Jockey-Weight Lever Machines For Force And Torque

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Abstract

This paper describes a new type of standard machine, based on a travelling (jockey) weight moving along a lever which is supported on strain-controlled elastic hinges. It is equally applicable to the quantities force and torque. In addition to step-by step loading, the machine can perform continuous calibrations without having to rely on a reference transducer. Furthermore, testing through the zero load condition is possible with suitable mounting components.

In the case of force machines, the jockey-weight design allows to tare the weight of all load introduction components, so that loads as low as 0.05 N can be applied without a reduction of accuracy.

Design and operating principles of the standard machines are described, with particular emphasis on their application to modern calibration practices such as continuous calibration, together with some typical test results obtained so far.

Introduction

Strain gauge based sensors for force and torque invariably experience non-static loads in their applications, and in many cases the applied load is alternating, i. e. it passes through zero. So far, however, in the majority of their calibrations static loading conditions prevail. Apart from a lack of applicable standardised procedures, this situation so far has been characterised by a lack of suitable standard machines.

Although in the past this seemingly did not cause significant problems in the use of load cells and torque transducers, current and future trends may well require a different approach. There are developments which will demand more advanced calibration methods:

- Increasing measurement ranges. Load cell applications already cover ranges exceeding 100:1, and the lower the minimum relative force, the larger the relative influence of errors such as hysteresis at zero becomes.
- Cheaper, lighter and more highly engineered components will require test conditions to match their application closely, in particular in the field of integrity (i. e. dynamic) testing. Hence the requirement to calibrate the reference devices similarly.
- For systems of only low and medium precision, the calibration times and thereby costs are too high. A faster method of loading and data acquisition is required.
- Research and development applications will require knowledge about the true response of a sensor to conditions of continuously changing load.

Following nomenclature established in torque metrology [1], by which these recent advances were initiated, we will in the following use the terms continuous calibration and through-zero testing instead of the word “dynamic”, due to the low frequencies encountered. Also, the term “load” in this context is not limited to the quantity of force, but used for torque as well.

In recent times, calibration machines for very small forces featured strongly in current development [2]. Since servo-driven machines are more suitable for high forces, and as the scalepan of a deadweight machine necessitates substantial weight in its construction, existing low-capacity force calibration devices usually suffer from limitations of accuracy and operation.

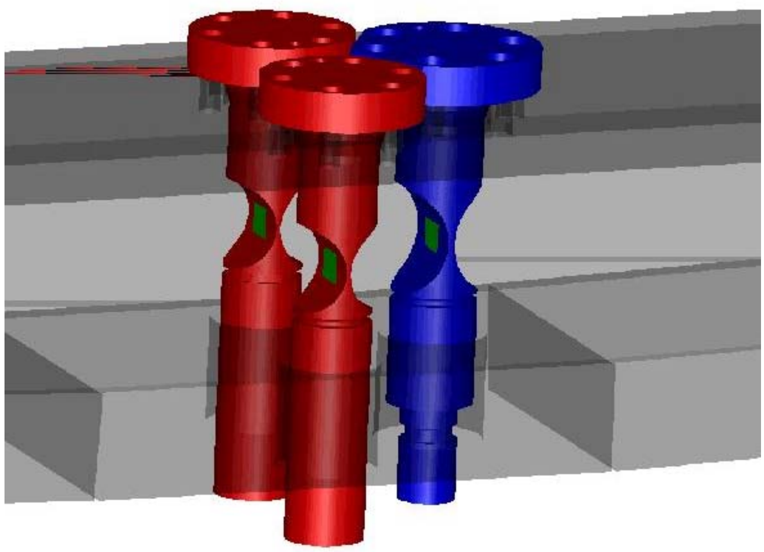
Following from these considerations, a new type of standard machine has been developed, and will be outlined in the following.

Principle machine design

GTM GmbH have developed and built a large number of lever-amplified deadweight force standard machines. The design principles and test results of these have been given elsewhere

[3, 4]. The lever support is designed as elastic hinges, i. e. strain-controlled bending springs, which act both as the fulcrum points and force coupling elements.
The adoption of a travelling, or jockey weight, in conjunction with this lever machine concept instead of a deadweight stack addresses the tasks as given in the Introduction. The example of a 25 kN force standard machine (Figs. 1 and 2) outlines this principle.

Figure 1: Front view of a 25 kN jockey weight machine (force)



The patented strain-controlled elastic hinge, basis of highly reliable, accurate and consistent lever amplification systems, forms the central device of the jockey-weight machine.
The precision of the test load (force or torque) is determined by:
- how accurate the product of jockey weight times effective lever length is known (traceability),
- the determination and maintenance of the exact equilibrium condition and in conjunction with this,
- the quality of the lever bearings.

Figure 2: Cross section of the lever support

Following from [3, 4] and further research into strain-controlled hinges, it is clear that their quality as lever bearings is sufficiently high even for machines having very large measuring ranges, up to 5000:1, in particular when taking into account the precision and reliability of modern strain gauge amplifiers and digital controllers. A typical example from a 5 kN·m torque standard machine is a reliable and stable resolution of the lever bearings of 0.1 mN·m, so that at 1 N·m torque level, the residual moment in the lever bearings can be kept as low as $1\cdot10^{-4}$. Similar conditions apply for force standard machines.

During the early development of the new principle, three aspects of mechanical design were identified to have a significant influence on the weight positioning:

- The centre of gravity of the masses must coincide with the measurement (drive) axis of the position sensing system, so that a certain amount of detected movement actually applies to the movement of the centre of gravity.
- The centre of gravity of the masses (and hence the centreline of the drive system) must lie in the plane of the lever bearings, so that acceleration forces during starting and stopping do not contribute a bending moment around the lever axis.
- The centre of gravity of the whole lever system does not necessarily have to lie in the bearing plane, as long as the machine is calibrated and linearised using transfer standards. In so doing, linearity and span errors caused by c of g errors are automatically corrected.

The generation of forces (or torques) depends on an equilibrium of moments. The primary moment is caused by the weight force of the jockey weight multiplied by its (adjustable) distance from the fulcrum position. This is balanced by a moment either equal to the test torque (for torque machines), or equal to the test force multiplied by the (fixed) distance between the strain controlled hinges in the case of force machines.

The fact that the moment shunt into the frame is measured electronically in both cases, and maintained at zero throughout the machine operation has a number of important effects:

- The strain gauge bridges serve as a mere zero indicator, will not see high strain levels, and thereby are free of creep and fatigue. They are only required to achieve a high degree of short-term repeatability.
- The sensitivity and state of frictionless operation can be verified at any time.
- The signals (together with that of some auxiliary bridges) can be used to stop the machine in cases of emergencies, in particular before overloading occurs.
- The fulcrum and load application points remain constant over very long periods.

<u>Design details of the force machine</u>

The frame supports the lever via elastic bearings (the so called hinges), and guides the movable crosshead in the vertical direction. See Fig. 1.

At the centre of the lever, above the support hinges, a mechanical weight changer has been provided. It allows manual or automatic switch-over of the jockey weights, so that the machine can operate in several load ranges. Thus, within a single machine frame, a very large range of forces (up to 2500:1 for certain capacities) can be generated.

Three strain-gauged elastic hinges are used for lever support and load introduction: Two parallel hinges form the fulcrum, and the loading hinge couples the lever to the load introduction components which interface with the test load cells. See Fig. 2.

The lever lengths are defined as: Short arm (fixed) = distance between support and loading hinges; long arm (variable) = distance between support hinge and centre of gravity of jockey weight. Under equilibrium condition, the test load is equal to the weight times the lever ratio.

There is only one test space for the transducer to be calibrated, both for tension and compression forces, a pre-requirement for through-zero testing.

In order to facilitate the movement of the jockey weight and determine its exact position, a precision ball screw spindle drive coupled with a high-resolution absolute encoder is arranged along the lever axis.

The movable crosshead is driven such that the test transducer exactly balances the force generated by the lever and weight. This precision drive is the actuator part of a closed loop control system, where the summed-up signal of the strain gauges bonded to the elastic hinges is the variable to be controlled, with a setpoint of zero. The strain gauges are orientated and wired such that they are sensitive to bending moments only, with all other influences (axial load in particular) cancelling each other out.

When the net sum of moments acting on the lever is zero, the test load is equal to the weight force of the jockey mass, multiplied by the respective ratio of lever lengths. This allows a large

range of infinitely adjustable forces to be generated by using one or more suitably designed movable weights.
The lever is of the double-sided type. When the weight is on the same side of the fulcrum position as the test device, compression forces will be generated. In the case of weight and load acting on opposite sides of the lever, the device under test will be in tension, and if the jockey weight is positioned exactly at the fulcrum, the test load is zero. Controlled by a precision ball screw spindle, the travelling weight thereby allows the load to "sweep" from compression through zero into tension, and back again.

<u>Design details of the torque machine</u>

A typical torque standard machine (3 kN·m capacity, 1 N·m minimum torque) is shown in Fig. 3.

Figure 3: View of a 3 kN·m jockey weight machine (torque) at Dr. Staiger-Mohilo, Germany

Compared to the force machine, the coupling hinge to the test load cell has been omitted and the bending moment generated by the lever and weight is now directly taken by a torque transducer mounted at right angles to the main lever at its centre. The centre bearing (fulcrum) is designed as two sets of two elastic hinges set at right angles, positioned at either side of the lever. The adjustable crosshead of the force machine has been replaced by a servo-controlled counter-torque drive, precisely aligned with the main torque axis. This can be moved axially to adjust the test space of the machine lengthways. Most other components, such as weight drive, weight changer and the whole electronic system are essentially identical to the force machine.
In order to achieve a precise torque value, the moment taken by the lever support hinges must be controlled to zero. In this case, the equilibrium is simply between the test torque and the weight force multiplied by the effective lever length.
Naturally, the lever is also double-sided. This allows clockwise and anticlockwise torques to be generated. Zero torque corresponds to the jockey weight remaining exactly at the fulcrum. Continuous testing is possible in the same manner as with the force machine; the travelling weight allows the load to "sweep" from one direction of torque through zero into the other.

Metrological characteristics

Overview

Two machines of 25 kN, one of 3 kN·m and one of 5 kN·m capacity have so far been built. Based on the design principles outlined above, capacities ranging from 1 kN to 100 kN and from 50 N·m to 5 kN·m are feasible. The calibration can be in arbitrary units, such as lbf (lb·ft for torque) or kg, for special purposes like load cell testing or in countries still using imperial units.
A machine may be equipped with up to five jockey weights, each representing one measuring range and covering a ration of 25:1 or even higher. The 25 kN machine has the following ranges: 0.1 to 1 kN; 0.2 to 5 kN and 1 to 25 kN, i. e. a total range of 250:1.

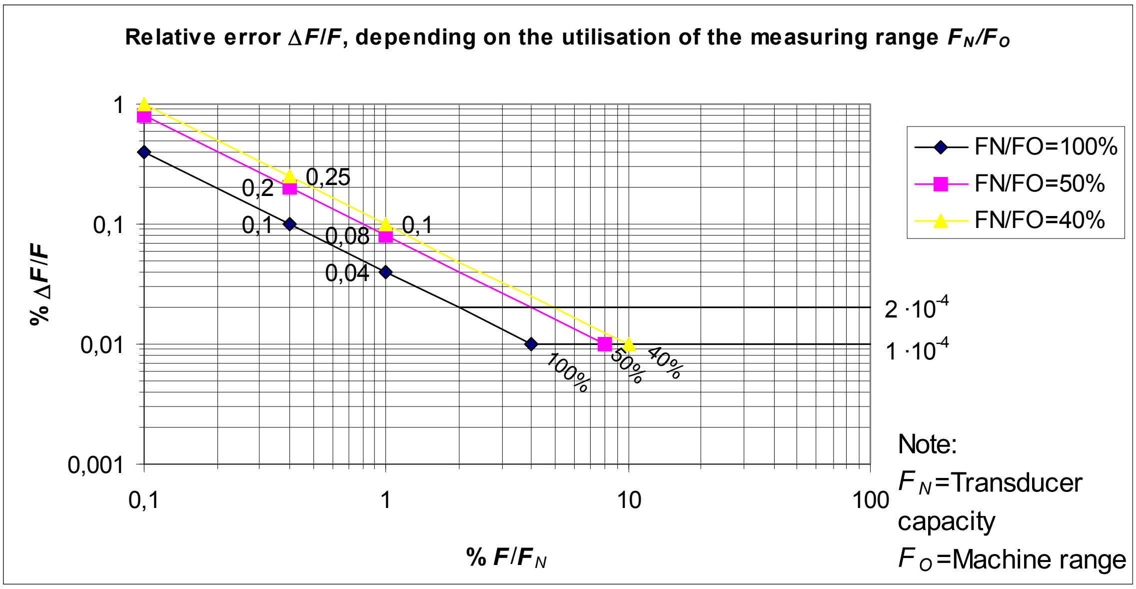


Figure 4: Logarithmic error diagram of a jockey weight machine (force)

The accuracy of the machine is represented by an error diagram as per Fig. 4, showing the permissible deviation from a reference. The relative deviation (and thereby the measuring uncertainty) is constant over a large percentage of each measuring range. This originates from the fact that a large portion of the total error is purely and linearly dependent on the applied load. At the bottom of each range, errors which are constant in absolute terms (as e. g. the control error and resolution of moment measurement) begin to outweigh the former constituent, leading to a relative error that increases with decreasing loads.
Calibration and traceability are achieved using transfer standards of force or torque (as required):
Neither the jockey weights nor the weight positioning system have to be precisely calibrated. The weights are made from stainless steel to the usual specifications adhered to for force standard machines. It is advantageous if the drive system (in this case a ball screw spindle) shows good linearity, but this is no strict requirement. However, the drive system must be very repeatable, i. e. an indicated distance of weight travel must always coincide precisely with the distance its centre of gravity has actually moved.
The zero position is determined by a fixed value of the signal from the lever support hinges. This means that every time the machine is “tared”, the weights are moved to such a position as to give a pre-determined reading from the strain-controlled hinges.
In the commissioning process of the machine, transfer standards of force or torque which previously have been calibrated against a primary standard are then mounted and loaded in the machine. By comparing these readings with the initial calibration one can determine the linearity and span (sensitivity) error for each of the measuring ranges, i. e. jockey weights. The process is somewhat time consuming as a large number of transfer standards may be required, due to

the large total range of such machines. However, the required measurements are automated and can be run overnight.
From their results, correction values for linearity and span are calculated and entered into the software controller. The software uses these values in the normal operation of the machine to position the weight such that the applied force or torque generated coincides with the setpoint determined by the operator.
This sequence of commissioning measurements may be followed by a full inter-laboratory comparison. In so doing, it is possible to verify the uncertainty of the machine to a level of $1 \cdot 10^{-4}$ or even less, using an independent set of transfer standards, if required.
For a measurement uncertainty of $2 \cdot 10^{-4}$ or higher, an abridged procedure of linearity measurements is usually sufficient. This makes use of a smaller number of transfer standards and measuring sequences, and in mutual agreement with the end user, the results from these calibrations may suffice for the purpose of traceability, i. e. without a separate inter-comparison.

<u>Performance of a 3 kN·m torque standard machine</u>

In the following, typical results from a torque standard machine are given. Similar tests on a force standard machine are currently being carried out and are expected to show principally the same behaviour.
The results of a comparison measurement carried out with the PTB torque standard machines of 1 kN·m and 20 kN·m are given in Fig. 5. This shows the excellent performance under static conditions over a large torque range.

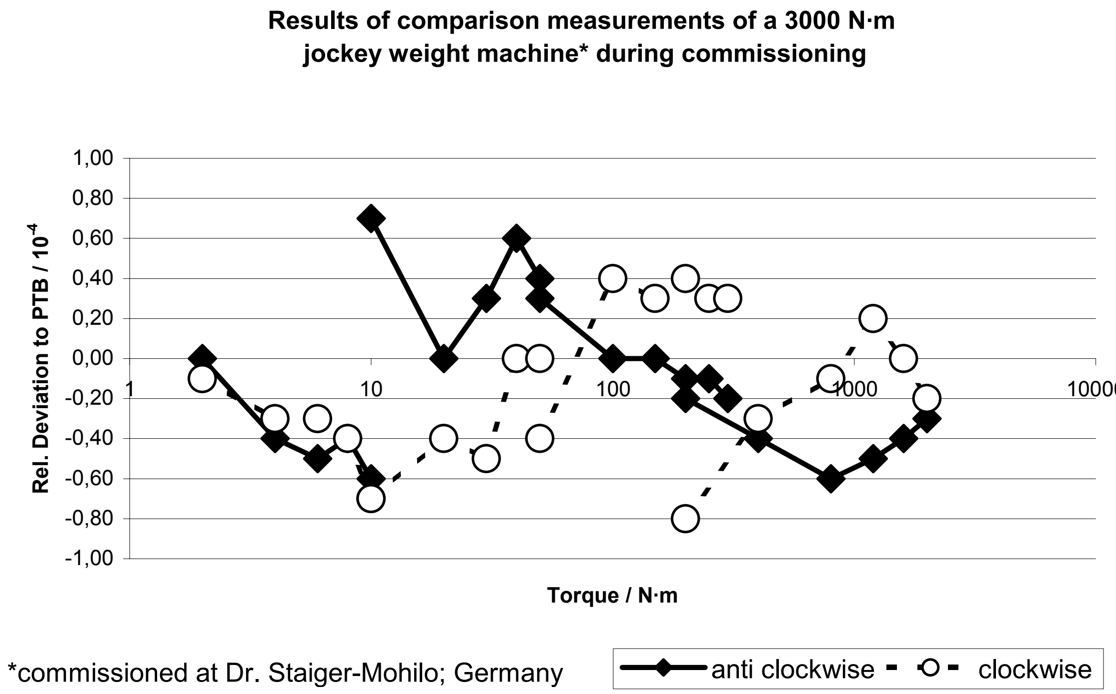


Figure 5: Results of comparison measurements of a 3 kN·m jockey weight machine during commissioning

To indicate the potential of the continuous mode, a torque transducer of 2 kN·m capacity was calibrated both statically and continuously with the machine.
The transducer was selected to exhibit very little creep, making its response essentially independent of time. From Fig. 6 it follows that there are only negligible differences between the two methods. The results gained under continuous loading exhibit somewhat higher hysteresis and a slight span deviation. Further research should establish the mechanism causing these changes in the transducer behaviour.

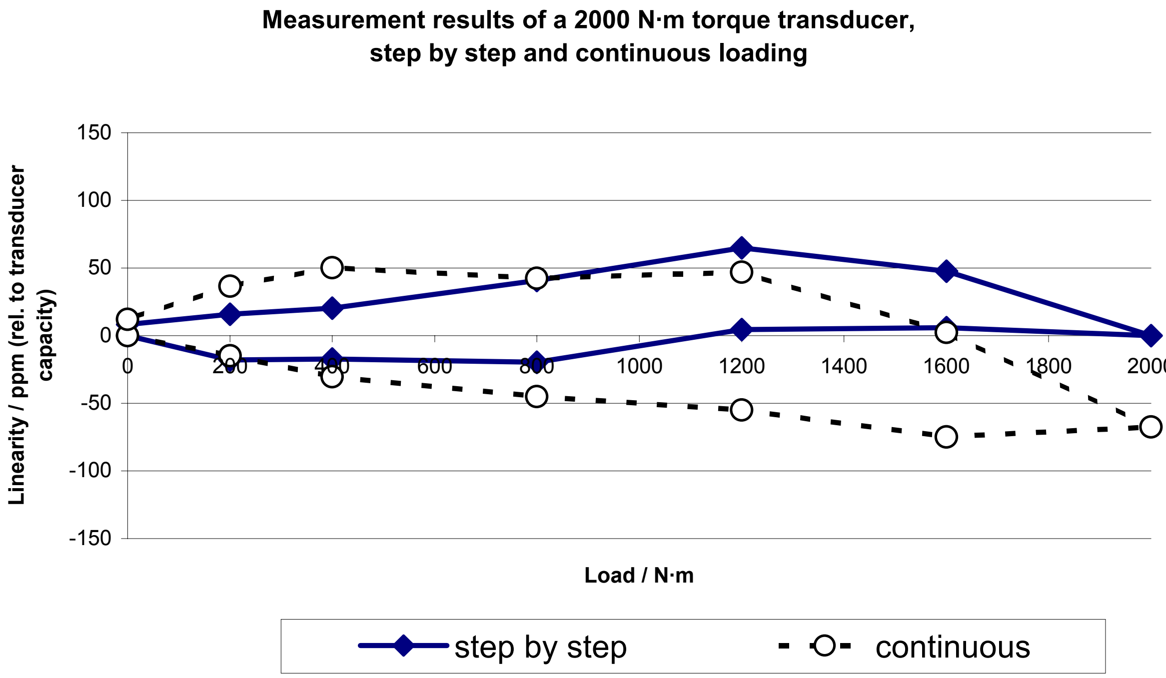


Figure 6: Measurement results of a 2000 N·m torque transducer, step-by-step and continuous loading

It is of particular importance to note that the overall calibration time required for the continuous test is only about 30% of a step-by-step calibration. Accordingly, in some countries the preparations of national standards to take such modern approaches into account have been called for. This follows from similar recent experience in the area of torque [1].

The effects of zero-point hysteresis (mechanical remanence) in torque transducers have been dealt with very thoroughly [5]. They cause the same problems in load cells, i. e. a large increase in measuring uncertainty, especially if the load is only a small percentage of the transducer capacity. Since alternating forces can be applied in a single test space with the jockey-weight machine (step by step or continuous with suitable mounting components), the remanence behaviour of force transducers can now be quantified. Fig. 7 shows test results of a 25 kN load cell tested with alternating loads using the arrangement displayed in Fig. 8.

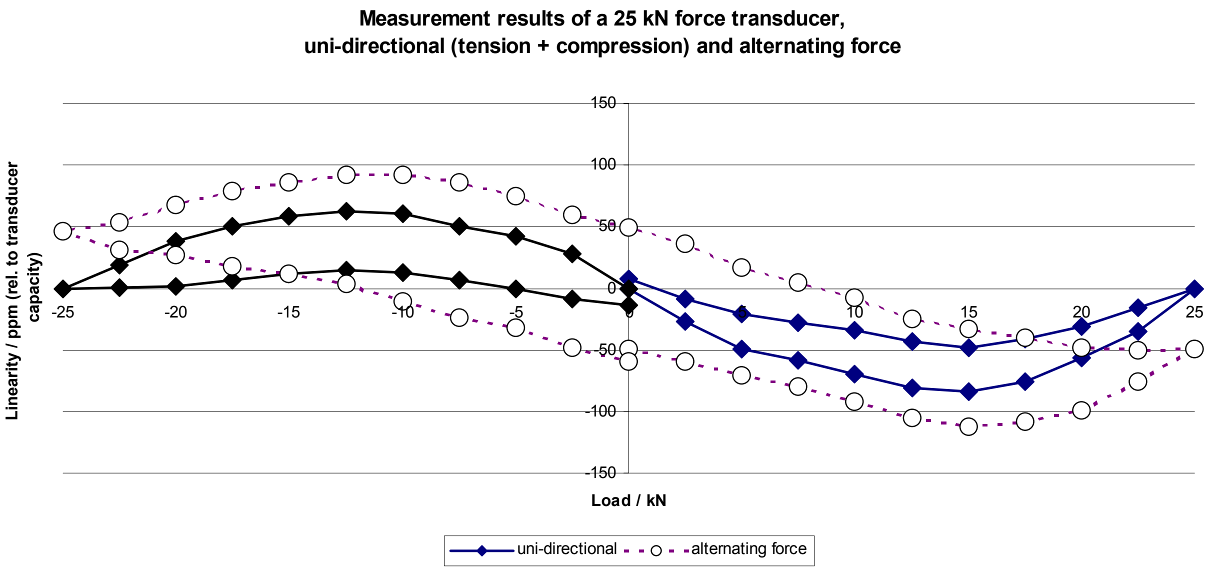


Figure 7: Measurement results of a 25 kN force transducer, uni-directional (tension + compression) and alternating force

Figure 8: Test setup for loading with alternating forces

It is clear from this that the behaviour of load cells under such conditions is basically similar to that of torque transducers. This will in future allow to quantify the added measuring uncertainty caused by load reversal, and benefit load cell development.

Conclusions

Based on well-established principles, the jockey-weight design of lever force and torque standard machines has already proven to be a valuable contribution to the various existing types. This is due to a number of new characteristics, which enable calibration work hitherto impossible to be carried out. Continuously increasing and decreasing forces, through zero testing in a single test space, and the potential for very small load steps all contribute to the possibility of a better characterisation of load cells and torque transducers:

- Jockey weight machines are the only type of force or torque standards which allow true continuous measurements. All other machines require some kind of reference transducer, which has to be calibrated statically, assuming that its continuous behaviour is the same. It is known that this is not the case, as creep effects usually depend on the rate of load change. Jockey weight machines allow traceability to the quantities of mass and length even under continuous conditions, and without time-dependent contributions.
- It is estimated that continuous calibrations will be possible with loading times (from 0 to 100 % load) of 10 seconds, and with measuring uncertainties not exceeding the corresponding values under static conditions.
- Various measuring amplifier systems have been identified which can be implemented for continuous measurements. These include DVM's as well as DC and AC strain gauge

amplifiers. However, in the same way as with static calibrations, the precise output of any strain gauge transducer depends on the conditions of excitation (magnitude of AC or DC voltage). Hence, large deviations can be expected if readings of static and continuous calibrations are compared, unless they were both taken with the same amplifier system.

- The reference devices as used for industrial calibrations, in the true sense of the metrological calibration hierarchy, will have to be calibrated initially against continuous primary standards if the final products are to be used for non-static applications. At present, the jockey-weight force standard is the only machine able to fulfil this function.

Although the jockey-weight design is by no means the only possibility to arrive at low capacities, its combined virtues suggest the application of the design to this task:

- The lever support and jockey-weight design easily allows nominal capacities of 500 N or even 100 N to be realised.
- The total force range of such machines can still be as high as 2500:1.
- There are no force application components, such as load frames (scale pans), to constitute a lower limit of load. This applies to tension and compression.

It is thereby possible to arrive at an automatic force standard machine for the calibration of Class 00 devices, at capacities of 1 N and even lower. If required, the other advantages of the design, such as continuous and through-zero testing can be maintained as well.

In conjunction with new test standards developed at present and in future, a dual approach to transducer calibration seems appropriate:
For transfer standards (force and torque) and load cells of mainly static application, and in particular devices used for comparison measurements of static calibration machines, the existing test standards and corresponding methods will remain satisfactory.
For industrial load cells and torque transducers, and indeed any device used in varying-load conditions, new procedures will be evolving in the future. These procedures require standard machines such as the one described here.

References

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