SHORT AND LONG-TERM BEHAVIOUR OF A 55 kN / 2.2 MN LEVER DEADWEIGHT FORCE STANDARD MACHINE

Chi Kah Lim [1], Bernd Glöckner [2], Thomas Allgeier [3]

[1] SPRING Singapore [2] PTB Germany [3] GTM GmbH Germany

ABSTRACT

This paper describes the latest results from the re-verification of a 55 kN / 2.2 MN lever deadweight force standard machine at SPRING Singapore. For the first time, a lever machine was successfully compared against deadweight machines (from PTB) at the high level of 2 MN in both tension and compression with an uncertainty in the 1E-4 range. Similarly, the same applies to the 55 kN machine with an uncertainty of ±2E-5. For the 55 kN machine, both short-term and long-term uncertainty has been established. The machine had been the subject of an earlier comparison measurement with the PTB in the compression range. In addition, the periodic maintenance results of this 55 kN / 2.2 MN lever deadweight force standard machine will also be discussed. To monitor the drift and stability of the force realised, a total of 5 SPRING FTS were measured according to fixed protocols over time. The lever amplification ratio was also checked at intervals using a 50 kN FTS. From an earlier maintenance check, it was discovered that there was a significant drift in the lever ratio in March 2003 (12 months after commissioning). However, the deadweight forces continued to be realised within the ±2E-5 uncertainty. The lever ratio has since been adjusted back to producing loads which are magnified exactly 40 times from deadweight forces, demonstrating that it is capable of achieving ±1E-4 short term uncertainty. This was confirmed by the comparison with PTB up to 2 MN in both loading directions. Subsequent measurements demonstrated that the lever ratio has been stable. The same is also true for load reproducibility and repeatability at both the deadweight and lever machine, indicating that the long-term uncertainty is now satisfactory as well.

1. INTRODUCTION

The 55 kN / 2.2 MN lever deadweight force standard machine at SPRING was the subject of an initial comparison with the PTB [1]. This covered only the range of compression forces. The performance of the machine, particularly its short and long-term behaviour and the tension range was examined during its subsequent re-verifications: Comparison measurements with the force scale of the PTB were carried out in both the tension and compression range for 50 kN, 1 MN and 2 MN. Measurements were also undertaken to compare the 500 kN and 1 MN compression range at the lever-amplified side of the machine. For the comparison measurements, mainly Force Transfer Standards (FTS) owned by PTB were used. The exercise marks the rare case of a comparison in the 1 MN and 2 MN tension range for lever-amplified force standard machines. The compression and tension comparison covers the range of 20 kN to 50 kN for the deadweight machine, and from 200 kN to 2 MN for the lever-amplified machine. In addition, compression comparison at the lever-amplified machine was also done for the range of 100 kN to 500 kN and from 200 kN to 1 MN.

2. EXAMINATION OF LONG-TERM BEHAVIOUR (COMPRESSION FORCES)

The following measurement concept aims on the one hand at investigating the force transducers used as transfer standards, and on the other to verify the stability of the principle used for force amplification. The time frame considered here amounts to up to 37 months, depending on the transducer under investigation, and begins with the commissioning of the Force Standard Machine in July 2001. The investigation is planned to continue until further notice.

2.1 FORCE TRANSDUCERS

In the period from July 2001 until August 2004 five compression force transducers with capacities of 1 kN, 25 kN (20 kN range), 50 kN, 500 kN and 2 MN were monitored with respect to their sensitivity and zero drift, readings being taken at various intervals. The investigation includes both the primary calibration at the beginning and a repeat of the calibration in 2002 by the PTB. For the comparison of the measurements the protocol of inter-comparisons was used, described as follows: The method of comparison measurements between calibration laboratories comprises measurement of the FTS in 4 positions, spaced at 90° to each other around the axis of the transducer. The measurement at the 0°-position is carried out with increasing values after 3 pre-loads of the capacity of the FTS. At all other positions, only increasing force values after one pre-load with the capacity of the FTS are applied. The time interval between subsequent force steps is kept constant and it is selected according to the required time for a load change of the slowest machine which takes part in the comparison. This ensures identical measuring conditions for both FSM to be compared and thereby minimises influences of creep of the zero point. 150 seconds was selected for the deadweight part, and 180 seconds for the amplified part. Generally, the FTS were utilised in a range from 40 % to 100 % of their capacity. The 1 kN, 25 kN and 50 kN FTS were employed for measurement at the deadweight side while the 500 kN and 2 MN FTS were used at the lever machine. The results are shown in Figure 1. In order to allow better comparison the deviations are shown relative to the primary calibration of the transfer standard. Shown are deviations at the nominal force value of the transfer standard. Significant deviations of the linearity at lower forces were not recorded so that Figure 1 can be taken as representative for the entire range of the relevant transfer standard. For the lever-amplified force range, i.e. for the force transfer standards of 500 kN and 2 MN capacity, the drift of the force transducer is superimposed to the drift of the amplification ratio of the lever. The drift of the amplification ratio has been compensated with respect to the sensitivity of the above named transfer standards, as will be outlined further below.

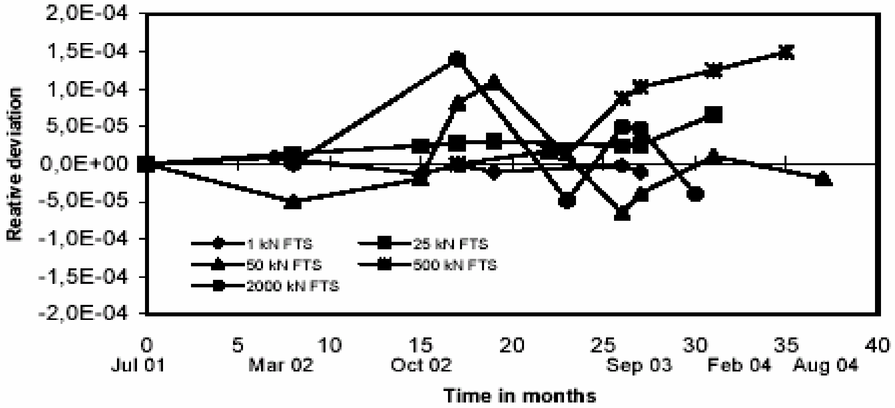

Figure 1: Relative deviation at nominal capacity

Continuously recording the zero indication of each transfer standard without any loading parts prior to each calibration can form a good indicator for changes of the structure of the transfer standard. Overloads or mechanical modifications cause significant, often irreversible, changes of the zero indication of the transducers and may have an effect on their sensitivities. Hence the zero drift was included in the observations. Figure 2 shows the change of the zero indications over time. For comparison purposes the absolute changes are given relative to the readings taken during the initial calibration. The curves show no exceptional behaviour.

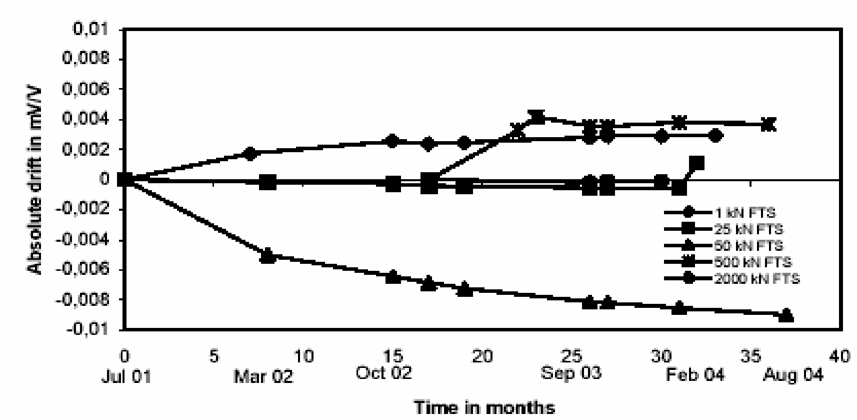

Figure 2: Drift of Zero-point

2.2 DRIFT OF THE AMPLIFICATION RATIO

The design and working principles of the machine have been described in detail in [1]. In short, the system consists of a deadweight force standard machine with binary mass stack of 55 kN capacity, capable of generating of forces ranging from 0.5 kN to 55 kN in steps of 0.5 kN (tension and compression). These forces are multiplied by a factor of 40 using a mechanical lever. Utilising an additional 0.25 kN mass disk in the stack this leads to a force range of 10 kN to 2200 kN in steps of 10 kN, again both in tension and compression. The lever is supported in elastic hinges, and the same principle is used for the coupling of the stack and the 2200 kN loading frame to it. Although based on well-established and proven principles the combination of 2.2 MN capacity, amplification ratio of 40:1 and loading range in excess of 200:1 coupled with an uncertainty aim of less than 1E-4 pushed the design to the very limit of the current state of the art. The following may serve as a visualisation: The „long" arm of the lever is approximately 1200 mm in length, meaning that the „short" arm is a mere 30 mm. If this length changes by as much as 0.003 mm during a measurement or over a period of time, the whole permissible error margin in terms of uncertainty or deviation is used up by this.

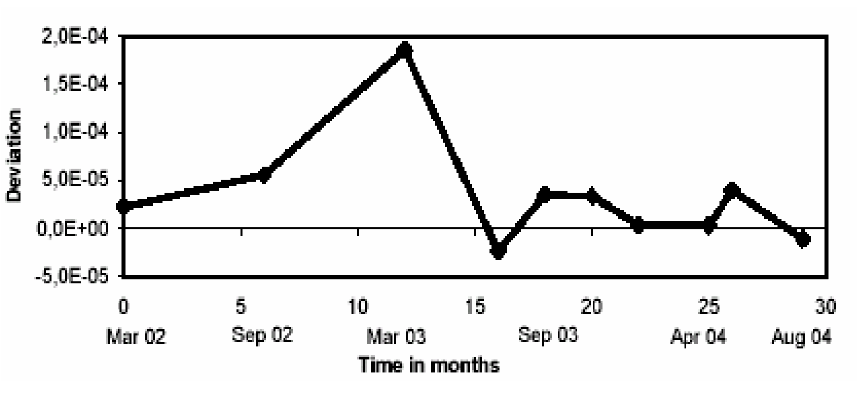

Figure 3: Drift of the lever-ratio

As early as during the conception phase it was clear that minute movements and dislocations in critical areas of mating surfaces could lead to changes of the amplification ratio. Therefore the design allowed for adjustments both by mechanical and electronic means.

relative deviation to PTB

The amplification ratio was monitored over reasonable periods. Towards this end the 50 kN force transfer standard was calibrated in the deadweight machine in three positions spaced at 120°, similar to ISO 376, but only in one load step of 50 kN. The same procedure was then repeated immediately afterwards in the amplified machine. Figure 3 shows the relative deviations of the lever machine relative to the indications of the deadweight machine for the 50-kN transfer standard, from the commissioning in 2002 onwards. There is a significant change visible about 12 months after commissioning. The reasons for this have not been established in detail, but it is expected that mechanisms such as were mentioned above have caused this change. Upon this the amplification ratio was re-adjusted to the correct value again. Since then, no significant changes of the ratio were recorded.

3. RESULTS OF THE COMPARISON MEASUREMENT AND SHORT-TERM BEHAVIOUR

The short-term behaviour of the machine was originally evaluated in the measurements described in [1]. This included observations and measurements of the repeatability of selected force values as well as the recording of force-time plots. These measurements were repeated in the course of the current work, and the results were found in agreement with those given in [1]. Furthermore, the current comparison measurements were used as an indicator of the short-term behaviour, since they were carried out immediately after the amplification ratio was adjusted back to the correct value.

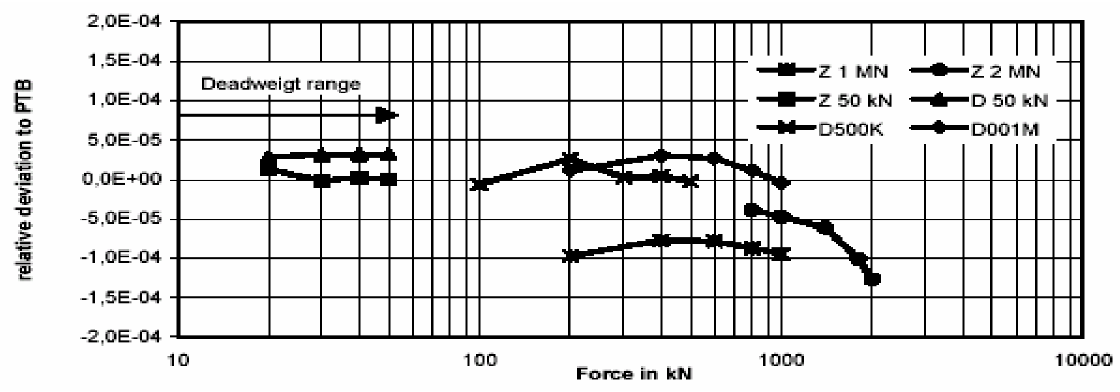

Figure 4: Relative deviation between SPRING and PTB

In continuing the comparison measurements between SPRING and PTB as described in [1] the main emphasis was now put on comparing the tension ranges. In addition the compression measurements in the range from 100 kN to 1 MN were repeated, due to the re-adjustment of the amplification ratio. For this comparison, force transfer standards of the PTB were used exclusively. All transfer standards were calibrated at the PTB with a measuring uncertainty of less than 2E-5 for k=2, using the procedure given in [1]. The measurements at SPRING were carried out in an identical manner. The results of the comparison are given in Figure 4. The measuring uncertainty was calculated in accordance with [2] and [3]. The *En*-Value was less than 1 in every case.

However, a certain amount of non-linearity, i.e. decreasing forces with increasing capacity, is noticeable in the range above 500 kN. This could be caused by a deformation of the lever, resulting in a reduced effective lever length. Further investigation is needed to establish the cause and reduce its effect. However, the amount of deviation is so small, well below the nominal measuring uncertainty of the standard machine, that fairly comprehensive studies may be needed to find the cause.

4. CONCLUSIONS

The 55 kN / 2.2 MN Singapore primary force standard machine has now been in operation for more than 3 years, and a considerable amount of experience and data has been accumulated in co-operation by the Singapore National Metrology Centre, the machine manufacturer, and the PTB. Two major comparison measurements and a program of continuous performance monitoring allow the following conclusions to be drawn: The state of the art in lever-amplified deadweight machines has been developed to cover capacities of over 2 MN, with a lever ratio of 40:1. An uncertainty target of 1E-4 is achievable in a measuring range of 200:1. Both mechanical and electronic adjustment is needed to achieve the correct amplification ratio and linearity across the load range. Further work may in future allow identifying the reasons for and reduce the amount of this adjustment. The short-term behaviour of the lever machine is not different to that of similar machines of lesser capacity, load range or amplification ratio. It is entirely satisfactory and approaches the characteristics of a deadweight machine of equal capacity. The long-term behaviour of the amplification ratio suggests that it is necessary to monitor its value; a procedure which the design of the machine allows to be carried out quickly and accurately. At the same time it is expected that maintaining a constant ratio over long periods of time is quite possible. Further work will show if this is indeed the case and may also allow identifying reasons for fluctuations and possibilities to reduce them. Finally, the work carried out here proves that both deadweight and lever force standard machines can be compared to other primary force standards with the same level of accuracy in tension as in compression, i.e. 2E-5 for deadweight and 1E-4 for lever machines. By selecting suitable force transfer standards and taking the necessary care in the measurements the uncertainty established does not depend on the loading direction, but is a function of the transfer standard’s own uncertainty and the performance of the machine in question.

ACKNOLEDGEMENT

The authors would like to thank Dr. A. Sawla and W. Herte (both PTB) for their invaluable assistance and support throughout the project.

REFERENCES

[1] Lim Chi Kah, Glöckner, B. and Allgeier, T.: New Developments in Lever-amplified ForceStandard Machines, Proceedings of the XVII IMEKO World Congress, Dubrovnik, Croatia, 2003
[2] EA-4/02: 1999 Expression of Uncertainty of Measurements in Calibration
[3] Sawla, A.: IMEKO 2000, Uncertainty Scope of Force Calibration Machines

Adresses of the Authors

Chi Kah Lim, Standards, Productivity and Innovation Board, 1 Science Park Drive, Singapore 118221, Singapore,
indylim@singnet.com.sg
Bernd Glöckner, Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
bernd.gloeckner@ptb.de
Thomas Allgeier, Gassmann Theiss Messtechnik GmbH, Philipp-Reis-Str. 6, 64404 Bickenbach, Germany
contact@gtm-gmbh.com