## < Final report >

# Report on the APMP.M.F-S1 supplementary comparison for 2 MN Force

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## 1. Introduction

NMIJ/AIST has renovated its 5 MN force standard machine of the hydraulic amplification type (5 MN FSM), especially its hydraulic control system. This bilateral comparison, namely the APMP.M.F-S1 supplementary comparison, in the 2 MN force range is planned to verify degree of equivalence of the 5 MN FSM of NMIJ/AIST to the 2 MN force standard machine of the deadweight type (2 MN DWM) of PTB, and capability of NMIJ/AIST in its ordinary calibrations using the 5 MN FSM. NMIJ/AIST organized this comparison as the pilot institute, while PTB provided the reference values as the reference institute.

This document describes the comparison scheme and reports the results of the comparison.

## 2. Organization

### 2.1 Participants

Participated institutes and force standard machines are listed in Table 1.

Table 1 Participated institutes and force standard machines

| Country | Institute | Force standard machine | | | Note |
|---|---|---|---|---|---|
| | | Capacity / MN | Type | Relative expanded uncertainty of applied force | |
| Japan | NMIJ/AIST | 5 | Hydraulic amplification | $86 \times 10^{-6}$ | Pilot institute |
| Germany | PTB | 2 | Deadweight | $20 \times 10^{-6}$ | Reference institute |

NOTE: Unless otherwise specified, expanded uncertainties in this report correspond to the level of confidence of approximately 95 % with coverage factors $k$=2.

### 2.2 Traveling artifacts

The following equipment was circulated as the traveling artifacts.

1) Force transducer #1 (Tr1)
   Capacity: 2 MN (compressive force)
   Manufacturer: Showa Measuring Instruments Co., Ltd. (JP)
   Type: RC-2MN-1013
   Serial No.: M160201
   Relative temperature coefficient: $(-68.2 \pm 6.6) \times 10^{-6}$ $K^{-1}$

2) Force transducer #2 (Tr2)
   Capacity: 2 MN (compressive force)
   Manufacturer: A&D Orientec Co. Ltd. (JP)
   Type: UL-2MN-KE1
   Serial No.: 110030
   Relative temperature coefficient: $(-21.2 \pm 6.9) \times 10^{-6}$ $K^{-1}$

3) Bridge calibration unit
  Manufacturer: HBM GmbH (DE)
  Type: BN100A
  Serial No.: 08112

### 2.3 Comparison scheme and environmental conditions

The comparison was carried out in the star formation. NMIJ/AIST made measurements firstly, PTB did secondly and NMIJ/AIST did again lastly to check stability of the traveling artifacts.

The target ambient temperature was chosen to be (23 ± 0.2) °C. However, temperature fluctuation up to ±0.5 K was allowed for in the measurements at NMIJ/AIST, as this is a comparison of a hydraulic amplification type FSM by referring to a deadweight type FSM.

Actual measurement dates and ambient conditions are shown in Table 3 and Table 7 in the latter sections.

### 2.4 Measurement procedures

Two types of measurement procedures were employed in this comparison. One, namely “KC loading pattern”, is according to the CCM force key comparisons in order to verify the degree of equivalence of the 5 MN FSM of NMIJ/AIST to the 2 MN DWM of PTB. The other, namely “ISO 376 loading pattern”, is according to the ISO 376 in order to confirm the calibration capability of NMIJ/AIST using the 5 MN FSM. Detailed procedures with these two loading patterns are as follows.

#### 2.4.1 The KC loading pattern

(1) Set following parameters on a DMP40 of each institute.
  - Bridge excitation voltage: 5 V (Imperative)
  - Measuring range setting: 2.5 mV/V (Imperative)
  - Resolution: 0.000001 mV/V
  - Filter setting: 0.1 Hz Bessel filter

(2) Calibrate the DMP40 by referring to the traveling BN100A.
  - Power source voltage for BN100A: AC 230 V
  - +0 mV/V, +0.2 mV/V, +1.0 mV/V, +1.2 mV/V, +1.4 mV/V, +2.0 mV/V, +2.2 mV/V, +2.4 mV/V and +2.5 mV/V
  - Also at the setting of DMP40 to “CAL”
  - Record the DMP40 calibration data on the data sheet

(3) Make measurements on each of the traveling force transducers according to the procedure of the CCM force key comparisons but reduced number of orientation changes.
  - Five orientations of 0, 90, 180, 270 and 360 degrees
  - Only increasing forces
  - Two force steps of 1.0 MN and 2.0 MN
  - One preloading and one measurement at each orientation except for at 0 degree orientation
  - One preloading and three measurements at 0 degree orientation
  - Take readings at each force step at 6 min time interval

- Record the readings on the data sheet

(4) Evaluate uncertainty of the measurement result at each force step
  - Evaluate uncertainty at each force step
  - Record the evaluated uncertainty on the data sheet

### 2.4.2 The ISO 376 loading pattern

(1) Set following parameters on a DMP40 of each institute.
  - Bridge excitation voltage: 5 V (Imperative)
  - Measuring range setting: 2.5 mV/V (Imperative)
  - Resolution: 0.000001 mV/V
  - Filter setting: 0.1 Hz Bessel filter

(2) Calibrate the DMP40 by referring to the traveling BN100A.
  - Power source voltage for BN100A: AC 230 V
  - +0 mV/V, +0.2 mV/V, from +0.6 mV/V to +2.4 mV/V with 0.2 mV/V increments and +2.5 mV/V
  - Also at the setting of DMP40 to “CAL”
  - Record the DMP40 calibration data on the data sheet

(3) Make calibrations on each of the traveling force transducers according to ISO 376.
  - Three orientations of 0, 120 and 240 degrees
  - Increasing and decreasing forces
  - Eight force steps of 0.6 MN, 0.8 MN, 1.0 MN, 1.2 MN, 1.4 MN, 1.6 MN, 1.8 MN and 2.0 MN
  - Take readings at 30 s after the force is applied or removed
  - Record the readings on the data sheet

(4) Carry out creep test
  - Carry out both loading and unloading creep tests at 2 MN and zero in case of 2 MN DWM of PTB, while carry out only unloading creep test at zero in case of 5 MN FSM of NMIJ/AIST
  - Take readings at 30 s and 300 s after the maximum calibration force of 2 MN is applied or removed
  - Record the readings on the data sheet

(5) Evaluate uncertainty of the calibration result at each force step
  - Evaluate uncertainty at each force step without applying a fitting curve through the all force steps
  - Record the evaluated uncertainty on the data sheet

## 3. Results

### 3.1 Stability of the traveling artifacts

#### 3.1.1 Stability of the BN100A bridge calibration unit

In the proceeding and succeeding measurements at NMIJ/AIST, output of the BN100A bridge calibration unit were monitored by the same DMP40 amplifier always kept in the laboratory environment. The BN100A was found to be stable within a drift up to 9 nV/V at the largest. Thus, the uniformity of different DMP40 amplifiers of the participating institutes was secured by referring to the same traveling BN100A bridge calibration unit.

### 3.1.2 Stability of the force transducers

As shown in Table 4 and Figure 1 in the latter section, the traveling force transducer Tr2 exhibited sufficient stability with drift up to $19 \times 10^{-6}$ relative. It is much smaller than the uncertainties of the proceeding and succeeding measurements by the 5 MN hydraulic amplification machine of NMIJ/AIST. On the other hand, Tr1 exhibited noticeable sensitivity drift up to $98 \times 10^{-6}$ relative.

## 3.2 Corrections

### 3.2.1 Correction for the use of different DMP40 amplifiers

Difference of the different DMP40 amplifiers were within 8 nV/V. As the BN100A was found to be stable within a drift up to 9 nV/V in the proceeding and succeeding measurements at NMIJ/AIST, corrections for different DMP40s were made systematically by referring to the traveling BN100A.

### 3.2.2 Correction for the different ambient temperature

NMIJ/AIST had evaluated temperature coefficients of the two traveling force transducers by varying the laboratory temperature from 20 °C to 26 °C. The relative temperature coefficients were determined as shown in **2.2**.

As shown in Table 3, temperature during the measurements was very close to the reference temperature of 23 °C at PTB, while it was not so close at NMIJ/AIST due to limitation of running the air-conditioning facilities at NMIJ/AIST at that time. Therefore, corrections for the temperature deviations were applied only to the results of NMIJ/AIST with the KC loading pattern and uncertainties associated with the corrections were taken into account.

On the other hand, temperature fluctuation during any measurement series did not exceed 0.1 °C both at PTB and NMIJ/AIST, as shown in Table 3 in the section 3.3. Uncertainties due to the temperature fluctuation are taken into account in all cases when evaluating the measurement uncertainties, even though this influence is quite minor.

### 3.2.3 Correction for the sensitivity drift

As Tr1 exhibited the noticeable sensitivity drift, in the measurements with the KC loading pattern, a weighted mean (N12) of the proceeding and succeeding measurement results of NMIJ/AIST (N1 and N2) was taken and was compared with the results of PTB (P1). This procedure is also applied to the results of Tr2 for uniformity of data processing. Uncertainty due to the sensitivity drift was also considered in the measurement uncertainty of the weighted mean results of NMIJ/AIST.

In the calibrations with the ISO loading pattern, however, no corrections are made for the sensitivity drift, and only the results of one single calibration by the NMIJ/AIST, which is the proceeding one (N1), are compared with the results of PTB (P1).

### 3.2.4 Correction for the creep effect

Table 2 shows relative creep errors defined in ISO 376 and evaluated by the creep test. However, no correction for the creep is applied to the measured results, since timings to take readings are adjusted in the measurements of the both institute. The uncertainty due to the creep is taken into account only when evaluating uncertainty of the calibration results with the ISO 376 loading pattern.

Table 2 Creep characteristics of the force transducers

| Institute | Direction of loading | Force / MN | Relative creep error / $10^{-6}$ | |
|---|---|---|---|---|
| | | | Tr1 (Showa RC-2MN-1013) | Tr2 (A&D Orientec UL-2MN-KE1) |
| PTB | Loading | 2 | 9 | 74 |
| | Unloading | 0 | 32 | 57 |
| NMIJ/AIST | Unloading | 0 | 42 | 49 |

### 3.3 Results of the measurements with the KC loading pattern

Table 3 shows dates and ambient conditions of the measurements.

Table 3 Dates and ambient conditions of the measurements with the KC loading pattern

| Institute | Code | Tr1 (Showa RC-2MN-1013) | | Tr2 (A&D Orientec UL-2MN-KE1) | |
|---|---|---|---|---|---|
| | | Date | Ambient conditions | Date | Ambient conditions |
| NMIJ/AIST | N1 | 2015-05-13 | 24.1 °C to 24.2°C<br>44 % to 43 %<br>1000.3 hPa to 1001.5 hPa | 2015-05-14 | 23.9 °C<br>45 % to 44 %<br>1005.4 hPa to 1006.0 hPa |
| PTB | P1 | 2015-06-12 | 23.08 °C to 23.05 °C<br>41 % to 42 %<br>1013.6 hPa to 1012.1 hPa | 2015-06-30 | 23.05 °C to 23.08 °C<br>41 % to 42 %<br>1021.5 hPa to 1021.1 hPa |
| NMIJ/AIST | N2 | 2015-07-27 | 23.7 °C to 23.8 °C<br>47 % to 43 %<br>1003.5 hPa to 1002.4 hPa | 2015-07-30 | 23.9 °C to 24.0 °C<br>51 % to 44 %<br>1005.4 hPa to 1006.0 hPa |

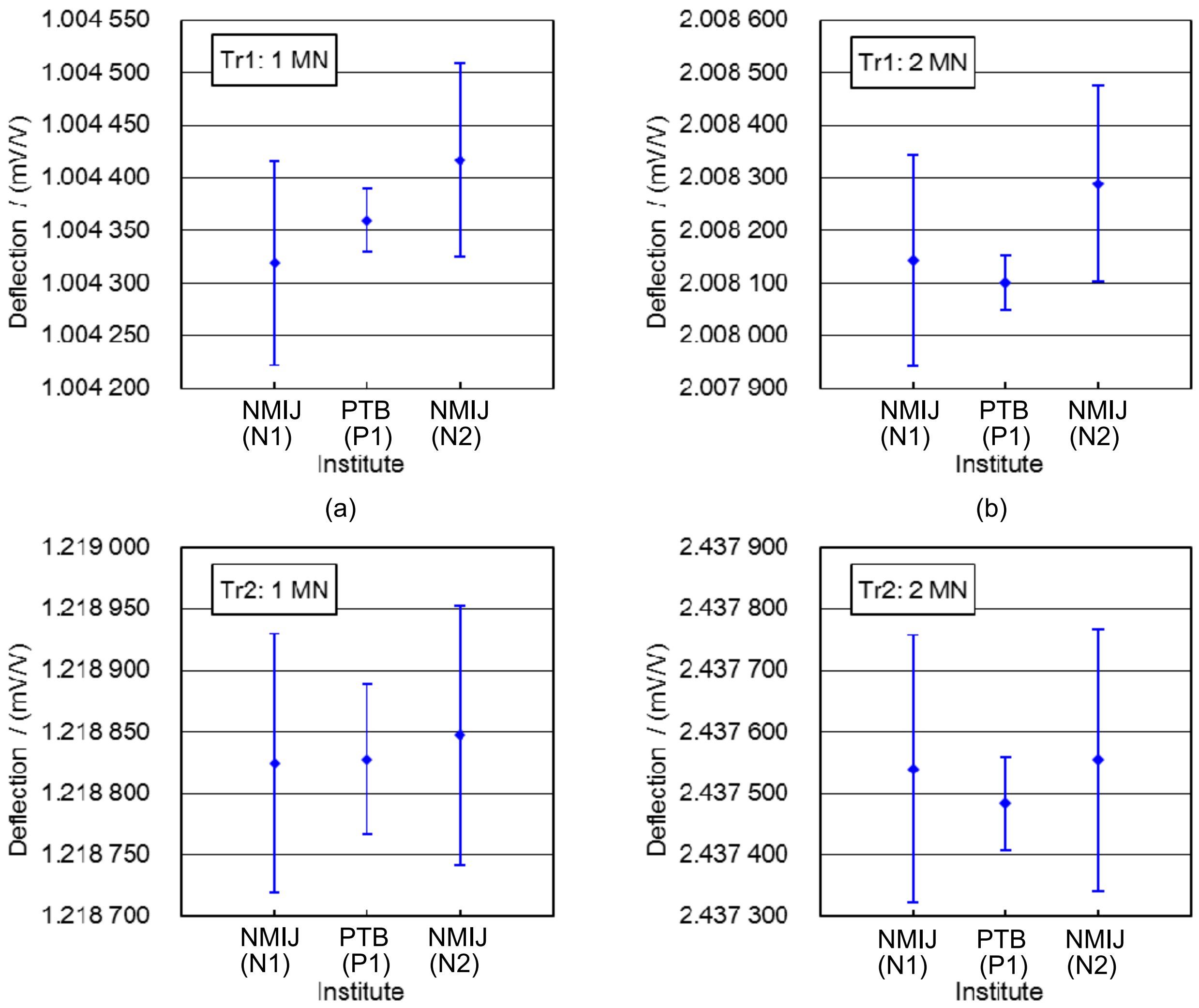
Table 4 and Figure1 show results and uncertainties of the measurements with the KC loading pattern. These values are corrected for the DMP40 indications referring to the common BN100A bridge calibration unit in all cases and for the temperature deviation from the reference temperature of 23.0 °C only in the cases of NMIJ/AIST.

The following uncertainty sources are taken into account when evaluating the uncertainties of the measurement results.

1) Uncertainty associated with the applied force
2) Uncertainty associated with reproducibility of the measurement results in four orientations of 90, 180, 270 and 360 degrees
3) Uncertainty associated with resolution of the DMP 40 indicator
4) Uncertainty associated with the DMP40 correction
5) Uncertainty associated with temperature fluctuation of the instrument during the measurement
6) Uncertainty associated with the temperature deviation correction (only in the cases of NMIJ/AIST)

Table 4    Results and uncertainties of the measurements with the KC loading pattern

| Institute | Code | Force / MN | Tr1 (Showa RC-2MN-1013) | | Tr2 (A&D Orientec UL-2MN-KE1) | |
|---|---|---|---|---|---|---|
| | | | Deflection *X* / (mV/V) | Relative expanded uncertainty *W*(*X*) / $10^{-6}$ | Deflection *X* / (mV/V) | Relative expanded uncertainty *W*(*X*) / $10^{-6}$ |
| NMIJ/AIST | N1 | 1 | 1.004 319 | 96 | 1.218 824 | 87 |
| PTB | P1 | | 1.004 360 | 31 | 1.218 828 | 50 |
| NMIJ/AIST | N2 | | 1.004 417 | 92 | 1.218 847 | 87 |
| NMIJ/AIST | N1 | 2 | 2.008 143 | 100 | 2.437 540 | 89 |
| PTB | P1 | | 2.008 100 | 25 | 2.437 483 | 31 |
| NMIJ/AIST | N2 | | 2.008 289 | 93 | 2.437 554 | 88 |



(a) (b) (c) (d)

Figure 1    Results and uncertainties of the measurements with the KC loading pattern
(a) for Tr1 at 1 MN and (b) at 2 MN and (c) for Tr2 at 1 MN and (d) at 2 MN

A weighted mean (N12) of the proceeding and succeeding measurement results (N1 and N2) of NMIJ/AIST is taken for each of the two traveling force transducers (Tr1 and Tr2) to cancel influence of the sensitivity drifts of the traveling force transducers, especially of Tr1.

Firstly, relative deviation $D_i$ from the reference value, that is chosen to be the measurement result (P1) by the 2 MN DWM of PTB, is calculated for each force transducer (Tr1 or Tr2) and for each force step (1 MN or 2 MN).

$$D_i = \frac{X_i - X_{\mathrm{P1}}}{X_{\mathrm{P1}}} \qquad ( i = \mathrm{N1}\ or\ \mathrm{N2} ) \tag{1}$$

Next, weighted mean $D_{\mathrm{N12}}$ of the relative deviations of the proceeding and succeeding measurement results of NMIJ/AIST (N1 and N2) is calculated for each force transducer (Tr1 or Tr2) and for each force step (1 MN or 2 MN) by the following equation.

$$D_{\mathrm{N12}} = \frac{D_{\mathrm{N1}}/w^2(D_{\mathrm{N1}}) + D_{\mathrm{N2}}/w^2(D_{\mathrm{N2}})}{1/w^2(D_{\mathrm{N1}}) + 1/w^2(DX_{\mathrm{N2}})} \tag{2}$$

where

$D_{\mathrm{N1}}$: Relative deviation from the reference value for the proceeding measurement result

$w(D_{\mathrm{N1}})$: Relative uncertainty of the deviation for the proceeding measurement result

$D_{\mathrm{N2}}$: Relative deviation from the reference value for the succeeding measurement result

$w(D_{\mathrm{N2}})$: Relative uncertainty of the deviation for the succeeding measurement result

As the proceeding and succeeding measurements were made by using the same 5 MN FSM of NMIJ/AIST, relative uncertainty of applied force by the FSM $w_{\mathrm{appl\ force\_N}}$ is considered to be correlated. Thus, relative uncertainty $w(D_{\mathrm{N12}})$ of each of the weighted means $D_{\mathrm{N12}}$ is calculated for each force transducer (Tr1 or Tr2) and for each force step (1 MN or 2 MN) as follows. The uncertainty due to the sensitivity drifts of the force transducers $w_{\mathrm{drift}}$ is also taken into account at this stage by assuming a linear drift model and rectangular probability distribution.

$$\begin{aligned} w^2(D_{\mathrm{N12}}) &= \left\{ \left(\frac{\partial D_{\mathrm{N12}}}{\partial D_{\mathrm{N1}}}\right)^2 w^2(D_{\mathrm{N1}}) + \left(\frac{\partial D_{\mathrm{N12}}}{\partial D_{\mathrm{N2}}}\right)^2 w^2(D_{\mathrm{N2}}) + 2\left(\frac{\partial D_{\mathrm{N12}}}{\partial D_{\mathrm{N1}}}\right)\left(\frac{\partial D_{\mathrm{N12}}}{\partial D_{\mathrm{N2}}}\right) w(D_{\mathrm{N1}}, D_{\mathrm{N2}}) \right\} + w_{\mathrm{drift}}^2 \\ &= \left\{ \frac{w_{\mathrm{N1\_uncorl}}^2/w^4(D_{\mathrm{N1}}) + w_{\mathrm{N2\_uncorl}}^2/w^4(D_{\mathrm{N2}})}{\{1/w^2(D_{\mathrm{N1}}) + 1/w^2(D_{\mathrm{N2}})\}^2} + w_{\mathrm{appl\ force\_N}}^2 \right\} + w_{\mathrm{drift}}^2 \end{aligned} \tag{3}$$

where

$w_{\mathrm{N1\_uncorl}}^2$: Combination of uncorrelated uncertainty sources (except for the uncertainty of applied force) in the relative deviation from the reference value for the proceeding measurement result

$w_{\mathrm{N2\_uncorl}}^2$: Combination of uncorrelated uncertainty sources (except for the uncertainty of applied force) in the relative deviation from the reference value for the succeeding measurement result

The weighted means and associated relative expanded uncertainties of the relative deviations of NMIJ/AIST are tabulated in Table 5. The table also shows the results of PTB.

Table 5  Relative deviations and uncertainties in the measurements with the KC loading pattern

| Institute | Code | Force / MN | Tr1 (Showa RC-2MN-1013) | | Tr2 (A&D Orientec UL-2MN-KE1) | |
|---|---|---|---|---|---|---|
| | | | Relative deviation $D_i$ / $10^{-6}$ | Relative expanded uncertainty $W(D_i)$ / $10^{-6}$ | Relative deviation $D_i$ / $10^{-6}$ | Relative expanded uncertainty $W(D_i)$ / $10^{-6}$ |
| NMIJ/AIST | N12 | 1 | +11 | 106 | +7 | 87 |
| PTB | P1 | | 0 | 31 | 0 | 50 |
| NMIJ/AIST | N12 | 2 | +60 | 100 | +26 | 87 |
| PTB | P1 | | 0 | 25 | 0 | 31 |

At the next step, a weighted mean $D_{\mathrm{Tr12}}$ of the relative deviations of the two traveling force transducers (Tr1 and Tr2) is taken for each of the participating institutes (N12 or P1) to evaluate the degree of equivalence by a single value. The weighted mean $D_{\mathrm{Tr12}}$ is calculated for each institute (N12 or P1) and for each force step (1 MN or 2 MN) by the following equation.

$$D_{\mathrm{Tr12}} = \frac{D_{\mathrm{Tr1}}/w^2(D_{\mathrm{Tr1}})+D_{\mathrm{Tr2}}/w^2(D_{\mathrm{Tr2}})}{1/w^2(D_{\mathrm{Tr1}})+1/w^2(DX_{\mathrm{Tr2}})} \tag{4}$$

where

$D_{\mathrm{Tr1}}$: Relative deviation from the reference value for Tr1

$w(D_{\mathrm{Tr1}})$: Relative uncertainty of the deviation for Tr1

$D_{\mathrm{Tr2}}$: Relative deviation from the reference value for Tr2

$w(D_{\mathrm{Tr2}})$: Relative uncertainty of the deviation for Tr2

As the two force transducers were measured by using the same FSM at each institute, relative uncertainty of applied force $w_{\mathrm{appl\,force}}$ by each FSM is considered to be correlated as well. Thus, relative uncertainty $w(D_{\mathrm{Tr12}})$ of each of the weighted means $D_{\mathrm{Tr12}}$ is calculated for each institute (N12 or P1) and for each force step (1 MN or 2 MN) as follows.

$$\begin{aligned} w^2(D_{\mathrm{Tr12}}) &= \left(\frac{\partial D_{\mathrm{Tr12}}}{\partial D_{\mathrm{Tr1}}}\right)^2 w^2(D_{\mathrm{Tr1}}) + \left(\frac{\partial D_{\mathrm{Tr12}}}{\partial D_{\mathrm{Tr2}}}\right)^2 w^2(D_{\mathrm{Tr2}}) + 2\left(\frac{\partial D_{\mathrm{Tr12}}}{\partial D_{\mathrm{Tr1}}}\right)\left(\frac{\partial D_{\mathrm{Tr12}}}{\partial D_{\mathrm{Tr2}}}\right) w(D_{\mathrm{Tr1}}, D_{\mathrm{Tr2}}) \\ &= \frac{w^2_{\mathrm{Tr1\_uncorl}}/w^4(D_{\mathrm{Tr1}})+ w^2_{\mathrm{Tr2\_uncorl}}/w^4(D_{\mathrm{Tr2}})}{\{1/w^2(D_{\mathrm{Tr1}})+1/w^2(D_{\mathrm{Tr2}})\}^2} + w^2_{\mathrm{appl\,force}} \end{aligned} \tag{5}$$

where

$w^2_{\mathrm{Tr1\_uncorl}}$: Combination of uncorrelated uncertainty sources (except for the uncertainty of applied force) in the relative deviation from the reference value for Tr1

$w^2_{\mathrm{Tr2\_uncorl}}$: Combination of uncorrelated uncertainty sources (except for the uncertainty of applied force) in the relative deviation from the reference value for Tr2

The weighted means and associated relative expanded uncertainties are tabulated in Table 6. Relative expanded uncertainties of the comparison $W_{\mathrm{comp}}$ is also shown. The table indicates that the forces realized by the 5 MN FSM of NMIJ/AIST are equivalent to those by the 2 MN DWM of PTB within the uncertainties at 1 MN and 2 MN force levels.

Table 6 Weighted means and uncertainties of the measurement results with the KC loading pattern

| Institute | Force / MN | Weighted mean of the relative deviation from the reference value $D_{\mathrm{Tr12}}$ / $10^{-6}$ | Relative expanded uncertainty $W(D_{\mathrm{Tr12}})$ / $10^{-6}$ | Relative expanded uncertainty of the comparison $W_{\mathrm{comp}}$ / $10^{-6}$ |
|---|---|---|---|---|
| NMIJ/AIST | 1 | +8 | 90 | 94 |
| PTB | | 0 | 29 | |
| NMIJ/AIST | 2 | +41 | 89 | 92 |
| PTB | | 0 | 24 | |

### 3.4 Results of the calibrations with the ISO 376 loading pattern

Table 7 shows dates and ambient conditions of the calibrations.

Table 7 Dates and ambient conditions of the calibrations with the ISO 376 loading pattern

| Institute | Code | Tr1 (Showa RC-2MN-1013) | | Tr2 (A&D Orientec UL-2MN-KE1) | |
|---|---|---|---|---|---|
| | | Dates | Ambient conditions | Dates | Ambient conditions |
| NMIJ/AIST | N1 | 2015-05-13 | 24.0 °C to 24.1 °C<br>45.5 % to 43.5 %<br>1000.5 hPa to 1000.6 hPa | 2015-05-14 | 24.3 °C to 23.9 °C<br>43.6 % to 46.7 %<br>1008.6 hPa to 1005.9 hPa |
| PTB | P1 | 2015-06-10 | 23.1 °C<br>41.8 % to 42.0 %<br>1019.4 hPa to 1018.8 hPa | 2015-06-29 | 23.0 °C to 22.9 °C<br>41.4 % to 41.6 %<br>1020.4 hPa to 1020.1 hPa |

Table 8 and Table 9 show the results and their relative expanded uncertainties of the calibrations with the ISO 376 loading pattern. The results in decreasing forces are also shown for information. The results are those calculated at each force step, not by applying an interpolation equation. The results are not corrected for temperature deviation from the reference temperature of 23.0 °C in this case, since the calibration conditions fulfilled specifications for ordinary calibrations at each of the institutes.

Figure 2 depicts characteristic curves of the two force transducers calculated from the calibration results shown in Tables 8 and 9. In Figure 2, a common baseline is used for the purpose of comparison of the results of NMIJ/AIST with those of PTB for each force transducer. The baseline is drawn by connecting the zero point and the deflection at the maximum calibration force obtained from the calibration results of PTB, and relative deviations from the baseline are plotted in the diagram.

Note that uncertainty due to reversibility (hysteresis) is not included, since this uncertainty source is to be considered at the time when the calibrated force transducer is used.

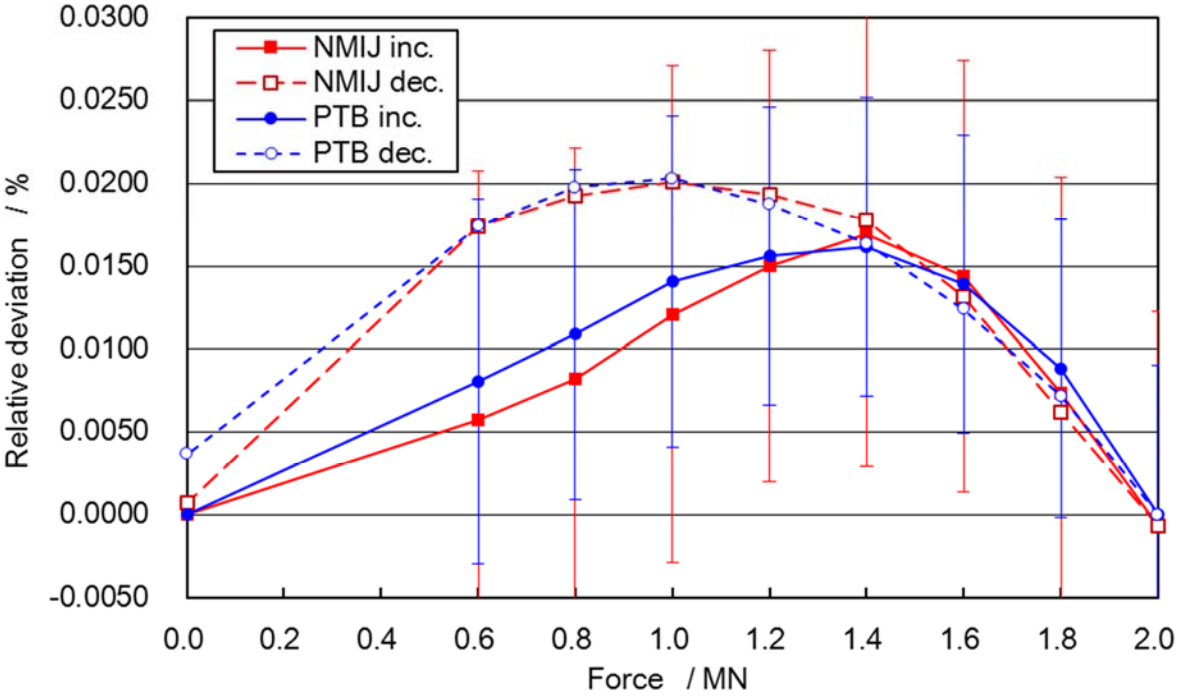
It should be also noted that, though relatively large uncertainties are observed in the results of PTB, these are attributable to creep and zero drift characteristics of the traveling force transducers, not to the 2 MN DWM.

Table 8 Results and uncertainties of the calibrations of Tr1 with the ISO 376 loading pattern

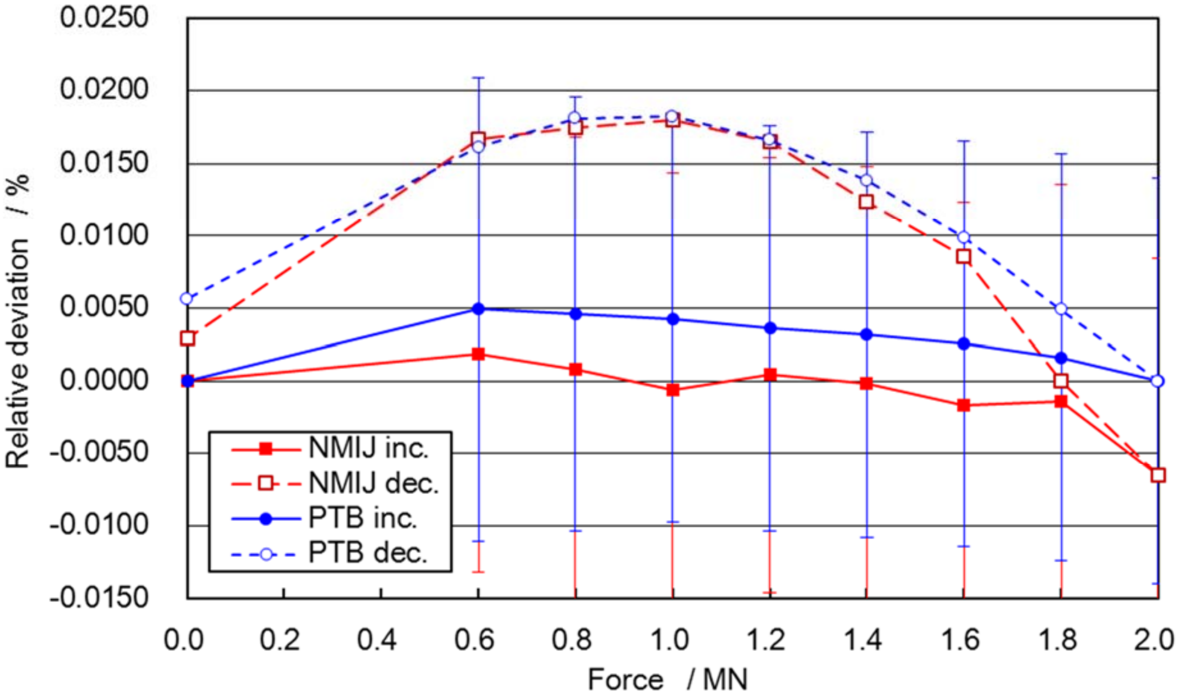
| Force / MN | | NMIJ/AIST (N1) | | PTB (P1) | |
|---|---|---|---|---|---|
| | | Deflection *X* / (mV/V) | Relative expanded uncertainty *W*(*X*) / % | Deflection *X* / (mV/V) | Relative expanded uncertainty *W*(*X*) / % |
| Inc. | 0 | 0.000 00 | | 0.000 000 | |
| | 0.6 | 0.602 55 | 0.015 | 0.602 596 | 0.011 |
| | 0.8 | 0.803 41 | 0.014 | 0.803 464 | 0.010 |
| | 1.0 | 1.004 30 | 0.015 | 1.004 340 | 0.010 |
| | 1.2 | 1.205 17 | 0.013 | 1.205 182 | 0.009 |
| | 1.4 | 1.406 02 | 0.014 | 1.406 004 | 0.009 |
| | 1.6 | 1.606 78 | 0.013 | 1.606 771 | 0.009 |
| | 1.8 | 1.807 45 | 0.013 | 1.807 480 | 0.009 |
| | 2.0 | 2.008 10 | 0.013 | 2.008 114 | 0.009 |
| Dec. | 1.8 | 1.807 43 | - | 1.807 447 | - |
| | 1.6 | 1.606 76 | - | 1.606 741 | - |
| | 1.4 | 1.406 04 | - | 1.406 009 | - |
| | 1.2 | 1.205 26 | - | 1.205 245 | - |
| | 1.0 | 1.004 46 | - | 1.004 465 | - |
| | 0.8 | 0.803 63 | - | 0.803 643 | - |
| | 0.6 | 0.602 78 | - | 0.602 784 | - |
| | 0 | 0.000 02 | - | 0.000 074 | - |

Table 9 Results and uncertainties of the calibrations of Tr2 with the ISO 376 loading pattern

| Force / MN | | NMIJ/AIST (N1) | | PTB (P1) | |
|---|---|---|---|---|---|
| | | Deflection *X* / (mV/V) | Relative expanded uncertainty *W*(*X*) / % | Deflection *X* / (mV/V) | Relative expanded uncertainty *W*(*X*) / % |
| Inc. | 0 | 0.000 00 | | 0.000 000 | |
| | 0.6 | 0.731 31 | 0.015 | 0.731 385 | 0.016 |
| | 0.8 | 0.975 04 | 0.016 | 0.975 132 | 0.015 |
| | 1.0 | 1.218 76 | 0.015 | 1.218 879 | 0.014 |
| | 1.2 | 1.462 54 | 0.015 | 1.462 619 | 0.014 |
| | 1.4 | 1.706 28 | 0.015 | 1.706 362 | 0.014 |
| | 1.6 | 1.950 00 | 0.014 | 1.950 103 | 0.014 |
| | 1.8 | 2.193 76 | 0.015 | 2.193 835 | 0.014 |
| | 2.0 | 2.437 39 | 0.015 | 2.437 550 | 0.014 |
| Dec. | 1.8 | 2.193 80 | - | 2.193 914 | - |
| | 1.6 | 1.950 25 | - | 1.950 280 | - |
| | 1.4 | 1.706 59 | - | 1.706 623 | - |
| | 1.2 | 1.462 93 | - | 1.462 936 | - |
| | 1.0 | 1.219 21 | - | 1.219 220 | - |
| | 0.8 | 0.975 45 | - | 0.975 462 | - |
| | 0.6 | 0.731 67 | - | 0.731 659 | - |
| | 0 | 0.000 07 | - | 0.000 137 | - |



(a)



(b)

Figure 2　Characteristic curves of (a) Tr1 and (b) Tr2 obtained from the calibration results with the ISO 376 loading pattern

From Table 8, Table 9 and Figure 2, it can be seen that the calibration results of NMIJ/AIST are consistent with those of PTB within the uncertainties in the force range from 0.6 MN to 2.0 MN.

## 4. Summary

The APMP.M.F-S1 supplementary comparison in the 2 MN force range has revealed the followings.

1) The forces realized by the 5 MN FSM of NMIJ/AIST are equivalent to those by the 2 MN DWM of PTB within the measurement uncertainties at 1 MN and 2 MN.
2) The results of NMIJ/AIST in its ordinary calibrations using the 5 MN FSM is consistent with those of PTB, proving the calibration capability of NMIJ/AIST in the force range from 0.6 MN to 2.0 MN.

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