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LOW UNCERTAINTY IN FORCE VALUES ACHIEVED IN A LEVER MULTIPLICATION DEADWEIGHT FORCE STANDARD MACHINE OF 1 MN

S K Jain [1], *S S K Titus* [1], *Falk Tegtmeier* [2], *Norbert Tetzlaff* [2] *and Daniel Schwind* [3]

[1] Force and Hardness Standards, National Physical Laboratory, New Delhi - 110012, India
[2] Physikalisch-Technische Bundesanstalt, FB 1.2, Bundesallee 100, 38116 Braunschweig, Germany
[3] GTM Gassmann Testing and Metrology, Philipp-Reis-Str. 6, 64404 Bickenbach, Germany

Abstract: Keeping in mind the need to have lower measurement uncertainties associated with force standard machines (FSM) to calibrate force instruments, the National Physical Laboratory of India (NPL(I)) has recently installed a new 1 MN force standard machine. The force is generated by dead weights up to 100 kN and a lever multiplication of dead weights up to 1000 kN. The machine has certain novel design features, which result in the lowest uncertainties. This paper contains a description of the functional principles and new design aspects of this machine. The uncertainties of measurements are calculated for both the lever and the deadweight side according to the new EURAMET calibration guide. The results of a comparison with the Physikalisch-Technische Bundesanstalt (PTB) are presented here, too.

Keywords: force calibration, comparison, lever amplification, deadweight,

1. INTRODUCTION

Realizing the need to have lower uncertainty associated with FSMs in order to be able to provide traceability in force measurement in compliance with the latest international standards and to have international compatibility of the standards established in different NMIs by demonstrating a degree of equivalence of standards in the CIPM key comparison of force, the National Physical Laboratory, India, recently took an initiative to establish a deadweight cum lever amplification FSM in the range of the lowest international uncertainties.

2. DESCRIPTION

The main principle and a detailed description of the machine are also given in [2, 3, 4]. Many optimized or new design features have been incorporated in the machine. These include:

1) A machine frame with different supporting beams for the deadweight side and the lever side respectively, for higher stiffness.

2) Further developed mass disks to avoid asymmetric distortions, to reduce the risk of mass contacts, to improve the smooth asymptotic load change and to reduce side-ways motion.

3) A lever designed for higher stiffness and higher stability of the lever ratio, which is covered an enclosure to reduce ambient influences (Fig. 1).

4) The mass stack comprising 26 mass disks of various denominations, adjusted to the local ‘g’ value and air density with a relative uncertainty of $5 \cdot 10^{-6}$ (k=2), so that all the forces in the ranges given in Table 1 can be applied sequentially.

5) A four column hanger made of an aluminium and steel combination to realize a low lying balance point and to allow a temperature chamber installation.

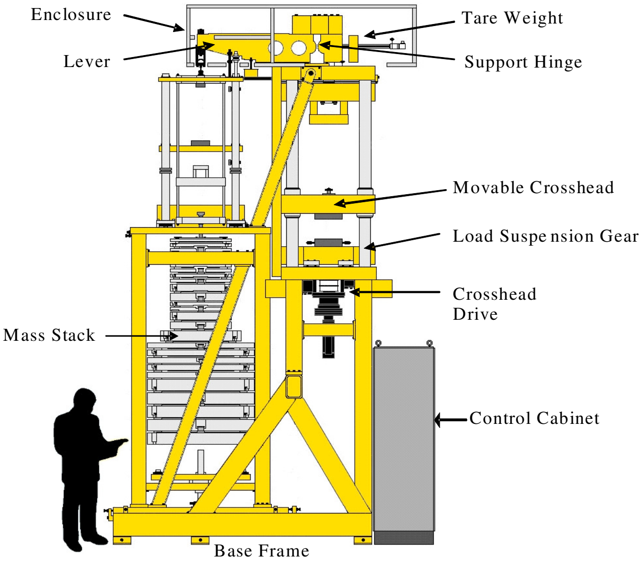

Fig. 1: Schematic view of the 1 MN FSM at NPL(I)

Machine Part	Deadweight	Lever
Measuring Ranges	1-10 kN 2-20 kN 5-50 kN 10-100 kN	10-100 kN 20-200 kN 50-500 kN 100-1000 kN

Table 1: Measuring ranges of the FSM

Using the deadweight side while the transducer to be calibrated is not loaded, the load frame hangs via a coupling on the lever. The transducer is loaded by lifting the ´deadweights´ crosshead together with the transducer towards the load frame, until the load frame is decoupled from the lever. When using the lever side, in the unloaded condition the load frame rests on a dummy on the deadweight crosshead with no contact to the lever. If the transducer should be charged, the crosshead moves down connecting the load frame to the lever.

To compensate an elongation of the load frame, the position of the crosshead is automatically adjusted by a three-step control while using the deadweight part.

Fig. 2: A view of the 1 MN FSM installed at NPL(I

The force machine operates using a PC through the ‘GTM Force Manager’, software which permits easy and clearly arranged operation of the machine through input screens with menu navigation. The entire operation of the machine is handled exclusively with this PC. The complete recording and archiving of measurement data is also carried out via the software, including optional entry for drivers for reading the force transducer output directly from different amplifiers. The software has the option to activate all commands manually and transfer the measured values by hand. The measured value files are stored in standardized format in ASCII so that they can be imported easily into subsequent application programs.

4. UNCERTAINTY OF REALIZATION OF FORCE

The force generated in the 100 kN deadweight side of the force standard machine can be described in a simplified way by the following model

$$F = m \cdot g_{loc} \cdot (1 - \frac{\rho_L}{\rho_m}) \cdot \prod_{i=1}^{2} (1 - \Delta_i) \qquad (1)$$

with the following quantities:

m	mass of deadweights
g_{loc}	local gravity at the position of deadweight
ρ_m	density of the deadweights
ρ_L	density of air
Δ_1	relative deviation due to other effects like force introduction
Δ_2	relative deviation due to magnetic forces

For uncorrelated input quantities the standard measurement uncertainty u(F) of the force F is given by the law of error propagation. According to the model, the relative standard uncertainty w(F)=u(F)/F of the force generated by deadweights can be calculated as follows:

$$w(F) = \sqrt{\begin{array}{c} w^2(m) + w^2(g_{loc}) + \left(-\frac{\rho_L}{\rho_m}\right)^2 w^2(\rho_L) \\ + \left(\frac{\rho_L}{\rho_m}\right)^2 w^2(\rho_m) + \sum_{i=1}^{2} w^2(\Delta_i) \end{array}} \qquad (2)$$

This model takes not only the gravitational force into account. There are also other effects - e.g. magnetic influences and effects of the interaction of the transducer with the force standard machine.

The machine was designed to have no relevant magnetic effects on the generation of the force. All mass plates were made of refined, nonmagnetic steel. The load frame was also made of refined steel and some parts were made of aluminium. In several tests with some high precision PTB standards, it was checked whether the signal change of the transducer between the load steps is exactly the same as predicted by the knowledge of the masses, the local gravity and the sensitivity of the transducer. No relevant deviations were determined. For that reason, the magnetic effects can be neglected as they are not relevant in this machine for an uncertainty of $2 \cdot 10^{-5}$ (k = 2).

Also all other listed possible contributions of section 4.1 of [1] are negligible due to the construction outline of the machine. Aerodynamic effects are strongly avoided by a complete housing of the mass stack system and the balance of the machine.

In the experience of NPL India and PTB, the uncertainty caused by the interaction between the machine and the transducer must be considered in the uncertainty model for a primary standard with lowest uncertainties of $2 \cdot 10^{-5}$ (k = 2). Eccentrics, the smallest deviations in the alignment of the pressure plates, quality and hardness of their surface, elastic deformations in parts of the machine, etc. can all differ and have an effect on the transducer. However, the influence of these effects on the transducer also strongly depend on and are caused by the quality of construction and production of the transducer. This interaction can be discussed considerably. But how can this uncertainty contribution be defined? If the transducer is of bad quality, it will be seen in the linearity, repeatability and hysteresis. For example, if a transducer of the lowest quality shows a very strong influence to sideways forces and the machine has an above average alignment – what part should be charged for the higher rotational effect to be seen in the calibration? According the EURAMET calibration guide [1] characteristics like compression plate stiffness and side force generation do not contribute to the uncertainty of force along the transducers axis, even in cases when the transducer output is affected. On the other hand the exact alignment of the transducer and the depending uncertainty components must be taken into account - but how can this be divided in this lowest range of uncertainty? Finally, these influences of the machine should be measured with several state-of-the-art transfer standards and should be checked with different types of transducers. The comparison and the pre-tests were done with several transducers of GTM, HBM and ASMW used for the comparison with PTB and some additional comparisons between NPL India and GTM´s DAkkS accredited laboratory. With the approach, that the gap in the overlapping force areas of a comparison is the result of the interaction between machine and transducer, this effect can be estimated. Keeping in mind that this gap is also caused by other effects, this is a very safe estimation. During all the measurements, the gap was typically in the range with a half width lower than $2 \cdot 10^{-6}$. In one single case, it was $1 \cdot 10^{-5}$. For that reason, this interaction can safely awarded this uncertainty. Another safe assumtion is the usage of a rectangular distribution due to the fact that this distribution is surely more triangular according to the long time experience at PTB.

The machine has the advantage of a very low first load step of 1% of its nominal load. This first load step is realized by the load frame of the machine. To enable such a low value, it was necessary to use aluminium in some parts instead of steel. In so doing, the density of the first load step is lower than the density under full load. This has to be taken into account for the uncertainty model as the density is lower and the influence in the uncertainty model stronger. In addition it has to be taken into account, that the measurement uncertainty for the mass of the first step – the frame – is a little different to that for other masses.
Finally, the uncertainty of the machine can be calculated as in table 2 below:

quantity	estimate	relative half width	distribution	divisor	relative standard uncertainty	sensitivity coefficient	relative uncertainty contribution
m	102.147 kg		Gaussian		2.51E-06	1	2.51E-06
g	9.79125 m/s²	5.00E-07	rectangular	√3	2.89E-07	1	2.89E-07
ρ_a	1.15 kg/m³	1.50E-03	rectangular	√3	8.66E-04	1.84E-04	1.59E-07
ρ_m	6255.0 kg/m³		Gaussian		1.12E-02	1.84E-04	2.06E-06
Δ_1	100 kN	1.00E-05	rectangular	√3	5.77E-06	1	5.77E-06
				Rel. Uncertainty:			6.6E-06
				Expanded relative Uncertainty			**1.3E-05**

Table 2: Uncertainty of 1 kN on the deadweight side

The estimation of the uncertainty contributions for the lever amplification forces are calculated according to the new EURAMET Calibration Guide [4]. Section 4.3 in the Guide describes the uncertainties. In addition, a contribution of the response sensitivity was included, which is not mentioned in the guide, but must be taken into account since all mechanical lever systems show a response behaviour. The complete model is discussed in [3]. In this article, only a short discussion of the single contributions according to the EURAMET guide is added. Page 5 of the EURAMET calibration guide [1] presents a list of the contributions to be observed. They are discussed in the following. The values of these contributions are presented in table 3, which represents the highest uncertainty for the leaver side as it is the smallest force step on that side.

Lever ratio w_{DW} w_L: The lever ratio is determined by a comparison of the 100 kN force value first measured on the deadweight side and secondly on the lever side. The uncertainty contribution is based on the measurements of the 100 kN force value in four mounting positions with two series in each mounting position and including an uncertainty contribution of the amplifier. As the knowledge of the exact amplification factor is gained by these two measurements, both uncertainty components w_{DW} and w_L were added in the model to describe the uncertainties in the knowledge about the lever dimensions.

Here the “lever ratio” is assumed to be constant, however, a variable part must also be assumed and is included in the “distortion of lever system” contribution.

Distortion of lever system w_{Dis}: The distortion of the lever system is compensated by the evaluation and sensitivity adjustment of the measured bending moments. An uncertainty contribution is estimated based on the comparison measurements of PTB and contains the overall uncertainties of the measurements. A residual distortion effect hereby will be covered by E_n criterion.

Instability of control system w_{Inst}: The instability of the control system was determined by the measurement of a transducer output over a period of ten minutes at 100 kN and the deviations of the control system appeared cumulatively in the middle of the distribution, so that a triangular distribution is assumed according to the GUM [5], chapter F.2.3.3.

Alignment w_{Ecc}: An eccentricity contribution of the imprecise adjustment of the transducers was estimated by eccentricity measurements of a force transfer standard at 100 kN. The contribution is always less than 10^{-5} / mm. Due to the fact that the transducers are easy to adjust to a fraction of one millimetre, the half width is amply dimensioned, so that also here a triangular distribution is assumed.

Response sensitivity of lever system w_{Sens}: The response sensitivity of the lever was determined by adding during the measurement small masses to the lever part and is about 0.3 N.

Due to the construction of the machine, **other Influences** named in [1] must not taken to account. The strain controlled elastic hinge system is wear-free and no contribution has to be considered. The strain controlled elastic hinge-system works without any friction, so no contribution comes from this point. A temperature effect has also to be taken into account for a lever machine because it could result in influences on the amplification factor. Due to the fact that the lever components of NPL´s 1 MN FSM are made of steel with the same thermal expansion coefficient, a change of the ambient temperature will affect both lever arm sides and the lever ratio will remain constant and hence, also here, no contribution has to be considered.

In the EURAMET Calibration Guide [1], the reproducibility of moveable parts is also named as a contribution for the combined uncertainty. The lever system incorporates a tare system as the only moveable part. The single use of the tare system is to balance the weight of the devices under test in unloaded condition. After loading, no moveable parts are able to act on the force and no contribution has to be considered. The strain controlled elastic hinge system is wear-free and, thus, also here no contribution has to be considered.

quantity	estimate	relative half width	distribution	divisor	relative standard uncertainty	sensitivity coefficient	relative uncertainty contribution
m	102.14678 kg		Gaussian		2.51E-06	1	2.51E-06
g	9.79125 m/s²	5.00E-07	rectangular	v3	2.89E-07	1	2.89E-07
π_a	1.15 kg/m³	1.50E-03	rectangular	v3	8.66E-04	1.84E-04	1.59E-07
π_m	6255 kg/m³		Gaussian		1.12E-02	1.84E-04	2.06E-06
$w\pi_{DW}$	100 kN		Gaussian		1.10E-05	1	1.10E-05
$w\pi_{L}$	100 kN		Gaussian		1.20E-05	1	1.20E-05
$w\pi_{Dis}$	0 kN	5.00E-05	rectangular	v3	2.89E-05	1	2.89E-05
w_{Inst}	0 kN	1.00E-05	triangle	v6	4.08E-06	1	4.08E-06
$w\pi_{Ecc}$	0 kN	1.00E-05	triangle	v6	4.08E-06	1	4.08E-06
$w\pi_{Sens}$	0 kN	1.50E-05	rectangular	v3	8.66E-06	1	8.66E-06
				Rel. Uncertainty:			3.5E-05
				Expanded relative Uncertaint			**7.0E-05**

Table 3: Uncertainty of 10 kN on the deadweight side

4. MEASUREMENTS AND RESULTS

The repeatability of the force transducers in the machine was observed to be within ± 0.002% on the dead weight side and within ± 0.0035% on the lever side. The hysteresis due to the machine was practically within ± 0.001% over the full range i.e. 1 to 1000 kN (see Fig. 3).

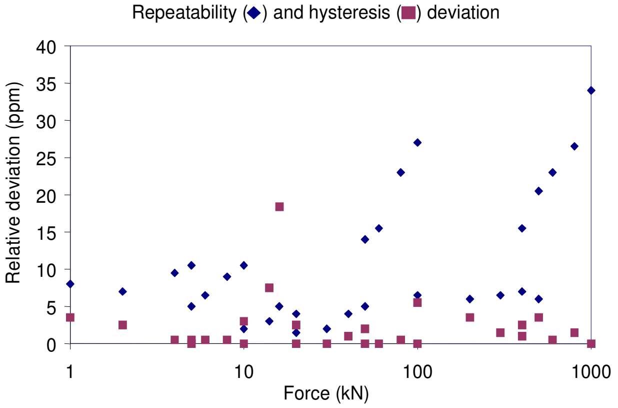

Fig. 3: Repeatability and hysteresis during the comparison

In order to establish the CMC of the force standard machine, comparison measurements were undertaken between this machine and the force standard machines at PTB, Germany using transfer standards calibrated at PTB. A number of transfer standards of different capacities were calibrated from 40% to their full scale in order to cover the complete range of the force standard machine. The measurements were taken at various force steps at four rotational positions. The combined uncertainty of measurements was evaluated taking into account the drift of the transducers. The relative deviation of the average values of the indicator output between NPL and PTB measurements was found to be within the claimed expanded uncertainty of the NPL machine as ±0.002% and ±0.009% on the deadweight side and the lever multiplication side, respectively.

The overall normalized error of the inter-comparison was found to be much less than unity.

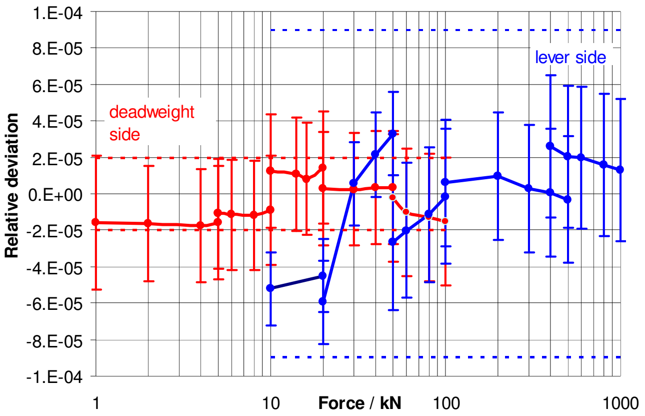

Fig. 4: Deviations between NPL-India and PTB during the comparison

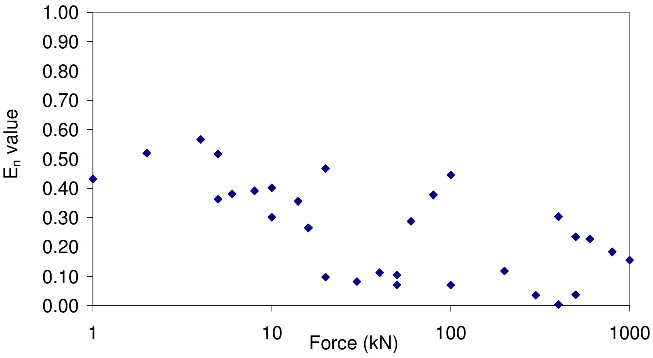

Fig. 5: E_n values of the comparison

5. CONCLUSIONS

A new one MN force standard having lower associated uncertainty than NPL´s former machine of that range has been established at the National Physical Laboratory, New Delhi. The new standard would enable NPL(I) to provide traceability for the calibration of class ‘00’ force instruments as per the latest international standards. The CMC of the standard has shown a compatibility with that of PTB. It is expected that the machine would show very good agreement with the key comparison reference values of the ongoing APMP key comparisons for 50 kN, 100 kN, (pilot laboratory KRISS, Korea) 500 kN and 1000 kN forces (pilot laboratory NIM, China).

5. REFERENCES

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