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Operation of a New Force Standard Machine at Hellenic Institute of Metrology

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Abstract

The following paper gives a detailed overview of the characteristics of the new state-of-the-art force standard machine commissioned in July/August 2000 at site of the Hellenic Institute of Metrology by the manufacturing company GTM. The fully automated force standard facility is a combined dead weight - lever amplification machine with 110 kN direct load capacity and a 10:1 lever multiplication part and is to be the National Force Standard of Greece. The 110 kN dead weight section is equipped with a mass stack of nickel-plated steel weights realising discrete forces in compression and tension mode. The forces are applied in 10 % steps up to 110 % of usual nominal loads of transducers starting with 1 kN. Comparison measurements were carried out with five precision force transfer standards with capacities of 10 kN, 50 kN, 100 kN, 500 kN and 1 MN, all of which were initially calibrated at PTB. Effects of parasitic components on the lever system were submitted to a careful examination. The results of tests to determine the performance of the force standard machine are discussed in detail.

1. Introduction

Force measurements are used to determine masses, to measure mechanical properties of materials, in safety engineering systems etc. In order to assure reliable calibrations of force measuring devices a fundamental requirement is the realisation of a force scale by means of force standard machines (FSM's). Usually the national metrology institutes responsible for the traceability of the SI units in every country have one or more of such FSM's at proper sites installed. It is well known that FSM's operating with dead weights in the earth's gravitational field (the so called direct load machines) are the most accurate way to generate forces because the realisation is traceable to the base units of mass, length and time. The best measurement uncertainty achieved by this method is near the uncertainty of the mass and gravity determination (about 5 ppm), and exceeds 20 ppm for the actual force value. On the other hand cost limitations for high capacity machines lead to technical solutions using force amplification of the direct loading by hydraulic or by mechanical lever systems [1]. The best measurement uncertainties reached with hydraulic amplification are in the range from 100 ppm up to 500 ppm, and 50 ppm up to 200 ppm for lever systems.

With respect to needs of the Greek industry and economy the commissioning and installation of a new 110 kN / 1,1 MN combined dead weight / mechanical lever FSM at the new Hellenic Institute of Metrology (EIM) was decided. The FSM of EIM was designed and constructed by the German company Gassmann Theiss Messtechnik GmbH (GTM) and it is the third machine of this type and nominal load worldwide.

In order to characterise the metrological behaviour of the 110 kN / 1,1 MN FSM several series of measurements were carried out to give information about the repeatability and the linearity of the machine as well as about the comparability between the direct loading part and the lever transmission part. The measurements were undertaken using force transfer standards, which were initially calibrated at PTB.

A systematic investigation of the influence of parasitic forces onto the lever amplification system based on strain controlled elastic hinges is outlined whereby the results are discussed in terms of error estimations.

2. The 110 kN / 1,1 MN Force Standard Machine

and the lever amplification part, which are constructed on one common machine frame. Figure 1 shows a schematic drawing of the FSM.

The deadweight part uses discrete mass disks for each force value, and comprises the following force ranges (each from 10 % to 110 %): 10 kN, 20 kN, 50 kN, 100 kN. All masses are made from nickel-plated mild steel.

The functionality and the advantages of this type of lever machines are described in detail elsewhere [1,2,3]. The construction of the lever system is strictly based on the theory of the lever principle: The lever is in equilibrium when the moment of force (of masses) is equal to the moment of load.

$$\sum M = 0 = M_{mass} - M_{load} \qquad (1)$$

$$F_{mass} \cdot l_1 = F_{load} \cdot l_2 \qquad (2)$$

For high accuracy, no additional moments beside the moment of force and the moment of load are allowed to act on the lever. To guaranty the equilibrated state of the lever of the FSM, the lever bearings with their strain controlled hinges measure all additional moments at these points where forces are acting. The sum of these moments is permanently controlled to zero by moving up or down the moveable crosshead while measuring forces.

3. Influences of Parasitic Moments on the Lever System

The lever system is affected by disturbing (parasitic) moments that are caused by:

- eccentric coupling of the masses to the lever (M_a in Figure 1)

- eccentric mounting of the test transducer (M_b in Figure 1)

Eccentric mass coupling and transducer mounting are errors of a random type, linked to tolerances of manufacturing and measurement, as well as to chance. For an evaluation of the repeatability, the determination of these influences is therefore of particular importance.

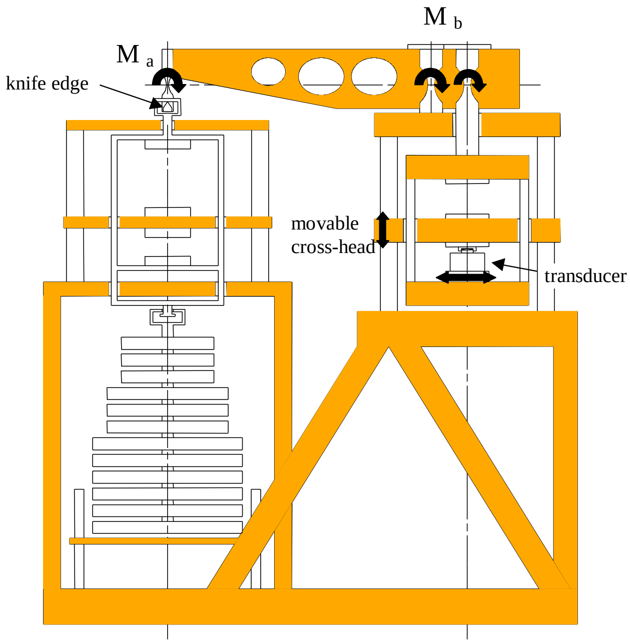

Figure 1: Lever system with disturbing moments

3.1. The Moment Influence of Mass Coupling

The weight force of the masses and of the load frame acts onto the corresponding strain controlled elastic hinge through a coupling system having a knife edge and plane bearing. Since the knife edge has a tip radius, the force introduction line of the bearing is not clearly defined, and thereby disturbing moments can be applied to the lever. In order to determine the influence of these disturbing moments, a force transfer standard (FTS 100 kN) is mounted and loaded in the amplification side of the machine. If now an arbitrary additional mass is added centrally in relation to the elastic hinge axis, the output signal of the transfer standard will change by a certain amount. However, exactly the same amount of change is expected to happen with an eccentrically applied mass, as long as the system is adjusted such that disturbing moments do not produce net force variations, in other words as long as the adjustment renders the lever system insensitive to parasitic moments.

Table 1. Moment influences of eccentric mass application, measured with FTS 100 kN

Additional mass (10 kg) centrally	Additional mass (10 kg) eccentric (135 mm)
0,01965 mV/V	0,01964 mV/V

From this, the maximum error caused by a bending moment at the mass hinge can be calculated, taking into account the maximum knife edge width of b/2 = 0,2 mm as maximum eccentricity:

$$\frac{\Delta F}{F} = \frac{0{,}00001\, mV/V}{0{,}01965\, mV/V} \cdot \frac{\pm 0{,}2\, mm}{135\, mm} = \pm 0{,}8\ ppm \qquad (3)$$

The result of this test shows two important results: Firstly, the system is highly insensitive to applied disturbing moments. Secondly, the multiplication ratio can be expected to be still correct even with quite significant elastic deformations of the joints. With other words: Even if there is a visible deflection of the elastic hinges, the multiplication ratio will be the same.

It is the fact that the applied disturbing moments are measured, and thereby compensated for by the control system, which makes all the difference here: If a pure knife-edge and plane coupling were to be used, the effective lever arm changes under the same conditions would produce the following ± 0,2 mm at 1260 mm lever length, i. e. ±160 ppm error! This simple consideration explains clearly why the strain controlled hinges are absolutely essential for the correct functioning of the FSM, and why its performance and characteristic are quite different from conventional lever systems.

3.2. Moment Influences Caused by Effects on the Amplified Side

Central mounting of force transducers in FSM's is usually achieved as follows: In compression, the transducer is either located by an auxiliary device, or simply set centrally with the aid of a vernier calliper or depth gauge. Tension mounts are often «self-centring», i. e. relying on their mounting components and the machine receptacles for the definition of the force axis. It is assumed here in this context that in normal circumstances an eccentricity of less than ± 0,3 mm can be achieved. Such an eccentricity would then naturally cause an additional moment to the lever system of the FSM. This consideration suggests evaluating the influence of such parasitic moments by deliberately mounting a force transfer standard by a definite amount:

Table 2. Moment influences caused by eccentric load axis, measured with FTS 100 kN

Span, centrally mounted	Span, eccentric (10 mm, along lever axis)	Span, eccentric (10 mm, perpendicular to lever axis
2,00230 mV/V	2,00233 mV/V	2,00224 mV/V

Relative to the maximum eccentricity as stated above, the maximum error due to this follows as:

$$\frac{\Delta F}{F} = \frac{(2{,}00224 - 2{,}00230)\ mV/V}{2{,}00230\ mV/V} \cdot \frac{\pm 0{,}3\ mm}{10\ mm} = \pm 0{,}9\ ppm \qquad (4)$$

Again, the importance and success of the lever system design is clearly demonstrated. The measurement of the moment effects, in conjunction with the control system allows the almost complete compensation of alignment errors.

3.3. Influence of Creep Effects

Regarding the lever control system with its strain controlled elastic hinges as a transducer for bending moments, creep effects should be discussed. The definition of creep means: A change of measured values with time, at constant load. In principle there are two kinds of loading on the strain-gauged hinges: Firstly, there are bending moments for some seconds while the load is changing and the control system is smoothly working to reach zero bending moment. Because the time is very short and the maximum of bending moments is limited by mechanical stops to a very small amount, the creep effect in this case is negligible. To be sure in this point, the lever of the FSM was inclined by an additional weight at the end of the lever, while the regulation system was inactive. This test is very severe because of the long time of inclination, but the measured values of the elastic hinges were absolutely constant.

Secondly, there is a theoretical influence caused by the high axial force. But the strain gauge application of the elastic hinges is insensitive to axial forces, it is optimised for bending moments and only the amount of cross talk is disturbing. The cross-talk for the elastic hinges can be assumed as less than 0,5 % and the creep of the strain gauges as less than 0,05 %, so the influence of this kind of creep is in multiplication less than 2,5 ppm. Obviously creep affects the system in a negligible way.

4. Performance Measurement Procedures

The characterisation of FSM's as well as the inter-comparison of these systems is usually undertaken with high accuracy strain gauge force transfer standards. In every case the measurement signal reflects the interaction between the FSM with the strain gauge force transducer under load.

To characterise the metrological behaviour of the EIM FSM different force transducers were measured following the procedure of the EN 10002 - 3 standard [4] in compression mode. All force transducers were of the bending ring type [5], manufactured by GTM and initially calibrated at PTB. The calibrations of the force transducers were carried out against a 20 kN, a 100 kN, and a 1 MN direct load FSM of the PTB at 21,4 °C using the same measuring sequence. The force transducers with nominal loads of 10 kN, 50 kN, 100 kN, 500 kN and 1 MN are used in combination with a HBM DK 38 as amplifier / indication unit.

All measurements were carried out at ambient conditions, 21,4 ± 0,2 °C in order to adjust comparable environmental conditions as given through the initial calibration at PTB.

First, to investigate the linearity and the repeatability of the EIM FSM, measurements were undertaken with the 10 kN, 50 kN and 100 kN at the direct loading part and with the 100 kN, 500 kN and 1 MN force transducers at the lever loading part. All measurement procedures with respect to the EN 10002-3 standard were repeated at least three times for every force transducer at different dates starting in January 2001 over a period of four months. On the other hand the comparison of both parts, i. e. the direct loading part with the lever part can be achieved only in the range from 10 kN up to 100 kN. For this purpose the force transducers with nominal loads of 10 kN, 50 kN and 100 kN were used with a modified EN 10002-3 procedure where the 10 kN transducer is measured at the maximum load only, the 50 kN transducer at 20%, 40%, 60%, 80% and 100% of the nominal load and the 100 kN transducer is measured beginning at 10 kN in 10% steps up to 100 kN. The modification concerned only the number of measuring steps with respect to the loading ranges of each force transducer.

5. Measurement Results and Discussion

Because all the above mentioned five force transfer standards were calibrated at PTB with the procedure according to the EN standard before their use in the EIM FSM, all measurement results are presented as a relative deviation (RD) expressed in parts per million as described by formula (5):

$$RD = \frac{X_{EIM} - X_{PTB}}{X_{PTB}} \quad (5)$$

where X_{PTB} symbolises the measurement series obtained from the PTB and X_{EIM} means the series measured at EIM. The values for X_{PTB} and X_{EIM} are the average values of three different angular positions of the force transducer within the machine frame at each load step. Figure 2 shows the values of RD obtained from the measurement series of the direct loading part for each force step realised. Each RD value is an average of three measurement series undertaken at three different time periods using the 10 kN, the 50 kN and the 100 kN force transducer. The bars at each point symbolise the standard deviation of the results of the direct loading part.

It can be estimated that the relative deviation of the direct loading part with respect to the calibration data of the PTB is in the order of ± 20 ppm and the repeatability of the interaction between the transfer standards and the FSM up to 100 kN is in the same order.

In figure 3. the RD values calculated from the results of the lever transmission part are plotted versus the loading force. Each of the curves corresponds to the respective force transducer used.

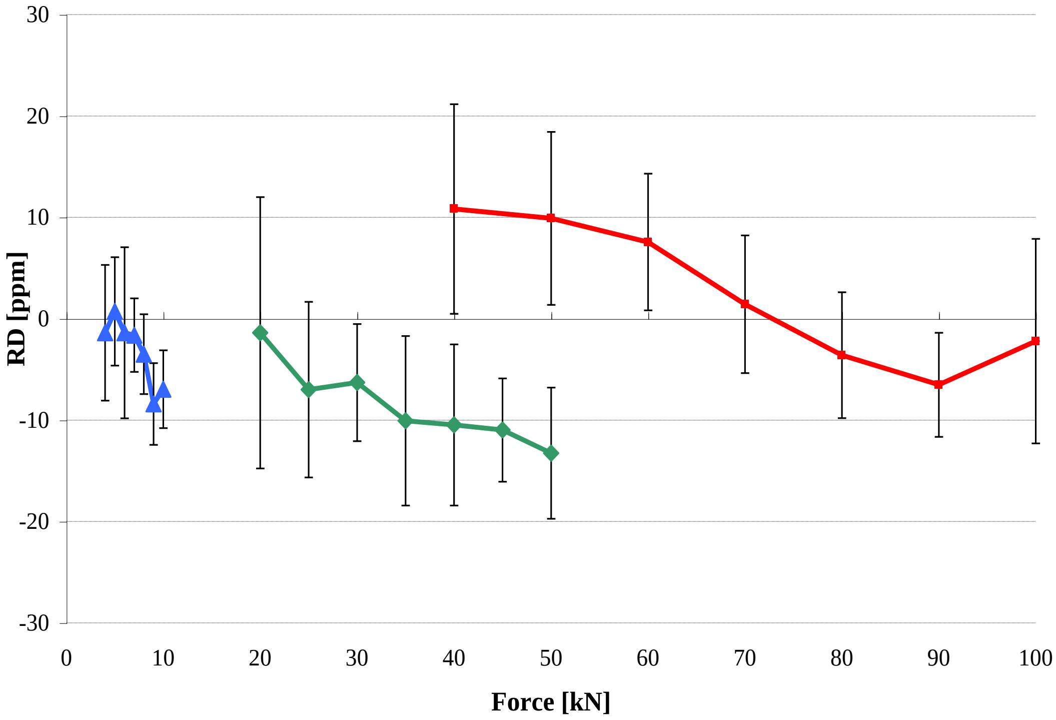

Figure 2. Graphic representation of measuring results obtained from the 110 kN direct loading part at three different days using a 10 kN, a 50 kN and a 100 kN transfer standard force transducer.

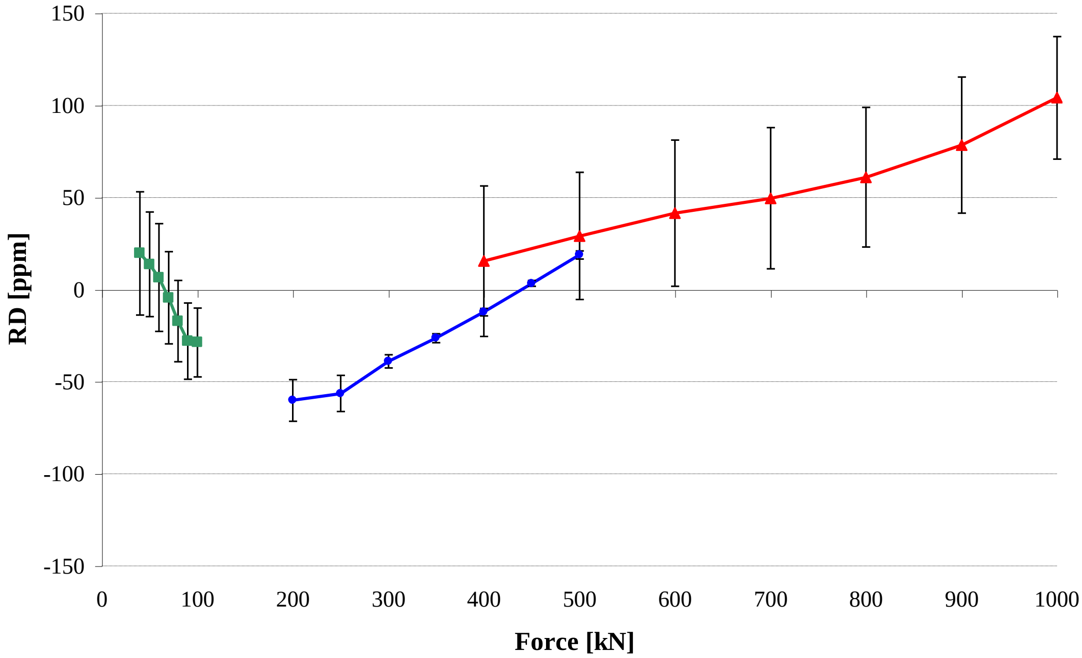

Figure 3. Graphic representation of measuring results obtained from the 1,1 MN lever amplification part at three different days using a 100 kN, a 500 kN and a 1 MN transfer standard force transducer.

The bars on the RD values reflect the repeatability of the measurements in the same manner as for the direct loading part. In the case of the lever transmission part one observes agreement with the PTB results within 100 ppm approximately. The respective repeatability of the measurements is in the order of about 70 ppm for the 100 kN and 1 MN force transducers. The measuring behaviour of the series obtained with the 500 kN force transducer is much more reproducible. Thus it may be concluded that the reproducibility of the results is mainly affected by the behaviour of each force transducer and its individual interaction with the FSM.

The random character of the curves with respect to the zero line in figure 2 and 3 suggest that the relative deviations are probably not affected by systematic misalignments of the EIM FSM. The significantly higher random deviations obtained from the lever transmission part are probably due to an imperfect force transmission by means of the lever system. This fact is emphasised additionally by a slightly higher spread of the 100 kN force transducer measured at the lever loading part.

The comparison of the direct loading part with the lever transmission part up to 100 kN is illustrated in figure 4.

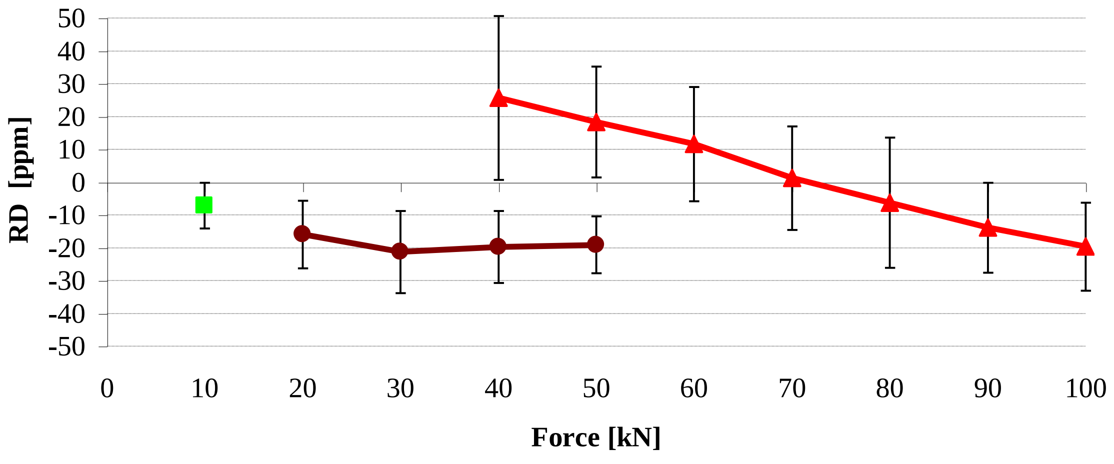

Figure 4. Graphic representation of the relative deviation between the direct loading part and lever amplification part using a 10 kN, a 50 kN and a 100 kN transfer standard force transducer up to 100kN.

Measurements were carried out at one load step with the 10 kN, at five load steps with the 50 kN and at 10 load steps with the 100 kN force transducer. The relative deviation values are calculated according to

$$RD = \frac{X_L - X_D}{X_D} \quad (6)$$

where X_L means the average of the measurement signals obtained at the lever transmission part and X_D is the average value of the signals obtained at the direct loading part of the machine.

The results in figure 4 show an agreement of the lever part with respect to the direct loading part less than ± 30 ppm. The random character of the results indicate that at least up to 100 kN the consistency of the force amplification ratio realised by the lever transmission is at a satisfactory level and it is not expected to change furthermore at higher forces.

6. Conclusion

The National Institute of Greece EIM in conjunction with GTM GmbH has concluded a project which covered the installation, commissioning and evaluation of a 110 kN / 1 MN FSM. From the work carried out and the measuring results taken, it follows that the range and uncertainties of the machine can be stated as 1 kN to 110 kN (deadweight part), having a measuring uncertainty for the force generation of less than 20 ppm, and 10 kN to 1100 kN (lever part), with a measuring uncertainty for the force generation of less than 100 ppm.

Comprehensive further tests carried out gained a high level of confidence in the machines operation, with particular respect to alignment tolerances and the very small measurement errors caused by it.

Thereby equipped with state of the art technology and equipment, the EIM of Greece looks forward to taking an active part in the community of force laboratories around the world.

7. References

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