. 3. Force steps on the vertical axis from F1 to F4 correspond to 20, 30, 40, and 50 kN for the 50 kN force transducer and 50, 60, 80, and 100 kN for the 100 kN one. Following to three preloads between 0 and the rated capacity, three repetitious measurement cycles at each measuring step were performed in the first force transducer's orientation of 0° in order to check simple repeatability of the measurement in the same orientation. After that, three sets each consisted of a preloading and a measurement cycle at each measuring step were carried out in three orientations of 90°, 180°, and 270° to evaluate reproducibility in the four different orientations. Finally, a measurement was performed in the last orientation of 360° with both increasing and decreasing steps to check performance of the transducer. Readings were noted in 3 minutes time intervals except for following two cases: 4.5 minutes interval from zero to the first force step F1 and 6 minutes interval from the maximum force step F4 to zero. Hence, the total time for one measurement sequence was 238.5 minutes. Such loading-time exceptions were unavoidable for the linkage-weight structure; that is, many small weights had to be stacked one by one before applying the first force step F1. However, influence of undesirable creep caused by viscoelastic properties of the transducers was minimized by adopting the same loading procedure both at NIMT and NMIJ.

All the measurements were carried out at room temperature of (23.0 ± 0.5) °C. The force transducer was regarded to be insensitive to fluctuations of ambient pressure and humidity.

Table 2. Date and conditions of each measurement.

Identification	Date	Force standard machine	Ambient conditions
J1-50	15 Mar. 2017	100 kN DWM of NMIJ	22.8 °C to 23.0 °C, 38 % to 39 % 100.4 kPa to 100.7 kPa
T-50	7 Jun. 2017	100 kN DWM of NIMT	22.5 °C to 22.7 °C, 53 % to 55 % 100.3 kPa to 100.5 kPa
J2-50	28 Jun. 2017	100 kN DWM of NMIJ	23.2 °C to 23.3 °C, 47 % to 49 % 100.9 kPa to 101.1 kPa
J1-100	13 Mar. 2017	100 kN DWM of NMIJ	22.9 °C to 23.0 °C, 38 % to 39 % 101.2 kPa to 101.4 kPa
T-100	4 Jun. 2017	100 kN DWM of NIMT	22.3 °C to 22.9 °C, 47 % to 50 % 100.3 kPa to 100.5 kPa
J2-100	28 Jun. 2017	100 kN DWM of NMIJ	23.1 °C to 23.3 °C, 46 % to 48 % 101.0 kPa to 101.2 kPa

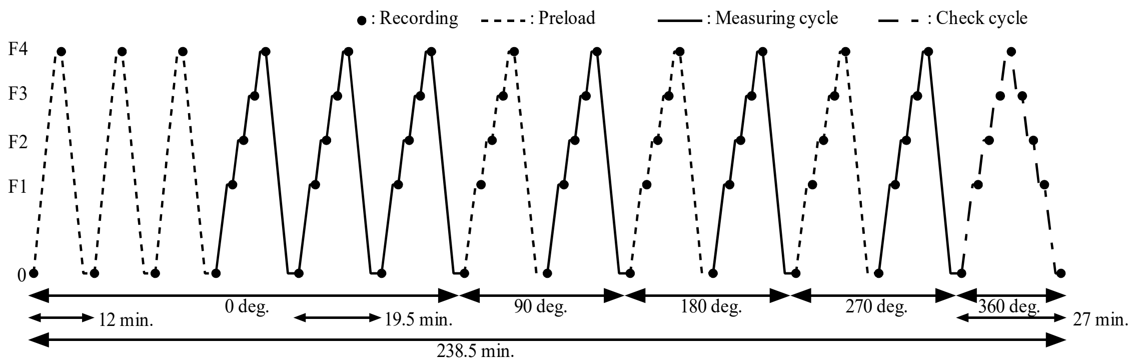

Fig. 3. Loading chart for the comparison.

5. Results

5.1 Stability of the traveling artifacts

Stability in sensitivity of the traveling artifacts consisting of the force transducers and the measuring amplifier was estimated by the difference between the first and last measurements at NMIJ; that means the sensitivity drift was evaluated from the difference between J1-50 and J2-50, and between J1-100 and J2-100, for each. These values of the sensitivity drift were taken into account when estimating uncertainty of the comparison. The sensitivity drift of the 50 kN transducer did not exceed 14 nV/V; however, that of the 100 kN transducer reached 149 nV/V in the worst case. Such large sensitivity drift might have been caused by insufficient breaking-in of the new 100 kN transducer, due to limited time period between its production and its use in the comparison. This insufficient stability in sensitivity made the comparison insignificant for the 100 kN range, while the comparison in the 50 kN range was meaningful.

The bridge calibration unit was also monitored using the same measuring amplifier. It also demonstrated sufficient stability, since changes in indications of the same measuring amplifier were 10 nV/V at the largest during the comparison. The value was also taken into account in the uncertainty estimation.

5.2 Uncertainty evaluation of each measurement

Following uncertainty sources are taken into account for each measurement tabulated in Table 3.

1) Uncertainty arisen from the applied force, w_{fsm}
2) Uncertainty arisen from the reproducibility among four orientations of 0°, 90°, 180°, and 270°, w_{rot}
3) Uncertainty arisen from the resolution of the measuring amplifier, w_{res}
4) Uncertainty arisen from the temperature fluctuation of the artifacts during the measurement, w_{temp}
5) Uncertainty arisen from the DMP40 correction, w_{dmp}
6) Uncertainty arisen from the sensitivity drift of the force transducer (only for NMIJ), w_{drift}

Here, uncertainty sources of w_{rot}, w_{res}, w_{temp}, and w_{dmp} are regarded as uncorrelated, and combined using propagation law of uncertainty when weighted means are calculated as mentioned below. Other uncertainty sources are treated as correlated ones and combined by taking square root of sum of squares of these uncertainties, after calculation of weighted mean values. Uncertainty arisen from the DMP40 correction was estimated using the maximum change in the amount of corrections referring to the same BN100A between the first and the last measurement groups.

The maximum pressure difference among all of the measurements was only 0.9 kPa and was regarded as negligible against the comparison uncertainty. The temperature fulfilled the regulation described in section 4 when measurements of the 50 kN transducer were performed. The minimum temperature for the measurement of the 100 kN transducer slightly exceeded the regulation; however, sensitivity difference due to the temperature fluctuation for the transducer were estimated to be approximately 14 nV/V which is below the maximum sensitivity fluctuation of 29 nV/V including the reproducibility in T-100, was insignificant compared to the large sensitivity drift.

Mean deflections and uncertainties of each measurement are listed in Table 3 and depicted in Fig. 4. The mean deflection at each force step of each measurement was an average of four values measured in four orientations of 0°, 90°, 180°, and 270°. In this phase, relative expanded uncertainty was calculated with considering only the uncertainty sources of w_{fsm}, w_{rot}, w_{res}, w_{temp}, and w_{dmp}. Note that all of the expanded uncertainties given in this report correspond to the level of confidence of approximately 95 % with coverage factors *k* of 2.

Table 3. Mean deflection and uncertainty of each measurement.

ID	Force step / kN	Deflection X / (mV/V)	Relative expanded uncertainty $W(X)$ / 10^{-6} “
J1-50	20	0.799486	20
	30	1.199227	18
	40	1.598993	17
	50	1.998764	17
T-50	20	0.799496	15
	30	1.199253	13
	40	1.599016	12
	50	1.998789	12
J2-50	20	0.799494	19
	30	1.199241	18
	40	1.599003	17
	50	1.998774	17
J1-100	50	1.000162	14
	60	1.200270	13
	80	1.600590	13
	100	2.001020	12
T-100	50	1.000143	14
	60	1.200211	13
	80	1,600499	12
	100	2.000910	12
J2-100	50	1.000096	15
	60	1.200188	15
	80	1.600477	15
	100	2.000871	15

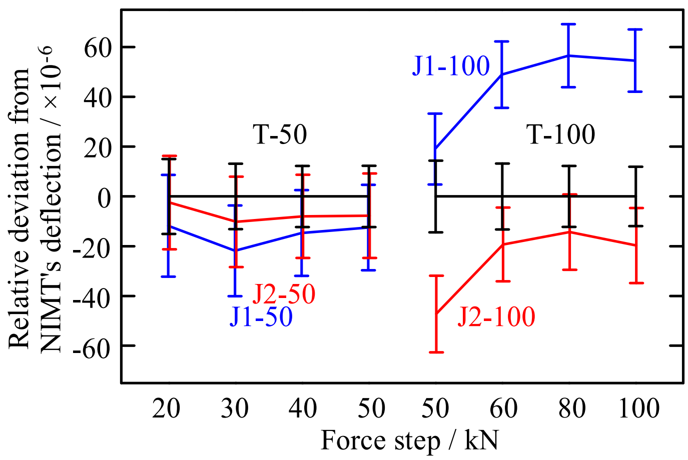

Fig. 4. Mean deflections and uncertainties of each measurement.

5.3 Weighted mean of the first and last measurements at NMIJ

Weighted mean deflection of X_{J12} was calculated from two deflections of X_{J1} and X_{J2} to cancel influence of the sensitivity drift of the force transducer as eq. (1). Here, $w(X)$ means relative combined standard uncertainty of the deflection X.

$$X_{\mathrm{J12}} = \frac{\dfrac{X_{\mathrm{J1}}}{w^2\left(X_{\mathrm{J1}}\right)} + \dfrac{X_{\mathrm{J2}}}{w^2\left(X_{\mathrm{J2}}\right)}}{\dfrac{1}{w^2\left(X_{\mathrm{J1}}\right)} + \dfrac{1}{w^2\left(X_{\mathrm{J2}}\right)}} \tag{1}$$

Relative uncertainty w_{J12} was calculated as eq. (2). Here, $w(X_{\_\mathrm{uncorr}})$ means combined uncertainty arisen from uncorrelated sources; that is, combination of w_{rot}, w_{res}, w_{temp}, and w_{dmp}.

$$\begin{aligned} w\left(X_{\mathrm{J12}}\right) &= \sqrt{\left\{\left(\frac{\partial X_{\mathrm{J12}}}{\partial X_{\mathrm{J1}}}\right)^2 w^2\left(X_{\mathrm{J1}}\right) + \left(\frac{\partial X_{\mathrm{J12}}}{\partial X_{\mathrm{J2}}}\right)^2 w^2\left(X_{\mathrm{J2}}\right) + 2\frac{\partial X_{\mathrm{J12}}}{\partial X \partial_{\mathrm{J1}}}\frac{\partial X_{\mathrm{J12}}}{\partial X_{\mathrm{J2}}} w\left(X_{\mathrm{J1}}, X_{\mathrm{J2}}\right)\right\} + w_{\mathrm{drift}}^2} \\ &= \sqrt{\left[\frac{\dfrac{w^2\left(X_{\mathrm{J1\_uncorr}}\right)}{w^4\left(X_{\mathrm{J1}}\right)} + \dfrac{w^2\left(X_{\mathrm{J2\_uncorr}}\right)}{w^4\left(X_{\mathrm{J2}}\right)}}{\left\{\dfrac{1}{w^2\left(X_{\mathrm{J1}}\right)} + \dfrac{1}{w^2\left(X_{\mathrm{J2}}\right)}\right\}^2} + w_{\mathrm{fsm}}^2\right] + w_{\mathrm{drift}}^2} \end{aligned} \tag{2}$$

The mean deflections and relative uncertainties are listed in Table 4.

Table 4. Weighted mean deflections of the first and last measurements and their uncertainties.

ID	Force step / kN	Deflection X / (mV/V)	Relative expanded uncertainty $W(X)$ / 10^{-6}
J12-50	20	0.799490	17
	30	1.199234	16
	40	1.598998	15
	50	1.998769	15
J12-100	50	1.000131	40
	60	1.200233	41
	80	1.600543	43
	100	2.000959	45

5.4 Equivalence between the force standard machines

Equivalence between forces realized by the DWMs are evaluated using relative deviation and comparison uncertainties as listed in Table 5. Relative expanded uncertainty of the comparison W_{comp} was calculated by taking square root of the sum of square of the two relative uncertainties $W(X)$ of the two related measurements.

Although the force range of this comparison had to be reduced from initially planned “10 kN to 100 kN” to actually executed “20 kN to 100 kN” due to the accidental overloading on the 20 kN force transducer, the comparison was carried out for the most part of the force range of the 100 kN DWMs and all absolute values of the relative deviations in the table are within the respective relative expanded uncertainty of the comparison. Thus, it has been demonstrated that forces realized by the 100 kN DWMs of NIMT and of NMIJ are equivalent to each other.

Table 5. Relative deviations and comparison uncertainties between the DWMs.

Force step / kN	ID	Deflection X / (mV/V)	Relative expanded uncertainty $W(X)$ / 10^{-6}	Deviation / (mV/V)	Relative expanded uncertainty of comparison W_{comp} / 10^{-6}	Normalized error E_n
20	T-50	0.799496	15	0.000006	23	0.30
	J12-50	0.799490	17			
30	T-50	1.199253	13	0.000019	21	0.76
	J12-50	1.199234	16			
40	T-50	1.599016	12	0.000018	19	0.59
	J12-50	1.598998	15			
50	T-50	1.998789	12	0.000020	19	0.53
	J12-50	1.998769	15			
50	T-100	1.000143	14	0.000012	43	0.27
	J12-100	1.000131	40			
60	T-100	1.200211	13	−0.000022	43	−0.42
	J12-100	1.200233	41			
80	T-100	1.600499	12	−0.000044	44	−0.62
	J12-100	1.600543	43			
100	T-100	2.000910	12	−0.000049	46	−0.53
	J12-100	2.000959	45			

6. Summary

The APMP.M.F-S2 supplementary comparison has been conducted between NIMT (Thailand) and NMIJ (Japan) at force range from 20 kN to 100 kN. The comparison results revealed the equivalence of forces realized by the 100 kN DWM of NIMT to those by the 100 kN DWM of NMIJ within their claimed uncertainties in the range up to 50 kN. In the upper range up to 100 kN the uncertainties can not be confirmed because of the last drift of the 100 kN transducer.

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