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TORQUE CALIBRATION DEVICES FROM 0,1 N·m UP TO 20 kN·m

Aimo Pusa[1], *Michael Sachs*[2]

[1] MIKES – RAUTE Mass and Force Laboratory, Lahti, Finland, aimo.pusa@rauteprecision.fi
[2] MIKES-RAUTE Mass and Force Laboratory, Lahti, Finland, michael.sachs@rauteprecision.fi

Abstract: The article gives an overview about the present state of torque calibration facilities in the MIKES-RAUTE Mass and Force Laboratory in Lahti, Finland. The laboratory utilises four high-level torque calibration devices in a range from 0,1 N·m to 20 kN·m. Also in use are several facilities for the calibration and testing of torque wrenches and other torque devices. The main components of the calibration devices are described briefly. Beside that the main steps of the development history of the devices during the past 10 years – as a reaction to the needs of the customers – are presented.

Keywords: Torque measurement, Torque calibration, Torque standard machine, Torque reference machine

1 INTRODUCTION

The MIKES-RAUTE Mass and Force Laboratory is the highest-level laboratory in the field of force and torque calibration in Finland. In 1991 the Finnish Centre for Metrology and Accreditation MIKES accredited the laboratory as the contract laboratory for force. In 1996 the laboratory also became responsible for maintaining the traceability for torque in Finland.

At this time the laboratory utilised a 2 kN·m torque standard machine and a bench for the calibration of torque wrenches up to 2 kN·m. During the past 10 years the laboratories equipment and experience in torque calibration have been developed and grown in a wide manner. This article deals mainly with the laboratories calibration devices. The laboratories most important calibration devices are described in a short way in their main metrological quantities, their way of use, their construction and the hence resulting advantages and disadvantages. The article points out the development of the machines mainly as a result of the laboratories reaction to the requirements from the industry.

Beside that there is undertaken a trial to describe the way of developing of the calibration machines. Starting from the expectancies during the construction and production of the devices, which has all been done inside the MIKES-RAUTE Mass and Force Laboratory, their final use and way of development are presented. Also the needs for torque calibration by the industry on the Finnish market are shortly analysed. Their influence on the further development of the calibration facilities is mentioned as well.

2 TORQUE CALIBRATION REQUIREMENTS IN FINLAND

The establishment of the torque section in the MIKES-RAUTE Mass and Force Laboratory took place in 1996. It has been a reaction to the increasing demand of traceable high quality torque calibrations by the Finnish industry. An evaluation of the Finnish Centre for Metrology and Accreditation from the year 1993 among 30 bigger Finnish companies showed already their need for torque calibration with an amount of almost 800 calibration pieces per year ([1]). The required range for calibration reached up to 25 kN·m. Nevertheless the main industrial needs, from the view of calibration pieces per year, was at this time in a range up to 2 kN·m. The calibration objects were all possible kinds of torque measurement equipment. The main groups were torque wrenches, calibration devices for torque wrenches (Torque Testers) and torque sensors and transducers.

Nowadays the main branches of industry in Finland, which need traceable torque calibration, are the communication sector, metal working industry and automation industry. These branches require a widely spread calibration capability of a torque calibration laboratory. While the communication industry for example quite often requires torque calibrations in the range of a few N·m or even below 1 N·m, the metal working industry needs calibrations in the range between 100 N·m up to few 10 kN·m.

The most important facts for the industrial customer are, beside the calibration range, the traceability of the torque calibration and the measurement uncertainty. The traceability of the calibration done in the calibration laboratory gives the customer the safety and proof that the results are – within the uncertainty limits and under the view of the actual state of the art – correct. The required measurement uncertainty depends strongly on the customer's application. In general it can be said that the required relative uncertainty very seldom exceeds $5 \cdot 10^{-4}$.

In 2005 the laboratory had in the field of torque calibration about 150 calibration pieces per year. 60% of the pieces were torque wrenches, 25% calibration devices for torque wrenches and 15% torque transducers. The development of the laboratories torque calibration equipment was and is still closely related to the requirements of the customers. This concerns mainly the requested uncertainty of the calibrations, so it is more a metrological question than an economic one.

3 2 kN·m TORQUE STANDARD DEVICE

The laboratories first realized torque calibration device was the 2 kN·m torque standard machine. It was built in 1996. The decision to build that device was based on the evaluation among Finnish industry about the need for torque calibration. There the most requested range occurred to be between 10 N·m and 2 kN·m. With the construction of the 2 kN·m device with a measurement range from 20 N·m (as smallest calibration step) up to 2 kN·m it was expected to get the best experiences and success. The best measurement capability (relative) was planned to be at least $1 \cdot 10^{-3}$, but preferably better ($5 \cdot 10^{-4}$).

The original concept of the machine was based on a lever with an arm length of 1 m. The lever sides were furnished with a radius to compensate for the angular deflection that occurs during loading of the transducer. On the radius the load scales were fixed with steel cables. Here the torque could be generated by the use of in Newton calibrated mass pieces. The mass loading happened manually. The lever was mounted into a bearing system, so that on the calibration object only pure torque was applied. The bearing system was made as a counter rotating bearing system ([2]). By the use of this system could be reached sufficient calibration uncertainties respectively best measurement capabilities (relative) of down to $1 \cdot 10^{-3}$. For a versatile use of the beam as well in another calibration stand the central shaft was manufactured in a split way, so that the beam could be taken out very easily. In the first set up the counter bearing of the calibration object was a simple fixed shaft. The mounting of the calibration object was right from the beginning done by the use flexible couplings with lamellae to reduce the influences of possible radial, axial and angular misalignments. The use of cardan shafts as flexible element also has been tried, but soon rejected due to the relative big clearance, the large axial dimensions and the low radial stability of the elements. Also the use of hydraulic clamped hub shaft connectors of type ETP was introduced quite in the beginning, since they ensure a uniform distribution of forces on the bearing points.

With this set-up it was possible to carry out most of the requested calibrations. Also the facility provided good possibilities to widen the experience in calibration and to investigate particular behaviours of transducers during calibration.

Later on, in 2002, it was decided to increase the best measurement capability of the 2 kN·m device up to $5 \cdot 10^{-4}$. This seemed to be necessary since the requirements of the industry slightly increased and also the laboratory's own needs for high level calibrations, for example for comparison measurements, increased. Due to that it has been decided to replace the beam with a new one to provide a more accurate arm length. So the problems with the inconsistency of the old lever radius and also the load depended diameter of the used steel cables should be avoided. Also the high stress on the bearings during mounting and remounting of the beam were a fact that had to be revised.

The new lever system now is made of a steel beam in truss design. That saves weight by increasing the stability at the same time. The determining beam length of 1 m is reached by the use of a knife-edge, where the loading scales are hanging in a pan. The beam has been measured in a 3D coordinate measuring device. According to the results the knife-edges have been manufactured so that the resulting length in unloaded condition is 1 m with an uncertainty of 50 µm (this uncertainty includes uncertainties of the beam length and knife edge dimension as well as uncertainties caused by eccentricities of the main shaft). At the same time also the bearings itself have been renewed. The latest comparison measurements with PTB, Germany, were done in the end of the year 2005. Figure 1 shows the results for the clockwise calibration of a 2 kN·m transfer transducer. The maximum relative deviation between PTB and MIKES-RAUTE is 0,018%. The highest relative uncertainty occurred at the 10% load step with a relative amplitude of 0,02%. So the sum of uncertainty and deviation lies deep within the accredited relative uncertainty limit of $5 \cdot 10^{-4}$ (k=2).

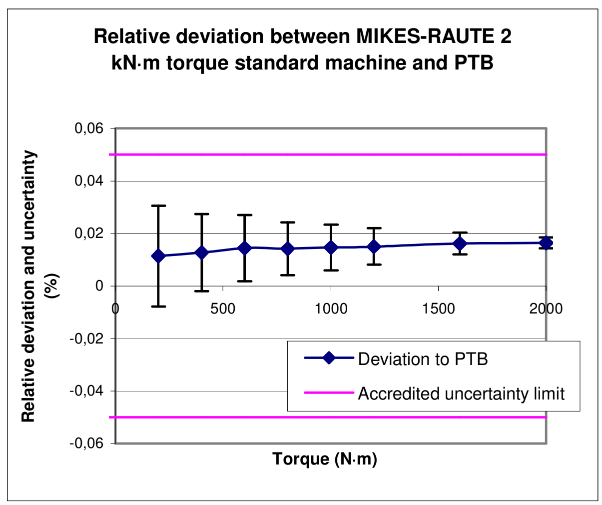

Figure 1 - Relative deviation and uncertainty of MIKES-RAUTE 2 kN·m torque standard device in comparison to PTB

Due to the new beam design also a compensation of the angular displacement during load application on the calibration object became necessary. For that the former fixed shaft got removed. It has been replaced by a bearded shaft, which can be rotated by the means of a beam and a linear guide with screw drive. This arrangement enables angular compensations in the range of ± 30°. Figure 2 gives an overview on the MIKES-RAUTE 2 kN·m torque standard device. The calibrations made in the 2 kN·m device are directly traceable to highest mass and length standards. The performance of the device is additionally ensured by regular comparisons with torque laboratories all over the Europe.

Figure 2 - View of the MIKES-RAUTE 2 kN·m torque standard device

4 CALIBRATION DEVICES UP TO 50 N·m

4.1 50 N·m torque standard device

To meet the demands also for high-level calibrations in the lower torque ranges, in 1999 the MIKES-RAUTE 20 N·m torque standard device has been built. Although its range has been widened in the beginning of 2006, it was originally planned only for a measurement range from 0,1 N·m to 20 N·m. During planning, construction and production of the device the experience gained earlier with the 2 kN·m device was of great value. Also many principles for the design of components have been adapted from the bigger device to the smaller one.

The first beam also was made with rounded edges, so that the intended length of 250 mm could be realized despite angular displacements in loading condition. The load scales were fixed by the means of metal band with a nominal thickness of 50 µm. The dimensions of the metal band are less dependent from the load condition. The radius was made so that the centre line of the metal band had – within uncertainty range – a distance of 250 mm to the rotation centre. An air bearing was utilised to support the beam and keep any bending forces away from the calibration object. The beam was mounted from one side to the air bearing. The mounting of the calibration object also was done using flexible couplings. Due to the very small calibration objects and the not standardised shaft diameters of torque shafts the use of hydraulic hub shaft connectors was in the beginning impossible. Instead flexible couplings with integrated screwed clamps were used. This made the turning of the transducer during calibration more time consuming.

The original set-up already included a system for the compensation of the deflection of the calibration object. It consisted of a stepping motor, a planetary gearbox and a harmonic drive. The harmonic drives output shaft formed the fixed bearing for the calibration object. The angular compensation system was made in such a way that it keeps the beam fully automatic in its horizontal position. Nevertheless, due to the beam with radius ends, the angular compensation system has not been used – except for tests – until 2005.

The 20 N·m standard machine has been planned such that all kinds of calibration objects could be calibrated here. That means that especially the disturbing forces and moments (axial and radial forces, bending moments) that act from the calibration object back on the intermediate bearing could only be estimated. For that reason and for reasons of availability a spherical air bearing type has been chosen, since this type can stand as well axial as also radial forces. Nevertheless, during the use and testing of the 20 N·m device the used air bearing in combination with the one side mounted beam occurred to be unsuitable for the occurring radial forces. The maximum calibration torque had to be limited to 10 N·m, since above that limit there occurred friction in the air bearing. To increase the performance of the air bearing the beam has been modified. The new used beam system consisted of two beams, one mounted on each side of the bearing. Figure 3 gives an overview on that. This construction was expected to move the gravity centre of the applied load pieces to the middle of the bearing, so that the bending moments on the bearing got strongly reduced. Nevertheless, also this modification did not increase the usable calibration range up to 20 N·m.

Figure 3 - View of the 50 N·m torque standard device before changing of the air bearing

Based on these experiences and also to realize a wider torque range by the means of torque standard machines in the laboratory, in 2006 a reengineering of the complete bearing unit has started. Basically a new one replaces the old air bearing. The new air bearing is of a H-type, which means that it can stand bigger radial forces. The chosen type, which is working with two different pressures in the lower and upper nozzles to increase the load, will be able to stand radial forces of up to 900 N. The mounting and testing of the air bearing will be completed in May 2006. After that the torque standard machine will be used up to 50 N·m, what also explains the machines name in the headline. The uncertainty is expected to be in the range of $1 \cdot 10^{-4}$ to $5 \cdot 10^{-5}$, depending on the actual size of the calibration object. Since the high-level calibration in the field of lower torques is one of the most growing areas, the purchase of this new air bearing also offers the laboratory possibilities to react on the changing requirements. Now it is still possible to increase the calibration range up to 100 N·m without any constructive changes. The realisation of the lower ranges down to 0.1 N·m is also expected to show better performance concerning the uncertainty due to the more accurate lever system.

Another positive effect is the now realized overlapping area to the 2 kN·m torque standard device. Since the first calibration step of the 2 kN·m device is 20 N·m, the overlapping area which is present in both devices between 20 N·m and 50 N·m, can be used for directly comparison of both machines. A detailed view of the overlapping of the different torque devices inside the laboratory is given in Figure 5 on the following page. Also here the traceability of the calibrations in the device is given directly by highest mass and length standards. Regular comparisons with the laboratories other torque calibration devices and with other laboratories also guarantee a stable performance.

4.2 50 N·m torque reference device

In addition to the torque standard device for lower torques in 2002 a torque reference device for the range from 1 N·m to 50 N·m has been planned and built in the laboratory. The device is accredited with a best measurement capacity of $5 \cdot 10^{-4}$ (relative). As calibration objects were planned any kind of torque measuring devices, such as transducers, but also small torque wrenches and screwdrivers and torque testers. Nowadays the device is mainly used for the calibration of torque testers and small torque tools, while the 50 N·m standard device is used only as a reference and for high level calibrations of torque transducers.

The first reason for building of that reference device was to get a calibration device for the daily work. Normal calibration objects in that torque ranges do not need a high level calibration with such low uncertainties as the 50 N·m torque standard device can offer. Also the costs of the calibration for the customers can be strongly reduced by the use of a reference machine. Another reason for the development of this reference machine was that the laboratory needed to gain experience with reference devices. Especially for the construction and building of the 20 kN·m torque reference device (see chapter 4) the experiences with the small reference device were of a great value.

The arrangement of the 50 N·m reference device is vertical. The measurement chain, consisting of a reference transducer and a calibration object, is supported in the middle by an air bearing. The air bearing has right from the beginning been oversized due to the experiences gained with the smaller torque standard machine and the fact that the kind of calibration object could be different. The air bearing has been chosen so that it can withstand high radial forces and medium bending moments. All transducer connections are also made with flexible couplings and hydraulic hub shaft connectors, since their uncertainty contribution and handling is the best available. The generation of the torque is realized by a gearbox, where the other side of the calibration object is fixed. It has two different speeds, realized by two different pre-gearboxes. The gearbox is momentarily operated manually, but has options to proceed to an automatic operation. Figure 4 gives an overview on the reference device.

The traceability of the device is ensured by internal calibrations of the reference transducer in the 50 N·m torque standard device. Before the standard machine's calibration range had reached 50 N·m, the references had been regularly calibrated in the German PTB in Braunschweig. By regular internal comparisons the functionality of the torque reference device is checked.

Figure 4 - View of the 50 N·m torque reference device with a Torque tester as calibration object

5 20 KN·M TORQUE REFERENCE DEVICE

The newest device for torque calibration inside the MIKES-RAUTE Mass and Force Laboratory is the 20 kN·m torque reference device, introduced in the IMEKO TC3 meeting in Cairo 2005 ([3]). The decision to build the device has been made in 2003, when some customers started to demand calibrations in the range up to 10 kN·m. An analysis about the needs to a calibration device up to 10 kN·m came to the conclusion, that the constructive and financial efforts for a 10 kN·m reference device and a 20 kN·m reference device would be in the same area. So the laboratory built up a device that exceeded the actual customers needs, but that also would offer higher capacities when required. The lowest calibration step lies at 500 N·m, but a use down to 200 N·m can be realized with slightly increased uncertainty.

The gained relative expanded uncertainty level has been during the construction phase estimated to $5 \cdot 10^{-4}$ (k=2). Later on comparison measurements also showed that the device reaches that uncertainty level. The main sources for that uncertainty are the three utilised reference transducers, which have nominal loads of 5 kN·m, 10 kN·m and 20 kN·m. All of them have been chosen such that their relative expanded uncertainty (k=2) does not exceed a value of $2 \cdot 10^{-4}$. Since the laboratory has no possibility for traceable calibration of the reference transducers, they are calibrated regularly in the PTB. This also is necessary to monitor the long-term stability of the torque transducers. An internal checking of the 20 kN·m torque reference device is done by the means of the 2 kN·m torque standard device. By using the overlapping range between both machines from 500 N·m up to 2 kN·m, the performance of the 20 kN·m reference machine can be checked with a 2 kN·m torque transfer transducer. Figure 5 gives an overview about the overlapping ranges of all used torque calibration devices.

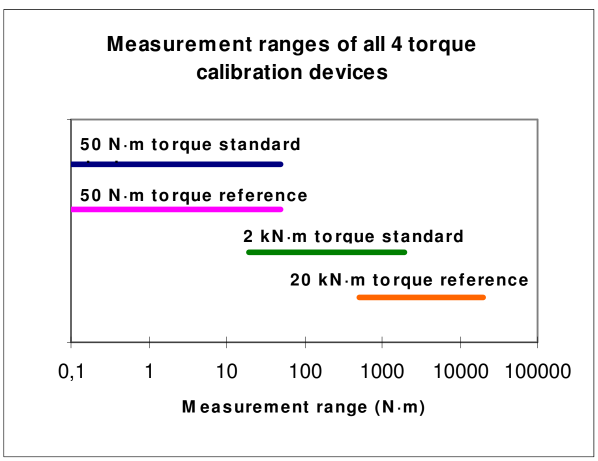

Figure 5 - Overlapping ranges of all laboratories torque calibration devices

The 20 kN·m torque reference device is also built in a vertical orientation. In Figure 6 is an overview of the device. The construction had been made in such a way that the machine is usable for all possible calibration objects. Although the main use has been planned for torque transducers, also bigger torque wrenches and other torque tools can be – with a bigger uncertainty – calibrated. Calibration object and reference transducer are in line, supported by a mechanical intermediate bearing system. The bearing system applies the principle of counterrotating ball bearings. Reference transducer and intermediate bearing are mounted into an inner frame, which is relocatable inside the main frame. All transducer connections are realised by flexible couplings and hydraulic hub shaft connectors.

The other end of the calibration object is fixed to a high ratio planetary gearbox with two stages. The gearbox has, due to its construction principle, a clearance. In this torque range it is impossible to purchase a gearbox without any clearance. The play leads during the calibration process to problems in returning to the zero point. Although the application of a slight preload directly before starting the calibration process already solves the problem, the preload influences the calibration results. Some experiments with an external preloading of the gearbox by springs have been undertaken. In some cases and transducer combinations the use of the external preloaded gearbox decreased the uncertainty of the zero point significantly. In other cases there did not occur any difference. The effect is still being investigated.

Since the device is also used for the testing and calibration of torque tools such as torque wrenches, the stability of the frame is of a very high importance. By the calibration of torque wrenches for example the radial forces may reach very high levels. For example a hydraulic torque wrench with a nominal torque of 5 kN·m and a reaction arm length of only 200 mm produces at nominal torque a radial force of 25 kN. This requires a very stable and stiff frame of the torque device.

Figure 6 - View of the 20 kN·m torque reference device

Although the Finnish market for calibrations above 2 kN·m is manageable, the reference machine is regularly in use. A lot of experience has already been gained. This concerns mainly the calibration process inside the machine itself, the control software and the electrical measuring equipment.

The applied calibration process is mainly based on the EA-guideline 10/14. So momentarily the reference machine imitates a step-by-step procedure, as it is done up to now by any kind of known standard machine. The machines control software will be revised during the second half of 2006. Then different procedures to gain calibration values will be tested and examined. This will include a real step-by-step procedure, quasi static procedures which still imitate the step-by-step procedure and a quasi-static process that drives all through the measurement range.

Although the machine is fully computer controlled, also the possibility of manual calibration methods is important. This is especially necessary when the calibration object cannot be connected to a PC or simply has no electronic reading possibility. For this some special calibration procedures are currently under test.

In the field of torque transducer calibration the use of the right electrical measurement equipment is very important. In any case it has to be realized that the measuring values from reference and calibration object can be read out simultaneously. The best way to realise high quality measurements is to use amplifiers that offer several channels and also the possibility to apply different principles of measurement, such as bridge voltage, DC-voltage or frequency outputs. The trial of using different electronic units for the simultaneous measuring of two transducers with different output signals might lead to wrong calibration results. Especially different ways of filtering and/or different integration times in the amplifiers or different communication times with the control unit may influence the calibration results strongly.

6 CONCLUSION

The MIKES-RAUTE Mass and Force Laboratory offers torque calibrations in the range from 0.1 N·m up to 20 kN·m. This range is up to now sufficient to serve the requirements of the market. The reached uncertainty level (bmc) of $5\cdot10^{-4}$ or better all through the calibration range is satisfactory. Although the need – from the view of calibration pieces per year – for torque calibration in Finland and Scandinavia is quite small, the laboratory develops and offers torque calibrations since 10 years.

The most important aim for the laboratory is to offer the customers traceable high-level calibrations with a sufficient measurement uncertainty. This is reached, amongst others, by the following points:

- Constantly improving and developing of the calibration devices, regarding the requirements of the customers
- Good knowledge of the whole measurement chain, starting from the mechanical set-up of the calibration device over the calibration objects to the measurement electronics
- Regular comparisons with other laboratories in Europe
- Regular internal checking of the calibration machines against each other and checking of the laboratories transfer transducers
- Close contact to customers and regularly checking for the demands from the market

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