

Qualification of force standard machines

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Abstract:

The 5.2 kN (id. Mgl) and the 50 kN (id. Mnz) force standard dead-weight machines of the Isaac Newton Laboratory of CETEC, Minas Gerais, Brazil, underwent a process of re-qualification by INMETRO. The process was based on an inter-comparison programme in which the reference values were generated by the 100 kN dead-weight / 1 MN lever amplification machine of INMETRO Force Laboratory – LAFOR. The 5.2 kN machine was verified for compressive forces of 2 and 5 kN, and the 50 kN machine was verified for 2, 5, 20, and 50 kN compressive forces. Calibration activities were carried out in November, 2006 and in August, 2007. Relative deviations and estimated best measurement capabilities are within the expected range for machines of the type. Considered the eight-year time span since the first qualification programme, the Laboratory has significantly improved its best capability values and the relative deviation of the forces it realises.

Key-words: force, standard, inter-comparison, dead-weight machine

1. Introduction

The Isaac Newton Laboratory of the Technological Centre Foundation – CETEC of the State of Minas Gerais, Brazil deals with hard mechanical quantities: force, mass, and torque. At the primary level, force is kept and disseminated by the laboratory in the not-continuous range of 10 N to 50 kN, in tension and compression, and is realised by means of three dead-weight machines of nominal capacities 110 N (id. Ddr), 5.2 kN (id. Mgl) and 50 kN (id. Mnz). The 110 N machine is CETEC-made and the other two are 1997 model American-made Morehouse machines.

The 5.2 kN and the 50 kN machines were first qualified in 1998 by the National Institute of Standardisation, Metrology and Industrial Quality of Brazil – INMETRO, by means of an inter-comparison programme designed to this end [1]. The aim of the process was to integrate the machines in the accreditation scope of the Laboratory to the Brazilian Calibration Service – RBC. In the present year of 2007, ten years after their inception and eight years after they were first qualified, the machines underwent re-qualification in order to verify the stability of the quality parameters of the realised forces, that is, the deviation relative to the forces

realised with the Brazilian standard machine, and the Laboratory best measurement capability.

Re-qualification was based upon an inter-comparison programme in which the reference values were realised with the Brazilian standard maintained by INMETRO Force Laboratory – LAFOR.

2 Force Standards

2.1 Re-Qualified Machines

The re-qualified force standard machines are equipped with dead-weights as shown Table 1. In addition to the dead-weights, the machines are composed mainly by a loading frame, itself a dead-weight, and a fixed frame onto which is mounted an adjustable loading stage. All dead-weights including the loading frame are made of AISI-304 stainless steel. The 50 kN machine is operated by means of a computerised set of pneumatic actuators and the 5.2 kN machine is manually operated by means of mechanical weight elevators [1].

Table 1 – Re-qualified machines' dead-weights / No. and made-up forces

Dead-weight / N	Mgl			Mnz				
	5.2 kN	2 kN	5 kN	50 kN	2 kN	5 kN	20 kN	50 kN
5	1							
10	2							
25	1							
50	2 ^a	1x	1x					
100	1							
200	1	1x	1x					
250	1	1x	1x					
500	9	3x	9x	10 ^a	4x	10x	10x	10x
5000				9			3x	9x

^aIncludes loading frame

2.2 Reference Machine

Reference forces were generated by the Brazilian national force standard machine maintained by INMETRO Force Laboratory – LAFOR. This is a German-

made GTM machine, already described in literature [1, 2, 3], which is composed of two parts: a 110 kN direct action dead-weight and a 1.1 MN lever amplification section. Best measurement capabilities of INMETRO Force Laboratory – LAFOR are 20 ppm (1 kN to 100 kN) and 100 ppm (10 kN to 1000 kN), respectively for the forces realised with dead-weight and the lever amplification sections [4]. In this study, all reference forces were generated in the direct action dead-weight section.

3 Methodology

3.1 Transfer Standards and Ancillary Devices

The programme employed as common instruments a 5 kN and a 50 kN HBM C3H2 force transducers, a 100 kN HBM TOP-Z4A force transducer, and a single HBM BN100 reference bridge. INMETRO-LAFOR and the Isaac Newton Laboratory of CETEC used their own HBM DMP40 signal conditioners (absolute mode, excitation 5 V, range ± 2.5 mV/V, 10^{-6} resolution, 0.22 Hz Bessel filter). Except for the signal conditioners, all instruments used as transfer standards are properties of CETEC. Each laboratory used its own ancillary devices, e.g., load pads and centering pieces.

3.2 Comparison Procedure

3.2.1 Measurement Protocol

The programme was guided by the prescriptions of the measurement protocol especially laid out for the 2004-2006 medium force measurements BIPM-CCM key-comparison undertaken by INMETRO [5]. The protocol included the procedures, which were followed by both laboratories, and an MS-Excel[®] spreadsheet with the measurement steps, that is, sequences of force levels and time intervals between them. A deviation from the prescriptions was the excitation voltage, prescribed to be 10 V and agreed by INMETRO and CETEC to be 5 V. The requisites laid out by the measurement protocol are represented by the flowchart of Figure 1.

Both the DMP40 signal conditioners checks performed with the BN100 reference bridge and the measurement of the environmental parameters in the laboratories (Figure 1) were performed merely to verify the stability of the force measurement conditions. No corrections were made on the force values, derived from these results. All cases considered, temperature in LAFOR ranged between 19,0°C and 19,8°C; the relative humidity range was 51-55%; and atmospheric pressure lied in the range 1015-1029 hPa. The corresponding ranges for the Isaac Newton Laboratory were 22-25°C, 45-52%, and 920.1-927.5 hPa

As a complement to the protocol requisites, and in order to take transducer drift into account, a circular procedure was adopted by which the forces generated by CETEC's re-qualified machines were measured in two cycles, that is, before and after the measurements performed at INMETRO-LAFOR

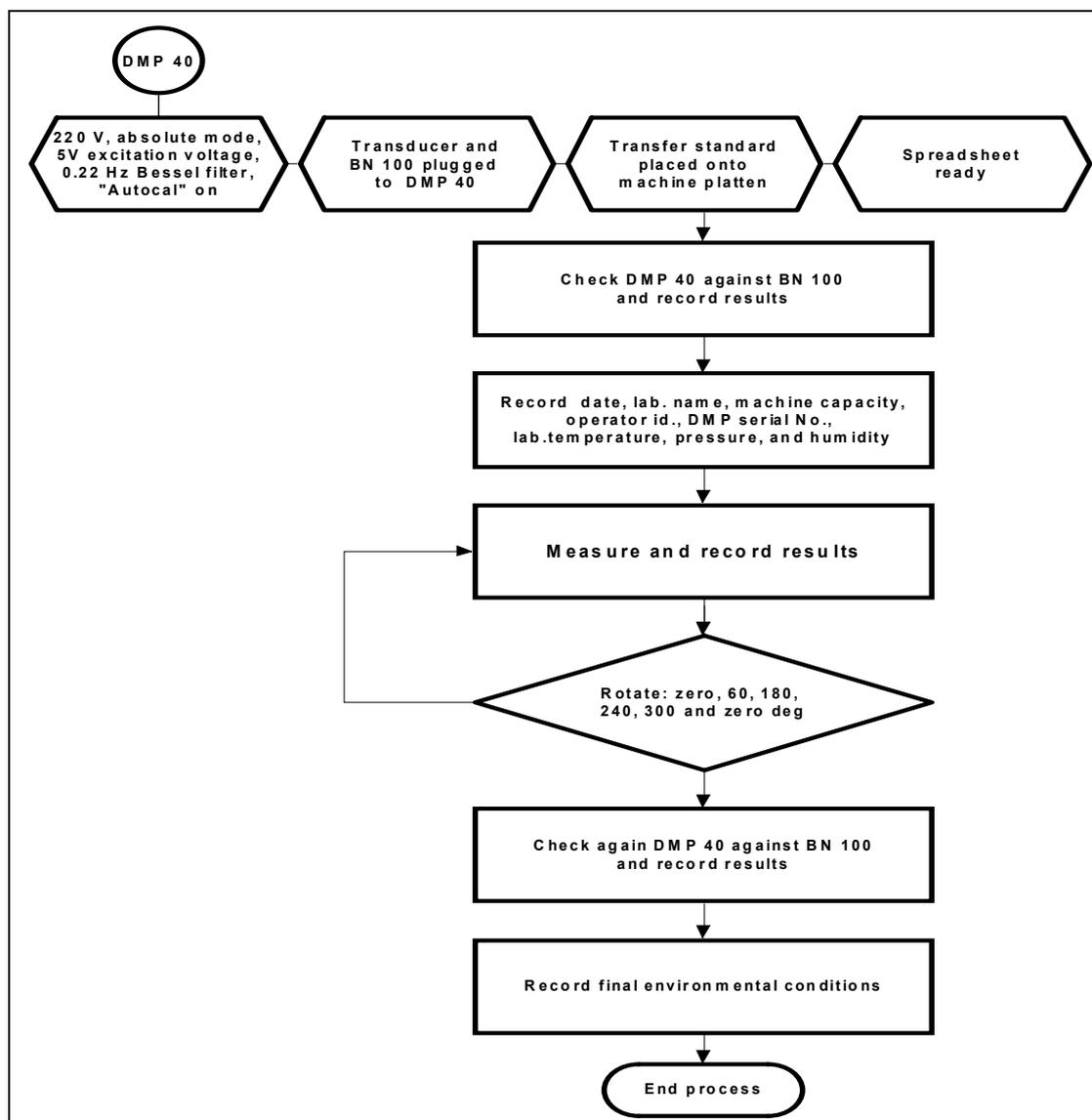


Figure 1 – Flowchart representing the measurement protocol

3.2.2 Measured Forces and Measurement Steps

Apart from the zero-force state response, the forces measured within the scope of this programme were 2, 5, 20, and 50 kN, all in compression. The 5.2 kN machine was verified for forces of 2 and 5 kN, while the 50 kN machine was verified for 2, 5, 20, and 50 kN forces. For each force triplet, that is, 0-2-5 kN and 0-20-50 kN, 94 measurement steps were performed, 31 for each triplet plus a final return to the zero-force state. A 360 s interval was observed between subsequent readings. Figure 2 shows the first 28 measurement steps for the 0-2-5 kN force triplets. In Figure 2, figures on the x-axis of the graph represent the measurement steps at zero-force states.

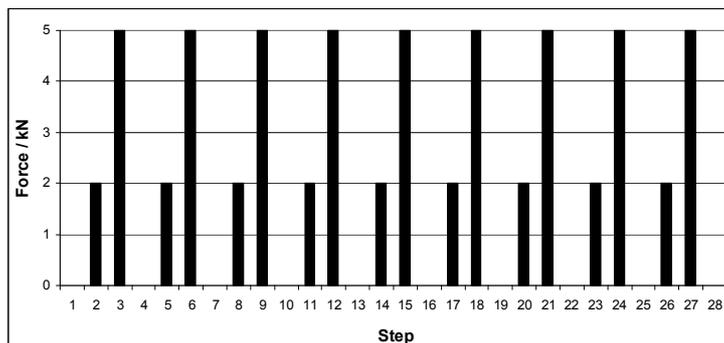


Figure 2 – Measurement steps for the 0-2-5 kN force triplets

With the transducer positioned at an arbitrary zero-degree fixed reference on the machine platten, three pre-loads were applied to the nominal values of the forces to be measured by each machine (sequences starting at steps 1, 4, 7, and 10 in Figure 2). Still at the zero-degree position, the transfer standard signal output for each force was recorded three times in succession (sequences starting at steps 13, 16 and 19).

The transducer – together with the ancillary devices – was then rotated to the 60° position. At this point, a pre-load sequence was applied (starting at step 23) and the output signal was successively recorded for each force (starting at step 25 and ending at step 28). After these measurements were completed, the transducer was rotated to the other positions (120°, 180°, 240°, 300°, and 0°) and measurements were made corresponding to those made at the 60° position. After the transducer had been rotated a complete turn, the process was once repeated for all positions (60°, 120°, 180°, 240°, 300°, and 0°).

3.2.3 Measurement Campaigns

Measurements were carried out in two campaigns, in November, 2006, and in August, 2007. In the first campaign, preliminary data treatments have shown that important response dispersions for the 20 kN and 50 kN forces had been caused by the 50 kN HBM C3H2 transducer position (Figure 4). Therefore, in August, 2007, a second measurement campaign was put into effect, now employing the 100 kN HBM TOP-Z4A force transducer. Although of a higher than the desirable range for the measurement of 20 kN forces [6], this transducer was chosen because it was the best available at the time.

4 Results

4.1 Comparison Force Value

The comparison force value was the mean net signal, in mV/V, measured at each rotating position. Net signals were calculated by subtracting the zero-force signal from the absolute signal recorded at a given non-zero force. It was then calculated the mean of each two net signals for the measurements made at each position. Furthermore, in the case of CETEC, it was calculated the grand mean of

the mean net signals obtained in the two measurement cycles and this grand mean was employed for the calculation of the quality parameters, that is, the relative deviation of the forces and the best capabilities of the Isaac Newton Laboratory.

4.2 Transducer-Machine Interaction

The transducer-machine interaction patterns were graphically compared by plotting the initial, final and overall coefficients of variation for each comparison force value, calculated for the corresponding measurement cycles (Figures 3, 4, and 5). A comparison between the coefficients of variation calculated for the initial and final measurement cycles gives an idea of the stability of the measurements as influenced by drift of the response of the transfer standards. Only the overall coefficient of variation, which included the force values of both measurement cycles, was used for comparison purposes.

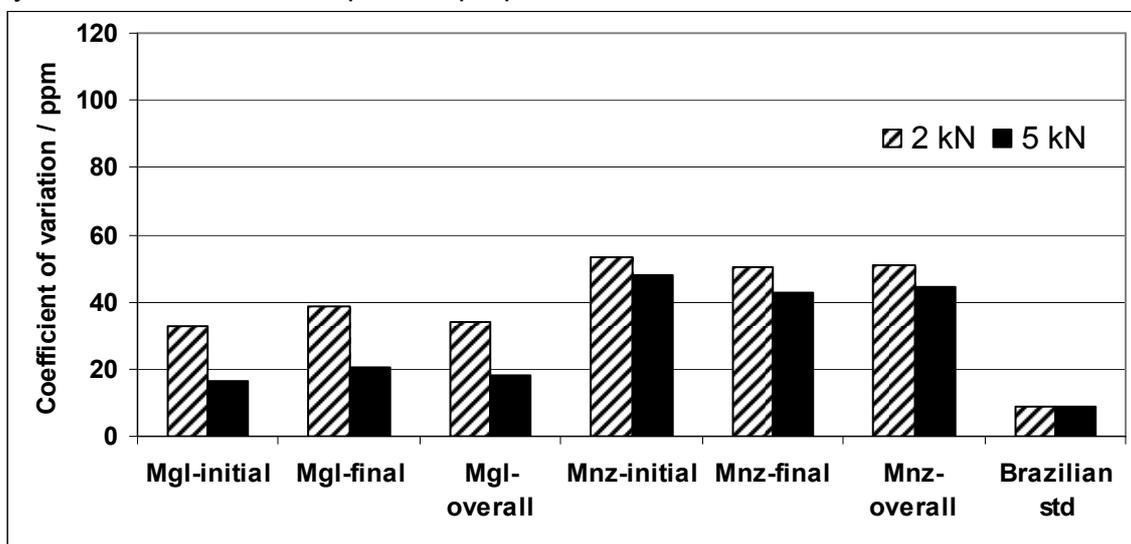


Figure 3 – First campaign – CV of the 2 kN and 5 kN force values

Figures 3 and 5 demonstrate that transducer-machine interactions had little influence on the 2 kN and 5 kN, as well as on the second campaign 20 kN and 50 kN force values transferred by LAFOR. Coefficients of variation of these values were about 10 ppm, that is, half the best measurement capability of INMETRO-LAFOR, what makes it possible to suppose that they are a component of LAFOR's best measurement capability.

On the other hand, Figure 4 shows that the first campaign 20 kN and 50 kN transferred forces were significantly influenced by transducer-machine interactions. In this campaign, the coefficients of variation of the force values produced with the Brazilian standard were considerably larger than LAFOR's best measurement capability. Moreover, the coefficient of variation of the force values resulting from the 50 kN reference force was about twice the corresponding one, calculated for the 20 kN reference force. This contradicts the expectation of having lower coefficients of variation for higher force values measured with a transducer-machine set. Figure 4 also shows that the dispersion of the first campaign force

values measured by CETEC with Mnz, were much higher for the 20 kN and 50 kN than for the 2 kN and 5 kN forces. This findings constituted the motivation to undertake the second measurement campaign and to discard the 20 kN and 50 kN force values obtained in the first campaign.

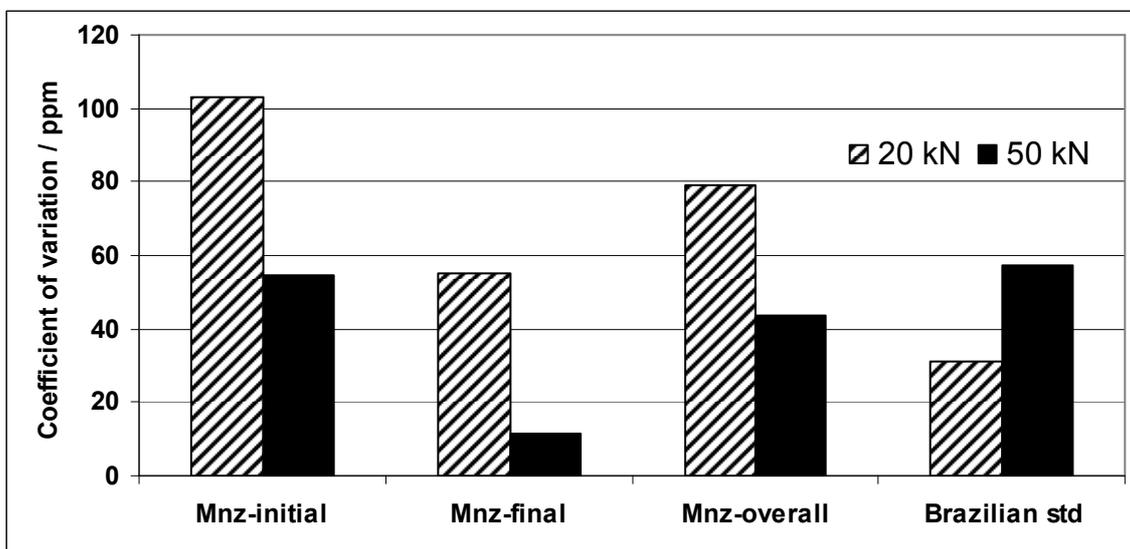


Figure 4 – First campaign – CV of the 20 kN and 50 kN force values

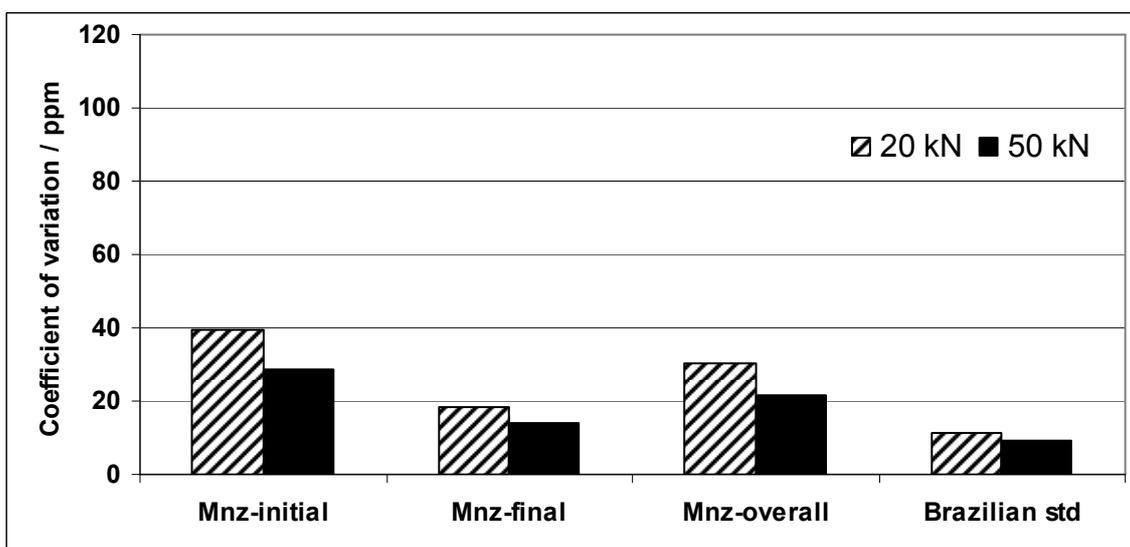


Figure 5 – Second campaign – CV of the 20 kN and 50 kN force values

As shown in Figure 3, the influence of transducer-machine interactions on the dispersion of 2 kN and 5 kN force values was higher for CETEC's 50 kN machine (Mnz) than for the 5 kN machine (Mgl).

4.2 Relative Deviation of the Force Values

The deviation of the forces realised by CETEC relative to the references maintained by INMETRO are presented in Table 2. This table also presents the relative deviations measured in the first qualification programme, carried out in 1999 [1].

Table 2 – Relative deviations of the forces realised by the Laboratory

Force / kN	Relative deviation / ppm				
	1999 programme		1st. campaign		2nd. campaign
	Mgl	Mnz	Mgl	Mnz	Mnz
2	140	150	-60	-62	-
5	180	180	-31	-67	-
20	-	-180	-	200	-29
50	-	-210	-	150	35

4.3 Best Measurement Capability

Table 3 presents the best measurement capabilities of the Isaac Newton Laboratory, which were estimated by taking in consideration the uncertainty contributions of: a) the relative lack of reproducibility of the comparison force values, as measured by the overall coefficient of variation, that is, the one calculated with the comparison force values of both the initial and final measurements; and b) the relative uncertainty of the reference values, taken as half the best measurement capability of INMETRO-LAFOR (1) [7].

$$W_{bmc} = 2 \cdot \sqrt{w_{refV}^2 + w_r^2} \quad (1)$$

Where W_{bmc} is the best measurement capability of the laboratory; w_{refV} is the uncertainty of the reference forces, here taken as the half the best measurement capability of LAFOR; and w_r is the coefficient of variation of the force values measured by the Isaac Newton Laboratory.

Similarly to Table 2, Table 3 also presents the best measurement capabilities estimated with the results of the first qualification programme [1]. It must be noticed that, both for the 1999 and the latest results, the relative deviation of the force values were not taken into consideration for the estimation of the best measurement capability because the Isaac Newton Laboratory normally corrects the realised forces when performing calibrations of force measuring devices.

Table 3 – Best measurement capabilities, W_{IN}

Force / kN	Estimated best measurement capability / ppm				
	1999 programme		1st. campaign		2nd. campaign
	Mgl	Mnz	Mgl	Mnz	Mnz
2	140	120	68	100	-
5	76	76	36	88	-
20	-	180	-	160	60
50	-	150	-	90	43

4.4 Normalised Error

Given the force deviations and the estimated best measurement capabilities of the Isaac Newton Laboratory, the value of the normalised error was calculated according to equation (2) [8].

$$E_n = \left| \frac{R_{IN} - R_{LAFOR}}{\sqrt{W_{IN}^2 + W_{LAFOR}^2}} \right| \quad (2)$$

Where, R_{IN} and R_{LAFOR} are the force values and W_{IN} and W_{LAFOR} are the expanded measurement uncertainties, here taken as the best measurement capabilities of the respective laboratories. In (2), the numerator represents the deviation of the forces measured by the Isaac Newton Laboratory and LAFOR. In (2), both the numerator and the terms of the denominator must be taken in compatible units or be dimensionless.

All calculated values are in the range 0,44 – 0,82, which lie within the set of acceptable values, $E_n \leq 1$ [8].

5 Conclusions

The inter-comparison programme for the qualification of the force standard machines of the Isaac Newton Laboratory of CETEC was carried out in two measurement campaigns. The resulting best measurement capability of the Isaac Newton Laboratory of CETEC was estimated to be in the range of 70 – 40 ppm for the force range of 2 – 5 kN. As for the 20 – 50 kN force range, the estimated best measurement capability lies in the interval 60 – 40 ppm. The best measurement capability interval for the 20 – 50 kN force range was established considering only the results obtained in the second measurement campaign. In addition, it has been shown that the forces in the superimposed range of Mgl and Mnz should be realised by the Isaac Newton Laboratory with the aid of the former, because it yields smaller relative deviations and best measurement capabilities. This is the case of the 2 kN and 5 kN forces measured in the scope of this programme.

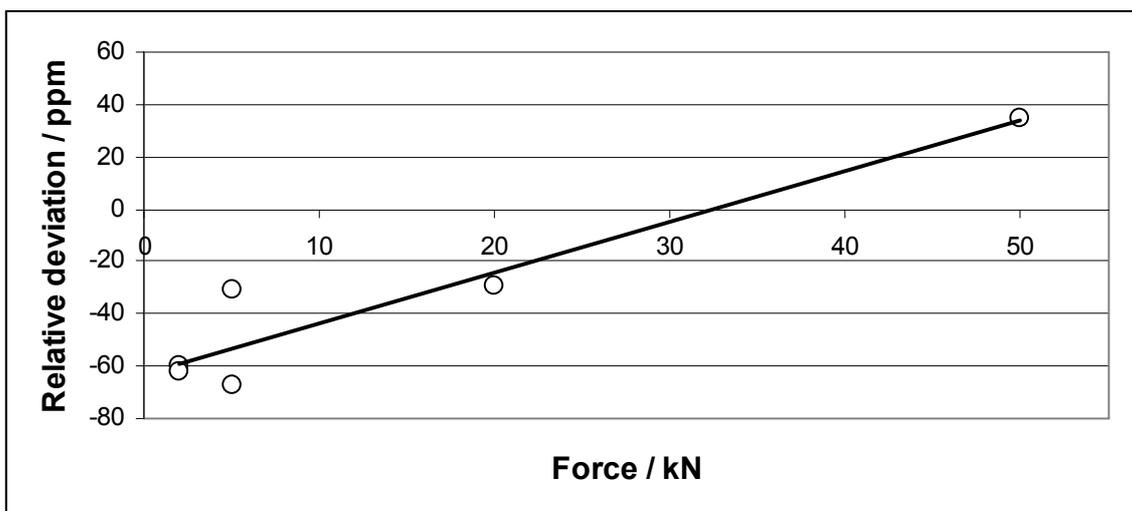


Figure 6 – Relative deviations

The graph in Figure 6 is a plot of the relative deviations of the forces realised by the Isaac Newton Laboratory. As suggested by the fitted straight line, the relative deviations seem to follow a trend for the forces in the 2 – 50 kN range. The noticed trend may be due to deviations of the (added) masses of the weights used to make up the realised forces.

Finally, the analysis of the results of the inter-comparison programme indicate that considered the eight-year time span since the first qualification programme, the Isaac Newton Laboratory has significantly improved its best capability values and the relative deviation of the forces it realises. This is attributed mainly to a refinement in measurement methods, that is, the protocol, the electronics and an improved force transducer employed as a transfer standard.

Acknowledgements

The authors acknowledge the kind support provided by INMETRO and CETEC.

References

- [1] Cruz, J.A.P; Saffar, J.M.E; Chagas, A. R; Ferreira Marques, E.M; Sawla, A. Intercomparison Programme for the Qualification of Force Standards. IMEKO XV International World Congress. Osaka, Japan, 1999. CD-ROM. 7p.
- [2] Fank S., Sawla A., Özbay H.Ö. and Gassmann, H. Establishment of national force scale at UME and results of intercomp. meas. between UME and PTB. Proc. XV Intern. Conf. IMEKO-TC3. Madrid, 7-11 Oct. 1996. pp65-74.
- [3] Fank S., Sawla A. and Özbay H. Long-term observn. of newly devel. 110 kN/1.1 MN lever-amplif. deadweight force std. machine at UME. Proc. XIV IMEKO World Congr. Tampere, 1-6 June 1997. Vol.III, pp7-12.
- [4] Sawla A., Allgeier T. and Souza M.R.A. Funktionsprüfung der 110-kN/1,1-MN-Kraft-Normalmeßeinrichtung. INMETRO. Xerem, 28 May 1998. 1p.

- [5] BIPM. CCM.F-K2.a Key-comparison protocol: Medium force measurements. 2004-2006.
- [6] Sawla, A. and Robles, J.A, 1996. Intercomparison of force standard machines between PTB and CEM. Proc. 15th. Intl. Conf. IMEKO TC-3. Centro Español de Metrologia. Madrid, Spain, 7-11.10.1996. p.49-55.
- [7] EA-10-04. EAL-G22: Uncertainty of Calibration Results in Force Measurements. August 1996.16p.
- [8] NIST, 1995. NVLAP Calibration Labs. Tech. Guide. NIST Handbook 150-2 (draft). Aug.95. 370p.

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