LEVER OPTIMIZATION FOR TORQUE STANDARD MACHINES

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Abstract: The lever arm length, i.e. the distance between the force-acting line [1] and the rotation axis of the lever, directly defines the torque that is acting in a torque measuring machine of the lever type. Therefore, already in the design process of the 20 kN·m static torque standard machine finite element calculations had been carried out at PTB to optimize the lever geometry in order to guarantee the constancy (within the limits of the uncertainty of measurement of the machine) of the lever arm length, even during loading [2]. The absolute measurement of the lever arm length had still been a problem at this time.

The present work describes the method of defining the lever arm length using a calibrated precision end gauge. With this gauge the above mentioned constancy of the length during the loading procedure can also be proved. Furthermore, the chosen lever geometry has an additional advantage – it permits the very sensitive adjustment of the lever arm length in the µm-range, when the bent side plates are tightened against each other. The measurement results demonstrate the success of this procedure.

Keywords: Torque metrology, torque standard machine, lever, end gauge

1   INTRODUCTION

The lever arm length, that is the distance between the line of action of the force at the end of a lever and its axis of rotation, plays a significant role in the realization of torque for metrological purposes. To achieve a relative uncertainty of measurement in a measuring facility of just a few 10^{-5} the lever arm length (in the usual range of about 0.5 m to 1 m) must be **accurately known** to within a few µm and **stable** [1]. In using the term "accuracy" we mean the problem of the absolute determination of the length of the lever as described in the following. "Stability" deals mainly with the question of the effect of temperature on the length: thermal expansion, as well as bending as a consequence of loading and resulting changes in lever arm length. The best solution to these problems is an on-site measuring system to determine the lever arm length as a function of diverse boundary conditions. A system of this kind and a new principle for the adjustment of the lever length are presented here.

2   RETROSPECT

Within the scope of the design, construction and setup of the torque standard measuring device (dead weight type), in the last few years comprehensive studies were undertaken in the PTB torque laboratory of the lever geometry, and its length determination or the variation thereof. In order to determine a length as the exact distance between two points, the position of these two reference points must be known with the appropriate accuracy. For the generation of torque we have the problem that a force must be applied at the end of a lever arm, whereby there are various possibilities for the technical realization of this force application, using e. g. conical or spherical loading pads, knives or thin metal belts. In all these cases the force is introduced in an area in the µm range. It would be not correct to call it a force introduction at a point or along a line at this scale.

From the point of view of a best possible definition of the lever arm length, the principle of the force application via thin metal belts was chosen in the PTB. It could be experimentally proven that an effective "force acting line" could be found in this case. Moreover, the position of this line was determined with an uncertainty of ±1 µm [1]. Less difficulties were caused by the definition of the axis of rotation. The levers of both the 1 kN·m and the 20 kN·m are fixed to the rotor of an air bearing. For the first machine (1 kN·m) the whole system consisting of the bearing (stator and rotor) and the lever was placed on a co-ordinate measuring machine. The distances between several key points were measured and the lever lenght was determined with an uncertainty of about 1 µm. Due to the large

dimensions and the big masses of the air bearing and the lever of the second machine (20 kN·m), it was not possible to use the co-ordinate measuring method for this machine with the same accuracy. Therefore an alternative method was needed.

The material of the lever side plates of the two levers is a special steel ("super invar") with a very low coefficient of thermal expansion (about -1,9·10^{-7}/K at 20°C). It minimizes changes of the lever length caused by temperature variations. In addition, the measuring facilities are located in an air-conditioned laboratory, therefore the thermal expansion of the lever can be neglected. This is not the case for the changes of the lever length due to loading. Depending on the geometry, large shifts of the force acting line of some 10 µm can arise [2]. This effect occurs especially with levers which show no symmetry related to a horizontal mid-plane containing the axis of rotation. Such an unsymmetrical lever had to be designed for the 20 kN·m torque standard machine for reasons of the available space. Therefore, finite element calculations had been carried out with the aim to optimize the design of the lever side plates and to guarantee a minimal change of the effective lever arm length during loading of the lever.

3   THE PROBLEMS

After this analytical and numerical work it was necessary to solve the experimental problems. A method (procedure and equipment) had to be developed which allowed to measure the length of the lever of the 20 kN·m torque standard machine (see figure 1) under unloaded and loaded conditions. These measurements should also be possible at different temperatures.
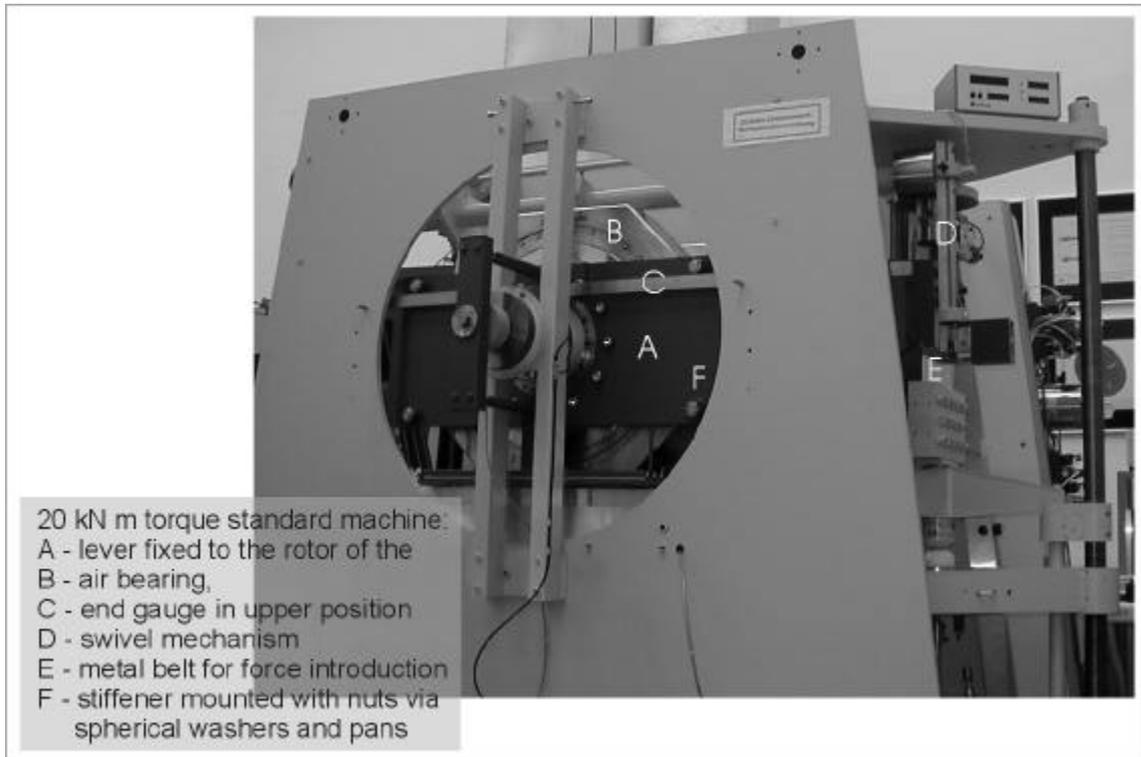

20 kN m torque standard machine:
A - lever fixed to the rotor of the
B - air bearing,
C - end gauge in upper position
D - swivel mechanism
E - metal belt for force introduction
F - stiffener mounted with nuts via
   spherical washers and pans

Figure 1. 20 kN·m torque standard machine

The lever end plates had been manufactured with a small oversize. It was intended to carry out the fine adjustment of the lever arm length on these end plates. From the length measurement results it should be calculated by how much micrometers the thickness of the end plates had to be reduced by grinding to size. This would require to remove the plates from the lever. On the other hand, the removal of these plates is a source of additional uncertainty contributions. Therefore it was desirable to find an alternative method and to avoid the dismounting and mounting process.

4   THE NEW IDEAS AND RESULTS

The comparison and adjustment must be carried out using a reference or standard. Consequently, the machine was equipped with an end block (end gauge). It is placed in the machine close to the lever in a way that its end surfaces are parallel to the lever end plates (in the lower position it can be used for the measurements, the upper position is for storing it). Furthermore, a special swivel
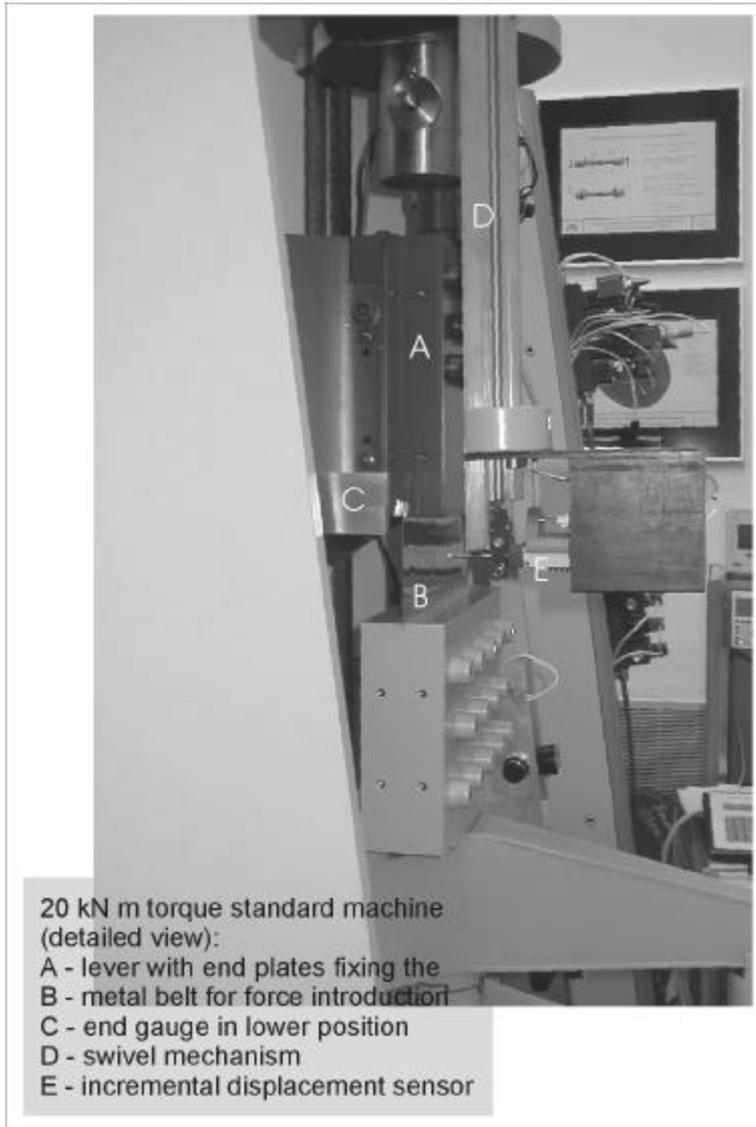
20 kN m torque standard machine
(detailed view):
A - lever with end plates fixing the
B - metal belt for force introduction
C - end gauge in lower position
D - swivel mechanism
E - incremental displacement sensor

Figure 2. Detailed view of the 20 kN·m torque standard machine

mechanism allows to place two incremental displacement sensors alternately on both ends of the lever and of the end gauge (see figure 2). By measuring the distances from the zero positions of the sensors to the end surfaces and calculating the sum for the lever and the end gauge, the deviation can be found with an uncertainty of about 1 µm.

These developments and investigations were accompanied by finite element calculations of the lever with the aim to calculate its deformation and deflection due to the loading, but also the change of the lever arm length. These calculations were based on already existing models for the lever optimization [2].

Figures 3 and 4 show some results. The loading of the lever with a force of 20 kN causes a deflection at its end of about 0,3 mm. The transverse bars (stiffeners) at the beginning of the tapered section are strained only to a small extent. Therefore the calculations were repeated on a model without these stiffeners. The result (figure 4) differs very strongly from the previous one: the deflection amounts to about 1,5 mm and the lever showed a large deformation of 3,6 mm near the transition from the straight to the tapered section! In addition, the change of the lever arm length was calculated at more than 60 µm.

The following conclusions can be drawn from these numerical results: although the stiffeners were only moderately strained, they had to perform an important function: they prevent a large deformation of the lever and contribute substantially to its overall stiffness. Furthermore, a striking new method was found: the lever length can be very sensitively adjusted in the µm range via small changes in the sub-mm range in the length of the stiffeners. When the stiffeners have threads at their ends, it is possible to fix them to the lever side plates by means of spherical washers and pans (figure 5). This allows to finely adjust the lever length to the end gauge.

The described design of the transverse bars was realized. During the adjustment of the lever length it was necessary to observe the temperature and to minimize its variations. The measurements confirmed the expected results for the overall length and its change due to loading: the length could be linked up to the end gauge. The succeeding measurements had the aim to determine the ratio between right and left lever arm lengths. Therefore the machine was operated as a balance and loaded with equal weights on both sides taking advantage of the very small friction in the air bearing. A resulting torque was then mainly caused by a difference in the two lever arm lengths. This difference was minimized in an additional fine adjustment of the lever arms. This method allowed to compensate unsymmetries between the two sides. In the result the two lever arm lengths could be adjusted with a relative uncertainty of measurement better than $0,5 \cdot 10^{-5}$ ($k = 2$), corresponding to 5 µm at a length of 1 m. Additional investigations showed that this length was constant within 1 ... 2 µm even when the lever was loaded.
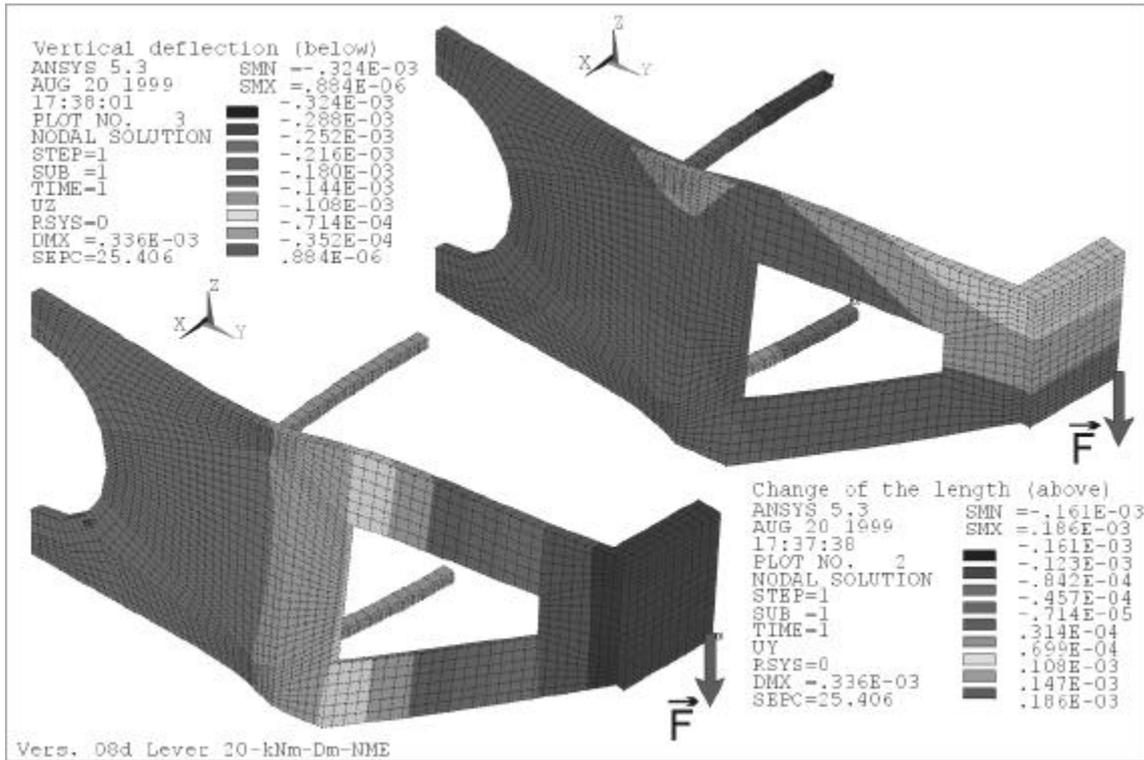
Figure 3. Deflection (deformation in the vertical) and change of the length of the lever with stiffeners (results of FE calculations)
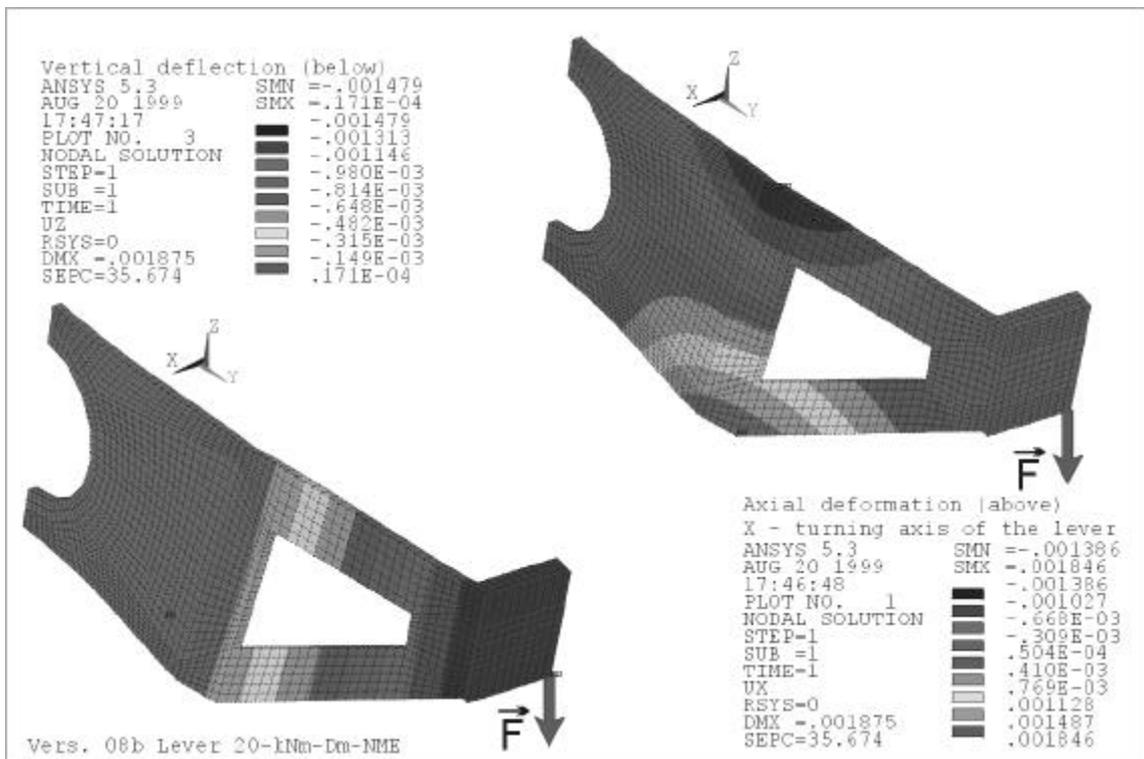

Figure 4. Deflection and axial deformation of the lever without stiffeners (results of FE calculations)

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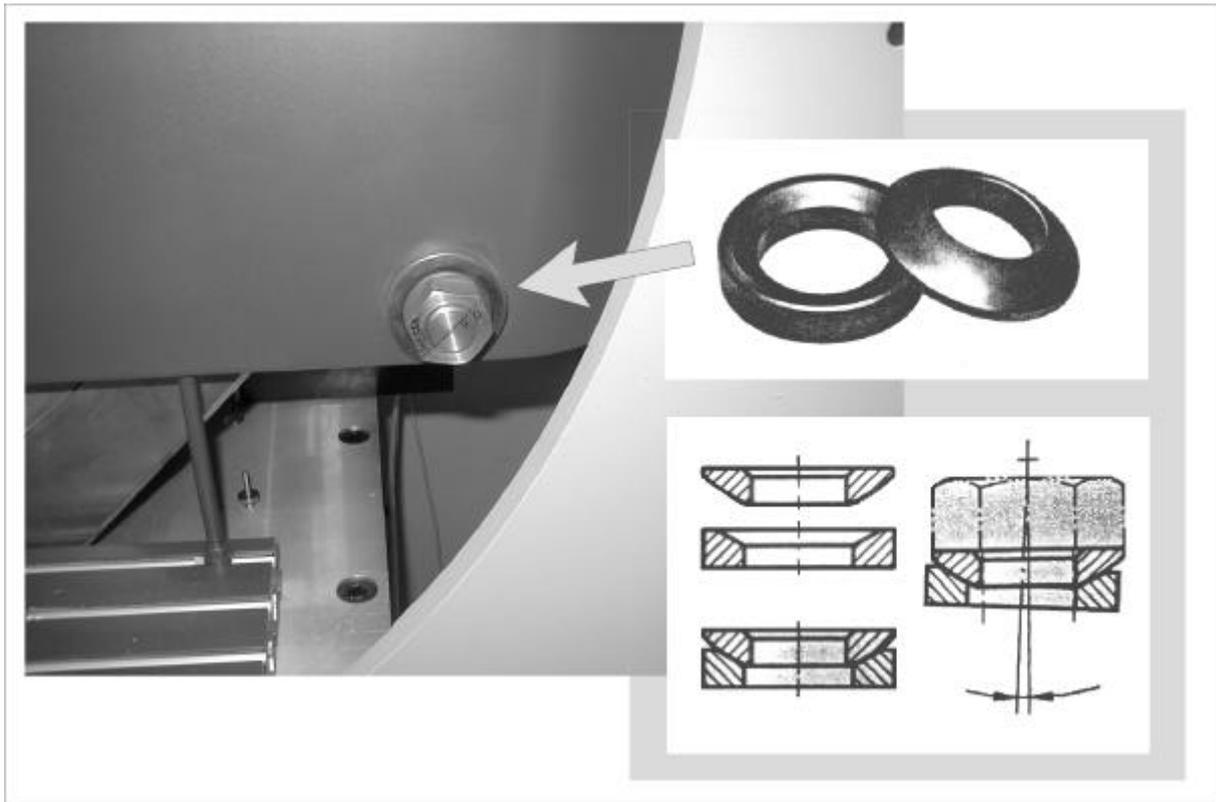Vienna, AUSTRIA, 2000, September 25-28

Figure 5. Spherical washers and pans: working principle and use in the machine [3]

With these results the problem of the measurement and adjustment of the lever arm length of the 20 kN·m the torque standard machine could be solved successfully and in a very efficient way on the site. In addition, the lengths can be checked and adjusted again at any time.

5   CONCLUSION

New design ideas and measuring methods allowed a very efficient and reproducible adjustment of the lever arm length of the 20 kN·m the torque standard machine. Especially the on-site measuring system with a calibrated end gauge offers the possibility of a periodic re-adjustment of the length. The special design of the lever with its tapered ends allows a very sensitive adjustment of the lever length by changing the distance between the fixing points of the transverse bars. Measurements of the residual torque generated when the lever was loaded with equal weights on both sides make it possible to adjust the separate lever arm lengths for each of the two sides.

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