Self-calibration of the 1 MN deadweight force standard machine at INRiM

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SELF-CALIBRATION OF THE 1 MN DEADWEIGHT FORCE STANDARD MACHINE AT INRIM

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Abstract:
The INRiM 1 MN deadweight force standard machine (DFSM) was installed in 1995. It adopts a binary sequence of ten weights whose combinations generate forces up to 1 MN. The advantage of this system lies in the self-calibration of its weights. The procedure is based on the comparison between two forces generated by a single weight and by a group of smaller weights, nominally equal. After 25 years, a verification of the DFSM was performed. Results are within the declared CMC limits, i.e. a relative expanded uncertainty of 2×10^{-5}.

Keywords: deadweight force standard machine; self-calibration; uncertainty

1. INTRODUCTION

Back in 1995, the advancement of technology and available resources allowed to design and install the 1 MN DFSM at INRiM [1, 2]. The machine is able to generate known forces and is generally used as a reference for the calibration or verification of force transducers and load cells. The DFSM has a declared CMC with a relative expanded uncertainty of 2×10^{-5} [3]. Twenty-five years after the installation, despite several positive international comparisons, it was necessary to carry out a verification of the machine. For this purpose, a self-calibration method was developed. Measurements were performed between November 2018 and April 2019. This paper deals with the description of the self-calibration method and the analysis of experimental results.

2. DESCRIPTION OF THE 1 MN DEADWEIGHT FORCE MACHINE

The 1 MN DFSM was designed to obtain a reference standard capable of keeping its metrological characteristics unchanged. It consists of three macro-components: a main frame that supports the entire structure, a loading frame, and a series of weights acting in the local gravitational field. The main frame consists of three columns anchored to the load-bearing structure arranged at 120° on a diameter of about 6 m (Figure 1).

Figure 1: The 1 MN deadweight force standard machine

The 1 MN DFSM adopts a binary sequence of ten weights (two 10 kN weights, three weights of 20 kN, 40 kN, and 80 kN, four weights of 160 kN, and one weight of 200 kN), consisting of stainless steel discs. Each of them can be applied to the loading frame independently to the others. In this way, it is possible to generate a large number of force values from 10 kN up to a maximum capacity of 1 MN with steps of 10 kN, and to perform a self-calibration of the weights to check the stability of the standard without dismantling the whole system [4]. The selection of the weights is performed by an electro-pneumatic system, software controlled, and supported by an electric motor able to generate a constant load on the force transducer during weights replacement operations. The load is kept constant by a feedback system exploiting the deformation elasticity of the loading frame.

3. SELF-CALIBRATION PROCEDURE

The self-calibration method is based on the comparison between two nominally equal forces alternatively generated by a single weight and by an equivalent group of smaller weights [5]. The reference force transducers adopted for the self-calibration were a TOP-Transfer HBM (Z30A and Z4A), with HBM DMP40 amplifier. The initial reference force was provided by the smallest weight, associated with a force of 10 kN (M10/1), which was previously calibrated against a reference mass standard before the installation of the machine. Another advantage of this method is that it can consider any influences due to the behaviour of the whole structure under load since it directly compares the force vectors applied on the force transducer and not the force generated in centre of mass as in the standard method for calibrated force standard machines. For each force value (10 kN, 20 kN, 40 kN, 80 kN, 160 kN, 200 kN), two identical forces were alternately generated: one generated by the single nominal weight (Measure B), the other by the sum of smaller weights of equivalent total force (Measure A). The forces generated for each weight comparison are shown in Table 1.

Table 1: Weights used for the comparison

Weight	**Single weight force / kN (Measure B)**	**Combination of smaller weights with equivalent force (Measure A)**
M10/1	10	-
M10/2	10	M10/1
M20	20	M10/1 + M10/2
M40	40	M10/1 + M10/2 + M20
M80	80	M10/1 + M10/2 + M20 + M40
M160/1	160	M160/4
M160/2	160	M160/4
M160/3	160	M160/4
M160/4	160	M10/1 + M10/2 + M20 + M40 + M80
M200	200	M160/4 + M40

A comparison scheme was then adopted to identify an ABAB…BA type sequence. This sequence was chosen since the most significant causes of disturbance are due to weights replacement operations and to creep effects of the force transducers. For each pair of equal forces, *j* = 10 measurement runs were performed. During each *j*-th run, *i* = 20 force values were acquired in a time interval of 20 s.

4. ANALYSIS OF RELATIVE DEVIATIONS

Once measurements were performed, data analysis was carried out for each force value. First, the average, corrected by subtracting the zero value, of the i-th temporal acquisition values of the j-th run, $F_{a,ij}$ and $F_{b,ij}$, related to the two forces alternately generated and nominally equal ($F_{a,ij}$ corresponds to the force generated by the reference 10 kN weight, M10/1, or by the sum of the smaller weights for forces greater than or equal to 20 kN, and $F_{b,ij}$ corresponds to the force generated by the single weight), was performed according to equation (1).

The average of the temporal mean values $\overline{F_{a,J}}$ and $\overline{F_{b,J}}$ of the 10 runs is given by equation (2).

$$\overline{F_{a,J}} = \sum_{i=1}^{20} \frac{F_{a,ij}}{20} \qquad \overline{F_{b,J}} = \sum_{i=1}^{20} \frac{F_{b,ij}}{20} \tag{1}$$

$$\bar{F} = \sum_{j=1}^{10} \frac{\left(\frac{\overline{F_{a,J}} + \overline{F_{b,J}}}{2}\right)}{10} = \sum_{j=1}^{10} \frac{\overline{F_{a,J}} + \overline{F_{b,J}}}{20} \tag{2}$$

To minimize creep effect, although the short time elapsed between two replacements (about 100 s), a processing scheme, based on the differences between a single value and the mean value between the previous and next measurement, was used. According to this scheme, the absolute deviations d_j, equation (3) and relative deviations δ_j, equation (4), were calculated for each force value F.

$$d_{a,j} = \frac{\overline{F_{a,J}} + \overline{F_{a,J+1}}}{2} - \overline{F_{b,J}} \qquad d_{b,j} = \overline{F_{a,J}} - \frac{\overline{F_{b,J}} + \overline{F_{b,J+1}}}{2} \tag{3}$$

$$\delta_{a,j} = \frac{d_{a,j}}{\bar{F}} \qquad \delta_{b,j} = \frac{d_{b,j}}{\bar{F}} \tag{4}$$

In this way, it was possible to calculate the mean relative deviation $\bar{\delta}$ according to equation (5).

$$\bar{\delta} = \frac{\sum_{j=1}^{10} \frac{d_{a,j} + d_{b,j}}{20}}{\bar{F}} = \sum_{j=1}^{10} \frac{\delta_{a,j} + \delta_{b,j}}{20} \tag{5}$$

To check the actual force values generated by the individual weights, it was necessary to add the mean relative deviations $\bar{\delta}$ of the smaller weights used. In this way, the total mean relative deviations $\bar{\Delta}$ can be obtained. Assuming that the force $F_{\mathrm{M10/1}}$ generated by the reference M10/1 weight is exactly 10 kN with relative expanded uncertainty of 2.82×10^{-6} [6], the mean relative deviation of the reference 10 kN weight (M10/1), $\bar{\delta}_{\mathrm{M10/1}}$, is equal to zero, with an associated uncertainty equal to the uncertainty of the reference force $U(\bar{\delta}_{\mathrm{M10/1}}) = U(F_{\mathrm{M10/1}})/F_{\mathrm{M10/1}} = 2.82 \times 10^{-6}$. In this way, equations (6) and (7) are obtained.

$$\bar{\delta}_{\mathrm{M}10/1} = \bar{\Delta}_{\mathrm{M}10/1} = \frac{F_{\mathrm{M}10/1} - 10}{10} = 0 \tag{6}$$

$$\frac{F_{\mathrm{M}10/1}}{10} = 1 + \bar{\delta}_{\mathrm{M}10/1} \tag{7}$$

As a consequence, the mean relative deviation of M10/2 weight, $\bar{\delta}_{\mathrm{M}10/2}$, can be written as

$$\begin{aligned}\bar{\delta}_{\mathrm{M}10/2} &= \frac{F_{\mathrm{M}10/1} - F_{\mathrm{M}10/2}}{10} = \\ &= 1 + \bar{\delta}_{\mathrm{M}10/1} - \frac{F_{\mathrm{M}10/2}}{10}\end{aligned} \tag{8}$$

from which, the total relative deviation of weight M10/2, $\bar{\Delta}_{\mathrm{M}10/2}$, is obtained:

$$\bar{\Delta}_{\mathrm{M}10/2} = \frac{F_{\mathrm{M}10/2} - 10}{10} = \bar{\delta}_{\mathrm{M}10/1} - \bar{\delta}_{\mathrm{M}10/2} \tag{9}$$

By operating in the same way for weight M20, the following relations are obtained:

$$\begin{aligned}\bar{\delta}_{\mathrm{M}20} &= \frac{F_{\mathrm{M}10/1} + F_{\mathrm{M}10/2} - F_{\mathrm{M}20}}{20} = \\ &= \frac{1}{2}\frac{F_{\mathrm{M}10/1}}{10} + \frac{1}{2}\frac{F_{\mathrm{M}10/2}}{10} - \frac{F_{\mathrm{M}20}}{20} = \\ &= 1 + \bar{\delta}_{\mathrm{M}10/1} - \frac{1}{2}\bar{\delta}_{\mathrm{M}10/2} - \frac{F_{\mathrm{M}20}}{20}\end{aligned} \tag{10}$$

$$\begin{aligned}\bar{\Delta}_{\mathrm{M}20} &= \frac{F_{\mathrm{M}20} - 20}{20} = \\ &= \bar{\delta}_{\mathrm{M}10/1} - \frac{1}{2}\bar{\delta}_{\mathrm{M}10/2} - \bar{\delta}_{\mathrm{M}20}\end{aligned} \tag{11}$$

Iterating the same procedure for all other weights, the following equations are obtained:

$$\bar{\delta}_{\mathrm{M}40} = \frac{F_{\mathrm{M}10/1} + F_{\mathrm{M}10/2} + F_{\mathrm{M}20} - F_{\mathrm{M}40}}{40} \tag{12}$$

$$\begin{aligned}\bar{\Delta}_{\mathrm{M}40} &= \frac{F_{\mathrm{M}40} - 40}{40} = \\ &= \bar{\delta}_{\mathrm{M}10/1} - \frac{1}{2}\bar{\delta}_{\mathrm{M}10/2} - \frac{1}{2}\bar{\delta}_{\mathrm{M}20} - \bar{\delta}_{\mathrm{M}40}\end{aligned} \tag{13}$$

$$\begin{aligned}\bar{\delta}_{\mathrm{M}80} &= \\ &= \frac{F_{\mathrm{M}10/1} + F_{\mathrm{M}10/2} + F_{\mathrm{M}20} + F_{\mathrm{M}40} - F_{\mathrm{M}80}}{80}\end{aligned} \tag{14}$$

$$\begin{aligned}\bar{\Delta}_{\mathrm{M}80} &= \frac{F_{\mathrm{M}80} - 80}{80} = \\ &= \bar{\delta}_{\mathrm{M}10/1} - \frac{1}{2}\bar{\delta}_{\frac{\mathrm{M}10}{2}} - \frac{1}{2}\bar{\delta}_{\mathrm{M}20} - \frac{1}{2}\bar{\delta}_{\mathrm{M}40} - \\ &- \bar{\delta}_{\mathrm{M}80}\end{aligned} \tag{15}$$

$$\begin{aligned}\bar{\delta}_{\mathrm{M}160/4} &= \frac{F_{\mathrm{M}10/1} + F_{\mathrm{M}10/2} + F_{\mathrm{M}20}}{160} + \\ &+ \frac{F_{\mathrm{M}40} + F_{\mathrm{M}80} - F_{\mathrm{M}160/4}}{160}\end{aligned} \tag{16}$$

$$\begin{aligned}\bar{\Delta}_{\mathrm{M}160/4} &= \frac{F_{\mathrm{M}160/4} - 160}{160} = \\ &= \bar{\delta}_{\mathrm{M}10/1} - \frac{1}{2}\bar{\delta}_{\mathrm{M}10/2} - \frac{1}{2}\bar{\delta}_{\mathrm{M}20} - \frac{1}{2}\bar{\delta}_{\mathrm{M}40} \\ &- \frac{1}{2}\bar{\delta}_{\mathrm{M}80} - \bar{\delta}_{\mathrm{M}160/4}\end{aligned} \tag{17}$$

$$\bar{\delta}_{\mathrm{M}160/1} = \frac{F_{\mathrm{M}160/1} - F_{\mathrm{M}160/4}}{160} \tag{18}$$

$$\begin{aligned}\bar{\Delta}_{\mathrm{M}160/1} &= \frac{F_{\mathrm{M}160/1} - 160}{160} = \\ &= \bar{\delta}_{\mathrm{M}10/1} - \frac{1}{2}\bar{\delta}_{\mathrm{M}10/2} - \frac{1}{2}\bar{\delta}_{\mathrm{M}20} - \frac{1}{2}\bar{\delta}_{\mathrm{M}40} - \\ &- \frac{1}{2}\bar{\delta}_{\mathrm{M}80} - \bar{\delta}_{\mathrm{M}160/4} + \bar{\delta}_{\mathrm{M}160/1}\end{aligned} \tag{19}$$

$$\bar{\delta}_{\mathrm{M}160/2} = \frac{F_{\mathrm{M}160/2} - F_{\mathrm{M}160/4}}{160} \tag{20}$$

$$\begin{aligned}\bar{\Delta}_{\mathrm{M}160/2} &= \frac{F_{\mathrm{M}160/2} - 160}{160} = \\ &= \bar{\delta}_{\mathrm{M}10/1} - \frac{1}{2}\bar{\delta}_{\mathrm{M}10/2} - \frac{1}{2}\bar{\delta}_{\mathrm{M}20} - \frac{1}{2}\bar{\delta}_{\mathrm{M}40} - \\ &- \frac{1}{2}\bar{\delta}_{\mathrm{M}80} - \bar{\delta}_{\mathrm{M}160/4} + \bar{\delta}_{\mathrm{M}160/2}\end{aligned} \tag{21}$$

$$\bar{\delta}_{\mathrm{M}160/3} = \frac{F_{\mathrm{M}160/3} - F_{\mathrm{M}160/4}}{160} \tag{22}$$

$$\begin{aligned}\bar{\Delta}_{\mathrm{M}160/3} &= \frac{F_{\mathrm{M}160/3} - 160}{160} = \\ &= \bar{\delta}_{\mathrm{M}10/1} - \frac{1}{2}\bar{\delta}_{\mathrm{M}10/2} - \frac{1}{2}\bar{\delta}_{\mathrm{M}20} - \frac{1}{2}\bar{\delta}_{\mathrm{M}40} - \\ &- \frac{1}{2}\bar{\delta}_{\mathrm{M}80} - \bar{\delta}_{\mathrm{M}160/4} + \bar{\delta}_{\mathrm{M}160/3}\end{aligned} \tag{23}$$

$$\bar{\delta}_{\mathrm{M}200} = \frac{F_{\mathrm{M}160/4} + F_{\mathrm{M}40} - F_{\mathrm{M}200}}{200} \tag{24}$$

$$\begin{aligned}\bar{\Delta}_{\mathrm{M}200} &= \frac{F_{\mathrm{M}200} - 200}{200} = \\ &= \bar{\delta}_{\mathrm{M}10/1} - \frac{1}{2}\bar{\delta}_{\mathrm{M}10/2} - \frac{1}{2}\bar{\delta}_{\mathrm{M}20} - \frac{3}{5}\bar{\delta}_{\mathrm{M}40} - \\ &- \frac{2}{5}\bar{\delta}_{\mathrm{M}80} - \frac{4}{5}\bar{\delta}_{\mathrm{M}160/4} - \bar{\delta}_{\mathrm{M}200}\end{aligned} \tag{25}$$

5. UNCERTAINTY ASSESSMENT

The uncertainty analysis was carried out according to GUM-JCGM 100:2008 [7]. For each force value, the uncertainty analysis of the total mean relative deviation $\bar{\Delta}$ was carried out in two consecutive steps. In the first, the uncertainty associated to the mean relative deviations $\bar{\delta}$ of the single weight comparisons was assessed, taking into account the maximum uncertainty among the time series of twenty measurements, corresponding to the different weights substitutions used for the evaluation of the relative deviations δ_j, and the reproducibility uncertainty contribution due to the ten measurement runs. In the second, by applying the law of propagation of errors, the expanded uncertainty, at a confidence level of 95 %, of the total mean relative deviations $\bar{\Delta}$ was evaluated.

5.1. Uncertainty of Mean Relative Deviations

First, among the j-th relative deviations δ_j, the one with maximum uncertainty due to repeatability of each force measurement of the three successive time series ($\overline{F_{a,J}}$, $\overline{F_{b,J}}$, $\overline{F_{a,J+1}}$ or $\overline{F_{b,J}}$, $\overline{F_{a,J}}$, $\overline{F_{b,J+1}}$) was evaluated. Once the j-th relative deviation δ_j with the maximum dispersione was identified, the uncertainty contribution due to the resolution of the HBM control unit was added for each force value. No uncertainty was associated to the value $\bar{F}$, since it was used only to calculate the relative difference from absolute measurements. By way of example, the detailed uncertainty budget for δ_j from the comparison between the 10 kN weights (M10/1 and M10/2) is shown in Table 2. Force values are expressed in mV/V.

Table 2: Uncertainty budget of the *j*-th relative deviation δ_j with maximum dispersion from the comparison between the 10 kN weights ($\bar{\delta}_{\mathrm{M10/2}}$)

Variable x_k			$u^2(x_k)$	c_k	$u_k^2(a_x)$
Symbol	**Value**	**Note**			
$\overline{F_{a,J}}$	0.999 494	Res.	1.7E-14	0.5	4.2E-15
		Repeat.	4.9E-14	0.5	1.2E-14
$\overline{F_{b,J}}$	0.999 500	Res.	1.7E-14	1.0	1.7E-14
		Repeat.	1.2E-12	1.0	1.2E-12
$\overline{F_{a,J+1}}$	0.999 499	Res.	1.7E-14	0.5	4.2E-15
		Repeat.	1.6E-13	0.5	3.9E-14
$\bar{F}$	0.999 490	-	-	-	-
$\delta_{a,j}$	-3.33E-06			Variance, $u^2(\delta_{a,j})$	**1.3E-12**
				Standard uncertainty, $u(\delta_{a,j})$	1.1E-06

Subsequently, the evaluation of the expanded uncertainty associated with the mean relative deviation $U(\bar{\delta})$ was performed, as shown in Table 3. The variance of the relative deviation, $u^2(\delta_j)$, obtained from Table 2 (in bold), was used as variance associated with the maximum standard deviation. As uncertainty contribution due to reproducibility, the standard deviation of the ten measurement runs δ_{aj} and δ_{bj} was considered. The expanded uncertainty $U(\bar{\delta})$ of the mean relative deviations was calculated at a confidence level of 95 %, i.e. $k = 2$. For each force value, the same procedure was repeated by assessing reproducibility and maximum standard deviation of the temporal series. Results of each weight comparison are shown in Section 6.

Table 3: Uncertainty budget of the mean relative deviation $\bar{\delta}$ from the comparison between the 10 kN weights

Variable x_k			$u^2(x_k)$	c_k	$u_k^2(a_x)$
Symbol	**Value**	**Note**			
$\bar{\delta}$	-2.49E-06	Reprod.	2.0E-13	1.0	2.0E-13
		Max. st. dev.	1.3E-12	1.0	1.3E-12
$\bar{\delta}$	-2.49E-06			Variance, $u^2(\bar{\delta})$	**1.5E-12**
				Standard uncertainty, $u(\bar{\delta})$	1.2E-06

5.2. Uncertainty of Total Mean Relative Deviations

By applying the law of propagation of errors to Eqs. (6), (9), (11), (13), (15), (17), (19), (21), (23), and (25), using as input the expanded uncertainties associated with the mean relative deviations $U(\bar{\delta})$ evaluated according to Section 5.1, the expanded uncertainties of the total relative deviations $U(\bar{\Delta})$ are obtained. By way of example, the uncertainties for the M10/2, M20, and M40 are reported in equations (26) - (28).

$$U(\bar{\Delta}_{\mathrm{M10/2}}) = \\ = 2\sqrt{\left(\frac{U(\bar{\delta}_{\mathrm{M10/1}})}{2}\right)^2 + \left(\frac{U(\bar{\delta}_{\mathrm{M10/2}})}{2}\right)^2} \tag{26}$$

$$U(\bar{\Delta}_{\mathrm{M20}}) = \\ = 2\sqrt{\left(\frac{U(\bar{\delta}_{\mathrm{M10/1}})}{2}\right)^2 + \left(\frac{1}{2}\right)^2\left(\frac{U(\bar{\delta}_{\mathrm{M10/2}})}{2}\right)^2 + \left(\frac{U(\bar{\delta}_{\mathrm{M20}})}{2}\right)^2} \tag{27}$$

$$U(\bar{\Delta}_{\mathrm{M40}}) = \\ = 2\sqrt{\left(\frac{U(\bar{\delta}_{\mathrm{M10/1}})}{2}\right)^2 + \left(\frac{1}{2}\right)^2\left(\frac{U(\bar{\delta}_{\mathrm{M10/2}})}{2}\right)^2 + \left(\frac{1}{2}\right)^2\left(\frac{U(\bar{\delta}_{\mathrm{M20}})}{2}\right)^2 + \left(\frac{U(\bar{\delta}_{\mathrm{M40}})}{2}\right)^2} \tag{28}$$

6. EXPERIMENTAL RESULTS

6.1. Mean Relative Deviations $\bar{\delta}$

Overall, nine mean relative deviations $\bar{\delta}$, were calculated, each referred to a particular force value (or weight comparison), according to Table 1. Summary of experimental results is shown in Table 4.

Table 4: Mean relative deviations

Weight	F / kN	$\bar{\delta}$ / -	$U(\bar{\delta})$ / -
M10/1	10	0.00E+00	2.82E-06
M10/2	10	-2.49E-06	2.55E-06
M20	20	-1.23E-05	5.38E-06
M40	40	-4.46E-06	6.54E-07
M80	80	8.02E-06	3.92E-06
M160/1	160	-2.13E-06	8.09E-07
M160/2	160	-3.31E-07	3.86E-07
M160/3	160	-3.51E-06	6.15E-07
M160/4	160	-3.19E-06	6.36E-07
M200	200	2.03E-06	2.57E-07

6.2. Total Mean Relative Deviations $\bar{\varDelta}$

Using data of Table 4 and equations (6) - (28), the total mean relative deviations $\bar{\varDelta}$ of all weights are obtained with the associated expanded uncertainties. Results show values lower than the limits declared in CMC, i.e. within an expanded uncertainty of 2×10^{-5}, as reported in Table 5 and in Figure 2.

Table 5: Total mean relative deviations of the weights

Weight	F / kN	$\bar{\varDelta}$ / -	$U(\bar{\varDelta})$ / -
M10/1	10	0.00E+00	2.82E-06
M10/2	10	2.49E-06	3.80E-06
M20	20	1.35E-05	6.21E-06
M40	40	1.18E-05	4.15E-06
M80	80	1.59E-06	5.68E-06
M160/1	160	6.65E-06	4.67E-06
M160/2	160	8.45E-06	4.62E-06
M160/3	160	5.27E-06	4.64E-06
M160/4	160	8.78E-06	4.60E-06
M200	200	7.36E-06	4.44E-06

6.3. Total Relative Deviations $\bar{\varDelta}$ of Typical Weight Combinations Used for the Calibration of Force Transducers

Finally, the total mean relative deviations of different force combinations were assessed. In fact, during ordinary calibration procedures of force transducers, according to UNI EN ISO 376:2011 [8], the 1 MN DFSM adopts predefined series of weights able to generate the required different force values.

For this purpose, the total absolute deviations $\bar{\varDelta}$ of each weight, previously shown, were combined in order to obtain the total relative deviations for each force generated by any combination of weights, with the associated expanded uncertainty calculated using the law of propagation of errors as in equations (26) - (28). Also in this case, results fall within the limits of the declared CMCs [3] as shown in the graph of Figure 3. Furthermore, 500 kN and 1 MN total relative deviations, which are around 7 ppm – 8 ppm, confirm results of Force Key Comparison CCM.F-K3 [9].

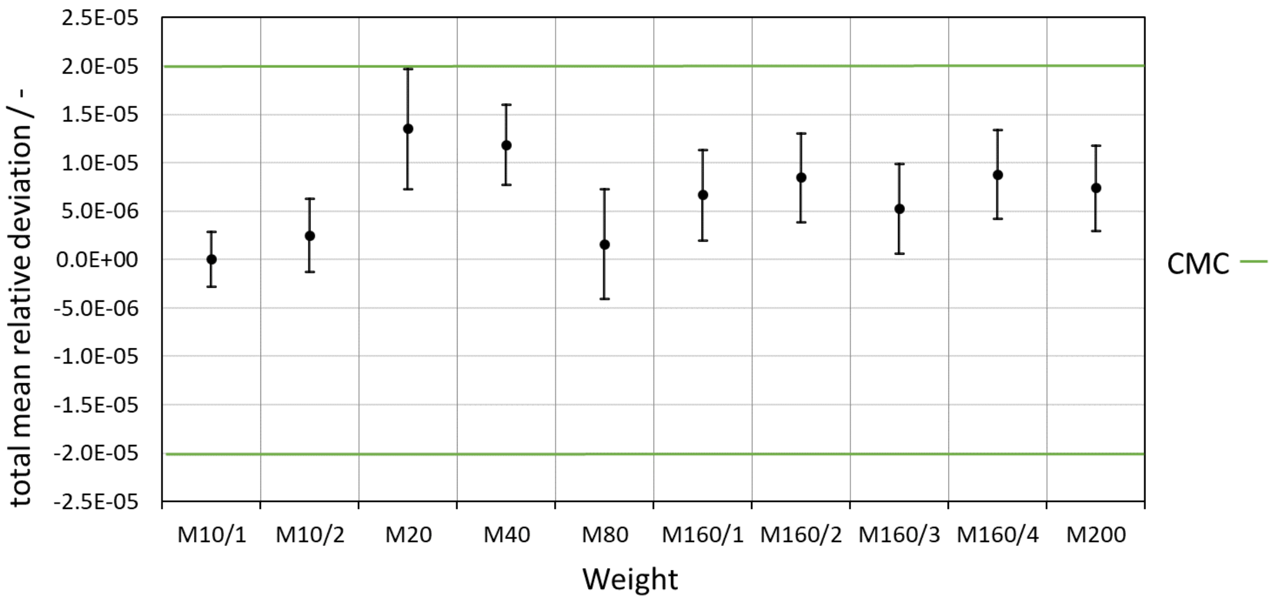

Figure 2: Total mean relative deviations of the 1 MN DFSM weights

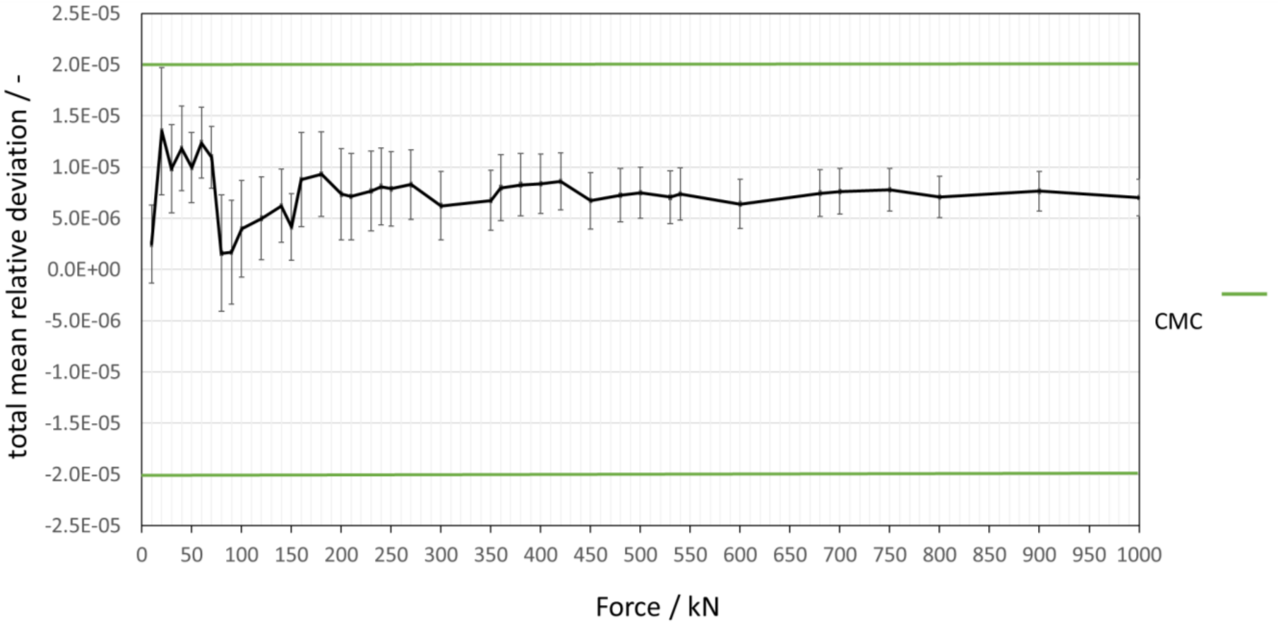

Figure 3: Total mean relative deviations of typical forces generated during ordinary calibration procedures

7. SUMMARY

The verification of the INRiM 1 MN deadweight force standard machine was performed with a self-calibration procedure. The self-calibration method is based on the comparison between two nominally equal forces alternatively generated by a single weight and by an equivalent group of smaller weights. Experimental measurements and the uncertainty budget assessment were performed. Results are within a relative expanded uncertainty of 2×10^{-5}, i.e. within the limits declared in the CMCs. In the future, the possibility to correct these deviations during ordinary calibration procedures will be investigated.

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