The Design, Development and Commissioning of a 2 kNm Torque Standard Machine

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This paper describes NPL's 2 kN·m torque machine — the UK's first national torque standard — a lever deadweight machine with a vertical torque axis and an uncertainty of ±0.002 %. Despite the greater difficulty in applying torques to a vertically mounted transducer, this design was selected as it enables a symmetric "pure" torque to be applied. In addition, this design provides adaptability, enabling comparisons with the application of asymmetric torque and "on-the-fly" torque calibrations to be studied. The vertical transducer orientation is made possible through several innovative sub-assemblies, including boron fibre tapes and a twin-beam carbon fibre lever, both developed within NPL. The machine will be used to calibrate transducers and to disseminate the unit of torque within industry.

Introduction

From the tightening of wheel nuts on an automobile to the assembly of caps for pill bottles, or maximising the output of an internal combustion engine, the accurate measurement of torque is essential to UK industry. The need to provide national standards for torque was recognised by the UK's Department of Trade and Industry when the National Physical Laboratory (NPL) was commissioned in 1996 to design and manufacture the first national standard torque calibration machine. The provision of this calibration machine was welcomed by UK industry with much consultation during the conceptual design stage. The aim of the project was to create a torque calibration machine of the highest accuracy, which would then be used to calibrate transfer devices to disseminate the unit of torque within industry.

Conceptual Design

The 2 kN·m torque machine, designed with a vertical torque axis, generates a symmetric pure torque via identical weightstacks located at either end of a lever beam (see Figure 1). Most torque standard machines are designed with a horizontal torque axis because this is the most simple and direct way of applying torque. The disadvantage is that a force produced from a single weightstack will produce a bending moment that can affect the transducer under test. A vertical torque axis machine can produce equal and opposite forces via two identical weightstacks at either end of a lever beam — the moments cancel out to leave a symmetric pure torque. A complication arises from the need to convert the vertical force generated by the weightstack into a horizontal force transferred to the lever beam. This is achieved via an arrangement of boron fibre tapes and a pulley air bearing.

The need to apply clockwise and anti-clockwise torque loading provided additional complexity to the pulley system design. This was overcome by designing a lever beam that can be rotated independently

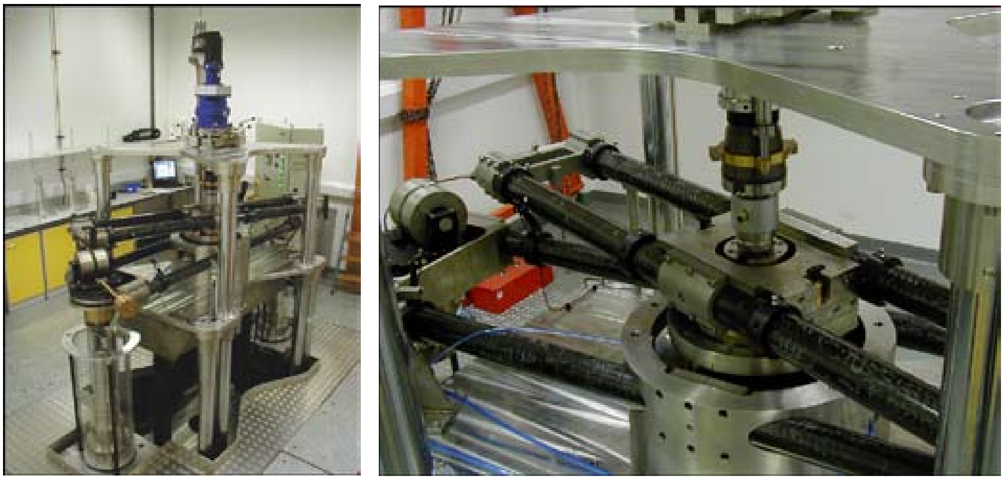

Figure 1. Views of the NPL static torque calibration machine.

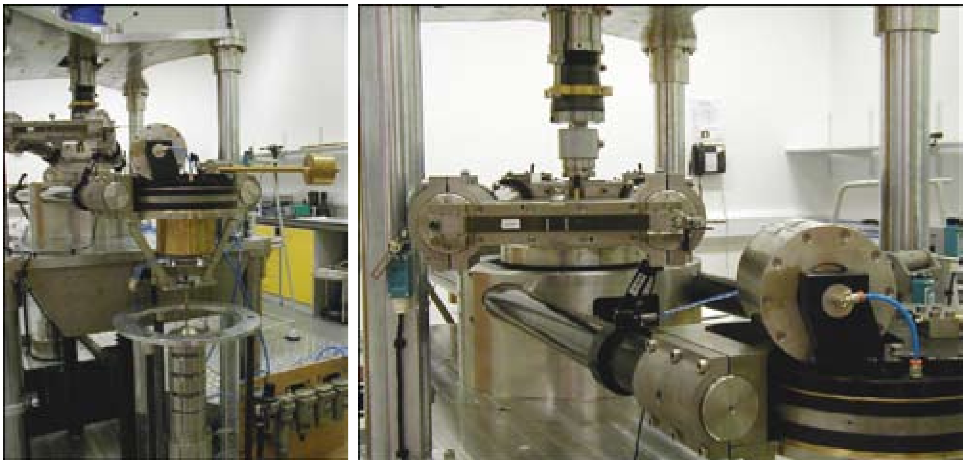

Figure 2. Views of the end of the machine showing the transfer of the force.

of the torque transducer, to two neutral positions either side of a pulley system. This arrangement necessitates the pulley system to be castored to enable rotation about its vertical axis such that the force axis remains unchanged for both clockwise and anti-clockwise torque application.

The photographs of the 2 kN·m torque calibration machine (Figures 1 & 2) show a twin beam construction with castored pulley bearings mounted on a reaction beam. Identical materials are used for both beams so that thermal effects will be identical, thus minimising errors of pulley misalignment relative to the lever beam.

The primary range of the machine from 40 N·m to 2000 N·m has 15 torque increments. A pair of smaller weightstacks provides a secondary range with 14 further torque increments between 2 N·m and 100 N·m.

The machine can also be used for continuous torque calibration. The lever beam can be mechanically locked and the reaction drive gearbox then used to generate a torque controlled by a reference transducer. This enables a torque calibration to be produced in a fraction of the time taken for an equivalent static calibration.

The machine is PC controlled through a Visual Basic 6.0® program. This provides a graphical user interface and enables complicated motion sequences to be compiled. The weightstack platforms slow as each weight is added or removed, minimising inertial effects. After a weight is either added or removed the reaction drive gearbox drives the lever beam back to its datum position. The software gives the operator real time information on the status of the machine.

Air Bearings

Design of the air bearings for both the central pivot of the lever beam and the castored pulley systems will influence the uncertainty of torque measurement [2]. The prime requirements were that the air bearing systems provide both radial and axial stiffness to support the predicted forces, with minimal friction, to achieve their target uncertainty range of (0.1 to 0.5) μN·m. Friction within a hydrostatic air bearing is a combination of boundary and viscous shear of the air film plus turbine torque.

Both the boundary and viscous shear influences are time dependent, such that once the lever beam has been driven to its measurement position by the reaction drive gearbox and stopped, subsequent relaxation within the air film occurs and zero friction will be detected. However, the reaction of the airflow as it is discharged through orifices into the bearing clearance can impart a low but detectable turbine torque within the bearing. If the bearing does not rotate but acts as a low friction pivot, as in the case of this torque calibration machine, it is necessary to evaluate and minimise the friction attributable to turbine torque.

The central pivot air bearing (Figure 3) is a double journal and thrust air bearing system that can be air energised separately. The upper bearing enables the rotation of the lever beam to enable clockwise and anti-clockwise torques to be applied without disturbance to the transducer. The lower main bearing is pivotal to the performance of the torque machine and must operate with near zero friction. Incorporated into the bearing design is a drag-cup damper to compensate for the dynamic natural frequency of the lever beam system. The results from the FEA analysis of the modal frequency response of the beam sub-assembly were used as the input to optimise the damper design.

The balancing of the central pivot air bearing was carried out with its spin axis horizontal, although in operation the spin axis is vertical. Assuming the bearing operates vertically to within ± 0.5°, then this out-of-balance component will be 3.6 μN·m. In operation the bearing is deployed in one position and this dictates the positioning of the air slip rings that distribute the supply air to support the lever beam assembly. The turbine torque is minimised by optimising the air supply pressure, the requirements of which are dependent upon the magnitude of the applied torque. The magnitude of the turbine torque was therefore evaluated

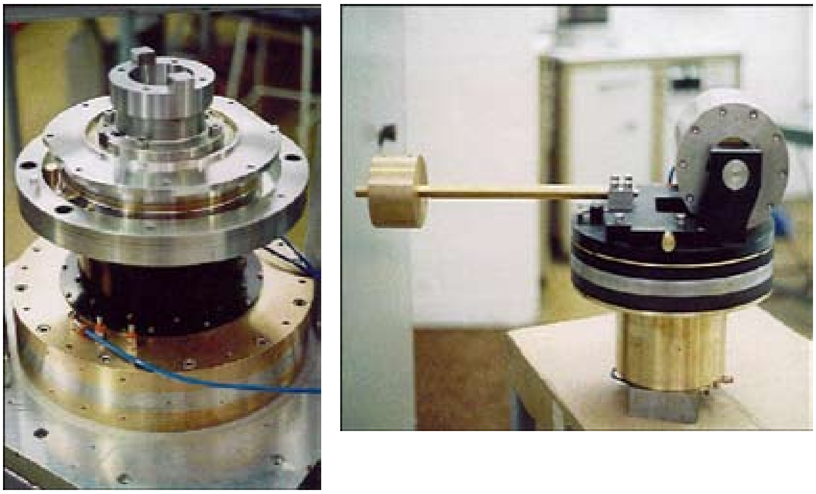

Figure 3. The central air bearing; photograph of the castored pulley bearing.

over the angular position of bearing operation and at an air supply pressure ranging from 280 kPa to 480 kPa.

At this pressure the shaft of the bearing rotated in an anti-clockwise direction when viewed from above due to the generated turbine torque. The magnitude of the turbine torque was evaluated by measurement of the bearing acceleration and the force required to stop rotation and hold the bearing in balance. The bearing balance force was determined using a combination of a capacitance probe to measure displacement and a calibrated "micro" air jet to provide a reactive force. The results of both studies confirmed that repeatable, unidirectional turbine torque ranging between 200 - 220 μN·m were recorded dependent upon the air supply pressure — the higher the pressure, the marginally higher (approx 10 %) the turbine torque. However, as this increase is so minimal it is recommended that the higher supply pressure is used to ensure rigidity of the bearing air film over the 30 years predicted life of the torque calibration machine. For calibrations of torque transducers of less than 20 N·m capacity the turbine torque (220 μN·m) will need to be considered and "tared" such that the target uncertainties of the calibration machine are not exceeded.

The design of the torque calibration machine enables asymmetric torque application. This application of a torque moment necessitates that the main bearing is also able to resist bending forces. To monitor the effect of bending forces on deflections within the air film, two pressure sensors were positioned within the lower thrust main bearing. The first pressure tapping is positioned at 7.5° from the radial plane and the second at 90° from the first. To simulate the mass of the lever beam an axial force of 912 N is applied, whilst the bending forces ranged from 400 N to 750 N. The aim of the test was to apply a bending force until the thrust plate had deflected by 4 μm, i.e. one half of the semi-axial clearance. The results show that the higher bearing air supply strategy, suggested to provide greater rigidity to the bearing air film, enabled the highest bending forces to be supported with minimal variations monitored by the pressure sensors.

The castor pulley bearing system (Figure 3) provides both horizontal and vertical rotation and is designed to carry a load of 1 kN transmitted by a suspension tape under tension at a supply pressure of 345 kPa.

The Lever and Reaction Beam

The design provides a balanced 1 m long lever beam, i.e. a total length of 2 m. The design specification required that the beam sub assembly is of a lightweight construction to reduce inertia and to have a very low deflection under load. Thermal expansion of the beam is also considered critical [3].

In consultation with NPL colleagues working in materials research, it was agreed to use two parallel 2 m long, high-modulus carbon fibre tubes with stainless steel end fittings and central boss. Onto the end fittings, connectors are attached for the application of the weightstacks. The steel central boss and end fittings are clamped and pinned, using 12.5 mm taper dowels, such that the expansion of the steel components will have minimal effect on the overall expansion of the beam. Expansion of the beam will also be minimised by a laboratory controlled to a temperature of (20 ± 0.5) °C. The identical material construction of the lever and reaction beam sub-assembly minimises the thermal effects on the alignment of the castor pulley system to the lever beam reference axis. Furthermore all dimensional measurements are referenced to the central axis of the pivot bearing and allow for the sub-assembly to be measured off the machine.

The lay of the carbon fibre was designed to minimise thermal expansion and optimise the performance of the beams. The principal longitudinal fibres provide both rigidity for bending moments and a calculated coefficient coeffcient of thermal expansion of $-3\times10^{-7}\ \mathrm{K}^{-1}$. For the target uncertainty of the machine to be met, it was calculated that the deflection contribution for the lever beam and reaction beam should not exceed 1.0 mm and 1.1 mm respectively. Hoop wound fibres of various orientations maintain the longitudinal fibres, provide additional torsional strength, and provide strength in the areas of machining for the fixing pins to secure the mounting of the stainless steel central boss and end fittings. Additionally, the hoop wound fibres provide a reduced thermal expansion in the radial direction.

To provide confidence in the

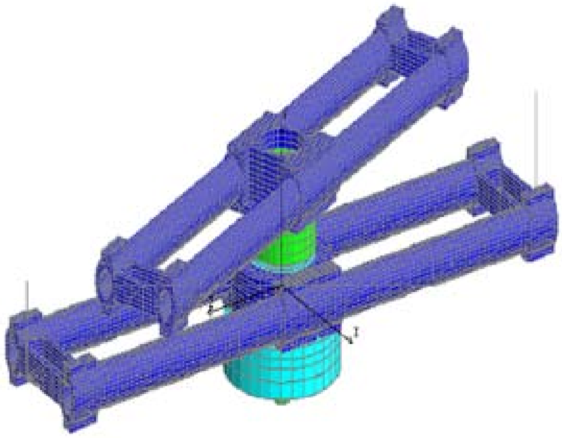

Figure 4. The lever and reaction beam sub-assembly.

design of the composite lay-up a detailed finite element analysis (FEA) of the lever beam and the reaction beam was undertaken [4]. The FEA study predicted that the deflections of the beam sub-assembly are within those allowable for the target uncertainty budget of the machine.

Boron Fibre Tapes

A problem with the use of deadweights is the uncertainty (coming from alignment and friction) associated with using a pulley to transform a vertical force to the required horizontal force, and the additional effects of the components used to connect the lever beam to the weightstack [3].

Accurate measurement and control of the lever beam length as defined by the line of action (reference line) of the applied force must be maintained within a few microns. The required material for suspending the deadweights must therefore not deform upon loading, it must be lightweight, and it must possess the flexibility to ensure that it conforms to the radii of the end-fitments of the lever beam and the surface of the castor pulleys.

Experimental work at NPL identified boron as being the ideal suspension material and initial studies were carried out to evaluate a boron fibre foil made up from individual 0.29 mm diameter mono-filaments. Problems with handling the multi-fibre foils was of a major concern and subsequent research identified a suitable boron tape. This material is an epoxy pre-impregnated tape of 150 μm boron fibres, produced using chemical vapour deposition of a boron tri-chloride gas on to fine tungsten wire [5]. The properties of the boron tape are as shown in Table 1.

The width of the tape is dependent upon the weightstacks suspended; a 5 mm tape for the 50 N stack and a 20 mm tape for the 1 kN stack. The tapes are "sandwiched" and bonded between a titanium end connector.

Tensile strength	1 520 MPa
Tensile modulus	195 GPa
Flexure strength	1 790 MPa
Flexure modulus	190 GPa
Inter-laminar shear	97 MPa
Coefficient of thermal expansion	4.5 x 10^{-6} K^{-1}
Density	2.0 x 10^3 $kg \cdot m^{-3}$

Table 1. Properties of boron tape [5].

Extensive tensile testing of made-up boron tapes has shown that they have a safety factor greater than 4, whilst creep tests at 1.5 times the maximum applied force (1.5 kN) have recorded an elongation of between 0.04 % and 0.09 % dependent on the width of the tape and no measurable creep after the 40 hour test. The greater elongation was observed with the wider tape and suggests that this may be associated with either the titanium end connector or its bonding to the boron tape.

The tape is required to change orientation in the horizontal plane in order that it can pass around the end radius of the lever beam. The additional weight of any connectors added to facilitate this change will cause the tape to deviate from the horizontal introducing an error into the transfer of the force. For the 5 mm tape, a preformed 90° twist was put into the tape to eliminate the need for any sort of connector. For the larger weightstacks using a 20 mm width tape, a preformed twist was not an option because of a limit in the length over which the twist had to take place. An alternative was developed for the 20 mm tape whereby a small incision at the end of the two tape lengths allowed them to be intersected perpendicularly to each other (Figure 5). Bonding short lengths of carbon and glass fibre angle onto the area held the intersection length together.

Figure 5. Photograph of the 20 mm width boron tape with 90° joint.

Performance and Uncertainty

The machine's uncertainty is defined as that of the torque generated around the central axis of the machine. For the range 40 N·m to 2000 N·m the relative uncertainty is 2 x 10^{-5} for a k = 2 coverage factor, traceable to the base SI units. The major contributions to the uncertainty are discussed below.

Force: The uncertainty of the applied force is derived from the mass calibration of the weightstacks and includes contributions from buoyancy and magnetic effects.

Alignment: Measurements under load are made to ensure the alignment of the force within required limits taking into account any deflection in the lever and reaction beams and any deviation in the boron tape.

Length: The length of the lever beam has been measured on a coordinate measuring machine with a relative uncertainty of 3.3 x 10^{-6}. The beam length, including half the thickness of the boron fibre tape, gives a nominal overall lever arm length of 1.000 000 m. To ensure the constancy of the length, a series of tooling balls mounted along the lever beam are measured regularly with a length comparator, which compares the distances to a reference standard.

Friction: Friction is minimised through the use of the central air bearing on which the lever beam sits. Air bearings also allow the pulleys to rotate freely while a castor bearing enables rotation around the axis of the weightstack. Turbine torque has been experimentally determined at 220 μN·m, for a constant pressure in the central air bearing. As the air pressure is kept constant, this error can be tared. The level of balance of the bearing is within 3.6 μN·m. At the minimum torque value generated, this contributes a relative uncertainty of 1.78 x 10^{-6}.

Performance of the machine can be independently verified by means of comparison with a machine of similar uncertainty using a reference transducer. Recent work has supported the derived uncertainty budget. Figure 6 summarises the calibration result for a reference transducer calibrated in three orientations, both incrementally and decrementally. The graph demonstrates the repeatability and reproducibility of the machine together with the hysterisis of the transducer. In Summer 2006 the NPL machine will participate in the first CIPM intercomparison in the field of torque.

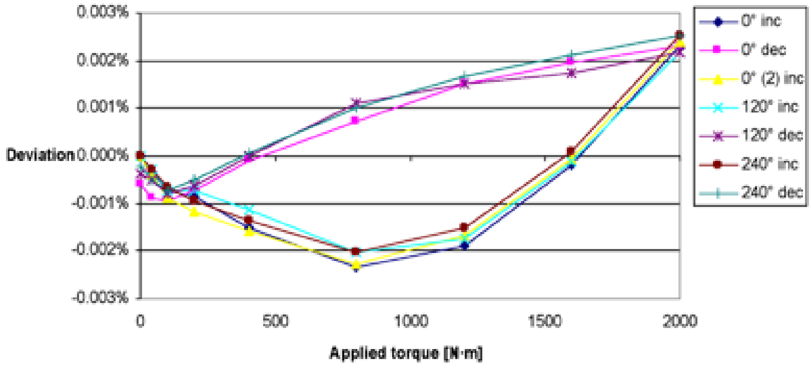

Figure 6. Percentage deviation from a first order straight line fit for clockwise torque.

Conclusions

Commissioning of the machine was completed at the end of the 2005 and a torque transducer calibration service has been subsequently launched. It is expected that the dissemination of the unit of torque will have a significant impact within industry. Using a novel and innovative design, the machine has met its design target in realising uncertainties at world leading levels. The flexibility of the machine will provide a powerful research tool in the field of torque metrology.

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