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# NOVEL APPROACHES TO REDUCE THE UNCERTAINTY OF TORQUE STANDARD MACHINES FOR SMALL TORQUES

*Wagner, A.[1]; Theska, R. [1]; Bitencourt, A. C. P.[2]; Lepikson, H. A. [3]; Weingaertner, W. L. [4]*

[1]Technische Universität Ilmenau, [2]Instituto Federal de Educação, Ciência e Tecnologia da Bahia, [3]Universidade Federal da Bahia, [4]Universidade Federal de Santa Catarina

## ABSTRACT

The number of small torque applications is increasing continuously – in the industry as well as in the science. To ensure the function of these applications, the required torque should be known and should be realized with an appropriate uncertainty. This fact reinforces the need of a working traceability chain up to a primary torque standard for nominal torques in a range from 1 N·m to 10 mN·m with torque steps down to 1 mN·m. The achievable relative uncertainty of current torque standard machines (TSM's) for the small torque range is no longer sufficient, especially not for torques less than 100 mN·m. This paper deals with new promising approaches to reduce the relative uncertainty in TSM's significantly.

***Index Terms*** **–** small torque, relative uncertainty, torque standard machine

## 1. MOTIVATION

Having a closer look inside modern electronic devices like cell phones or digital cameras, there is a large number of smallest screws. To fasten those screws without shear off or distortion, the tightening torque should be well known and intelligently controlled. Additional examples for those small torque applications are micro gears, micro tools or even implants in the dentistry, whereat the number of those applications is increasing continuously – in the industry as well as in the science. In every case it is essential to know the torque with an adequate relative uncertainty.

To permit this progress further on, the traceability needs to be ensured (Figure 1). Current TSM's for torque ranges less than 10 N·m reach relative uncertainties of $U_r = 5 \cdot 10^{-5}$ (k=2) [1]. However, for torques less than 100 mN·m the uncertainty increases significantly. A new primary torque standard for small torques with a relative uncertainty of $U_r = 1 \cdot 10^{-5}$ (k=2) over the whole torque range is required.

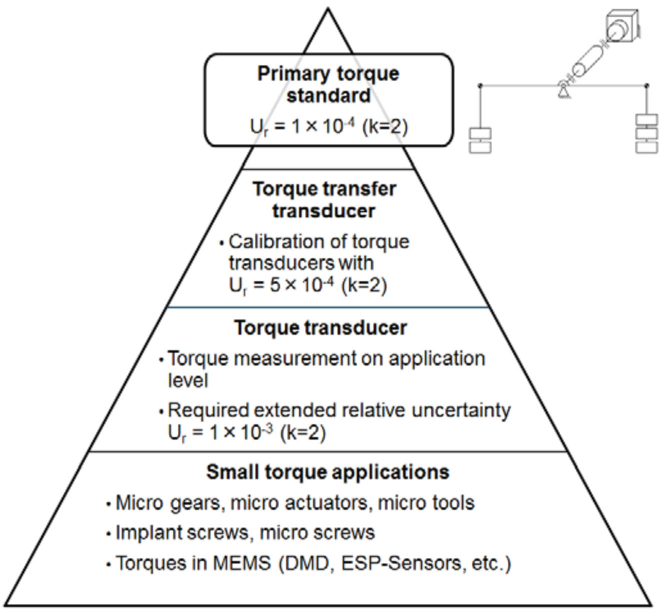


*Figure 1: Traceability chain for small torques*

## 2. STATE OF THE ART

The state of the art can be described by two examples. On the one hand, there is the 1 N·m TSM of the PTB (German National Metrology Institute), shown in Figure 2. A torque range of 1 N·m can be realized in steps down to 1 mN·m. The extended relative uncertainty is specified with $U_r = 1\cdot10^{-4}$ (k=2). [2]

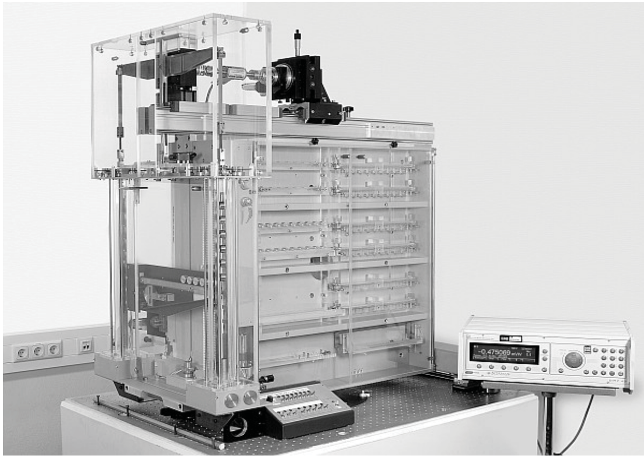

*Figure 2: 1 N·m TSM of the PTB, Germany* [2]

On the other hand, there is the TSM from China, which is able to realize torques in a range from 1 mN·m to 10 N·m [3]. In the torque range from 1 mN·m to 100 mN·m, it reaches an expanded relative uncertainty of $U_r = 1\cdot10^{-3}$ (k=2) and in the torque range of 100 mN·m to 1 N·m an expanded relative uncertainty of $U_r = 2\cdot10^{-4}$ (k=2). The Chinese TSM shows a different design compared to the German TSM. The lever bearing in the German TSM is designed as an air bearing while the Chinese TSM uses a knife edge bearing. Instead of a motor driven counter torque device on the German side, the Chinese TSM consists of two beams. The standard beam which realizes the standard torque and the balance beam which realizes the counter torque.

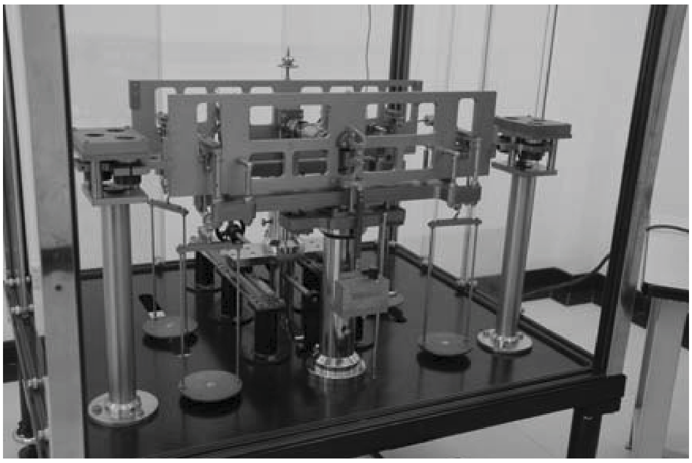

*Figure 3: 1 mN·m to 10 N·m TSM of China* [3]

Nevertheless, the current TSM's which correspond to the state of the art show one basic structure which is exposed in Figure 4. This abstraction of a TSM allows the definition of three main functional groups. The first main functional group realizes the standard torque. It consists of a symmetrically pivoted lever, where a mass stack is mounted at each lever end. By this means the standard torque $M$ is defined by the lever length $l$ and the force $F$ which is realized by the masses $m$ in the gravitation field $g$. The lever bearing is usually designed as an aerostatic bearing, but also knife edge bearings or leaf springs [1] are adopted. The second main functional group serves as torque measurement and consists of a fixation for the torque transducer which should be calibrated. To minimize lateral forces caused by position deviations, the fixation is connected to the other main functional groups by couplings. The last main functional group is called counter torque device and serves for the turn back of the lever into the horizontal position. This reduces the angle error caused by distortion of the lever. Commonly the counter torque device consists of an electric motor with worm gear.

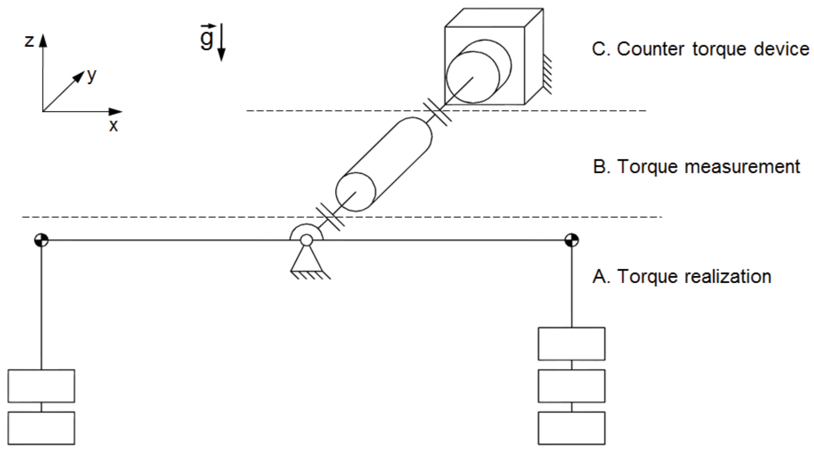


*Figure 4: Abstraction of a TSM*

## 3. ERROR INFLUENCES AND UNCERTAINTY BUDGET

Each main functional group has error influences on the standard torque, whereat the first group realizes the most significant error influence. An overview of all error influences of a TSM and the summarizing equation Eq. 1 are given in [4] for the 1 kN·m TSM of the PTB.

$$M = m \cdot g \cdot l \cdot \left(1 - \frac{\rho_L}{\rho_m}\right) \cdot \cos\alpha + \delta M_R + \delta M_D + F_L \cdot l + F_{Mag} \cdot l \qquad \text{(Eq. 1)}$$

Furthermore, in [4] the uncertainty budgets are shown for the 100 N·m and for the 1000 N·m torque steps. Scaling down these results to 1 N·m, a first theoretical statement of the error influences of a 1 N·m TSM can be done. At first sight, this assessment shows four main error influences: the air bearing friction $\delta M_R$, the parasitic moment caused by pressure deviations in the air bearing $\delta M_D$, the parasitic moment caused by air flow at the mass stacks $F_L \cdot l$ and the parasitic moment caused by magnetic fields of the mass pieces $F_{Mag} \cdot l$. These four influence factors were not measured but the uncertainty of measurement was set on 0,058 mN·m for each of them.

In contrast to the 1 kN·m TSM of the PTB the conceptual design of the new 1 N·m TSM provides encapsulated mass stacks to prevent parasitic influences by air flow. Furthermore, the mass pieces are going to have a greater distance in between each other to minimize the interacting magnetic effects. The influences caused by the air bearing are going to be avoided by using a flexure bearing. With these adjustments the uncertainty input of the mentioned influence factors will be reduced to a minimum.

By this means, there appear three further significant error influences: mass, length and air density [5]. Figure 5 shows the percentage uncertainty input of these three factors for the torque steps 1, 10, 100 and 1000 mN·m for a lever length of 500 mm. The remaining influence factors are summarized under the term "other". The overall uncertainty is shown as a wide grey bar for each torque step on the right axis.

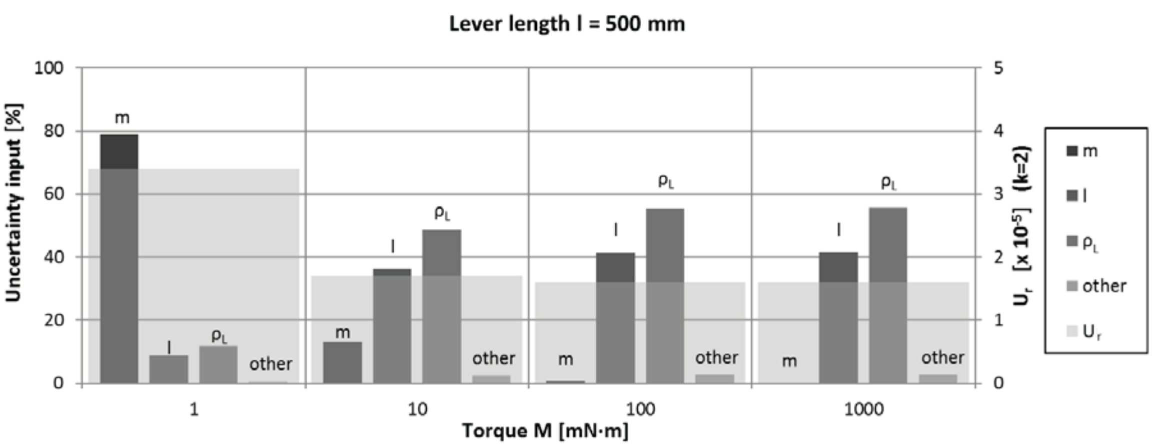


*Figure 5: Uncertainty input of main influence factors (lever length l = 500 mm)*

As Figure 5 shows, air density $\rho_L$ and lever length $l$ are the dominating error influences of the torque range from 10 mN·m to 1000 mN·m. For torques less than 10 mN·m, the mass is the dominating error influence, while the overall uncertainty has doubled. The increasing influence of the mass for decreasing torque is caused by the rising uncertainty of small masses. The challenge is now to reduce the uncertainty input of the air density and the lever length for the whole torque range and to find a solution how to minimize the mass influence for torques less than 10 mNm. The following chapter presents new promising approaches and developed concepts regarding this challenge.

## 4. NOVEL APPROACHES TO REDUCE THE UNCERTAINTY

The reduction of the relative uncertainty in small torque realization requires fundamental changes. The usual structure and especially the realized principles used in current TSM's reach the limit of what is technically and physically feasible. However, the dead weight principle gives the best metrological characteristic in torque realization. In the following paragraphs, new approaches are shown to expand the existing limitations based on the dead weight principle.

### 4.1. New torque realizing principle

The dead weight principle is most common used to realize a torque. Basically it consists of masses, which realize a force in the gravitation field. This force acts on a lever and realizes the torque. With that, the torque is realized by two SI base quantities, mass and length, and the local earth gravity. There are a number of variants of the dead weight principle. In most cases and especially for primary TSM a symmetrical pivoted lever with one mass stack at each lever end is common (Figure 6).

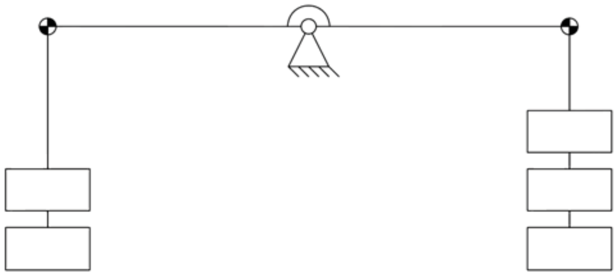

*Figure 6: Most common variant of the dead weight principle*

This variant has a relative simple structure and allows the highest accuracy in torque realization up to now. But there are obvious disadvantages in the case of small torque realization. For small torques, small masses are needed but as smaller the masses are, as higher is their uncertainty, what is obviously shown in Figure 5. Fortunately this problem can be solved by using higher masses on a shorter lever length. However, a short lever limits the torque range because of the need of very large masses for the upper torque range.

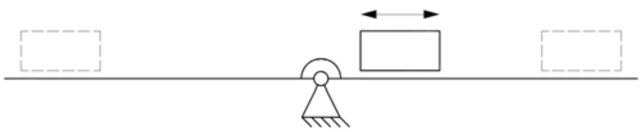

*Figure 7: Jockey-weight principle*

Another variant uses a mass, which can be moved along the lever and realizes different torques depending on the position on the lever arm (Figure 7). In this case, the lever length changes in contrast to the common dead weight principle, where the mass is variable to realize different torques. The so-called jockey-weight principle can realize very short lever lengths. However, to realize torque steps down to 1 mN·m very short moving steps of the mass are required. The problems of this principle are quite evident, how to move the mass along these small distances with the required accuracy and repeatability and furthermore how to hold the mass in the correct position without inducing parasitic forces and moments.

Therefore, a new variant of the dead weight principle has been developed to combine the advantages of the common dead weight principle and the jockey-weight principle. This new variant consists of more than one force application point per lever side. An example with three force application points per lever side is shown in Figure 8.

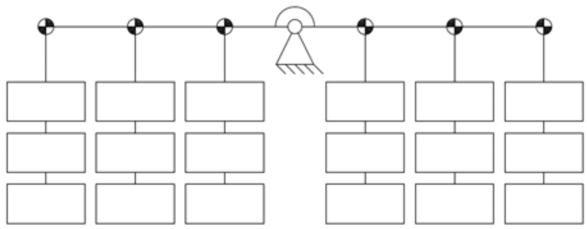

*Figure 8: Example of the new variant of the dead weight principle*

Therewith, different lever lengths are realizable. The application point with a short lever length serves for the realization of the small torque range with higher masses. For this reason, the uncertainty input of these masses can be reduced significantly. Even the overall relative uncertainty could be reduced for the small torque range down to the level of the upper torque range. An example for a lever length of 50 mm is given in Figure 9. In comparison to Figure 5, the difference becomes clear.

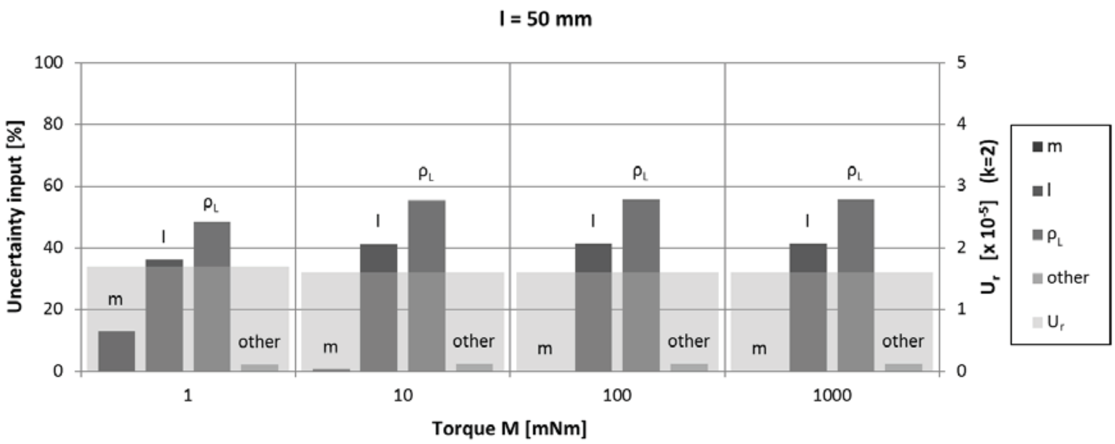


*Figure 9: Uncertainty input of main influence factors (lever length l = 50 mm)*

As an interim conclusion, the new variant of torque realization reduces the error influence of the mass for the small torque range. Thereby, the whole torque range from 1 mN·m to 1 N·m has an equal relative uncertainty, influenced by the remaining significant uncertainty influences lever length and air density.

**4.2. New method to determine the lever length**

The lever length is defined by the rotational axis of the lever bearing and the force application point. None of these points can be sampled directly with a measuring device. That is why the determination of the lever length with common measuring methods is fraught with uncertainty. A new measuring method has been developed to determine the lever length without any information about the position of the rotational axis or the force application point. A principle sketch of this new method is shown in Figure 10.

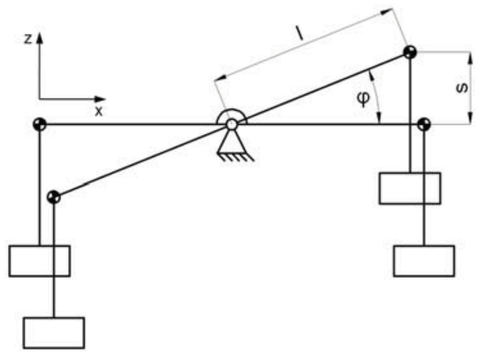


*Figure 10: Principle sketch of the new method to determine the lever length*

The basic procedure to determine the lever length *l* is to distort the lever and to measure the angle of distortion $\varphi$ and the dependent displacement *s* of the force acting point. The lever length *l* can be determined with the simple Eq. 2.

$$l = \frac{s}{\sin \varphi} \qquad \text{(Eq. 2)}$$

However, the standard torque will be realized when the lever is in a horizontal position ($\varphi = 0$). The lever length in a distorted position does not equal the lever length in horizontal position due to the shortening of the effective lever length and the displacement of the rotational axis in the lever bearing. Furthermore, this method does not allow the determination of the lever length in a horizontal lever position, because of the fact, that if $\varphi = 0$ then $s = 0$. To determine the lever length in the horizontal position, it is required to repeat the measurements with different angles close to $\varphi = 0$ and to calculate the dependent lever lengths $l\ (\varphi)$. Based on this, the lever length $l\ (\varphi = 0)$ can be determined.

Another problem is how to measure the angle $\varphi$ and the displacement *s*. To reduce the uncertainty significantly compared to the common measuring methods, both quantities need to be measured with highest accuracy. In upcoming experiments the autocollimation will be tested as angle measurement. The measurement of the displacement *s* is planned to be done by laser interferometry. A first rough calculation of the reachable relative uncertainty promises a significant reduction of the relative uncertainty.

### 4.3. Operation under constant environmental conditions

The remaining error influence is the air density. The air density is influenced by the local air pressure, the temperature, the air flow, the heat convection, etc. These influences only can be reduced by getting the environmental conditions under control. Therefore a pressure-tight chamber is necessary to reduce the alternations of environmental influences down to a minimum and with that the error influence of the air density.

## 5. CONCLUSION

A new primary TSM for the small torque range is necessary to permit the requirements of the progressing miniaturization. This paper defines the influence factors air density, length and mass as the main error influences in small torque realization. Especially the uncertainty of the mass increases significantly with decreasing torque and raises the overall uncertainty up to double.

New approaches are presented to reduce the uncertainty of each influence factor. The relative uncertainty of the mass can only be reduced by increasing the mass. To realize small torques with higher masses the acting lever length should be shortened. This was implemented into a new variant of the dead weight principle. The error influence of the lever length can be reduced by a new measuring method. Finally, the operation in a pressure-tight chamber is required to reduce the environmental influences, while the air density is the most critical influence factor. All these adjustments promise a significant reduction of the overall relative uncertainty down to the defined goal of $U_r = 1 \cdot 10^{-5}$ (k=2). The next step is to verify these assumptions experimentally.

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