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NEW DEVELOPMENTS IN LEVER-AMPLIFIED FORCE STANDARD MACHINES

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Abstract – This paper describes the unique features and metrological performance of a new 55 kN / 2200 kN lever deadweight force standard machine set up recently at SPRING Singapore. It uses a novel 55 kN deadweight stack with individual mass disk drives, a single lever of 40 times multiplication ratio and a 2,2 MN tension-compression loading device. The machine is of increased capacity, with a wider force range and larger amplification ratio than previously possible. The lever machine covers force range from 10 kN up to 2200 kN in intervals of 10 kN. For the first time, a force standard machine of this type and size uses an entirely digital control system. The machine has been the subject of a comparison measurement with the PTB, preliminary results of which are given. The uncertainties of the machine were found to be within $2\cdot10^{-5}$ for the deadweight part and $1\cdot10^{-4}$ for the lever part. The system now serves as a primary force standard for Singapore.

Keywords: Force standard machine

1. INTRODUCTION

The shortfalls of knife edge bearings (wear, need for maintenance, friction and undetermined line of contact) have been recognised for a long time. Their importance increases with the load on the bearing. From the 1970s, steel strips as elastic hinges were used to a limited extent for lever balances. They were not strain controlled and are unsuitable for high loads.

The principle of the strain-controlled elastic hinge was developed and subsequently patented in the late 1980s by GTM.

The first force standard machine to use the principle was built for the Siemens company in 1990. The first application to a primary standard at a national institute was in 1995 (1 MN machine at UME in Turkey). Further machines were built in Germany and abroad, notably another 1 MN machine at INMETRO of Brazil (1997). The highest capacity to be realised so far is the 2,2 MN force standard machine for SPRING Singapore in 2002, subject of this paper.

In parallel to the high-capacity development, the principle has been applied to jockey-weight force standard machines of low capacities, such as two 25 kN machines operating in Germany. Designs exist down to 1 kN capacity.

Additionally, a variant of the strain controlled hinge has been used for torque standard machines.

2. MACHINE DESIGN

2.1. Overview

Compared to existing lever-amplified Force Standard Machines, experience gained in the building of machines of similar design and applying advanced electronic systems with corresponding software has lead to:

- Increasing the amplification ratio by at least a factor of two, reaching 40 in the given case.
- Increasing the capacity by a factor of two over the largest machine built so far which uses the same type of lever support.
- Increasing the relative force range, by decreasing the minimum force and minimum force step to 0,5 % of the rated capacity.

As a result, the two parts of the FSM (deadweight and lever-multiplied, respectively) offer the following force ranges and accuracies:

- 500 N up to 55 kN, in steps of 250 N, with a measuring uncertainty of $\leq 2\cdot10^{-5}$
- 10 kN up to 2,2 MN in steps of 10 kN, with a measuring uncertainty of $\leq 1\cdot10^{-4}$

Fig. 1 shows the machine and identifies the principal components.

2.2. Lever design, bearings and mass coupling

To achieve this, the following design details were developed and implemented :

The principal design of the lever follows the example given in [3]. However, in order to achieve the required repeatability of the lever machine with the high amplification ratio of 40, the "short" arm of the lever was made from one single piece. This means that between the fixing points of the main hinge and the load hinge, no assembly joints are present. Therefore, the short lever arm length of 30 mm is consistent to a very high degree, leading to a highly constant amplification ratio.

The lever bearings were again designed following the outline of previously built machines, but naturally of much

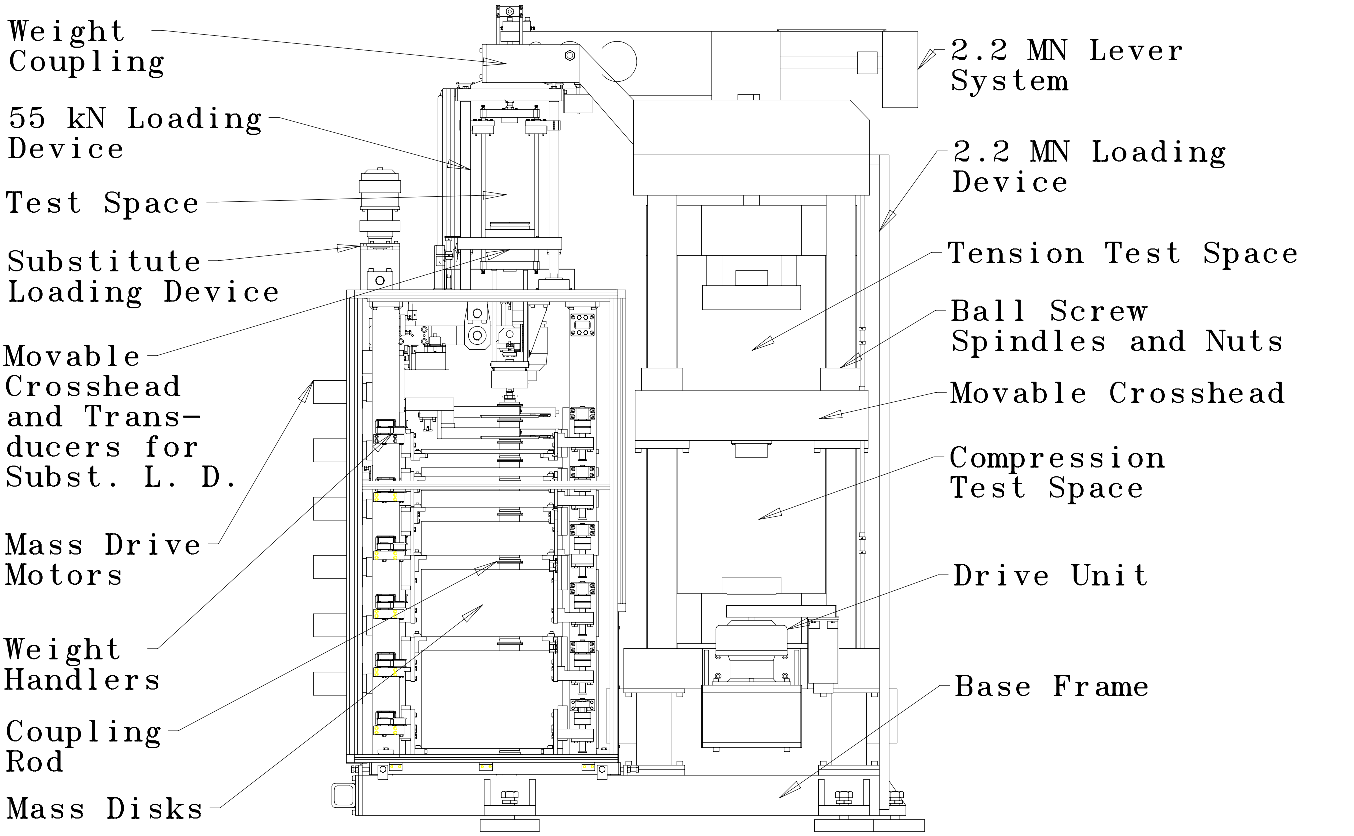

Fig. 1. General assembly drawing of machine with main components

larger size relating to the higher forces. Fig. 2 gives an outline of this design.

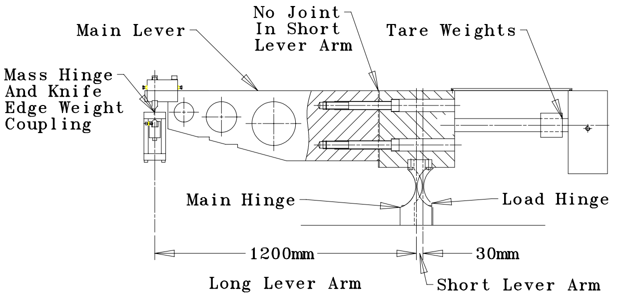

Fig. 2. Lever, lever support and weight coupling

In order to achieve somewhat higher resolution of the strain control circuitry, the strain gauges used were of 5000 Ω resistance, allowing the application of a higher excitation voltage.

The weight coupling was designed as a strain controlled elastic hinge as well, but in order to reduce the maximum bending moment applied to the hinge, a knife-edge bearing was incorporated between the elastic hinge and the load frame of the 55 kN machine.

2.3. 55 kN binary mass stack

Whilst maintaining the principal features of the GTM substitute mass stack [4], the drive system was changed to individual mass disk handlers. These position each of the disks separately as controlled by the operator's commands, achieving more precise mass movements as compared to a central lifting table. Fig. 3 shows a section of the mass stack with its drives.

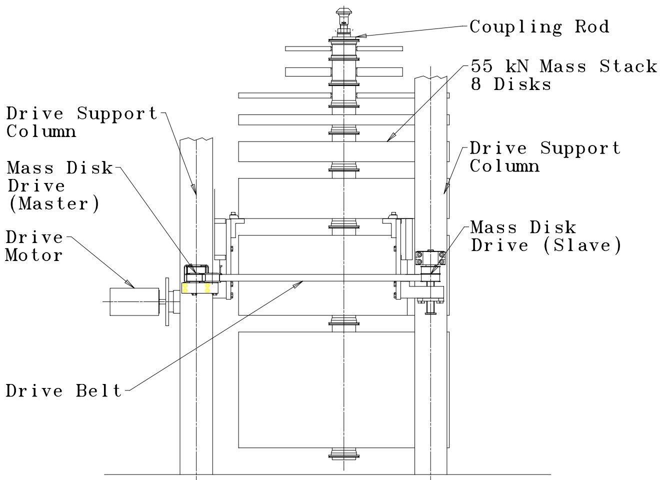

Fig. 3. Mass stack section

Deadweight Operation

For deadweight operation, the first force step is generated by the load frame, the second results from the additional weight of the coupling rod, and all further loads are achieved by an additional combination of any of the 8 mass disks.

Lever Operation

When the lever amplified machine is active, the 55 kN load frame and coupling rod are constantly applied as a tare weight. Thereby, the first force step generated is using the smallest mass disk of 250 N, leading to 10 kN force on the lever side. All other loads up to the maximum of 2,2 MN are generated by suitable combination of the mass disks.

2.4. 2,2 MN tension-compression loading device

The 2,2 MN loading device again is based on the design given in [3]. Naturally much stronger and heavier, it also uses two ball screw spindles as source of the counterforce. These are of a size and capacity that has of far not been applied to FSM design. See also Fig. 1. Each of them carries up to 1,1 MN of load and together they move the crosshead with relation to the fixed four-column frame. Both are driven in a synchronised way by a servo-electric motor through a multi-stage reduction gear train. Any force generated by the lever system (tension or compression) passes through the loading frame and the test transducer into the movable crosshead. Controlled according to the signals from the lever support springs, its position is adjusted until the moment-free condition of the lever system is restored.

2.5. Digital control system

Significant improvements of controllability and functionality were made possible by a fully digital control system. The signals of the elastic hinge lever bearings and of load cells fitted into the force path of the deadweight machine are digitised by a special design of measuring amplifier (LWL-DMS), which makes the digital values available to the control computer (UCR) through a fibre-optic link. The entire control algorithm is implemented as software, so that it can be configured and adapted very easily, allowing to modify the control parameters as a function of force, or any other quantity. The output of this control software is then transferred into the speed and power of an electric motor by a digital servo-controlled motor drive (Motor Contr.), via an I/O-unit. The operator chooses his commands from a PC graphic human-machine interface, which communicates with a programmable logic controller. The latter interacts with the machine sensors and motors through another I/O-unit. A block diagram of the electronics is shown in Fig. 4.

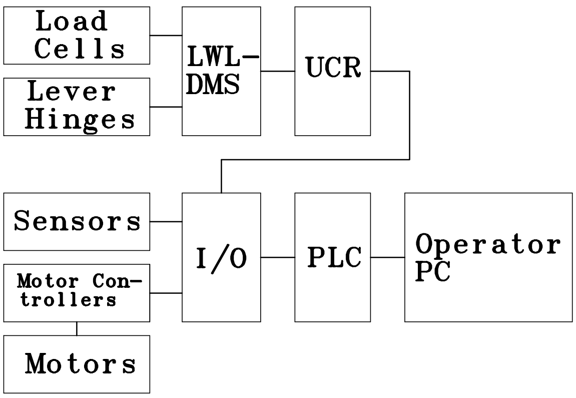

Fig. 4. Electronic block diagram

Both the substitute load controller and the crosshead controller for the lever amplified machine use this philosophy. As a result, the changeover of mass disks is possible with no load-reversal on the test transducer, since the test load is maintained precisely by the substitute load controller. Additionally, the crosshead controller of the lever machine achieves a highly precise, stable force on the test device from very low forces (0,5 %) right up to the full capacity of the machine. Fig. 5a shows a typical load change diagram of the deadweight part, and Fig. 5b is a load-time plot at constant load of the lever part.

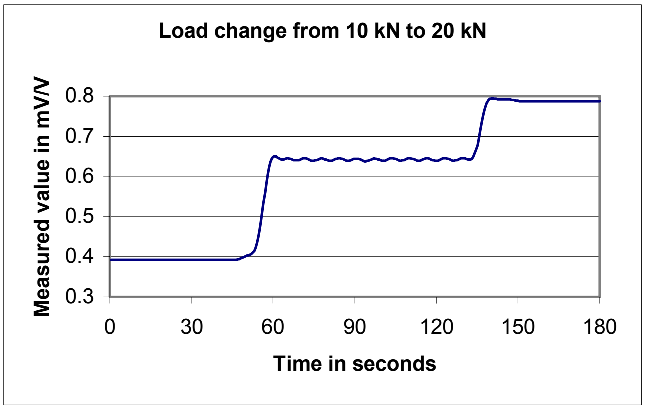

Fig. 5a. Typical load change sequence (deadweight machine)

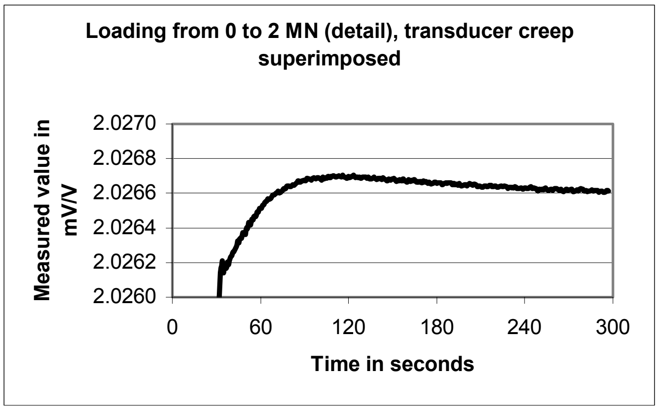

Fig. 5b. Typical load stability (lever machine)

The principles of control and operation follow [3] and [4]. For details on the software controller (UCR) see [5].

3. METROLOGICAL CHARACTERISTICS

3.1. Comparison measurement

To verify its metrological performance of the new Force Standard Machine (FSM) of SPRING Singapore, a comparison with the force scale of PTB was carried out by using SPRING Singapore's force transfer standards (FTS). These Force Transfer Standards were calibrated in 2001 at PTB (immediately after their manufacture from GTM hence the history of previous measurements was very limited) for the first time both according to EN 10002-3 as well as according to the method for comparison measurements for calibration laboratories (see below). Only for the range of 100 kN to 1000 kN were two FTS owned by the PTB used for the comparison measurements.

3.2. Measurement Sequence

The comparison measurements were carried out according to the method of comparison measurements for calibration laboratories. This involves 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 and decreasing force values after 3 pre-loads at 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 constant, it is selected according to the required time for a force 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. For the deadweight part, 150 seconds were selected, and 180 seconds for the amplified part. Generally, the FTS were utilised in a range from 40 % to 100 % of their capacity. The comparison covers the ranges of 500 N to 50 kN for the deadweight machine, and from 20 kN to 2 MN for the lever-amplified machine.

The second step comprised the re-calibrations at SPRING under identical conditions. All FTS were finally be re-calibrated at the PTB.

3.3. Measurement Results

Both the measurements of the PTB at SPRING compared to the initial calibrations at the PTB and the re-calibrations at SPRING compared to the measurements at SPRING which followed showed the relative uncertainty performance of $\leq 2 \cdot 10^{-5}$ for the deadweight side and $\leq 1 \cdot 10^{-4}$ for the lever amplified side. Fig 6 shows the first measurements of the relative deviation between SPRING and PTB. The measuring uncertainty U was determined according to [1] using the empirically measured standard deviation of the mean value and the nominal measuring uncertainty of the corresponding Force Standard Machine, allowing for a coverage factor of k=2.

The normalised error E_n is calculated according to [2] as follows

$$E_n = \frac{\Delta_{relDev}}{U_{tot}} \tag{1}$$

where Δ_{relDev} is the relative deviation between the measurements at PTB and at SPRING and U_{tot} is the total measuring uncertainty, resulting from the measurements at PTB and at SPRING:

$$U_{tot} = \sqrt{U_{SPRING}^2 + U_{PTB}^2} \tag{2}$$

Fig. 7 shows the calculated normalised error E_n. The E_n-value was < 0,5 in the whole measuring range of both the deadweight machine and the lever machine, except for the 50 kN force transducer. This force transducer showed a certain amount of creep with respect to its sensitivity. It is also suspected that this transducer suffers from a higher temperature sensitivity. Due to constraints of time and availability of force transducers of certain capacities, comparison measurements could not yet been carried out in the force range from 1 kN to 5 kN, 50 kN to 100 kN and in some cases the overlap between transducer capacities was minimal. However, additional measurements were carried out beyond the scope of this paper, which were aimed at determining any systematic errors in the calibration of the mass disks of the machine. No such discrepancies were found. For E_n-values < 1, the empirically determined magnitude of the measuring uncertainty U_{tot} can be relied upon. As a result it can be estimated that the measuring uncertainty of the new FSM of SPRING in the deadweight range is $\leq 2 \cdot 10^{-5}$ and $\leq 1 \cdot 10^{-4}$ in the lever amplified range.

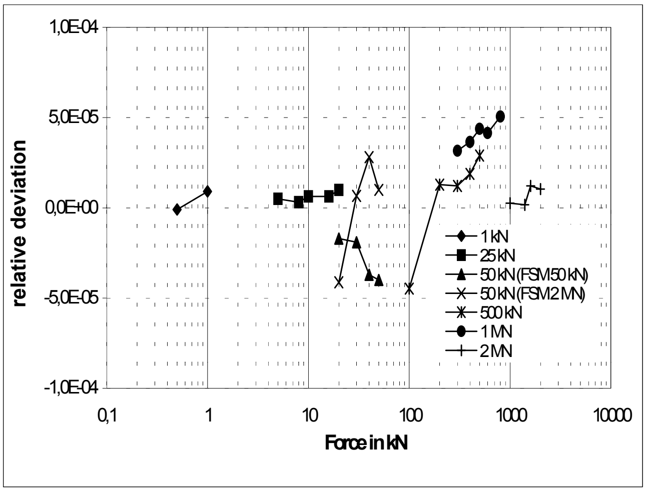

Fig. 6 Relative deviation between SPRING and PTB

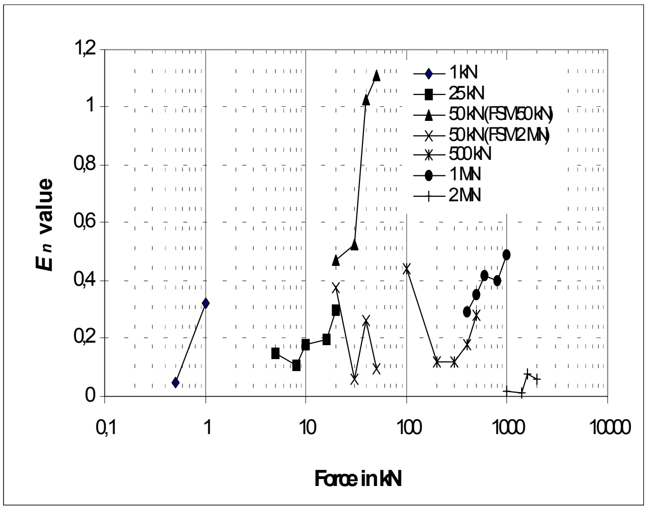

Fig. 7 Calculated E_n-values

4. CONCLUSIONS

New approaches were applied to existing principles in order to push the limits of lever-amplified force standard machines beyond previous boundaries. These included mechanical, electronic and software issues, and there was naturally a large amount of inter-dependency between them. As is often the case, only an integral solution taking into account all aspects of metrology performance can provide a real gain, as opposed to a small advance in one area which has to rely on some compromise in others.

From the outset, no such compromises have been accepted, aiming at a machine which satisfies all requirements in terms of metrology, size and cost.

The outcome is twofold: With the installation of this primary standard machine, the force measurement and calibration capability at SPRING has been improved greatly. With further optimisation, it will be used to participate in international comparisons of force measurement. At the same time, SPRING will provide high-accuracy calibration services to local industries and abroad.

Secondly, the technology now available offers an alternative to pure deadweight machines in this high capacity range at NMI's, especially under space and cost limitations. Further work is aimed at increases in accuracy, capacity, range and functionality.

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