Performance Evaluation and Metrological Characteristics of a Deadweight Force Standard Machine with Substitute Load Control System

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Abstract

A new dead weight force standard machine covering the range from 5 kN to 500 kN direct weights has been designed and constructed at the National Institute for Standards (NIS)-Egypt, by Gassmann Theiss Messtechnik GmbH (GTM). The machine capacity can be duplicated to 1000 kN by means of a substitute force generator.
The machine has been verified through a comprehensive Inter-laboratory Comparison Programme run over a period of two years at the Physikalisch-Technische Bundesanstalt (PTB) of Germany and NIS of Egypt. A well-selected set of high precision force transfer standards was used in the comparison calibration protocol. Rounds of measurements were carried out on deadweight machines at both the PTB and NIS. This paper presents the protocol followed to evaluate the metrological characteristics of the new machine as well as the Inter-laboratory Comparison scheme used in the verification process. The results prove that the machine achieve an uncertainty better than $2 \cdot 10^{-5}$ for calibration of force transducer by pure deadweights. Using the substitute force generator mechanism to double the machine capacity resulted in an uncertainty figure better than $1 \cdot 10^{-4}$.

1. Introduction

As part of a project to upgrade and modernise the force laboratory of the National Institute of Standards (NIS) of Egypt, three force standard machines (FSMs) were designed, constructed, installed, commissioned and verified through intercomparison scheme run between NIS and PTB. These are 50 kN deadweight FSM, load range 500 N to 50 kN, in steps of 500 N, tension and compression [1,2], 500 kN deadweight FSM and 5 MN hydraulic FSM, load range 100 kN to 5 MN, in steps of 50 kN, compression only.

2. Principle of Inter-comparison

For the intercomparison, NIS used a set of force transfer standards, which covered the whole force range of the machine (from 10% to 100% of the nominal load for the 500 kN FSM and 40% to 100% of the nominal load for the 1000 kN duplicated range). The force transfer standards were calibrated against the 500 kN deadweight FSM of NIS as well as the 100 kN and the 1 MN deadweight force standard machines of PTB. The measurements were performed following a protocol for the intercomparison developed jointly by PTB, NIS and GTM [2,3,4]. The capacities selected for the transducer overlapped in the force range to investigate the interactions of the transducers with the machine (overlapping effect) [5].

The measurements at NIS and PTB were performed according of the method of interlaboratory comparison for calibrations laboratories. Each force transducer was measured at four positions relative to the axis of the machine (0°, 90°, 180° and 270°). In the 0° position the transducer is loaded three times with a pre-load of 100% returning to zero after each maximum load application while at any of the other positions, the force transducer was exercised to the maximum load and returning to zero only once before starting the measuring cycles. At any position, the force steps were applied in two measurement cycles to show the repeatability of the measurements. In particular, the two measurement cycles at 0^{o} position were carried out with increasing and decreasing force to determine the hysteresis of the transducer. At other positions, measurement cycles were carried out with increasing force only. The force steps were selected so that no measurements are carried out below 25% of the force transducer capacity in order to obtain the best measurement performance of the transducer.

To minimise the effect of creep, for each force transducer included in the intercomparison, the time required to achieve a stable response following loading and unloading was determined prior starting the measurements. It was found that, after each action of loading or unloading, 150 seconds time delay before recording the force transducer response is quite sufficient.
The intercomparison was carried out mainly in the compression range. Loads were applied in compression on the 500 kN FSM in force steps of 50 kN, 60 kN, 80 kN, and 100 kN (100 kN force transducer); 100 kN, 160 kN and 200 kN (200 kN force transducer) and 200 kN, 300 kN, 400 kN and 500 kN (500 kN force transducer force). On the other hand, the tension force steps were: 50 kN, 60 kN, 80 kN and 100 kN (100 kN force transducer).
As for the 1000 kN range of the same machine (duplicated by means of the substitute force generator), loads were applied in both compression and tension modes in force steps of 400 kN, 500 kN, 600 kN, 800 kN and 1000 kN (1000 kN force transducer).

3. Inter-comparison Results

The mean values of the measurements carried out first at NIS, then at PTB and, finally at NIS on the 500 kN FSM and the 1000 kN duplicated range of the same machine are summarised in Table 1. The table shows the capacities of the force transducers used in the intercomparison, the applied deadweight force steps in kN, and the relative deviation values calculated from the following equation:

$$rel.\ deviation = \frac{X_{\mathrm{NIS(avg)}} - X_{\mathrm{PTB}}}{X_{\mathrm{PTB}}} \qquad (1)$$

The values of X_{NIS} (first set or second set) and X_{PTB} represent the mean response of force transducers at each load step for all loading cycles with the different positions (0^{o}, 90^{o}, 180^{o} and 270^{o}). The relative deviations of the measurements of NIS from PTB (initial, final and average measurements) are plotted in Fig. 1 for the range investigated (50 kN to 500 kN) while Fig. 2 shows the relative deviations in the tension measurements within a limited range (100 kN).

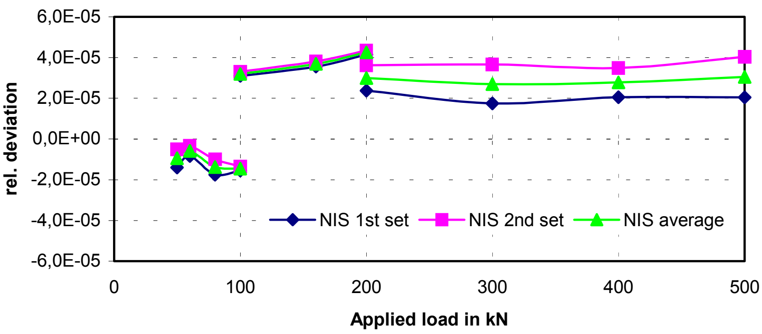

Fig. 1 Relative deviation between NIS and PTB (500 kN range Compression).

Figure 3 shows the same relations for the 1000 kN duplicated range of the machine.

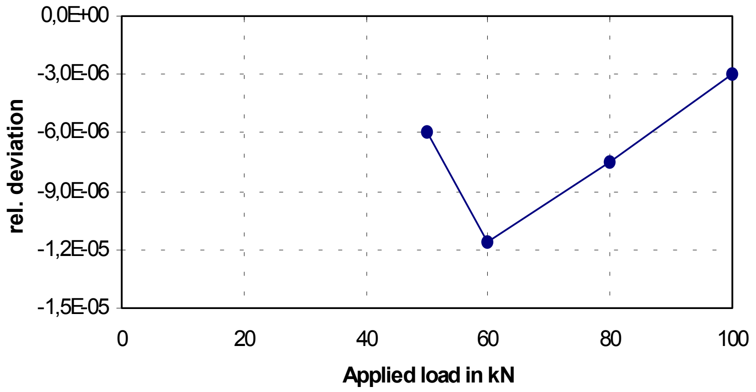

Fig. 2 Relative deviation between NIS and PTB (100 kN range tension).

The relative deviations between NIS and the mean values of PTB amount to less than $\pm 3.5 \cdot 10^{-5}$ in compression over the full range of the 500 kN while it amounts to $\pm 2 \cdot 10^{-5}$ in tension over the 100 kN range. As for the 1000 kN duplicated range of the machine the relative deviation values are within $9 \cdot 10^{-5}$ for the compression mode and $2 \cdot 10^{-5}$ for tension.

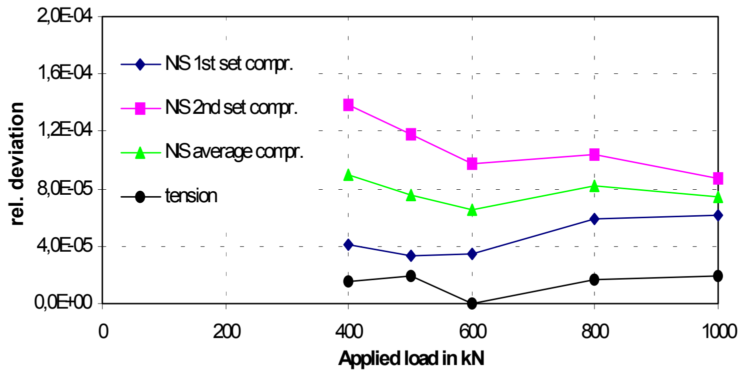

Fig. 3 Relative deviation between NIS and PTB (1000 kN range).

A convenient method of judging the quality of a measurement result is by calculating the deviation E_n normalised with respect to the uncertainty of intercomparison process. The E_n values are calculated for the intercomparison results from the following equation [6,7]:

$$E_n = \frac{X_{\mathrm{NIS}} - X_{\mathrm{PTB}}}{X_{\mathrm{PTB}} \cdot \sqrt{U_{\mathrm{NIS}}^2 + U_{\mathrm{PTB}}^2}} \qquad (2)$$

where X_{NIS}, X_{PTB} are the measurement results for NIS and PTB and U_{NIS} and U_{PTB} are the expanded uncertainties of the measurements for NIS and PTB respectively. An absolute value of E_n less than unity indicates good agreement between the intercompared values [5].

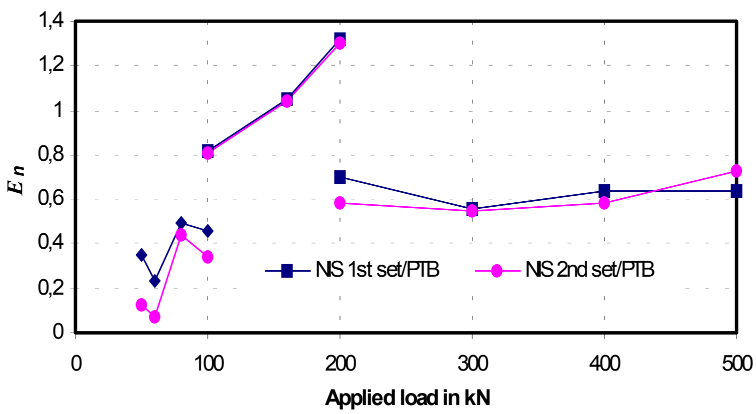

Fig. 4 E_n Value for the 500 kN range compression measurement

Force transducer capacity	Applied Load in kN	Relative Dev.	Force transducer capacity	Applied Load in kN	Relative Dev.
100 kN Compression	50	$-9 \cdot 10^{-6}$	**1000 kN Compression**	400	$9.0 \cdot 10^{--5}$
	60	$-6 \cdot 10^{-6}$		500	$7.6 \cdot 10^{-5}$
	80	$-1.4 \cdot 10^{-5}$		600	$6.6 \cdot 10^{-5}$
	100	$-1.4 \cdot 10^{-5}$		800	$8.2 \cdot 10^{-5}$
				1000	$7.4 \cdot 10^{-5}$
200 kN Compression	100	$3.2 \cdot 10^{-5}$	**1000 kN Tension***	400	$1.5 \cdot 10^{-5}$
	160	$3.7 \cdot 10^{-5}$		500	$1.9 \cdot 10^{-5}$
	200	$4.3 \cdot 10^{-5}$		600	$-1 \cdot 10^{-6}$
				800	$1.7 \cdot 10^{-5}$
				1000	$1.9.10^{-5}$
500 kN Compression	200	$3.0 \cdot 10^{-5}$	**100 kN Tension**	50	$-6 \cdot 10^{-6}$
	300	$2.7 \cdot 10^{-5}$		60	$-1.2 \cdot 10^{-5}$
	400	$2.8 \cdot 10^{-5}$		80	$-7 \cdot 10^{-6}$
	500	$3.0 \cdot 10^{-5}$		100	$-3 \cdot 10^{-6}$

* No first set NIS measurements were taken with the transducer.

Tab. 1 Intercomparison results for the 500 kN/1000 kN force standard machine

Figures 4 and 5 show the E_n values of the comparison results for the different force steps of the compression for the 500 kN range and up to 100 kN in tension respectively. The two figures show values of the normalised error (E_n) indicating good agreement of the intercomparison results in both compression and tension.

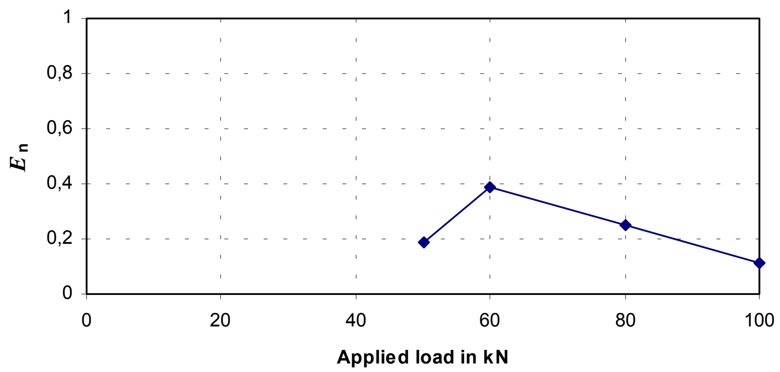

Fig. 5 E_n value for the 500 kN range tension

Figure 6 depicts the E_n values for the 1000 kN duplicated range of the machine in both compression and tension modes over the full duplicated range.

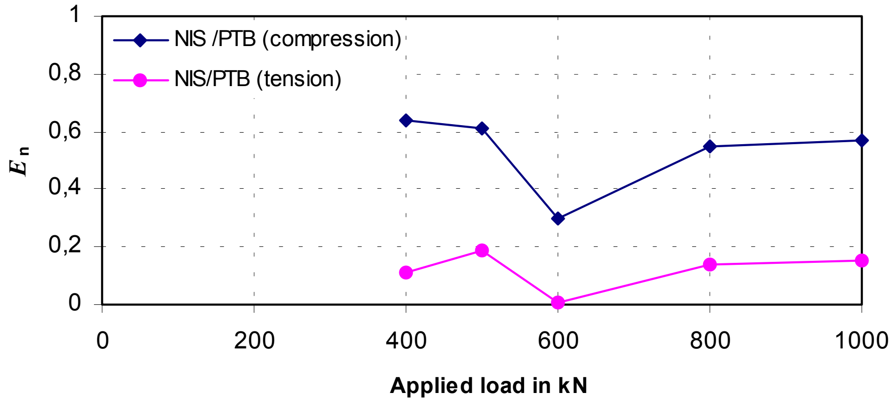

Fig. 6 E_n **values for the 1000 kN range**

4. The Uncertainty Elements in the Intercomparison Measurements

The determination of the measuring uncertainty follows the suggestions given in [6,7], type A. This method derives the standard measuring uncertainty from the empirically measured standard deviation of the average values. The calculated standard measuring uncertainty $u(r)$ of each measurement is added to the measuring uncertainty U_{FSM} of the used FSM according to equation (3).

$$U = k \cdot \sqrt{u(r)^2 + U_{\mathrm{FSM}}{}^2} \qquad (3)$$

The expansion factor k was chosen as $k = 2$.

The total measuring uncertainty U of the intercomparison measurements is the results of the combination of the measuring uncertainties as determined at the PTB U_{PTB} and at NIS U_{NIS}, respectively.

$$U = \sqrt{U_{\mathrm{PTB}}{}^2 + U_{\mathrm{NIS}}{}^2} \qquad (4)$$

This measuring uncertainty was used for the determination of the normalised error E_n. The measuring uncertainties of the measurements carried out at NIS and at PTB, respectively, do not differ significantly for the deadweight range. As could be expected, the measuring uncertainties in the load duplication range from 500 kN to 1000 kN are somewhat larger.

5. Conclusion

The normalised error values for the intercomparison measurements carried out at NIS on the new 500 kN force standard deadweight machine and at PTB on the 100 kN and the 1 MN force standard machines are smaller than 1 for both compression and tension over the range of comparison. The relative deviations for the measurements on the intercompared machines applying direct deadweights agree within $\pm 3.5 \cdot 10^{-5}$ whereas they reach $9 \cdot 10^{-5}$ for the 1 MN duplicated range. The maximum observed relative deviation is very close to the uncertainty in the forces realised by the machine under evaluation in both its direct deadweight application mode ($\pm 2 \cdot 10^{-5}$) and the mode of applying the substitute force generator mechanism ($\pm 1{\cdot}10^{-5}$). The relative repeatability and reproducibility for the measurements carried out at NIS are almost of the same order of magnitude to those obtained at PTB for both compression and tension. A remarkable agreement is concluded for the observed relative hysteresis of the measurements carried out on the intercompared machines in both compression and tension. As a general conclusion, over the whole force range of the inter-comparison, the forces realized at NIS are compared favourably with those realized at PTB and $\pm 2{\cdot}10^{-5}$ NIS force standard machine uncertainty is quite acceptable for direct application of deadweights (up to 500 kN) whereas uncertainty value of better than $1{\cdot}10^{-4}$ is applicable in case of using substitute mechanism (up to 1000 kN).

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