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COMPARISON OF FORCE STANDARDS BETWEEN NIS (EGYPT) AND NPL (UNITED KINGDOM)

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Abstract: This paper details the results of a bilateral comparison carried out between the national force standard machines of Egypt and the United Kingdom. The results indicate that the uncertainty claims of the two laboratories can, in general, be supported. Recommendations on revised protocols to be used for future comparisons are given.

Keywords: force, measurement, machines, intercomparison.

1. INTRODUCTION

It is recognised that, for the purposes of international trade and scientific collaboration, the national measurement systems of countries around the world should be in agreement – this is the basis of the SI. The centre of each country's national measurement system tends to be its national measurement institute (NMI), and it is important that NMIs compare their standards with each other on a regular basis. The CIPM's Mutual Recognition Arrangement (MRA) – whereby NMIs agree to accept each other's measurement certificates – has put these comparisons on a more formal footing, as successful participation in Key Comparisons is a condition of membership of the MRA. However, the MRA does not prohibit the carrying out of bilateral comparisons between NMIs, and these can be used as evidence to support an NMI's measurement capability claims – these exercises can be particularly useful where an NMI has recently established a measurement facility and there are no suitable Key Comparisons planned to be performed in that technical area.

2. PURPOSE

NIS has recently commissioned a range of new force machines, as follows:

- 50 kN deadweight machine (Fig. 1), with a stated uncertainty of 0.002 % (see [1])
- 500 kN deadweight machine (Fig. 2), with a stated uncertainty of 0.002 %, amplified by substitution up to 1 MN, with a stated uncertainty of 0.01 % (see [2])
- 5 MN hydraulic amplification machine (Fig. 3), with a stated uncertainty of 0.02 %

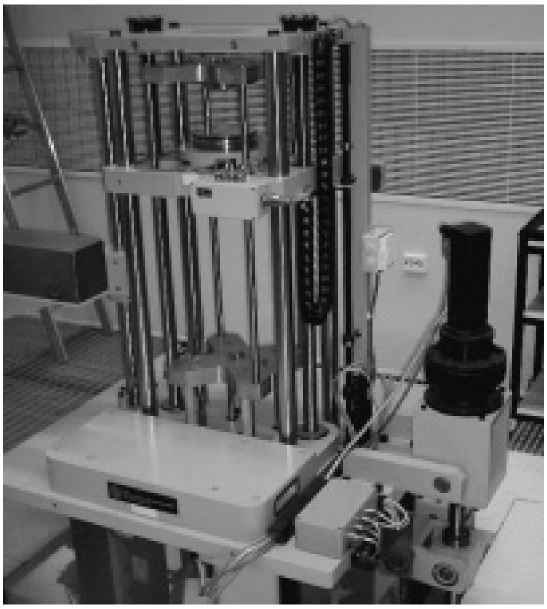

Fig. 1. NIS 50 kN deadweight machine.

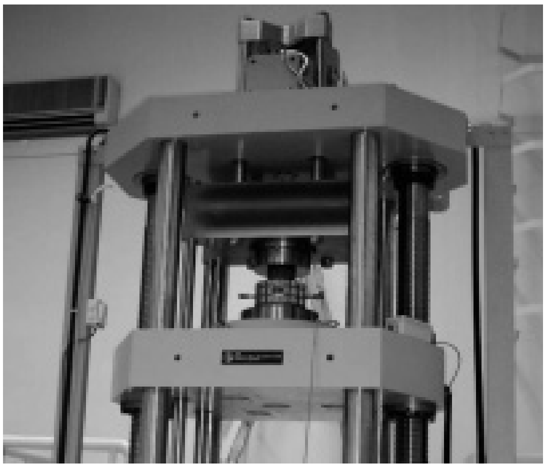

Fig. 2. NIS 500 kN / 1 MN machine.

Fig. 3. NIS 5 MN hydraulic machine.

In order to give support to these uncertainty claims, it was agreed that an international comparison with another NMI with machines of suitable capacity and uncertainty should be performed. NPL, the laboratory responsible for maintaining the United Kingdom's national force standards, agreed to participate in such a comparison, using its machines of the following specifications:

- 120 kN deadweight machine (Fig. 4), with a stated uncertainty of 0.001 % (see [3])
- 1.2 MN deadweight machine (Fig. 5), with a stated uncertainty of 0.001 % (see [4])
- 5 MN hydraulic amplification machine (Fig. 6), with a stated uncertainty of 0.02 % up to 3.6 MN and 0.05 % up to 5 MN (see [5])

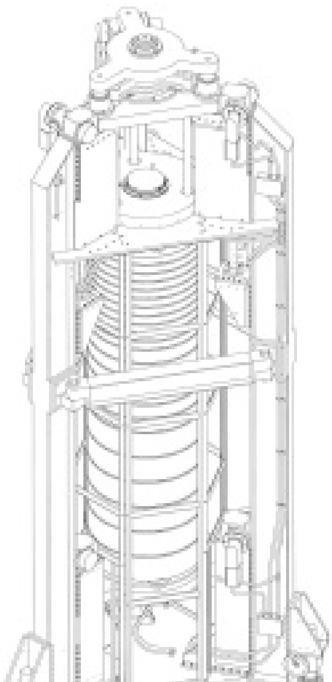

Fig. 4. NPL 120 kN deadweight machine.

Fig. 5. NPL 1.2 MN deadweight machine.

Fig. 6. NPL 5 MN hydraulic amplification machine.

3. METHOD

The machines at the two NMIs were compared in accordance with the scheme given in Table 1.

Table 1. Comparison scheme.

<table>
<tr><th>Exercise</th><th>NIS Machine</th><th>NPL Machine</th><th>Test</th><th>Force</th><th>Transducer</th></tr>
<tr><td rowspan="3">A</td><td rowspan="3">50 kN</td><td rowspan="3">120 kN</td><td>A1</td><td>5 kN</td><td>30623 (5 kN)</td></tr>
<tr><td>A2</td><td>20 kN</td><td>40242 (20 kN)</td></tr>
<tr><td>A3</td><td>50 kN</td><td rowspan="2">10518 (200 kN)</td></tr>
<tr><td rowspan="3">B</td><td rowspan="3">500 kN / 1 MN</td><td rowspan="3">1.2 MN</td><td>B1</td><td>200 kN</td></tr>
<tr><td>B2</td><td>500 kN</td><td rowspan="4">01565 (1 MN)</td></tr>
<tr><td>B3</td><td>1 MN</td></tr>
<tr><td rowspan="3">C</td><td rowspan="3">5 MN</td><td rowspan="3">5 MN</td><td>C1</td><td>500 kN</td></tr>
<tr><td>C2</td><td>1 MN</td></tr>
<tr><td>C3</td><td>5 MN</td><td>01603 (5 MN)</td></tr>
</table>

In total, five compression transducers were used to compare the machines, in conjunction with instrumentation of the highest resolution and stability. Each was used at its maximum capacity and two of them were also used at lower forces, to enable each pair of machines to be compared at three discrete force levels.

To minimise the effects of force transducer creep, each transducer calibration was carried out in accordance with a strictly-timed loading profile (see Fig. 7), including the preloads which were always performed at the start of each test and after each rotation of the transducer in the machine. Three values of deflection were obtained at each of three orientations, symmetrically distributed about the central axis of the machine - these deflections were calculated by subtracting the transducer output at zero force (prior to the application of the force) from the transducer output under force. The mean deflection was calculated as the mean of these nine deflection values.

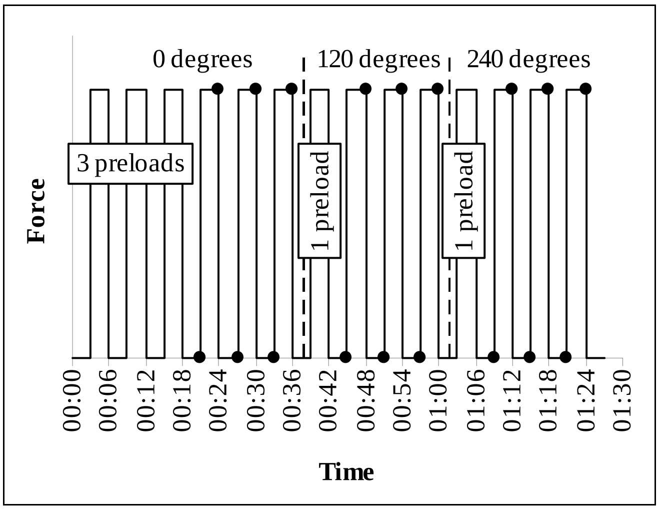

Fig. 7. Loading profile.

Tests were first performed at NIS, then at NPL, and then again at NIS. The two sets of tests at NIS determined a reference value for each calibration force, together with an associated uncertainty taking into account any drift of the transducer sensitivity throughout the exercise - the assumption is made that the performance of the NIS machine remained stable throughout the period.

4. RESULTS

4.1. Measured values

The measurement results are shown in Fig. 8 to Fig. 16 and summarised in Table 2. In the figures, the solid symbols represent measurement points whereas the hollow ones relate to the deflections measured during preloading. To aid clarity, the measurement points are plotted at only their approximate orientation, and are joined by lines denoting the order in which they were made.

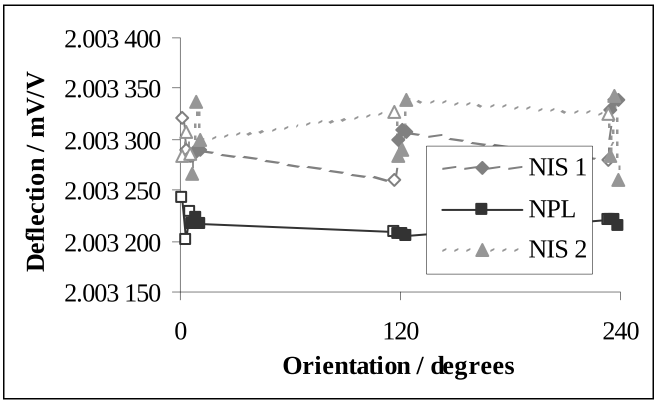

Fig. 8. Test A1 results.

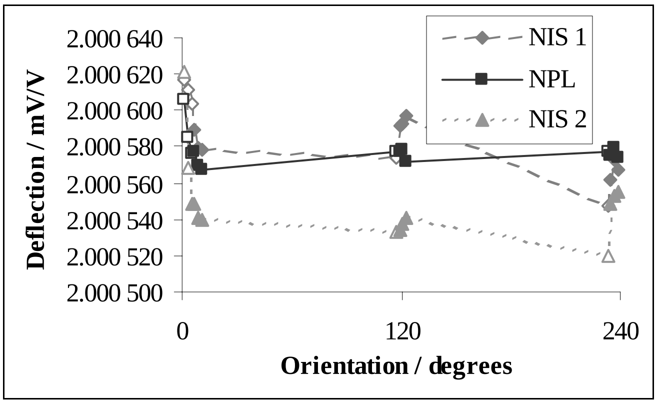

Fig. 9. Test A2 results.

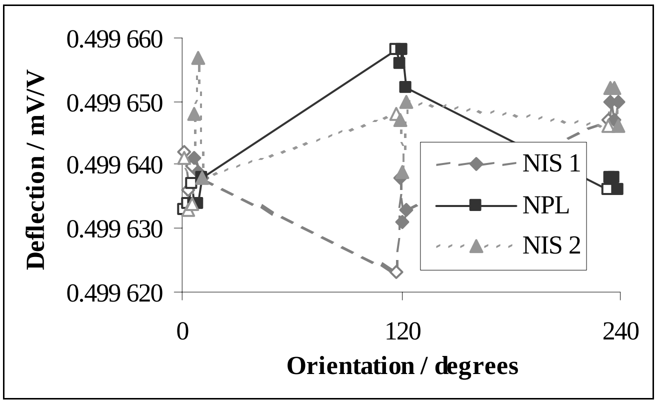

Fig. 10. Test A3 results.

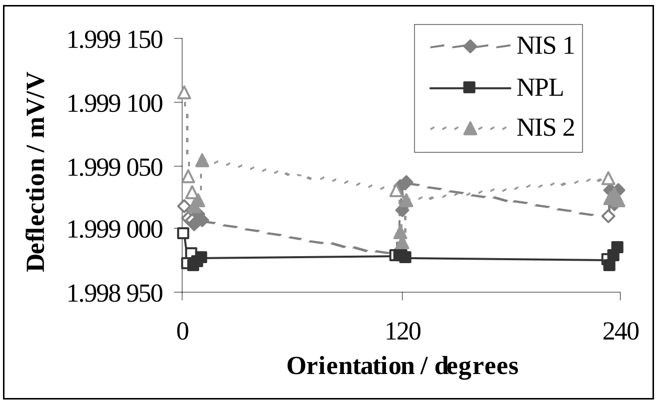

Fig. 11. Test B1 results.

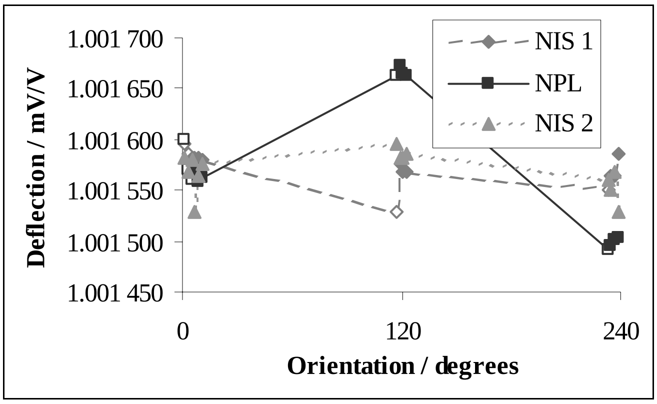

Fig. 12. Test B2 results.

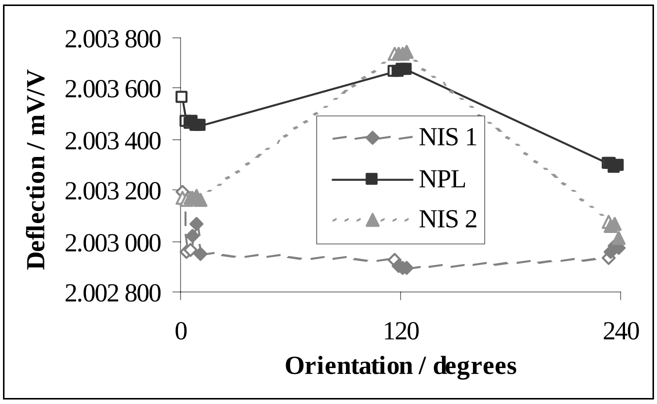

Fig. 13. Test B3 results.

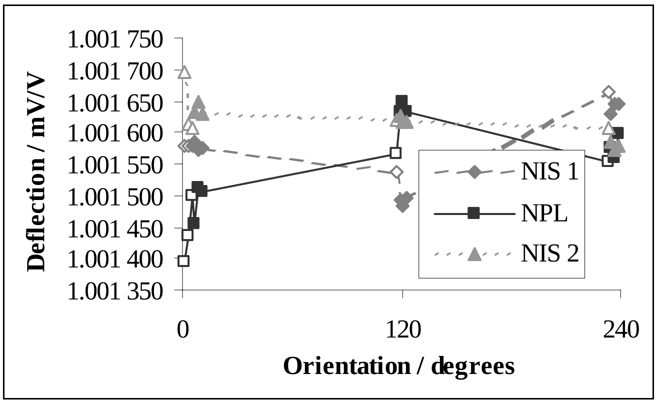

Fig. 14. Test C1 results.

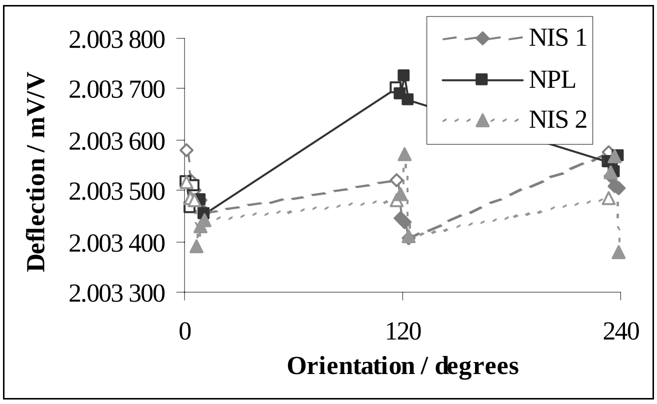

Fig. 15. Test C2 results.

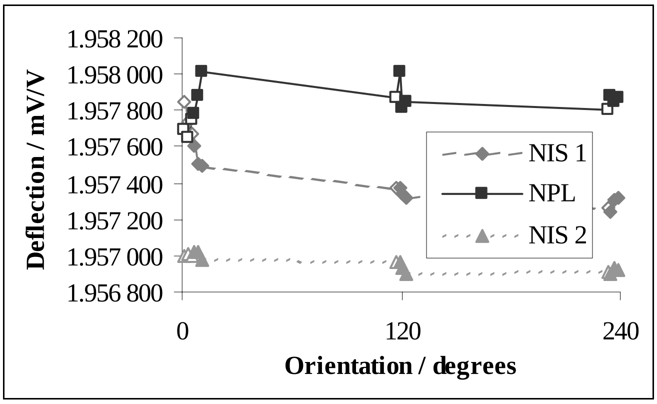

Fig. 16. Test C3 results.

Table 2. Comparison results.

Test	NIS mean deflection mV/V	Change at NIS mV/V	NPL deflection mV/V	NPL - NIS difference mV/V
A1	2.003 305	-0.000 009	2.003 215	-0.000 090
A2	2.000 563	-0.000 037	2.000 574	0.000 012
A3	0.499 644	0.000 007	0.499 643	-0.000 002
B1	1.999 020	-0.000 001	1.998 976	-0.000 044
B2	1.001 568	-0.000 012	1.001 577	0.000 009
B3	2.003 139	0.000 360	2.003 475	0.000 336
C1	1.001 591	0.000 042	1.001 568	-0.000 022
C2	2.003 471	-0.000 003	2.003 573	0.000 103
C3	1.957 169	-0.000 437	1.957 882	0.000 712

4.2. Uncertainty analysis

The main purpose of a bilateral comparison is to determine whether any difference in the results obtained at the two laboratories can be accounted for by a combination of the claimed uncertainties of the laboratories and any uncertainties arising from the comparison process. If any differences can be accounted for, the comparison lends support to the uncertainty claims of both laboratories. If, on the other hand, any differences cannot be accounted for, this could either suggest that one or both laboratories are underestimating their uncertainties or that not all uncertainty contributions due to the comparison process have been properly taken into account.

One method for determining the results of a bilateral comparison is use of the E_n value, defined as:

$$E_n = \frac{\left| x_{LAB1} - x_{LAB2} \right|}{\sqrt{U^2\left(x_{LAB1}\right) + U^2\left(x_{LAB2}\right)}} \tag{1}$$

where x is the value obtained at a given laboratory, with an expanded uncertainty of $U(x)$. An E_n value of greater than 1 indicates that the difference between the two laboratories may be significant, as it cannot be explained by the combination of the uncertainties.

It is therefore imperative that the correct uncertainty contributions are included in the analysis - the following sections detail the uncertainty components which have been considered in this exercise and explain how each has been dealt with in the analysis.

4.2.1. Reference force

The stated uncertainty of the force generated by the standard machine at each laboratory is incorporated in the laboratory's uncertainty value.

4.2.2. Transducer drift

The two calibrations of the transducer at NIS give a measure of the drift in the transducer sensitivity throughout the exercise - this drift is incorporated into the NIS uncertainty value as a component with a rectangular distribution with a width equal to the total drift. The one exception to this is Test B3, as Test B2 (carried out using the same transducer and applying a pure deadweight force) demonstrates that the sensitivity remained virtually stable throughout the period (as do Tests C1 and C2, although these were carried out in a hydraulic machine). Test B3 is analysed using the relative drift data obtained from Test B2 and is discussed further in Section 5.

4.2.3. Instrumentation

All calibrations used the same instrumentation, so there should be no contribution to the uncertainty budget from it - any instability or drift would be dealt with as repeatability or transducer drift.

4.2.4. Resolution

The resolution of the indicator should strictly be incorporated into each budget but, as the worst case has 500 000 bits, it is insignificant and can safely be ignored.

4.2.5. Repeatability

The repeatability of the transducer (i.e. the variation in deflection at a single orientation in a single test) is shown for each set of measurements in Fig. 8 to Fig. 16. Some of this variation may be due to the repeatability of the calibration force, particularly in the hydraulic machines, but some will also be due to the transducer performance. The repeatability is estimated as the mean spread of deflection values at the three orientations and incorporated in the uncertainty budget as a rectangular distribution, with a width equal to this mean spread.

4.2.6. Reproducibility

The reproducibility of the transducer (i.e. the variation in deflection at the three different orientations in a single test) is shown for each set of measurements in Fig. 8 to Fig. 16. Fig. 17 plots the mean deflections against orientation for the three calibrations in Test A3 (chosen as a typical example). It can be seen that a sinusoid of period 360º can be fitted to each set of data.

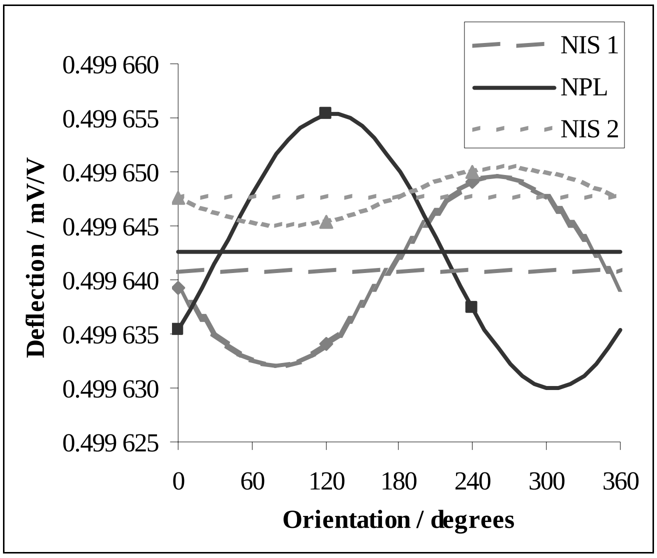

Fig. 17. Test A3 sinusoidal fits.

It could be argued that, as the expected relationship between orientation and deflection is indeed sinusoidal (due to the interaction between the transducer and the machine) and we are only interested in comparing the mean values, the variation of the sinusoid about the mean (i.e. the reproducibility) is irrelevant and should be ignored. However, a sinusoid could be fitted to any three points so the values acquired do not demonstrate that the underlying trend is sinusoidal, so a more cautious approach needs to be taken. The reproducibility is therefore incorporated into each laboratory's uncertainty budget as the standard deviation of these three mean deflections, divided by three (the square root of the number of values used to calculate this standard deviation).

4.2.7. Temperature

The calibrations at the two laboratories were carried out at different temperatures - from 20.0 ºC to 20.4 ºC at NPL and from 21.0 ºC to 23.6 ºC at NIS. The temperature sensitivities of the transducers are not accurately known, so the manufacturer's specification (better than 0.001 % per ºC) is used as a contribution to the uncertainty of the NPL deflection, assuming a rectangular distribution and using the measured temperature difference for each set of tests as the half-width of the distribution.

4.3. Machine comparison results

The uncertainties associated with the values obtained at the two laboratories are given in Table 3 and the associated E_n values are plotted in Fig. 18.

Table 2. Comparison results.

Test	Force	NIS uncertainty %	NPL uncertainty %	E_n value
A1	5 kN	0.002 4	0.003 8	1.00
A2	20 kN	0.002 3	0.003 5	0.14
A3	50 kN	0.002 4	0.003 7	0.07
B1	200 kN	0.002 1	0.003 5	0.54
B2	500 kN	0.002 5	0.006 7	0.12
B3	1 MN	0.012 3	0.007 4	1.16
C1	500 kN	0.020 5	0.021 0	0.08
C2	1 MN	0.020 2	0.020 7	0.18
C3	5 MN	0.024 0	0.050 3	0.65

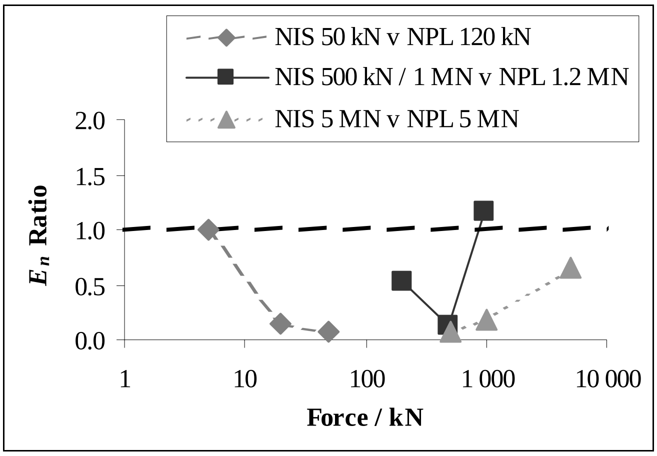

Fig. 18. Plot of E_n ratio values.

5. DISCUSSION

Fig. 18 shows that, of the nine points at which the three pairs of machines were compared, seven of the resulting E_n values are significantly smaller than 1, giving confidence in the claimed uncertainties of the machines at these values. Of the other two points, Test A1 yielded an E_n value of 1.00 - the difference of 0.004 5 % only just being accounted for by the combined uncertainties of the two laboratory values - and Test B3 gave an E_n value of 1.16.

The repeat value for Test B3 at NIS was close to the NPL value but the initial value was significantly lower. The reasons for this are unclear but it appears likely that there was a problem with the 120º values recorded during the initial NIS calibration, possibly due to extended loading times. This reinforces the need to ensure that common time loading profiles are used at laboratories participating in such comparisons - the creep of the transducer can be the most significant uncertainty contribution, particularly when comparing deadweight machines.

As detailed in Table 1, the same transducer was twice used at the same force to compare two pairs of machines - at 500 kN in Tests B2 and C1 and at 1 MN in Tests B3 and C2. The four machines thus compared agree very well at 500 kN (a spread of just 0.002 3 %) but less well at 1 MN (a spread of 0.021 7 %) - the outlier of the four values again suggests that it is the NIS value for Test B3 which is suspect. Carrying out calibrations on the same transducer at the same force in different machines at a single laboratory has therefore proved informative and it is recommended that, where the machine capacities allow, future comparison protocols should take advantage of such benefits.

For Tests A1, A2, A3, and B1, the NPL uncertainty value is dominated by the temperature component, with a maximum temperature difference between laboratories of 3.2 ºC - it is recommended that, in future, either the calibrations are all carried out at the same temperature or that the sensitivity of the transducer is determined so that a correction can be made, rather than its effect being incorporated as a large uncertainty contribution.

The most significant contribution to the NPL uncertainty for Tests B2 and B3 is the reproducibility - as discussed in Section 4.2.6, a protocol using a minimum of four orientations would enable a sinusoid to be fitted to the deflections and the uncertainty associated with the mean value estimated with a possibly lower uncertainty - it is recommended that future comparisons use such analysis methods.

6. CONCLUSION

The results of a bilateral comparison of force standards between NIS and NPL have been detailed and, in general, provide evidence to support the uncertainty claims of the two laboratories.

Recommendations for future comparison exercises have been made and it is hoped that these will help to engender further confidence in the worldwide system of force standards, to the benefit of all those who depend on them.

ACKNOWLEDGMENTS

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