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A NEW DESIGN OF PRIMARY TORQUE STANDARD MACHINES

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Abstract: GTM have developed a primary torque standard which covers the range from 1 Nm to 1 kNm with a single load frame and only one weight stack per direction of operation. The design comprises a double-sided lever, supported on strain-controlled elastic hinges, a binary weight stack of exchange disk design for each direction, mounting accessories for the transducer under test and a counter-torque drive with servo-controller. Compared to conventional types with air bearings and a multitude of several stacks, the chosen design offers distinctive advantages:
Higher reliability of the lever support, less complicated auxiliary systems, easier method of operation, low overall height. Calculations show that the parasitic moment of the crossed hour-glass shaped springs for the lever support can be controlled to less than 10^{-5} Nm for a 1 kNm machine, and that the uncertainty of lever length falls within a 20ppm band, including the equality of both sides. Using the same principle of elastic hinges, the overall torque range can be increased to stretch from 0.1 Nm to over 20 kNm, with only two separate load frames.
Keywords: torque measurement, primary standard, deadweight

1 INTRODUCTION

Over the past few years, much focus was given to the establishment of torque laboratories and torque standards in NMI's [1, 2]. This has included standards of primary and secondary status of various designs and followed a period during which the physical quantity of torque was comparatively neglected, as opposed to, say, that of force.

As far as the primary standards of modern make are concerned, the most successful design is the horizontal lever supported on air bearings and loaded by deadweights, usually arranged in a stack. However, despite its success, there are at least some potential disadvantages: The air bearings are expensive, delicate in operation and maintenance, and allow no measurement of friction during a calibration cycle. Also, the weight connection to the lever may give rise to difficulties, due to the delicacy of its design and the fact that the setup may have to be disturbed when stacks are changed over.

On the other hand, solutions to overcome exactly these shortfalls had already been found in the area of deadweight and lever-amplified force standard machines. GTM have demonstrated many times that the support of a lever on strain controlled elastic hinges not only gives superior consistency and reliability over knife-edges but that the residual torque of the springs can be measured and controlled very precisely during the operation of such a system (GTM Patent EP 0487546). Furthermore, their design of a binary arranged mass stack (arbitrarily selectable disks), together with its elastic hinge connection to the lever, allows one to build a very compact stack to cover a large range of forces with only a small number of disks and without the need to change stacks.

For these reasons, it was obvious that the combination of the know-how from the force standard machines and the ready availability of Finite Element Analysis and Computer Aided Design within the company would lead the way to a novel and superior design of torque standard machine.

As early as 1995, the first prototype of such a system was designed and built, then still based on lever-and-jockey weights, but already using the strain controlled hinge lever support. It proved repeatable to less than 100ppm in the first instance and helped to highlight the design tasks to be solved in making a true primary standard. Since then, such systems have been commercially sold.

From 1996 onwards, a clear interest of many NMI's to acquire torque standard machines has been noticed, so that a number of concepts were drawn up to suggest possible solutions, torque ranges and accuracies [3]. The Swiss Federal Office of Metrology, the OFMET, was the first to accept the GTM concept of a primary torque standard with binary exchange stack and strain-controlled lever support, and on our experiences with the design, manufacture and evaluation of their machine this paper is based.

2 DESIGN OF THE 1 kNm TORQUE-STANDARD MACHINE

2.1 Specifications

L x W x H: 2570 x 1900 x 1700 mm
Working space: 500 mm diameter (max), 200 to 900 mm long
Torque range: 1 Nm to 1100 Nm, in steps of 1 Nm, cw and ccw operation
Measuring uncertainty: <250 ppm at 1 Nm, linearly decreasing to 50ppm at 10 Nm
<50 ppm from 10 Nm to 1100 Nm
Lever length: 500 mm per side

2.2 Main frame

The machine is of welded and bolted steel construction, floor mounted without the need for special foundations due to its low height and weight. Viewed from the top (Fig. 1), it is of T-shape due to the two major axes joined at right angles: The axis of the transducer and the lever axis. One end of the former consists of the lever fulcrum point, itself being formed of elastic hinge supports, and the other end has the counterbalancing torque drive attached. In the gap in between, the machine bed has attachments fitted which allow easy levelling and centring of the transducer under test prior to and during it being mounted.

The front view (Fig. 2) shows the levelling base-frame, stack arrangement and auxiliary drives.

2.3 Lever

The main lever is of ferritic steel construction, consisting mainly of a tubular square section of about 1350 mm length. To it are bolted three sets of strain controlled hinge supports, one at its centre and one each at exactly 500 mm distance from the latter.

As the temperature control at the site of erection is outstandingly good, rarely departing more than a few tenths of a degree from 20°C, mild steel was taken as the most suitable material, giving good dimensional stability, low thermal expansion, good machineability and low cost. To protect it from corrosion, it is chemically nickel plated.

Care was taken in the mechanical design of the machine such that no face-to-face proximity occurs between any part of the lever and any other mild steel component. In order to avoid effects from influences of magnetic forces, all adjacent components were made from non-magnetic materials. Minimum distances to all the other parts made from mild steel were observed, these being 30 to 100 mm. Furthermore, the lever was de-magnetised prior to assembly.

The overall lever length of 1000 mm is adjusted by means of measuring the distance between the centres of the elastic hinges which form the couplings to the weight stacks. This was done on a coordinate measuring machine, traceable to the Swiss standard of length. The necessary mechanical adjustments to achieve this were carried out by means of inserting a special gauge together with slip gauges of suitable combination between specially machined faces of the hinges. This gauge combination may be inserted at any time even after full assembly of the machine, thereby verifying that the lever length is still correct.

In order to arrange the central elastic hinge support at the exact centre of the lever, a balancing operation was carried out after final assembly. This is the usual iterative method of initially balancing the lever by adjustment of a tare weight on one side, then loading both sides with exactly the same torque (by adding identical mass disks to the coupling of each side), finally moving the fulcrum point such that the lever is balanced again. This process is repeated until the lever does not tilt to either side when equal weights are added to both sides. A mechanism to allow µm-movements of the central elastic hinge support relative to the lever proper has been incorporated to achieve repeatable adjustment.

2.4 Strain controlled elastic hinges

The theory of the balanced lever is, of course, that the bending moment generated by the weight times the lever length is balanced exactly by the torque carried by the transducer under test. Provided the values of the weights are known, then the precision of the torque is determined by two quantities: The lever length and the amount of torque by-passing the transducer into the frame, the so-called torque-shunt. As long as nothing except the elastic hinges touches the lever, the only source of torque shunts are the latter, which in turn obviously also determine the active lever length.

The lever is carried by two pairs of hour-glass shaped flexure strips, one at each side of it and each pair consisting of two similar strips arranged at right angles (Fig. 3). At each end of the lever, a similar flexure strip is arranged to connect to the weight-carrier rod (Fig. 4). All of them are strain gauged, the application and wiring being arranged such that the so formed Wheatstone bridges are sensitive to bending moments with respect to these elastic hinges. Side effects such as cross-talk have been adjusted and compensated in the manufacture of these sensors, so that their signals are unaffected by any forces except moments around the fulcrum axis of the lever. In terms of resolution, the combined signal of the springs is about 2 mV/V for a torque of approximately 0,5 Nm, so that changes of 10^{-5} Nm can be well detected with the precision amplifiers used.

In other words, any bending moment acting on the lever will be measured by one or more of these bridges, and the net bending moment applied (except that of the weight times the lever length and the torque of the transducer under test) is exactly proportional to the sum of the signals of the six strain-controlled joints.

From this follows the principle of the machine: The torque on the transducer under test is equal to the weight applied to one side of the lever, multiplied by one-half of the distance between the elastic hinges supporting the connection rods, minus or plus an amount of torque proportional to the summed-up signals of all strain-controlled joints. If a controller governs the lever position such that this sum is zero, than the equation reduces to: torque = weight times lever length.

2.5 Binary exchange mass stacks and self-checking routine

The stainless steel mass stacks left and right are identical and conform to OIML R111 for F2 weights. They consist of 12 independently selectable masses spaced according to the geometric series 1; 2; 4; 8;..., the smallest of which being adjusted to 2 N, and each to within 5ppm or less of its nominal value, of course taking effects of air buoyancy and local gravity into account. Thereby it is possible to generate each torque from 1 Nm to 1100 Nm in steps of 1 Nm by selecting the corresponding discs.

There are two locations for each of them, between which they are moved by pneumatic actuators: supported on the main frame of the machine or hanging on the coupling rod. Care was taken to design the weight supports in a way to make them statically determined. In conjunction with the weight actuator mechanism, which is adjustable in speed and speed profile, a very smooth change-over of disks is achieved.

The uppermost, smallest weight of each stack is actually available twice, and one of them can be taken off the machine relatively easy for re-calibration. If required, all other masses can be verified *in situ* by the following self-calibration method: A reference torque transducer of suitable capacity is mounted in the machine, and after due warm-up and exercising loaded with the 1 Nm torque step. Without taking the load off, the first 1 Nm mass is replaced with the second one, and after balancing the lever, the readings for both disks are compared, in effect allowing one to compare the weights of the two disks. Assuming that the second one was in order, the transducer is now loaded with 2 Nm, using both 1 Nm disks together. Then, in the same manner as before, they are replaced with the 2 Nm disk, which enables the comparison of its weight to the combination known to be accurate. In this manner, each disk of each stack can be verified against the "master" 1 Nm mass disks.

2.6 Torque balancing drive

The principle of the machine as described above relies on the fact that the lever position is controlled such that the combined signal of the strain gauged springs is zero. In order to achieve this, a drive mechanism is installed at the non-measuring side of the transducer under test, which is able to build up counter-torque in both directions and allows very fine control of its magnitude.

It consists of a lever, attached to the device under test, and arranged to point vertically downwards, which is loaded at the other end by a servo-controlled ball-nut spindle unit. Springs are arranged between the lever end and the ball-nut, so that the resolution of the servo-control is enhanced, in other words more revolutions of the spindle are needed to produce a certain amount of torque (Fig. 5). In the normal operation mode of the machine, the counter-torque drive is the actuator device of the closed-loop servo controller, producing just the right amount of torque to keep the lever in its position as detected by the elastic joints.

Since in this way relatively large torques can be produced with relatively small and well-controllable motors, and adjustment of torsional stiffness is easy by simply selecting the right springs, this design was given the preference over a large direct-drive gearbox with a much more powerful motor and the inherent inflexibility of this arrangement.

2.7 Transducer coupling

In this matter, the designers owe a great deal of insight to Dr. Peschel of PTB, Braunschweig [4], and his guidelines were followed throughout. Several years of his research have revealed that for high-precision torque measurements, only the hydraulic clamping bush together with the BSD-Thomas coupling will give satisfactory, reaction-free transducer mounting and repeatable and comparable results.

Therefore, the torque transducer under test is arranged between two precision-machined bores, into which it is clamped by means of hydraulic expansion bushes of suitable size. Precision-machined slotted steel bushes allow the adaption to different size shaft ends. The precision bores mentioned above, in turn, are connected to the machine via two flexible steel couplings of the BSD-Thomas type, which have a relatively low bending and axial stiffness, whilst their torsional stiffness is high and the central alignment very precise.

This yields low bending moments and axial forces, caused by unavoidable minute misalignments, and acting in parasitic manner on the transducer under calibration. The success of this method will be verified by the use of a six-component transducer, also a GTM development, which allows to measure all forces and moments acting whilst a calibration run is carried out.

2.8 Load change sequence

Assume that a transducer of 50 Nm nominal torque was mounted in the machine, and loaded to 20 Nm by lowering the 16 Nm and the 4 Nm disk onto the coupling rod and bringing the lever to its neutral position with the counter-torque drive. The command to increase the torque to 25 Nm stops the control loop of the counter-drive and keeps the position of the corresponding lever fixed. An adjustable stop is brought into contact with the main lever, which causes a small increase in torque on the transducer. By combined action of the controllable stop and the springs between counter-drive and lever, this increase is typically less than 0.5 Nm. In other words, the torsional stiffness of the whole setup is such that a deflection of some 0.1 mm at the lever end leads to a torque change of some 0.1 Nm.

If now the 4 Nm disk is taken off, the torque on the transducer is kept constant by the simple fact that the lever presses against the stop somewhat harder, in this case by about 8N.

In order to produce 25 Nm torque, both the 8 Nm and the 1 Nm disks are lowered onto the coupling rod, thereby pulling the lever away from its stop. The closed-loop control of the counter-torque drive is activated again, the stop travels to its neutral position, and the transducer is loaded with 25 Nm once the controller has balanced the lever. In so doing, the maximum torque of 50 Nm is reached step after step, the latter consisting of the 32 Nm, 16 Nm and 2 Nm disks.

When the machine is supposed to reduce the torque to 45 Nm, again first of all the counter-drive is stopped, keeping the auxiliary lever fixed in position. The adjustable stop now travels towards the main lever, but stops several 0.1 mm before actually touching. This is measured with a non-contact laser displacement transducer. When now the 16 Nm and the 2 Nm mass disks are taken off the coupling rod, the lever travels upwards exactly this distance and makes contact to the stop. Further reduction of the torque is not possible, even if all the disks were taken off, as their action would be taken over by the stop. At this moment, the mass disks of 8 Nm, 4 Nm and 1 Nm are lowered onto the coupling rod, but as the torque is smaller than before, the lever remains tight against the stop. Only when the counter-balancing controller is brought into action again, the lever (and the stop) are both moved back into their neutral positions, leaving exactly 45 Nm on the transducer.

A typical torque-time-diagram of such a switchover is given in Fig. 6. It has to be said that although the machine is capable to produce any **torque value** from 1 Nm to 1100 Nm in steps of **1 Nm**, **torque changes** of the described manner are possible within the following ranges:

From 1 Nm to 30 Nm in steps of **1 Nm**
From 30 Nm to 1100 Nm in steps of **5 Nm**

This is due to the design of the spring boxes between spindle drive and counter-lever, which in order to give a manageable length of travel, were designed in a two-stage arrangement. This is of no practical concern, since there is rarely a need to load a transducer of 1000 Nm capacity from, say, 567 Nm to 568 Nm.

2.9 Electronics and PC

As with all GTM machines, the dual philosophy of machine controllers is followed (Fig. 7). There is a PC, with corresponding graphic interactive user interface software, which the operator deals with in day-to-day use. Called TorqueManager, the operator uses it to select transducer capacity, direction of rotation, amplifier options, load steps and many more commands by a mouse-click. Whole test sequences can be pre-programmed and stored, together with transducer and test details and sets of test results. The data acquisition from certain precision amplifiers is also a function of the TorqueManager.

On the other hand, all the actual machine operation, the liaison with all the electronic hardware, such as motor controller, sensors, measuring amplifiers for the strain gauged joints etc. is carried out by a programmable logic controller (PLC) together with its corresponding software. The user never interferes with this part, once the machine is commissioned all the functions described are performed in the background. In the case of malfunctions or faults, communication is entirely through the TorqueManager, which would in such circumstances display error messages or prompt the operator to carry out actions as required.

2.10 Possibility of continuous calibration (indirect comparator principle)

The joint action of various sub-systems of the machine also allow one to continuously calibrate torque transducers, i.e. without discrete torque steps, but by a steadily increasing and decreasing torque, whilst simultaneous readings are taken at exactly the same times, of both the transducer under test and a reference transducer.

In order to do so, reference transducers of 30 Nm and 1100 Nm, respectively, are in-built into the machine's counter-torque drive. They stay in the torque path all the time, whereby the smaller one is protected against overload by the action of a mechanical by-pass. When a dummy shaft, or indeed a torque transducer of sufficiently high capacity is mounted, they may be calibrated statically against the deadweights, their calibration data being stored in the PC.

If the dummy is now swapped for the sensor to be calibrated continuously, the main lever is simply blocked in its movement by the adjustable stop, and the torque on the system is steadily increased up to the nominal value, and then decreased again by the counter-torque drive. While this happens, the signals of both the reference and the transducer under test are taken synchronously and stored in the PC. Since the calibration data of the former are known, elimination of this variable leads to the correlation between test transducer reading and applied torque. Applications for this method have yet to be explored, it is believed to be of value for quick calibrations of low-precision transducers, with accuracies of 200 to 500 ppm of reading.

It should be noted that exactly synchronous readout of the two transducers is essential in order to achieve valid results. Therefore, GTM have developed special PC plug-in cards for this purpose, which fulfil this requirement whilst also achieving superior stability, resolution and measuring uncertainty. Two versions are available, called PC-DMS and LWL-DMS, the latter allowing synchronous readout of a very large number of channels (systems with 100 channels have been built) via an optical bus.

3 ESTIMATION OF THE MAJOR COMPONENTS OF UNCERTAINTY

3.1 Force

All the weights were adjusted in the mass laboratory of the OFMET, to within less than 5ppm of their nominal value. The latter was calculated using the known local gravity (9,8058849 m/s^2 +/- 0,0000002 m/s^2), the density of the weights (7903,5 +/- 0,5 kg/m^3...7937,5 +/- 0,5 kg/m^3) and an air density (1,068 kg/m^3 +/- 0,002 kg/m^3 ... 1,188 kg/m^3 +/- 0,002 kg/m^3), which will constitute the major part of the uncertainty to the generated force. The temperature change in the laboratory (well under +/- 1 K) may be neglected for these considerations.

The total uncertainty of force, using the linear addition of error spread, follows from that to be less than +/- 13 ppm.

3.2 Lever length and fulcrum position

By means of access holes in the main lever, it was possible to measure the distance between the centres of the elastic hinges with a 3-coordinate measuring machine. This device is available at the OFMET's length department and traceable to the national standard. The uncertainty of these measurements is about +/- 0,010 mm, and after final adjustment the value was 1000,010 mm. The major effect on this quantity is temperature, the steel used having a linear coefficient of thermal expansion of 10.5 ppm/K. Since the temperature control in the laboratory works exceptionally well, +/- 0,2 K seems a safe margin, and therefore +/- 10ppm is taken as the uncertainty of the lever length caused by temperature deviations.

The precision with which the fulcrum position was adjusted follows from this consideration: Sensitivity and resolution of the signal of the combined strain controlled support springs means that a residual torque of 10^{-5} Nm can be detected with certainty. In the balancing operation to establish the fulcrum point to, the two identical weights of 16 Nm were used. This means that per 1 µm out-of-centricity, $6.4x10^{-5}$ Nm net torque were produced, well detectable with our sensing method. The adjustment was carried out until no noticeable signal change occurred in loading both sides of the lever, which leads us to claim that the eccentricity of the fulcrum position is less than 1 µm, probably much less. This context was verified after final setting at loads of up to 1100 Nm per side, indicating that the deflection of the structures was sufficiently symmetric to be sure of the fulcrum point being correct even at high loads. In any rate, to allow for possible asymmetries beyond our means of recognition, a maximum fulcrum point deviation of 1 µm is assumed, giving rise to an additional uncertainty of 2 ppm of lever length.
The maximum uncertainty of a single lever side is again taken as the linear sum of these, amounting to +/- 17 ppm.

3.3 Torque shunts

Here, the magnitude of residual torque of the lever support springs after balancing the lever to its neutral position is being discussed.

Observations have shown that under all circumstances, modes of operation and applied torques, the maximum residual torque indication of the combined output of all springs is never more than $0{,}2x10^{-4}$ of the rated output, or about 100 µNm. Depending on the applied torque value this gives rise to the following approximate additional uncertainties of torque:
1 Nm : +/- 100 ppm
5 Nm : +/- 20 ppm
>10 Nm :<+/- 10 ppm
It is clear that although being a relatively high contribution at very low torques (incidentally the reason for quoting larger uncertainties in the specifications), this influence diminishes very quickly with higher torques, being almost negligible at 10 Nm and certainly above 20 Nm.

3.4 Overall uncertainty of applied torque

Once again assuming worst case conditions, i. e. linear addition of errors, we expect the uncertainty of applied torque to be:
1 Nm : +/- 130 ppm
5 Nm : +/- 50 ppm
>10 Nm :<+/- 40 ppm,
i. e. the sum of weight error, lever length error and torque shunt. As the error components are not usually acting all in the same direction, and at their full magnitude, and as some of them could be corrected by measurement and calculation (like the air density contribution), the precision of the machine should be easily within its specification.

3.5 Parasitic forces and moments

Again in this chapter, grateful reference is made to Dr. Peschel of PTB [4], who has identified the margins of parasitic quantities, in torque standard machines, below which their effects on the measuring results of the transducer under test can be neglected. In his view, bending moments under 1% of the transducer capacity and lateral and axial forces in the range of some Newtons cause only insignificant contributions to the measuring behaviour of the device.

GTM have acknowledged the importance of this issue and built the machine to very high standards of precision, such that all sources of misalignment, the cause of parasitic forces, were minimised. Beyond that, a special transducer was designed and manufactured which allowes to measure all six components of the force/moment vector to be measured *in situ*. The results of these investigations will be given as soon as the relevant experiments have been conducted.

4 TEST RESULTS OF OFMET MACHINE

Since the machine has only been installed for a short period of time, only limited tests have been carried out so far. Some of them took place during the installation and commissioning, some others were performed at the GTM factory before the delivery, during the initial assembly.

First, the basic repeatability of the machine was verified by applying the same torque 10 times to a reference transducer, which was previously mounted and pre-loaded with due care. Torque steps of 100 Nm up to 1000 Nm were selected, the results of these tests indicate a basic repeatability of 10 to 20 ppm. The same values apply to similar tests, in which the loading took place in a step-wise fashion from 10% to 100% of transducer capacity.

Shortly, it is planned to carry out a full intercomparison of the machine against the standards of the PTB. For this, reference torque transducers will be selected according to a low error of repeatability in changed mounting positions, and the results of this investigation will be published separately.

In order to verify the validity of the assumptions regarding the load change sequences, the outputs of suitable reference transducers were recorded over time during a change of torque took place, in the ascending as well as in the descending directions. A number of such torque-time plots were obtained, a representative one was given in Fig. 6.

5 DESIGN DERIVATIVES

The 1 kNm system described so far was designed and built to fulfil a customer specification, as it seems that machines of this capacity are of major interest to NMI's at present. The total range of primary torque standards is much wider, however, and probably covers values of 0.1 Nm to 20 or 25 kNm. In order to extend an existing installation of a 1 kNm-machine to this range, two additional frames and weight stacks are needed, adding to a total of three machines.

However, with today's experience on strain-gauged supports for lever deadweight machines, it seems possible to cover the mentioned torque range with only two machines, provided one gives up the idea of having a 1 kNm type.

According to the law of the equally spaced ranges, it would be more favourable to lay the breakpoint at 50 Nm, thereby each machine covering a range of 500:1. With a range of 1000:1 already proven, this should lead to a very economic installation. (Alternatively, if the ranges are stretched to 1000:1, putting the breakpoint to 100 Nm, a significant amount of overlap would be achievable between the two machines, i.e. 20 to 100 Nm.)

A second issue are machines for secondary standards. These would utilise one or a number of torque reference transducers, in a similar arrangement to that already employed in the 1 kNm type, i. e. permanently in line with the test transducer and protected against overload by mechanical stops. Two options are possible: The simpler one uses reference transducers only, which have to be calibrated in a primary standard machine, and which have to be removed for re-calibration from time to time. The second, more sophisticated design avoids just that, by means of a small number of deadweights, which can be applied by hand whenever a re-calibration is required. It is proposed here that only weights for the full capacity of the relevant transducers are used, and that the characteristics of these (i. e. linearity and hysteresis) are measured in a primary standard machine initially before assembly. The only parameter of such a transducer likely to change over time is its sensitivity, which can be measured with a single weight. The shape of the error curve is known from the primary calibration and will be the same all the time, provided no mechanical damage occurs to the sensor.

For uncertainties in the region from 100 to 250ppm (in ranges of 1% to 100% of machine capacity), secondary or semi-primary standard machines according to these principles will offer cost-effective and reliable means of torque transducer calibration.

6 CONCLUSIONS

It has been shown clearly in the above considerations that highly precise and reliable primary standards of torque can be built on the strain-controlled lever support design, very much similar to the already established lever force standard machines. 50ppm measuring uncertainty from 1% to 100% without the use of air bearings and a total range of 1000 to 1 within a single weight stack have been achieved at the first instance, demonstrating clearly the soundness of the concept and the potential for future installations.

The design principles and details are easily understood from technical mechanics and elements of mechanical engineering, following the good practice employed by GTM so often in the field of force standards. All important quantities and possible sources of error are transparent and measurable, so that the equipment is easy and reliable to use with confidence. The electronic systems and user interface also maintain the standards set out in the many NMI installations the company has produced over the years.

To sum it up, the primary torque standard machine has been moved on from a laboratory setup designed and built by scientists with all its implications, to a commercially available piece of equipment which can be specified and ordered to agreed standards, in the same way as force standards, transducers and electronics.

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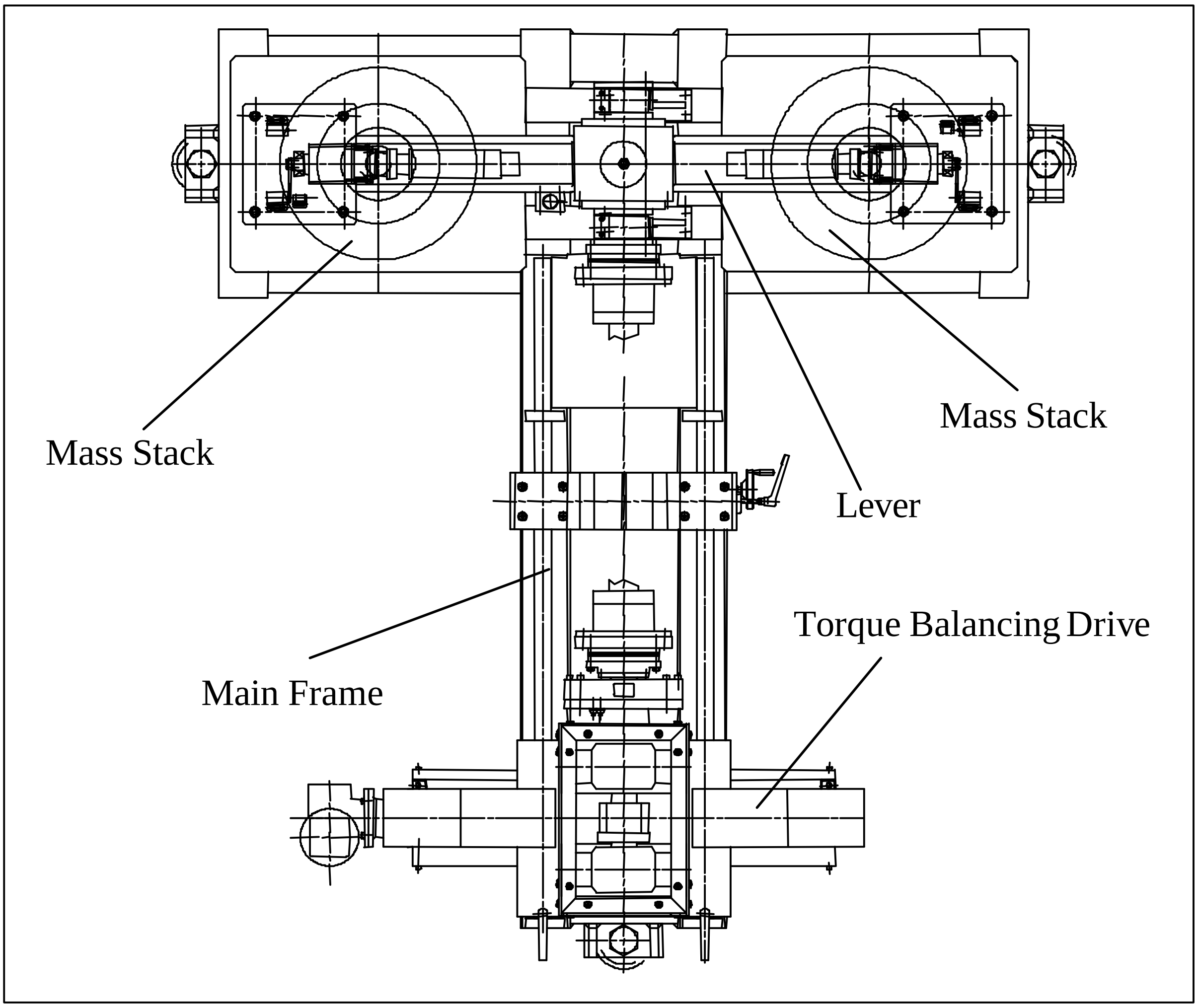

Figure 1. Top view of the 1 kNm Torque-Standard Machine

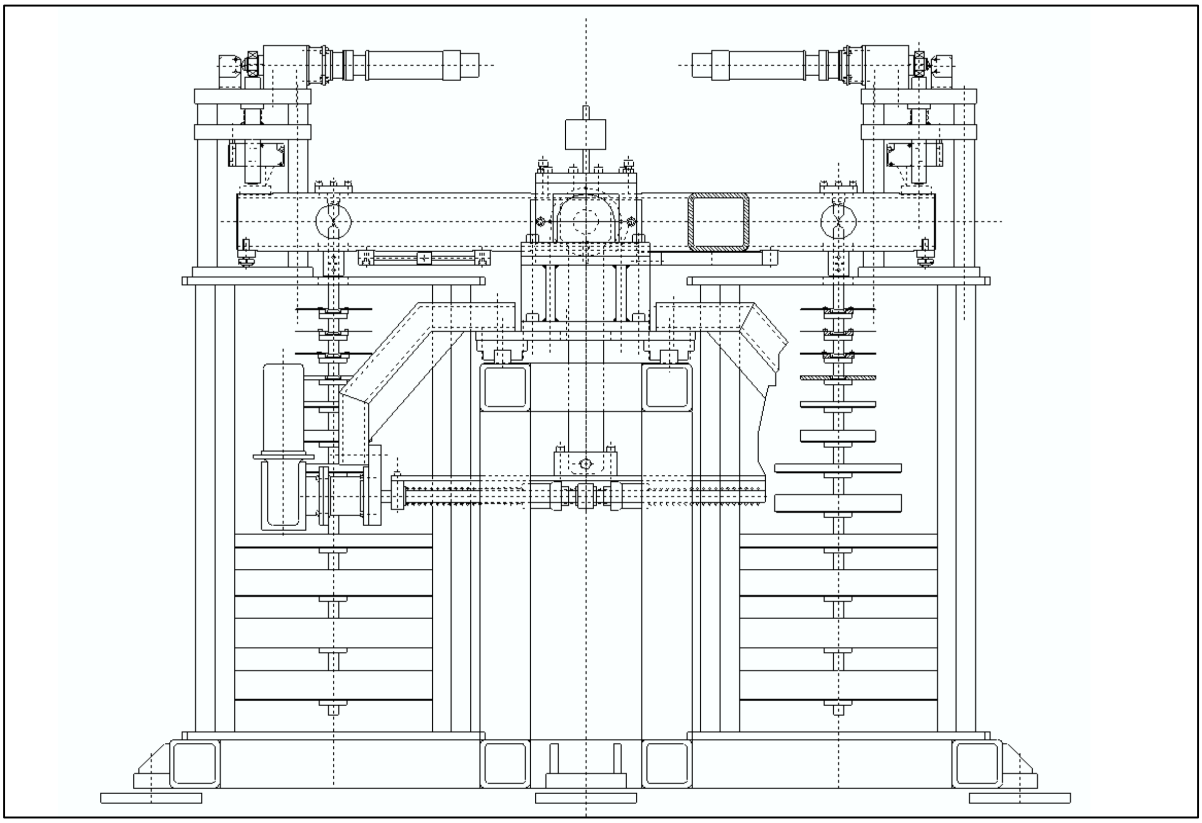

Figure 2. Front view of the 1 kNm Torque-Standard Machine

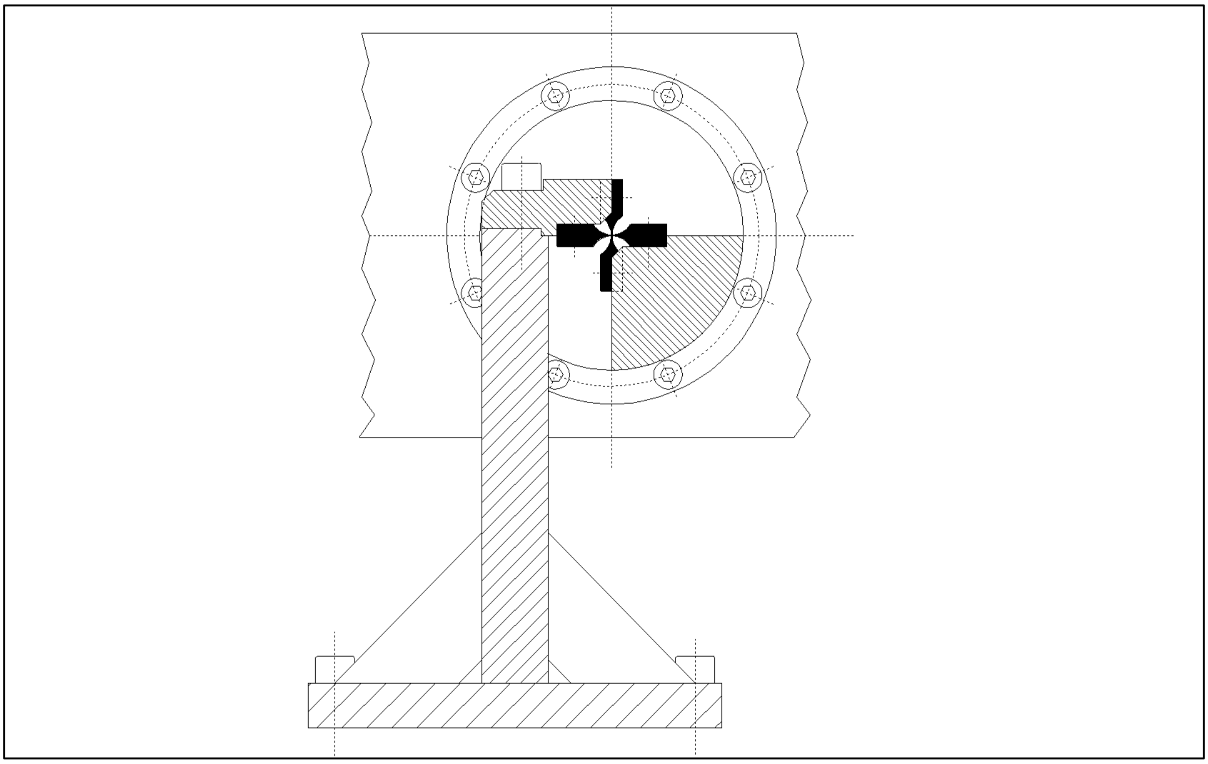

Figure 3. Crossed-hour-glass shaped flexure strip (strain controlled elastic hinge)

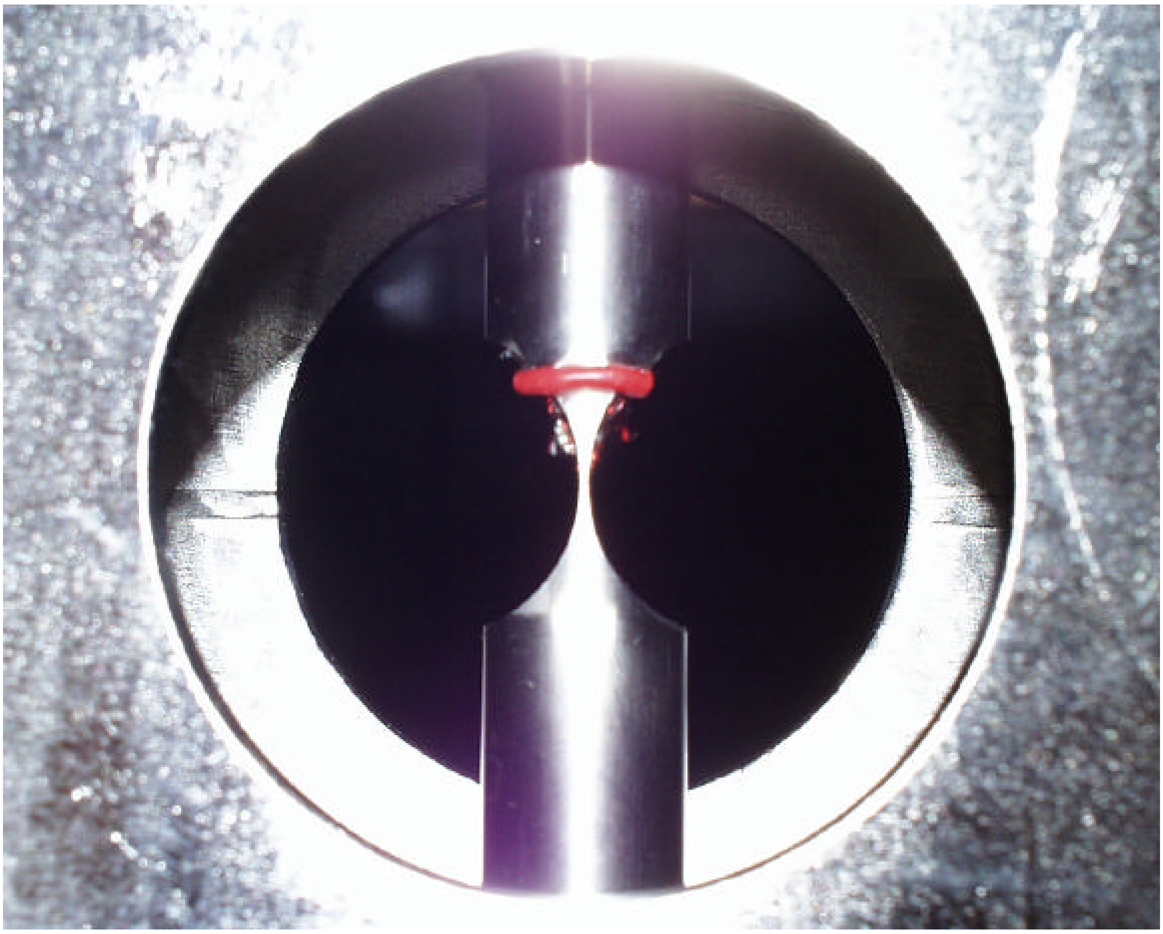

Figure 4. Flexure strip to connect lever and weight-carrier rod (strain controlled elastic hinge)

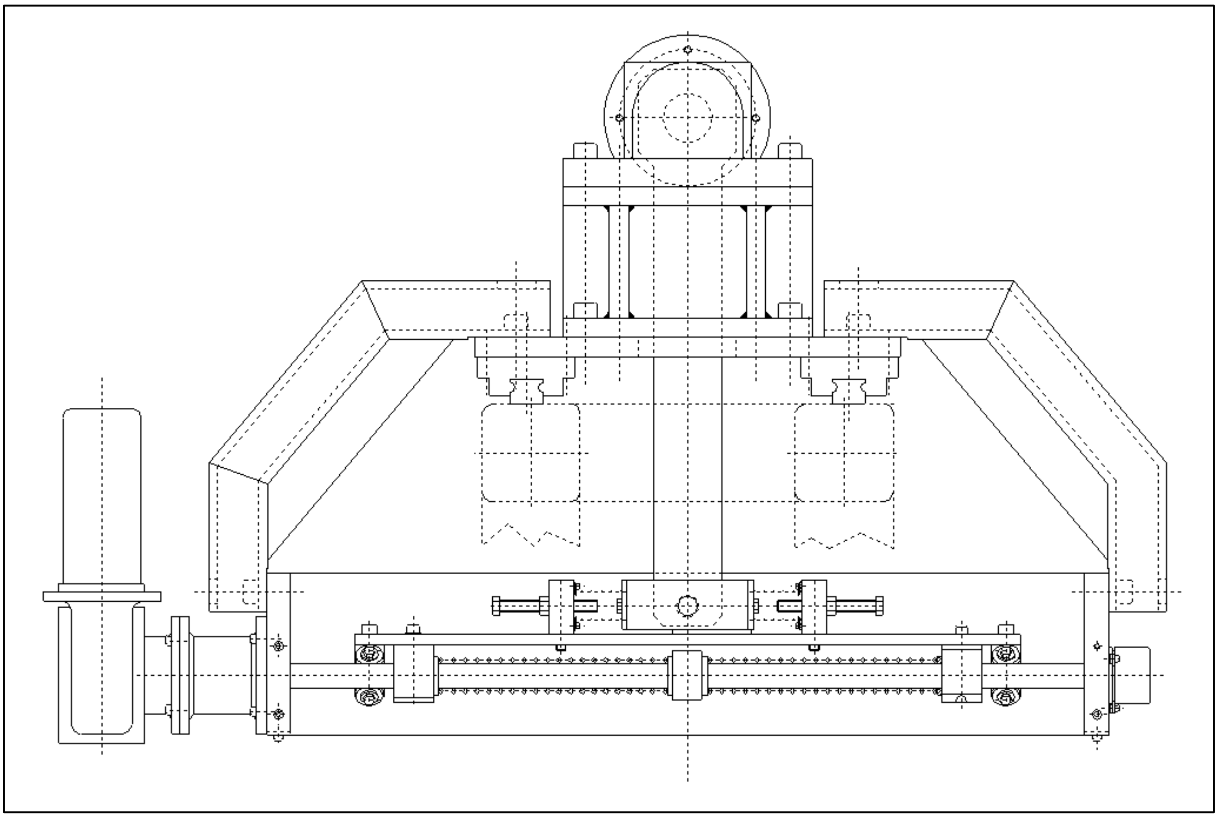

Figure 5. Torque balancing drive

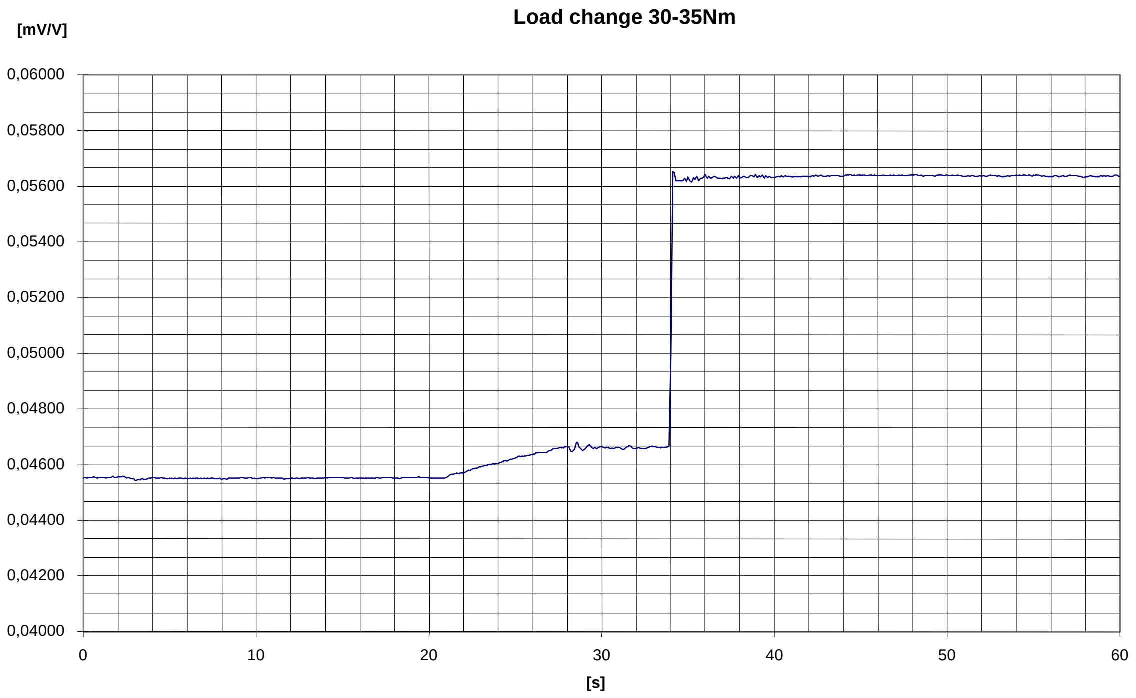

Figure 6. Torque-Time Plot

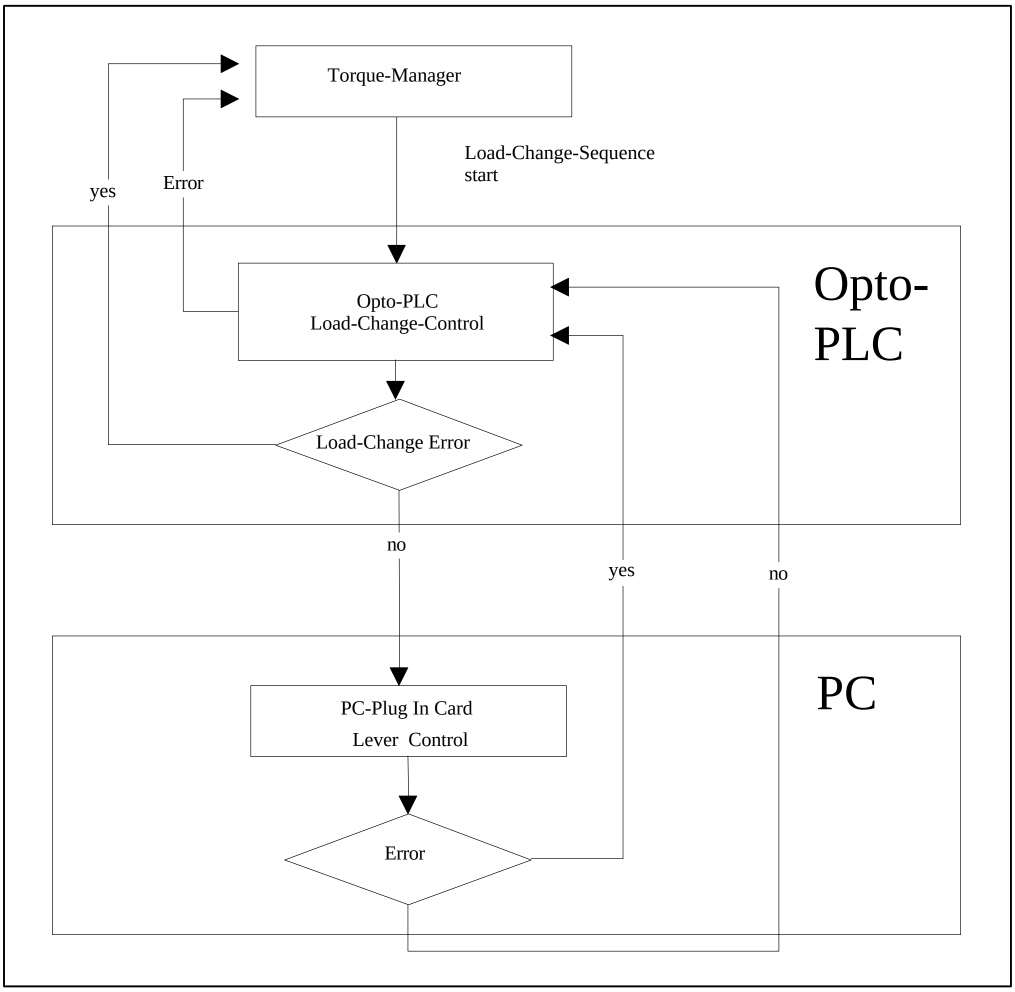

Figure 7. Electronic Machine Control