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INTERCOMPARISON BETWEEN LARGE FORCE STANDARD MACHINES IN CHINA AND UK

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Abstract – This paper describes an intercomparison at forces of 10 MN, 20 MN, and 30 MN between force standard machines located at FJIM, China, and NPL, UK. Two different types of transfer standard were used and the results demonstrated agreement between the two machines at each force of within 0,06 %, significantly lower than the relative expanded uncertainty claimed by either machine.

Keywords: force standard machine, intercomparison, build-up, force transfer system

1. INTRODUCTION

In recent decades, the National Measurement Institutes (NMIs) of both China and the United Kingdom (UK) have carried out a number of intercomparisons of force standards against NMIs of other countries, including Germany, Italy, Singapore, Turkey, Mexico, Thailand, Chinese Taipei, Finland, Japan, Egypt, and Korea. In addition, both countries have recently participated in all four major CIPM key comparisons, with forces ranging from 5 kN up to 4 MN [1] [2] [3].

In order to investigate the agreement at higher forces between the standards established by China and the UK, an intercomparison was carried out during August and September 2014 between the 60 MN build-up force standard machine established in 2014 at FJIM in China and the 30 MN hydraulic force standard machine established in the early 1970s at NPL in the UK. These two machines have claimed standard uncertainties of generated force of 0,05 % and 0,10 % respectively and are pictured in Fig. 1 and Fig. 2. The traceability of the FJIM machine is derived via three force transfer standards, each of which has been calibrated at NIM, being loaded in series with the instrument being calibrated. The NPL machine's legs are strain gauged, and the sensitivity of these bridges is determined from a build-up procedure using three sets of force transducers, giving ultimate traceability back to NPL's 1.2 MN deadweight force standard machine.

The transfer standards used in the intercomparison between the two machines were two 20 MN load cells, manufactured by HBM, and a 60 MN force transfer system (FTS), established by FJIM and shown in Fig. 3. The measuring instruments used were three HBM DMP40 precision AC ratio bridges, which were compared using HBM BN100 bridge calibration units.

Fig. 1. The 60 MN build-up force standard machine (60 MN BM) at FJIM, China.

Fig. 2. The 30 MN hydraulic force standard machine (30 MN HM) at NPL, UK.

Fig. 3. The 60 MN force transfer system (60 MN FTS) established by FJIM, China.

2. EQUIPMENT

2.1. Metrological characteristics of the load cells

The three 20 MN load cells used in the comparison had previously been calibrated, with HBM DMP 40 instrumentation, in accordance with ISO 376 [4] in NIM's 20 MN hydraulic amplification force standard machine (20 MN HM), which has a relative expanded uncertainty of 0,01 % (k = 3, level of confidence of approx. 99 %). The calibration results of the three cells are listed in Table 1, the major uncertainty components being the reproducibility with rotation R_{ot} and the 3-month sensitivity stability S_b.

Table 1. Calibration results for the three 20 MN load cells

Load cell ID	R %	R_{ot} %	I_p %	H %	S_b %	W_{cell} %
001	0,025	0,06	±0,002	-0,3	0,04	0,063
002	0,020	0,03	±0,002	-0,3	0,06	0,080
025	0,010	0,06	±0,002	-0,3	0,01	0,048

R = Repeatability, R_{ot} = Reproducibility with rotation, I_p = Interpolation error, H = Hysteresis, S_b = 3-month stability, W_{cell} = Relative expanded uncertainty of output (k = 2)

2.2. Metrological characteristics of the FTS

The FTS consists of the three 20 MN load cells loaded in parallel, together with other components. Its height is 1,23 m, its weight 3 500 kg, and its maximum diameter 0,83 m. The relative combined uncertainty w_{fts} of the sum of the outputs of the three cells is taken as the average of the relative combined uncertainty w_{cell} of each cell's output after considering the correlation of the outputs, as in (1).

$$w_{fts} = (w_{001} + w_{002} + w_{025})/3 \quad (1)$$

After considering the contribution of the connecting components, the relative expanded uncertainty of the force measured by the 60 MN FTS was taken as 0,077 % (k = 2, level of confidence of approx. 95 %).

3. COMPARISON METHOD

The method used in the comparison was similar to that used in the CIPM force key comparisons [1]. The tests were carried out by FJIM (test series A1), then NPL (test series B), and finally FJIM (test series A2), following the example time-loading sequences shown in Fig. 4 and Fig. 5.

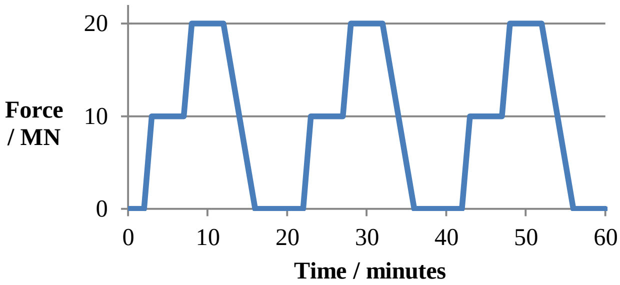

Fig. 4. Loading cycles for the 20 MN load cells.

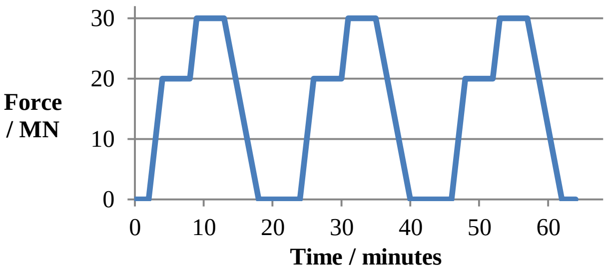

Fig. 5. Loading cycles for the 60 MN FTS.

For the 20 MN load cell tests, four preloads were performed at the 0° position, followed by three measurement runs. The load cell was then rotated through one complete revolution in 60° increments, with one preload and one measurement run carried out at each orientation.

A similar procedure was followed for the 60 MN FTS tests, the only difference being that the rotational increments were 120° rather than 60°.

4. TEST RESULTS

Table 2 summarises the main specifications of load cells 002 and 025 during tests A1, A2, and B, while Table 3 summarises the 60 MN FTS results in the two machines. The results of the tests on load cells 002 and 025 are shown graphically in Fig. 6 and Fig. 7 respectively, while Fig. 8 displays the results of the 60 MN FTS tests.

The contribution of the DMP40 instrumentation to the combined uncertainty is not larger than 1,5 × 10^{-5}, after being checked against the BN100 calibrators, and has therefore been ignored, as it has an insignificant effect on the combined uncertainty.

For the 60 MN FTS tests, the force applied to the system was calculated from the load cell outputs and the sensitivity equations derived during their calibration at NIM. The difference between these calculated applied force values at the same nominal forces in the FJIM and NPL machines enables a comparison to be made between the two machines, without needing to consider any uncertainty contribution from the load cells' NIM calibrations.

Table 2. Results of test series A1, A2, and B on load cells 002 and 025

Force MN	x_{ave} mV/V	R	R_{ot}	R_{es} mV/V	Z_r mV/V	R_{prd}	$W_{20MNcell}$
Test series A1, load cell 002							
10	1,073 12	2,8E-05	4,1E-04	0,000 02	0,000 07	1,7E-04	1,2E-03
20	2,141 77	3,3E-05	2,9E-04	0,000 02	0,000 07	1,2E-04	1,2E-03
Test series A1, load cell 025							
10	1,213 06	2,5E-05	1,3E-04	0,000 02	0,000 07	6,6E-05	1,1E-03
20	2,424 52	2,5E-05	7,8E-05	0,000 02	0,000 07	6,6E-05	1,1E-03
Test series A2, load cell 002							
10	1,073 21	5,6E-05	4,2E-04	0,000 02	0,000 07	5,6E-05	1,2E-03
20	2,141 97	1,2E-04	2,9E-04	0,000 02	0,000 07	2,8E-05	1,2E-03
Test series A2, load cell 025							
10	1,213 22	4,1E-05	2,0E-04	0,000 02	0,000 07	8,2E-05	1,1E-03
20	2,424 78	4,1E-05	1,5E-04	0,000 02	0,000 07	8,7E-05	1,1E-03
Test series B, load cell 002							
10	1,073 54	1,5E-04	3,8E-04	0,000 06	0,000 07	2,1E-04	2,1E-03
20	2,142 81	1,2E-04	2,3E-04	0,000 06	0,000 07	2,1E-04	2,1E-03
Test series B, load cell 025							
10	1,214 04	1,1E-04	9,9E-05	0,000 06	0,000 07	7,4E-05	2,1E-03
20	2,426 71	4,5E-05	9,5E-05	0,000 06	0,000 07	1,2E-04	2,1E-03

x_{ave} = Average of outputs x_1, x_4, x_5, x_6, x_7, and x_8, R = Repeatability, R_{ot} = Rotation effect, R_{es} = Resolution, Z_r = Zero recovery, R_{prd} = Reproducibility at 0° position, $W_{20MNcell}$ = Relative expanded uncertainty (k = 2) of load cell output

Table 3. Results of test series A1, A2, and B for the 60 MN FTS

Force MN	F_{ave} MN	R	R_{ot}	R_{prd}	R_{es} mV/V	Z_r	$W_{machine}$ $k = 2$	$W_{60MNFTS}$ $k = 2$
Test series A1 in 60 MN BM								
20	20,002 9	1,5E-05	2,9E-04	8,6E-06	0,000 03	3,0E-05	0,1 %	1,2E-03
30	29,995 7	2,8E-05	2,9E-04	4,5E-05	0,000 02	3,0E-05	0,1 %	1,2E-03
Test series A2 in 60 MN BM								
20	20,003 5	3,5E-05	1,6E-04	2,3E-05	0,000 03	3,0E-05	0,1 %	1,2E-03
30	29,999 8	2,4E-05	9,7E-05	7,9E-05	0,000 02	3,0E-05	0,1 %	1,2E-03
Test series B in 30 MN HM								
20	20,010 6	1,0E-04	4,1E-04	2,4E-04	0,000 05	2,0E-05	0,2 %	2,1E-03
30	30,009 1	1,3E-04	2,4E-04	2,0E-04	0,000 04	2,0E-05	0,2 %	2,1E-03

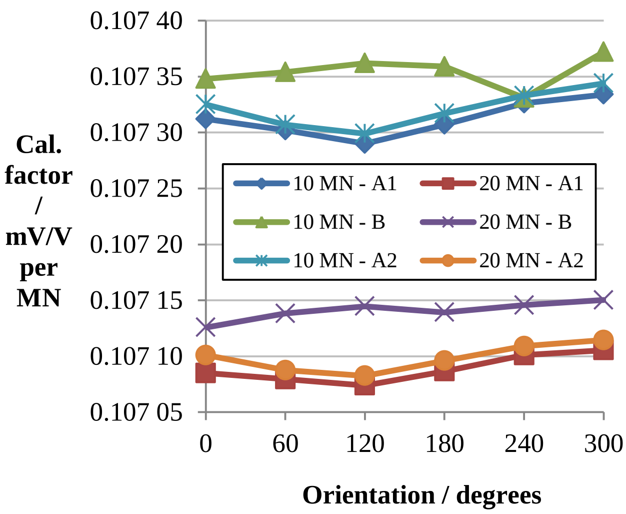

Fig. 6. Load cell 002 calibration results.

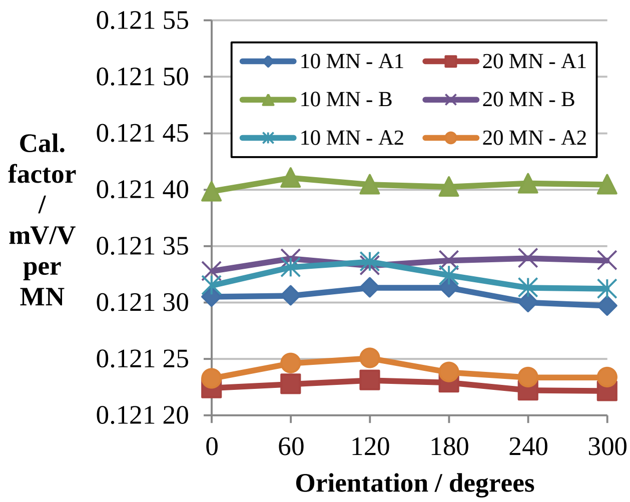

Fig. 7. Load cell 025 calibration results.

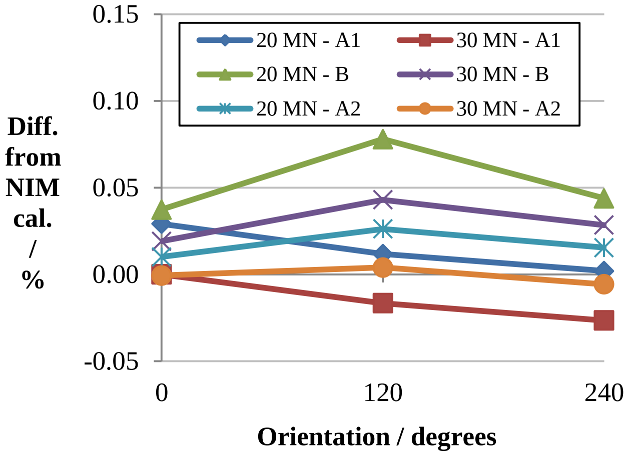

Fig. 8. 60 MN FTS calibration results.

The combined uncertainty of the output of each cell, and of the 60 MN FTS, incorporates uncertainty contributions due to repeatability, rotation, resolution, zero recovery, and uncertainty of the force generated by the machine. There are two further contributions: the temperature effect on output (being ±0.01 %·°C^{-1}, $\Delta T = \pm 2$ °C) and the long-term stability. It can be seen that the relative expanded uncertainty ($k = 2$) of the output of the load cells and 60 MN FTS is approximately 0.12 % within 60 MN BM, and 0.21 % within 30 MN HM, deriving mainly from the uncertainty of the machine's generated forces.

5. AGREEMENT BETWEEN THE TWO MACHINES

Fig. 9 shows the relative deviation between 30 MN HM and 60 MN BM for each of the three transfer standard systems. Load cells 002 and 025 both indicate an increase in deviation of about 0.01 % between force levels of 10 MN and 20 MN, while 60 MN FTS indicates a practically unchanging deviation in the range from 20 MN to 30 MN.

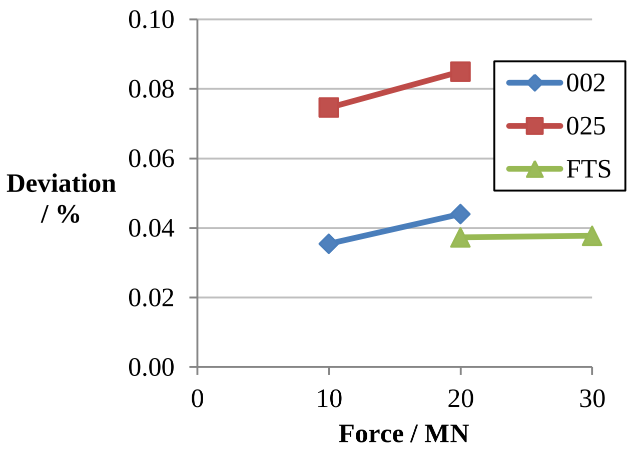

Fig. 9. Relative deviation between 30 MN HM and 60 MN BM.

Taken together with the best estimate of deviation at 20 MN of +0.055 %, given from the average of the three system results, the mean deviations at 10 MN and 30 MN can hence be estimated and are plotted in Fig. 10, together with standard uncertainty bars. The major contribution to this uncertainty is the spread in deviation determined at 20 MN, this contribution also being applied to the results at the other two force levels.

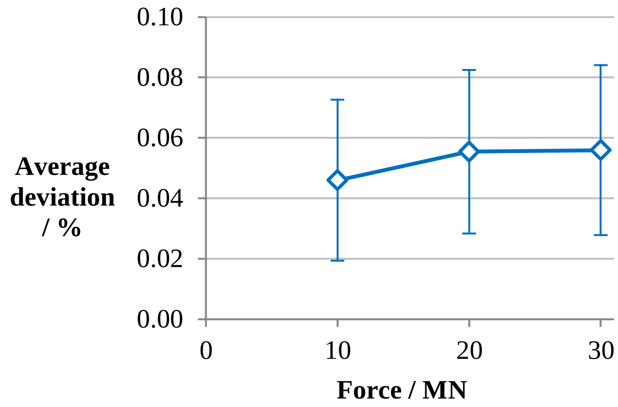

Fig. 10. Average relative deviation between the two machines.

In order to determine whether or not the two machines agree within their claimed calibration and measurement capabilities (CMCs), an E_n number was calculated for each force level. For this statistic, the numerator was taken as the average deviation, as plotted in Fig. 10, and the uncertainty of the reference value as the sum in quadrature of the uncertainty associated with this deviation and the claimed uncertainty of the force generated at FJIM. At each specific force, the uncertainty of the participant's result is simply the mean calibration uncertainty obtained in the NPL machine. These values are given in Table 4 and plotted in Fig. 11. As the magnitude of all three E_n numbers is lower than unity by a factor of over four, there is no evidence to suggest that either machine is failing to generate forces in accordance with its CMC.

Table 4. E_n numbers at the three force levels.

	F = 10 MN	F = 20 MN	F = 30 MN
δ / %	0,046	0,055	0,056
u_δ / %	0,027	0,027	0,028
u_{ref} / %	0,057	0,057	0,057
u_{NPL} / %	0.105	0,105	0,105
E_n	0,192	0,232	0,233

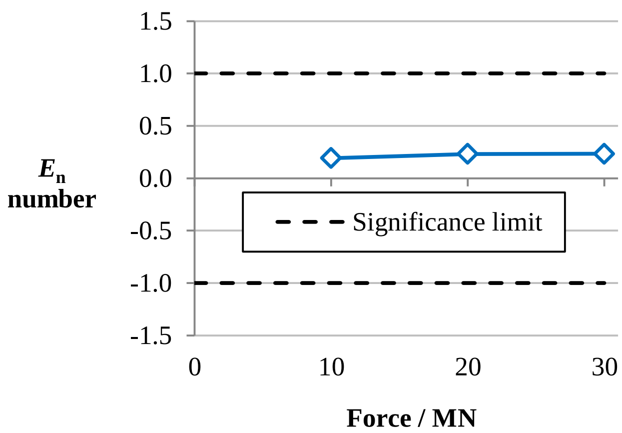

Fig. 11. E_n numbers and significance limits.

6. CONCLUSIONS

An intercomparison between the FJIM 60 MN BM and the NPL 30 MN HM has been carried out using two single 20 MN cells and the 60 MN FTS which consists of three 20 MN cells in parallel. The intercomparison comprised two sets of tests performed at FJIM and one set of tests at NPL. The results demonstrate that, at nominal forces of 10 MN, 20 MN, and 30 MN, the forces generated by the two machines agree to within 0,06 %, with an expanded uncertainty of less than 0,06 % (at a confidence level of approximately 95 % (k = 2)).

When the claimed uncertainty of the two machines is taken into account, there is no evidence to suggest that either machine is failing to generate force values in accordance with its CMC.

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