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A New Design of Deadweight Force Standard Machine with Substitute Load Control and Self-checking Systems

By Dr. T. Allgeier+, Prof. H. El-Hakeem*, Prof. A. El-Sayed* and Dipl. Ing. B. Glöckner#

+ *Gassmann Theiss Messtechnik GTM GmbH, Bickenbach, Germany*

* *National Institute of Standards (NIS), Cairo, Egypt*

Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany

Abstract

A new dead weight force standard machine covering the range from 10 kN to 1 MN has been designed and constructed at the National Institute for Standards (NIS)-Egypt, by GTM GmbH.

This machine incorporates an electromechanical system that allows the generation of any load from 10 kN to 500 kN in steps of 5 kN with only 10 masses by selecting a suitable combination of these, while keeping the load on the transducer under calibration constant. Furthermore, it allows the generation of additional loads of up to 500 kN, so that 1 MN is reached by full deadweight action and full substitute load at the same time without significant loss of accuracy.

The forces generated by the various masses can be checked against a reference mass without any dismantling operation. The machine also serves as a precision pressure balance of a 5 MN hydraulic force standard machine. The amplification system formed is of 10:1 ratio.

The paper presents the special design features of the machine and the design considerations with a brief account of the verification of the machine. A second paper will follow to present the evaluation of the metrological characteristics of the developed machine.

1. Introduction

As part of a project to upgrade and modernise the force laboratory of the National Institute of Standards (NIS) of Egypt, three force standard machines (FSMs) were decided upon:

- 50 kN deadweight FSM, load range 500 N to 50 kN, in steps of 500 N, tension and compression.
- 500 kN deadweight FSM, load range 10 kN to 500 kN, in steps of 5 kN, tension and compression. This machine has a second range of up to 1 MN, generating forces

above 500 kN with a mechanical lever. It also serves as a pressure balance for a hydraulic amplification system.

- 5 MN hydraulic FSM, load range 100 kN to 5 MN, in steps of 50 kN, compression only.

The 500 kN machine, being the centrepiece of the installation, is the main subject of this paper.

2. Design Concepts

A binary mass stack was decided upon. In a series of 1; 2; 4; 8; 16; 32....units, any step weight from 1 unit up to the full capacity can be assembled in steps of 1 unit, with the smallest number of mass disks. This would give the machine far greater flexibility in use. In the present design, it is decided to use the load frame as the first load step (scale pan system). Eliminating this weight to start loading with the first mass disk (tare balance system) would cause significant uncertainty, specially at low forces, beside the difficulties of maintaining its proper operation over long periods of time.

Provided the smallest mass disk is available twice, any mass can also be verified against the sum of all smaller masses, the latter having exactly the same nominal weight. In so doing, a so-called self-checking routine can be established which serves as a secondary verification; to ensure that no significant change of weight, initially adjusted by the Physikalisch-Technische Bundesanstalt (PTB) of Germany, has taken place without dismantling of the machine.

A servo-electric loading device with lever amplification is used to maintain the force on the test transducer constant, while the mass disks in the stack are re-arranged for the next test load. Hydraulic systems for the same purpose have been suggested and used in the past [1, 2]. As the system used here is load cell based and fully computerised, it also opened the way to the load duplication of the machine.

Hydraulic amplification, being the most economic and precise way to arrive at very high test loads, is adopted in the new machine design. On the ground of previous experience with sealed, rotating cylinder-piston system that maintain near-zero friction and zero-flow characteristic, excellent load stability and repeatability over a large range would be achieved [3]. Moreover, the 500 kN hydraulic cylinder can also act as a crash-protection when the machine is in direct-deadweight loading mode in case of transducer fracture under load.

Finally, the well-proven dual control philosophy of the machines built by GTM has been adopted, leading to a reliable PC-driven operation that is convenient to use.

3. Detail Designs of New Features

The machine frame consists of three columns (Fig. 1), spaced at 120° angle, between a base plate and an upper mounting plate. The mass stack is positioned centrally between these columns, and the carriers for the mass disks are incorporated into the column design.

Below the upper mounting plate, the lifting table for the mass stack is arranged, together with the lever arm of the substitute load generator. On top of the mounting plate, a classical four-column frame is erected, with a travelling crosshead and encompassing the four-column scale pan. This scale pan stretches beyond the top plinth of the frame, thereby creating the space where the hydraulic cylinder for load multiplication and crash protection is positioned.

3.1. Binary Mass Stack with Central Coupling Rod and Scale Pan

The weight distribution of the various components was chosen as follows: the scale pan weighs 10 kN, or 1% of the total capacity

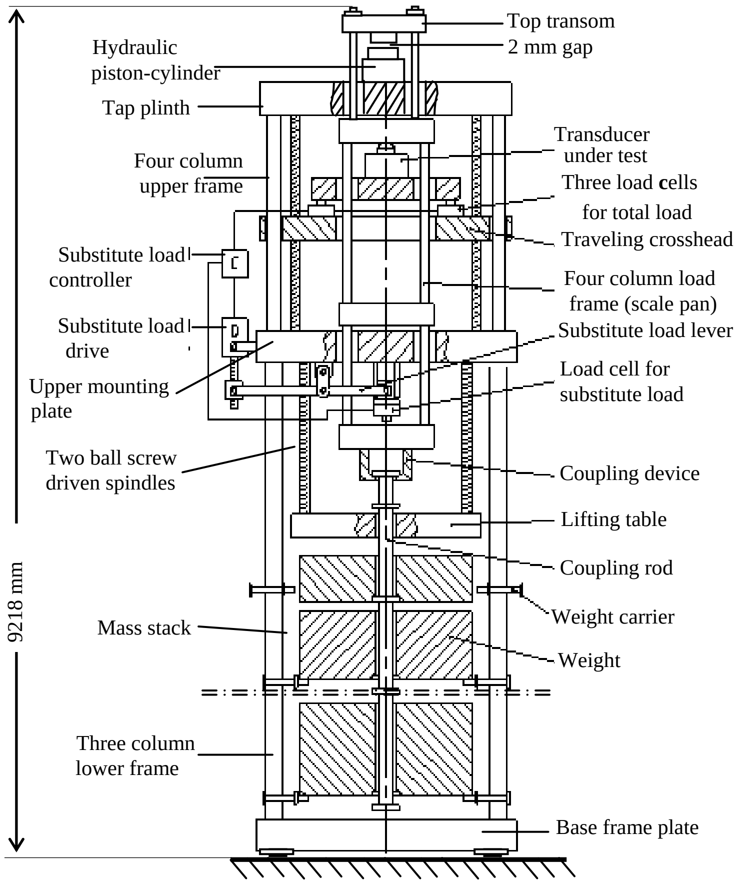

Figure 1. Schematic diagram of FSM with binary mass stack

of the machine. Nickel plated steel, aluminium and stainless steel are used in its construction. The coupling rod weighing 5 kN, as the second load step, and has shoulders attached on which the mass disks rest. This assembly is partly nickel-plated, partly stainless steel construction.

The next two mass steps are disks of 5 kN each, made from stainless steel. The remainder of the masses are disks of 10; 20; 40; 80; 160 and 165 kN, respectively, and are all made from nickel-plated steel. The masses of 80; 160 and 165 kN are actually composed of individual disks of 40 and 45 kN, respectively. In order to adjust the centre of gravity of the mass disks with their geometric centre, two movable weights are provided on each disk and clamped when set correctly by using a special centre of gravity weighing rig.

The disks can be either carried by the coupling rod or supported by three carrier bolts arranged at the mainframe columns. These bolts can be withdrawn or inserted by means of pneumatic cylinders.

3.2. Overhead Lifting Table

The main drive of the machine, i. e. the one that provides the movement of all the masses in preparation of, and during, a load change, is the so-called lifting table. When in operation it carries the coupling rod together with the mass disks. It is possible to position-control the height of the lifting table at will with a high degree of precision allowing the following actions. The coupling rod is connected to the scale-pan of the machine, and has no contact to the lifting table (Fig. 1). Moving the table upward will lift the coupling rod clear away from the scale pan. At this upper position, the mass disks will also be clear of their carrier bolts, allowing their setting to be altered at will.

3.3 Substitute Load Control and Load Duplication

The central fulcrum of the substitute lever is a swinging-link (Fig. 1) pivoting around a

A patented design exists for a hydraulic piston-cylinder unit for hydraulic force standard machines [3]. Because of the numerous advantages of this design, it was decided to use two such units for the hydraulic amplification system. The smaller one of these is mounted on the top plinth of the four-

bracket mounted on the upper plate, and at the long end of the lever, a servo electric spindle unit generates the forces as required. The short end of the lever is guided vertically, to engage with the scale pan as and when required, exerting a pulling force onto it. A load cell is provided at the short end of the lever to measure the substitute force precisely at all times. A further three load cells are arranged under the transducer platen of the movable machine crosshead. Their joint output is exactly proportional to the total load. All load cells used are of transfer standard quality.

The closed loop controller can be parameterised to allow arbitrary forces to be generated and precisely controlled. This action is called upon during all load change sequences and also for load duplication, i. e for forces above 500 kN.

3.4 Crash Protection and Hydraulic Connection to the 5 MN Machine

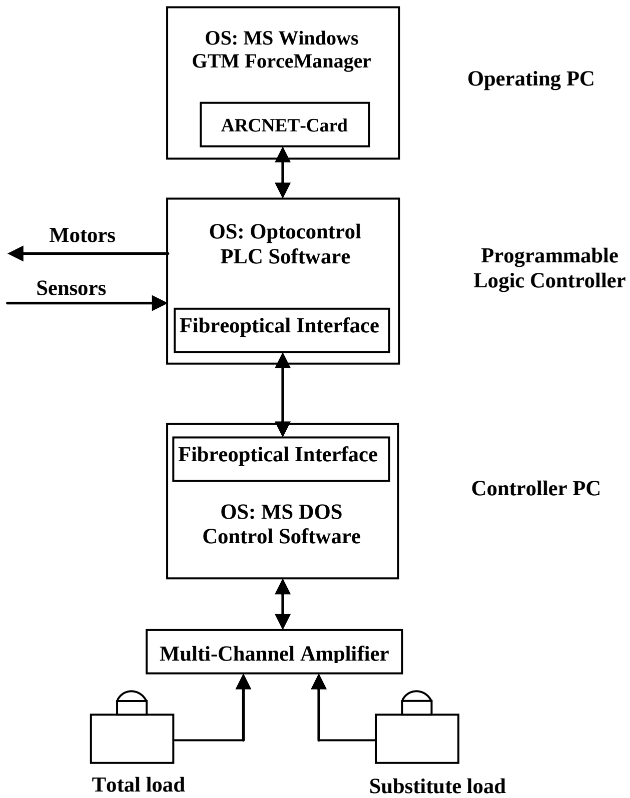

Figure 2. Schematic diagram of machine controller

column top frame, just below the top transom of the scale pan (Fig. 1), thereby functioning as a deadweight pressure balance for the 5 MN hydraulic machine.

The second mode of operation of these components is the aforementioned crash protection system by maintaining a distance of approximately 2 mm between piston top and scale-pan top transom whenever the 500 kN machine is under load. To achieve this, non-contact position sensors are arranged at the top transom and at the piston head and controlled by the hydraulic controller of the 5 MN machine. Failure of the transducer under test causes the scale pan to drop a small distance and the hydraulic unit acts as a spring/shock absorber.

3.5 Schematic Machine Control Diagram

Fig. 2 gives the main components of the machine control system. The operator selects and activates all the commands and values from the ForceManager, a Windows-based software. It handles the data acquisition of test results and corresponding filing. Operation can be fully manual, i. e. command after command is entered and executed consecutively, or fully automated, where the machine performs pre-programmed loading sequences.

The actual machine control software is written in a programmable logic controller (PLC) language. The control load cell readings are digitised by a multi-channel amplifier, and read out by a special single-board PC. This PC also runs the PID control software for the substitute loading system. Its operation is initiated at the appropriate times by the PLC.

4. Machine Operation

4.1 Principal Modes of Operation

There are three modes of operation which the operator can select: The 500 kN deadweight machine, either in tension or compression, then the option of load duplication, and the hydraulic amplified 5 MN machine. Only the functions resulting from the novel features of this machine are described here.

4.2 Load Change Sequence (10 kN to 500 kN range)

It is assumed that a test transducer is placed in the machine, loaded with an initial load of 50 kN, which is first increased to 100 kN and then decreased again to 50 kN. Figure 3 should be referred to.

At 50 kN, the following masses are applied: the scale pan (10 kN), the coupling rod (5 kN), one of the 5 kN, the 10 kN and the 20 kN mass disks. The first action on giving the command for a load change is that both the lifting table and the substitute load lever move from their reference position to be in contact with the coupling rod and the load frame, respectively (point 1). A small additional force (2 kN) is now generated by bringing the substitute load lever in contact with the load frame, which is measured by the load cell attached to its end. The total load thus produced is measured by the three load cells under the transducer platen and stored as the set point for the substitute load controller, which is now activated. The lifting table then moves upward, makes contact with the coupling rod and lifts it clear from the load frame. During this process, the substitute load lever increases its share to the total load until it reaches 100% when the coupling rod is no longer in contact with the load frame. The load is now about 52 kN (point 2). The lifting table rises further and collects all mass disks of the machine on the coupling rod, clearing the weight carrier bolts. At its topmost position (half-way between the points 2 and 3), the corresponding carrier bolts are activated for the new load value. In our example, the bolts for the 10 kN and 20 kN disks are pushed forward,

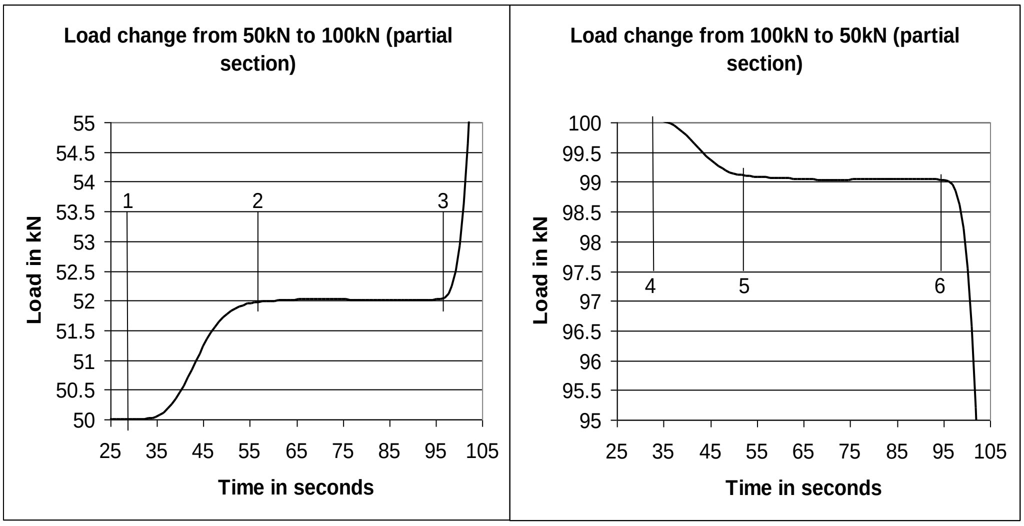

Figure 3. Load-Time-Plot (load change)

and the ones for the 80 kN disks are withdrawn. The lifting table, now on its downward stroke, puts the not required masses back on their bolts and approaches the coupling rod towards the contact position with the load frame (point 3). Once this contact has been made, and as the lifting table is driven towards its reference position, more and more of the total load is generated by deadweight action, while the contribution of the substitute system is reduced. At 52 kN deadweight contribution, the output of the substitute controller for the first time becomes negative and the lever end rises away from the load frame to its reference position. The test transducer at this time is loaded with 100 kN, generated purely by deadweight action.

The load change sequence in the reversed direction consists of the same basic steps, with the exception that in this case, the lifting table is advanced in time, so that it connects to the coupling rod before the substitute load controller acts on the load frame. This takes place at point 4 in Fig. 3.

4.3. Load Duplication (500 kN to 1 MN)

The concept of the 500 kN to 1 MN load range is as follows: The control load cell at the end of the substitute lever has been calibrated in situ against the deadweight stack: A 500 kN force transfer standard was placed in the machine, and calibrated in steps of 10% with deadweight load. Loading of this transfer standard was then repeated with the substitute loading system, also in 10% steps. From these measurements, a calibration curve for the substitute load cell was arrived at.

The calibration data were permanently stored in the memory of the substitute load controller. In so doing, the latter can be called upon to generate any load from 50 kN up to 500 kN, following a third-order polynomial.

When a load in excess of 500 kN is selected by the operator, the machine at first performs a load change to 500 kN (deadweight generated), no matter what the current load is. After that, the substitute load lever approaches and makes contact with the scale pan. The controller gradually increases the load to the required value and keeps it constant. Its set point is equal to the load target minus 500 kN. From then on, further increases or decreases of force in the range from 550 kN to 1 MN are achieved purely by the action of the substitute lever, with 500 kN dead load being permanently applied.

4.4 Operation of 5 MN Machine

The 5 MN machine to a very large extent mirrors all the main functions of the deadweight part. With a suitable compression transducer mounted in the 5 MN load frame, all forces generated on this side are simply multiplied by a known factor of approximately 10. Due to the leak-free units, a valve in the connection pipe between the two machines is closed during load changes, allowing switching the masses at the 500 kN side while the force on the 5 MN side stays constant.

5. Verification and Self-Check Process

5.1 Verification Measurements

Prior to final assembly, the centres of gravity of all masses were adjusted to coincide with their geometric centres. In order to further verify the line of action of the force vector, the bending moments generated by potential side forces and eccentricities were also measured. By means of special force transfer standards, the bending moments were recorded at various load levels, and calculated back into hypothetical eccentricities, according to

$$e = M_b / F \qquad (1)$$

in which M_b is the measured bending moment, F is the applied force and e is the apparent eccentricity.. A typical result of such a measurement is displayed in Fig. 4, it reveals that force eccentricities of less than 1 mm are achieved across the whole force range.

Upon establishing this, loading tests began, at first measuring the basic repeatability over 10 consecutive cycles of selected force steps across the working range. Deviation from average did not exceed 30 ppm for any force step, and was essentially 10 ppm for the deadweight range.

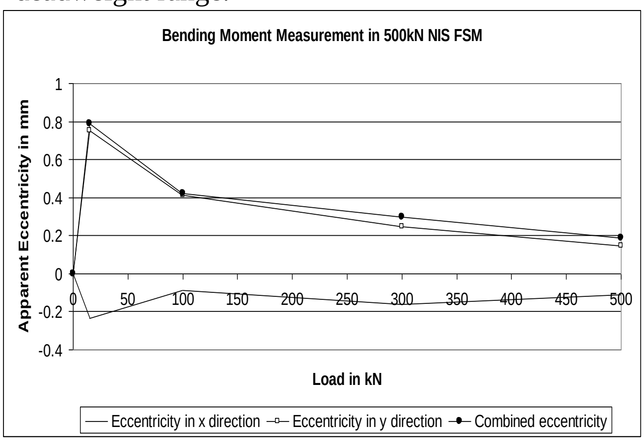

Figure 4. Result of eccentricity measurement

Much emphasis was then placed on investigating the stability of force during load changes, in particular the potential overshoot and load-reversal. The data obtained clearly demonstrates the soundness of the substitute control principle (Fig.

5.2 The Self-Check Process

All masses involved in the generation of force were previously adjusted by the PTB. However, the method will prove very useful for future re-verifications and potential faultfinding, and was therefore carefully tested. In short, it allows the comparison of all available masses to a single reference weight of 500 N by the use of suitable force transfer standards. The functionality of the ForceManager user software covers all relevant actions, including data acquisition, and a spread-sheet evaluation software was prepared to calculate the results.

6. Conclusion

The National Institute of Standards, of Cairo, Egypt, at present operates three primary force standard machines of 50 kN, 500 kN and 5 MN capacity. The design and workmanship of all three machines put the force laboratory at the leading position certainly in North Africa and further afield.

The design concepts established proved successful. The set targets in terms of performance and precision were achieved, together with ease of operation, reliability, and last but not least, cost. Consequent use of modern technology, in addition to the manufacturer's experience, has lead to an optimum installation with a minimum amount of parts and expense.

A full inter-comparison measurement programme between the PTB and NIS has been carried out since the end of the commissioning period. The results of these measurements will be presented in a separate paper.

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7. References

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Contact Person for Paper: Dr. T. Allgeier, e-mail: gtm.uk@talk21.com