THE NEW 1.1 MN·m TORQUE STANDARD MACHINE OF THE PTB BRAUNSCHWEIG/GERMANY

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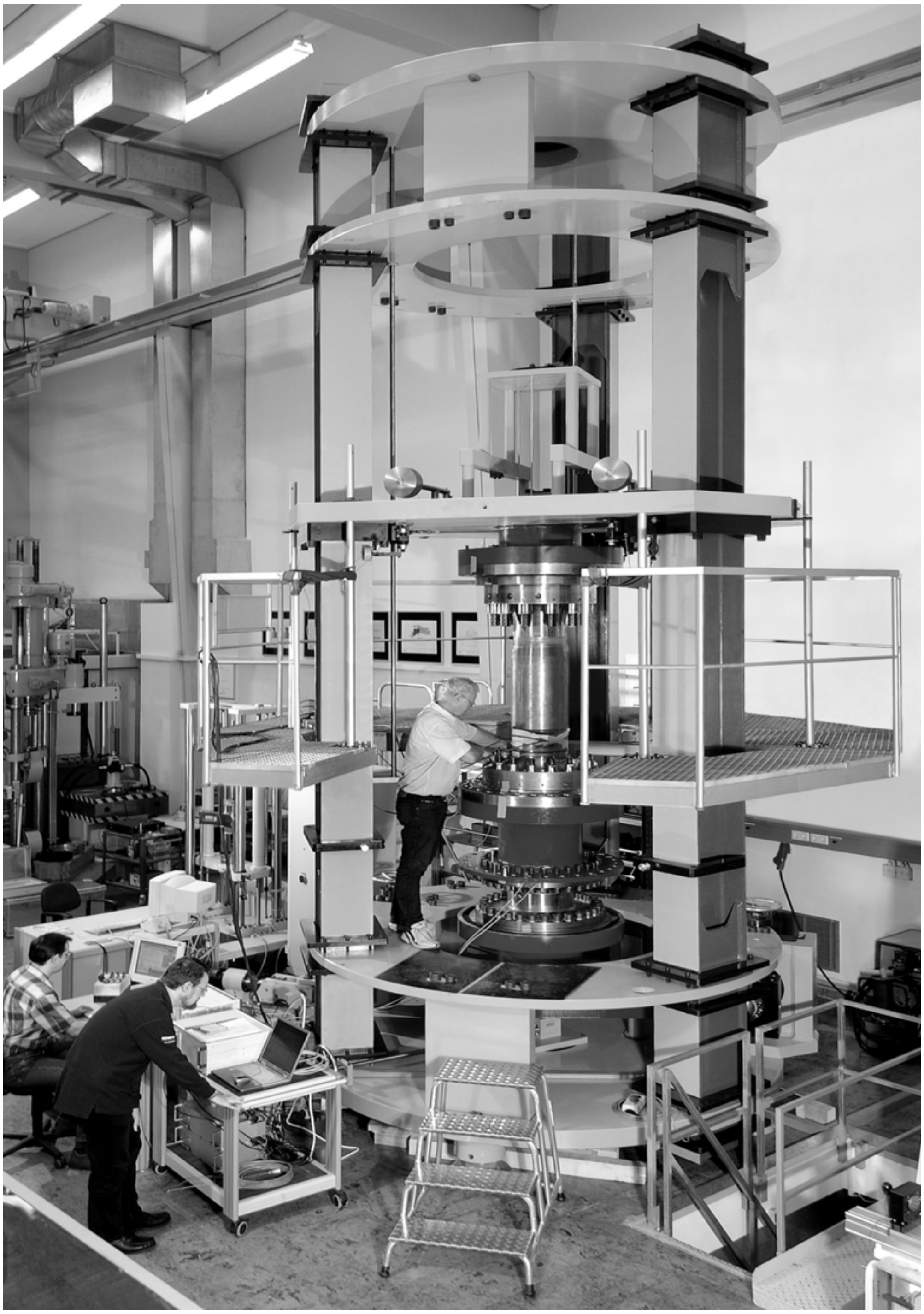

ABSTRACT

Until 2003 it was impossible to perform traceable calibrations for torque measuring systems above applied torque values of 200 kN·m anywhere in the world. Up to this figure such calibrations are possible at LNE/Paris. This is despite the fact that a number of applications with considerably larger torque values are known (energy generation, shipbuilding etc.). In addition there are requests for calibrations above the largest measuring range so far available at the PTB (20 kN·m), as realised with a deadweight torque standard machine (20 kN·m TSM) acting on a double-sided lever arm supported in an air bearing.
In 2002/2003, a new torque standard machine with a capacity of 1.1 MN·m was constructed and manufactured by GTM Gassmann Theiss Messtechnik GmbH in co-operation with the torque laboratory of the PTB. In 2004, initial evaluations and the analysis of the measurement uncertainty were concluded. First calibrations were already performed in May/June 2004.
The machine has a vertical test axis and the effective torque is determined by means of force transducers acting on a double-sided lever arm. Parasitic bending moments and transverse forces, which cannot be entirely avoided, at the locations of the force transducers are measured by strain-gauged bending joints. These disturbances are partly controlled by additional drives and partly electronically processed to correct the measuring signal. This allows to abandon the principle so far applied – i.e. the reduction of parasitic quantities by use of metallic multiple disk couplings which are torsionally stiff and flexible in bending – and to rigidly couple the object to be calibrated. Measurement of the mechanical parasitic quantities during loading and reducing them to a negligible amount with respect to the measurement uncertainty allows the system to be used as national standard with sufficiently small uncertainty of measurement. The aim is to achieve a value of 0.1 % ($k = 2$) in the measuring range from 5 kN·m to 1100 kN·m.
There are further requirements which call for a reduction of the measurement uncertainty in the measurement range up to 100 kN·m which will be dealt with in future.
The paper gives an overview of the design, construction and first results of the investigations into the measurement uncertainty.

1. INTRODUCTION

Measurements of torque are required in many different areas of industry, research, safety engineering, technical monitoring, medical technology, handicraft and others. In order to achieve the necessary measuring uncertainty calibrations which are traceable to national standards are required. It is the duty of the national institutes of metrology to provide these standards. However, limits are frequently reached due to the fact that the measuring ranges demanded by industry cannot be covered because of a lack of financial and personnel capacity.
Therefore the torque laboratory of the PTB has spent over 10 years on development and procurement of measurement equipment, so that more than 90 % of the user requirements could be performed in the past.
Frequent enquiries for calibrations at torque levels of 50 kN·m and more as well as 1 N·m and down to a few mN·m resulted in the necessity to complete the torque scale by adding standards for these measuring ranges. A direct loading machine with air-supported lever-mass system and a nominal torque of 1 N·m is at present being commissioned.

In 2004 the other end of the torque scale was completed by the installation of a standard machine with a capacity of 220 kN·m in the measuring range 1 and 1100 kN·m in the range 2.
The design uses strain controlled elastic hinges [1] for the transmission of force on the measuring lever. This method was developed by GTM and has been used more than 15 times already for force and torque calibration machines, more than half of which are standard machines of national institutes.

2 DESIGN OF THE 1.1 MN·m TORQUE STANDARD MACHINE

To reach the highest possible accuracy two conditions were invariably considered to be state of the art for torque calibration equipment:

• Force generation by acting of discrete load masses in the local gravity field (taking into account air buoyancy) in connection with a lever arm of calibrated length supported in low-friction bearings.

• Reduction of the various mechanically disturbing quantities (transverse forces, bending moments) by use of metallic multiple disk couplings which are torsionally stiff and flexible in bending for the mounting of the device under test in the measuring axis [2].

Both conditions could not be satisfied in the MN·m measuring range. Force generation by direct mass loading would increase both cost and size of such a machine beyond economic and practical limits. Elastic couplings which can withstand the stresses caused by the desired torque range from 5 kN·m up to 1100 kN·m are difficult to realise in practise and would require different sizes for different capacities and transducer designs, with correspondingly difficult mounting operations.

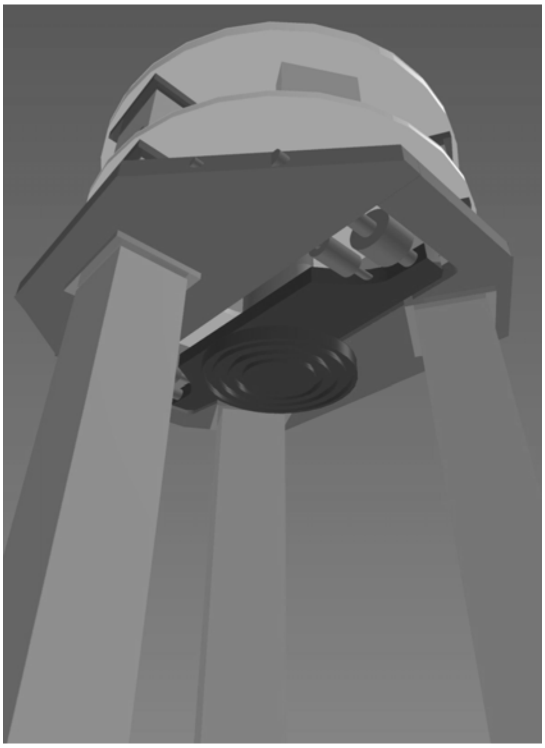

Figure 1: Top of the 1.1 MN·m TSM with force transducer sets acting on the measuring lever arm (computer design)

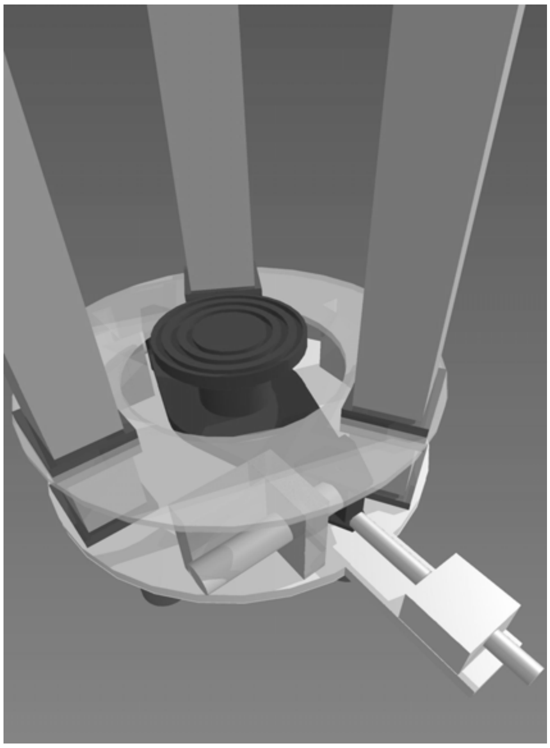

Figure 2: Base of the 1.1 MN·m TSM with actuating lever and electrical drives (computer design)

The design of the 1.1 MN·m TSM is based on a vertical measuring axis. The machine frame consists of three columns located at 120 degrees around the central test space. At the bottom of the frame is the drive unit, consisting of a double-sided lever arm with two servo-electric spindles. This lever is arranged in a free-floating matter, i.e. the electrical drives and support points are designed as cardanic joints to achieve a statically determined system (no over-constraining) in the operating condition.

At the other end of the frame the measuring lever is located. This is also a double-sided arm which resolves the measured torque into a couple of equal forces and transfers them into the frame by means of two multi-component strain controlled hinges. At the same time these forces are measured by the force transducer located between these hinges and the frame.

The lower crosshead supports the actuating lever, and the upper crosshead links the columns of the frame. Both are fixed and are clamped to the columns, the latter being of I-section, see Figs. 1 and 2. A third movable crosshead carries the double-sided measuring lever. It can be adjusted in height to accommodate test pieces of up to 4 m length. Once set correctly it is also clamped to the three vertical I-beam columns. Both the actuating and the measuring lever carry adapter plates with annular
T-grooves of the diameters 500 mm, 700 mm and 900 mm. The corresponding thread size is M36.
The established solutions of torque measurement by means of a force couple acting on an unsupported lever all suffer from influences such as deviations of the force direction and unavoidable parasitic components due to elastic deformations at or near the point of load application. A reliable determination of the measuring uncertainty budget was not possible in such cases.
The concept of the new torque calibration machine at the PTB permits the generation of the torque with quantifiable measuring uncertainty contributions. Thereby it is possible to achieve a best measurement capability (bmc) for $k = 2$ of 0,1 %. In order to arrive at this low bmc value it is essential that the transverse forces and bending moments which are superimposed to the measured forces are known. Fig. 3 shows such a measuring element. It consists of two compression force transducers arranged in series and pre-loaded with 50 % of the nominal force. This yields very low remanence effects upon load reversals, since each of the transducers is loaded from 0 % to 100 % in one direction only (compression) even though the assembly experiences a load reversal from tension to compression due to changing load directions (clockwise or anticlockwise torque). Both force measuring systems on

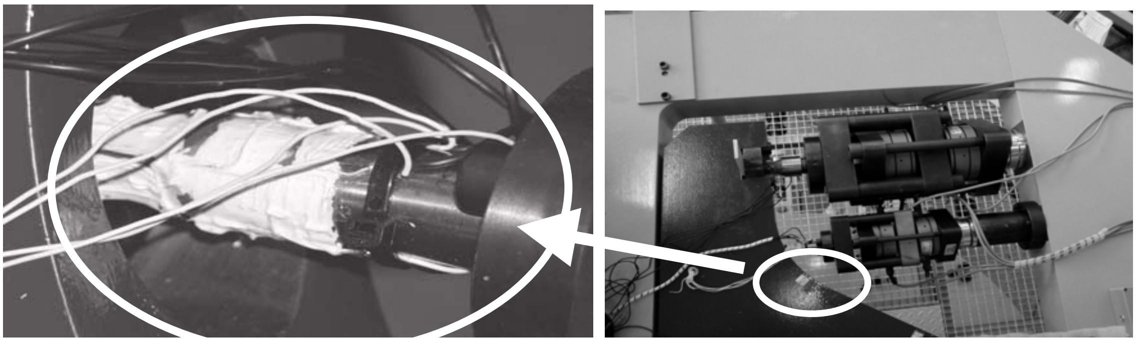

Figure 3: Force-transducer sets for 220 kN·m (small) and 1.1 MN·m (large) and elastic hinge element to measure the parasitic mechanical components in the contact area between force transducer and lever arm

the ends of the lever arm are orientated in the same direction. Thus one set is loaded in tension the complementary set is loaded in compression. The main contribution of typical non-linear characteristics of the force transducer sets are compensated in this way. The coupling of the force transducer sets to the measuring lever is made by the multi-component strain controlled hinges. Their strain-gauge bridges provide signals for both bending moments and both transverse forces which are used to generate the control signals for their compensation.
The principle of this new machine practically reverses the approach taken by the PTB with respect to parasitic influences: So far the machine designs were based on minimising these effects to negligible amounts by using certain principles of lever support and elastic de-coupling. However, in these designs the actual magnitudes of the effects were not measured during a calibration. The new approach does not rely on minimising the parasitic contributions, but on their accurate measurement and subsequent reduction by adjusting the load levers as well as electronic correction of the readings.
During a calibration, an existing or developed parasitic component will be reduced to a negligible amount by moving the actuating lever. Towards this end the actuating lever is

movable in three axes according to the indication of the strain controlled hinges. Three electrical drives are used: With the two main drives the torque is applied and transverse forces at right angle to the longitudinal axis of the measurement lever are eliminated. With the third auxiliary drive transverse forces in the direction of the longitudinal axis of the lever can be minimised. A fourth manual drive supports the actuating lever in the vertical direction, so that the axial force along the measurement axis can be reduced.
The auxiliary drive on the actuating lever as well as the two main drives permit to compensate the parasitic components and/or to adjust their symmetry, so that their sum reaches zero. Existing bending moments on the device under test can be minimised by operating both main drives in the same direction: Instead of a torque introduction a side movement results.
Flexible couplings in the torque measuring line are no longer necessary. The various disturbances are compensated or at least controlled so as to be symmetric so that their effects are negligible. The applied torque can then be calculated with sufficient accuracy from the measurements of the force couple acting on the lever as measured by the transducer sets.
In order to keep the relatively high weight of the measuring lever away from the measuring system and the device under test it is suspended from three wires attached to the movable crosshead. This arrangement is extremely weak in torsion and the existing torque shunt and its small elastic deformations are not relevant for the measurement uncertainty.
On the strength of past experiences with the strain controlled hinges in various force and torque standard machines the applied torque of the 1.1 MN·m TSM is calculated from the force couple as measured by the force transducers, taking into account bending moments about the vertical axis as measured by the strain controlled hinges.

In parallel with the development of the new standard machine reference torque transducers for the two measuring ranges of the machine have been developed together with HBM, which are based on the type TB2. They are used as an alternative measuring system. The 1100 kN·m reference torque transducer is already in use, and the "small" one for the measuring range 220 kN·m is under development. Due to the design this type is relatively insensitive to various mechanic parasitic components. Using this type of reference system these components must be minimised only with respect to the device under test during the calibration. At the same time the reference measuring system offers the important advantage of being able to monitor the long-term stability between the re-calibrations of the force transducer sets. Continuous monitoring of the measuring system with respect to stability is planned and would thereby give the possibility of introducing flexible re-calibration cycles for the force transducer sets (4 transducer sets in tension and compression force up to 120 kN and 500 kN, respectively).

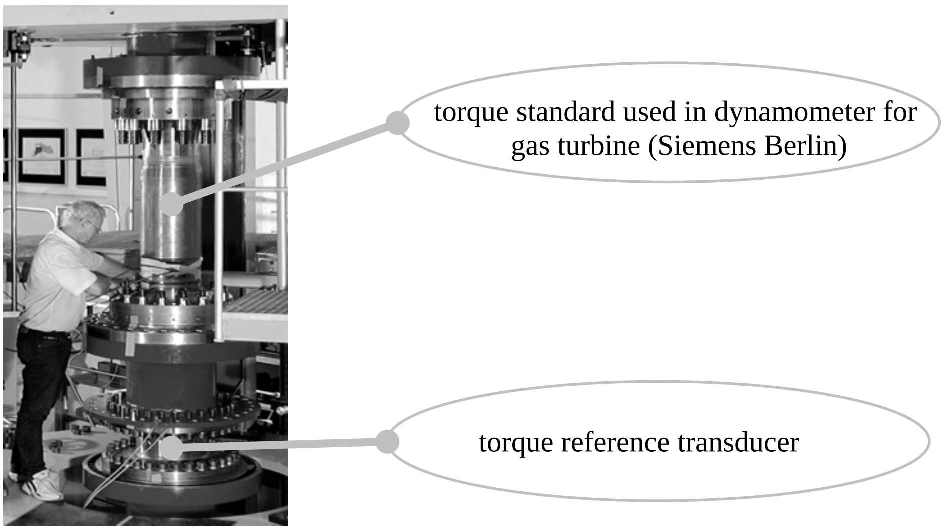

Figure 4: Device under test (700 kN·m) in line with the reference transducer (1.1 MN·m)

3. CONDITIONS OF TESTING

Extensive work was necessary for the evaluation and calibration of the force transducer sets. The creep characteristics were determined. With approximately 0.003 % over 30 minutes the creep is negligible, relative to the best measurement capability of 0.1 %. Non-linearity and hysteresis are to be considered for the interconnection of the two working force transducer sets. The interconnection causes a reduction, by cancellation, of the non-linearity when compared to that of the single transducers.
Remaining parasitic components are minimised to values of about 10 N·m (bending moments) and 50 N (transverse forces) at an applied load of 500000 N·m. From this it is clear that by using strain controlled hinges better conditions for the device under test are achieved than with metallic multiple disk couplings which are stiff in torsion and flexible in bending.

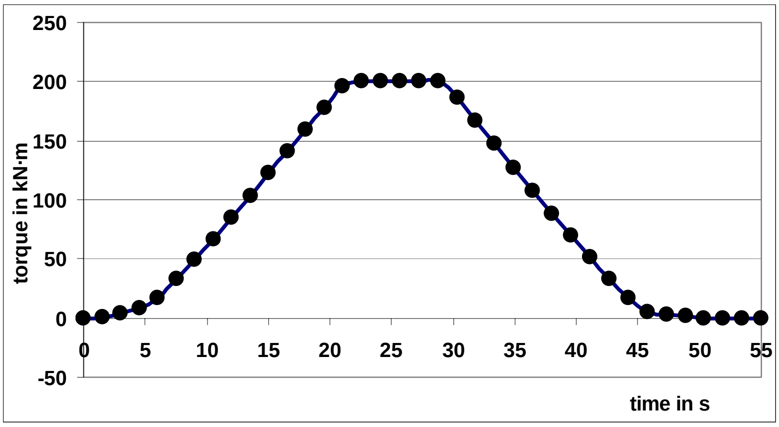

Figure 5: Typical loading diagram for 200 kN·m step

Fig. 5 shows a typical torque-time-diagram with the manual control. Each nominal torque up to 1.1 MN·m can be performed within 120 s.
With the achieved results of very small parasitic components in connection with the vertical mounting position of the device under test it may be possible in future to reduce the different mounting adaptations to only one. Corresponding investigations are carried out at present.
For a measuring sensor of 700 kN·m capacity the relationship between preparation time and real measuring time was determined. Mounting, bolt-up and removal of the measuring sensor took four times longer than the actual time required for the pure measurements. In addition during assembly and disassembly at least two technicians are needed, whereas the calibration itself is a one-man-operation and could be semi-automated in future.

4. DIMENSIONS AND TECHNICAL DATA

Maximum torque	1,100 kN·m
Measuring range 1:	5 kN·m to 220 kN·m
Measuring range 2:	30 kN·m to 1,100 kN·m
Best relative measuring uncertainty (*k* = 2):	0,1 %
Diameter x height:	4.5 m x 7.3 m
Mounting space: width x depth x height:	1.2 m x 1.9 m x 4.1 m
Maximum permissible weight of the transducers incl. adaptation:	2500 kg

5. SUMMARY

The world's largest torque standard machine allows calibrations at up to 1.1 MN·m with a measuring uncertainty of 0.1 %. Beyond that calibrations of partial ranges of transducers with extreme capacities can be carried out since the generous mounting space offers ample reserves compared to the dimensions of common transducers. However, the limits of the 1.1 MN·m TSM are reached relatively quickly when actual components are to be mounted since these are often much larger. In these cases the user can only obtain calibrated special reference transducers, corresponding to the main torque range of a national laboratory, which are then used within his own loading devices, and coupled in series with these components. This applies, for example, to drive shafts for ships.

The concept of a force introduction without parasitic quantities into a double-sided floating lever on the measuring side as realised here allows a reliable estimation of the uncertainty contributions and will enable to further reduce the currently achieved value of 0.1 % in future.

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