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COMPLETION AND MEASUREMENT UNCERTAINTY BUDGET OF THE MULTI-COMPONENT MEASURING DEVISE FOR FORCE UP TO 1 MN AND TORQUE UP TO 2 KN·M

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This paper present the completion and the measurement uncertainty budget of a multi-component measuring facility. The new facility is part of the 1 MN force standard machine [1] of the PTB. It enables the simultaneous generation of a torque in the range from 20 N·m to 2 kN·m in addition to axial forces 20 kN to 1 MN. This allows the characterization of measuring systems which require combined loads of axial forces F_z and torques M_z like friction coefficient sensors. The aim is a measurement uncertainty of ($k = 2$) for M_z < 0.01% and F_z < 0.002%. The physical model yields to extended measurement uncertainties (k = 2) for 20 N·m of $5.9 \cdot 10^{-5}$ and for the maximum load step 2000 N·m $4.2 \cdot 10^{-5}$.

Keywords: multi-component measurement, measurement uncertainty budget, torque, force, friction coefficient sensor

1. INTRODUCTION

There is an increasing number of measuring systems that can detect more than one force or torque component of these vectorial physical quantities. There is therefore an increasing need for traceability with regard to multi-component measurements. Realizations of such measuring facilities with sufficient measurement uncertainty and a suitable measuring range are complex and rare. PTB's hexapod [2] and the measuring facility at IMGC [3] are examples of such a realization. The PTB use the infrastructure that is already available at measuring facilities, to upgrade one facility by additional torque components. As a result of a project in PTB, within the 1 MN force standard machine (1 MN FSM) in addition to the force torques can now be generated by means of a lever/band/mass system. This extension of the FSM allows the combination of a force measuring range from 20 kN to 1 MN with a torque measuring range from 20 N·m to 2 kN·m. This, in turn, extends the service range of the measuring facility, and measuring systems such as friction coefficient sensors or wheel load sensors can, thus, be investigated specifically. The measurement uncertainty budget (MUB) for M_z is presented.

2. SET-UP

The additional torque device has a modular set-up and can be mounted into or removed from the force flow of the 1-MN FSM. It works on the basis of the principle of a two-armed lever at the ends of which a force couple acts. The force couple is equal value which, although parallel to each other, act in the opposite direction to each other. The cross forces thus neutralize each other and all in all, an active torque M_z is realized. The forces are generated via two mass stacks that are located symmetrically on either side of the 1 MN FSM (see Fig. 1). Each of these mass stacks (see Fig. 2) is composed of a lowerable set of masses. The mass disks are coupled to a metallic band. The metallic band is diverted by means of an air-bearing rotor. The vertical gravitational force of the mass stacks becomes a horizontal tensile force. The metallic band is coupled to the lever arm and thus transmits the force onto the system. Sensors and step motors stabilize the system position under load and changing load conditions. The synchronous triggering, monitoring and data acquisition are effected by EXCEL macros and a DMP 41.

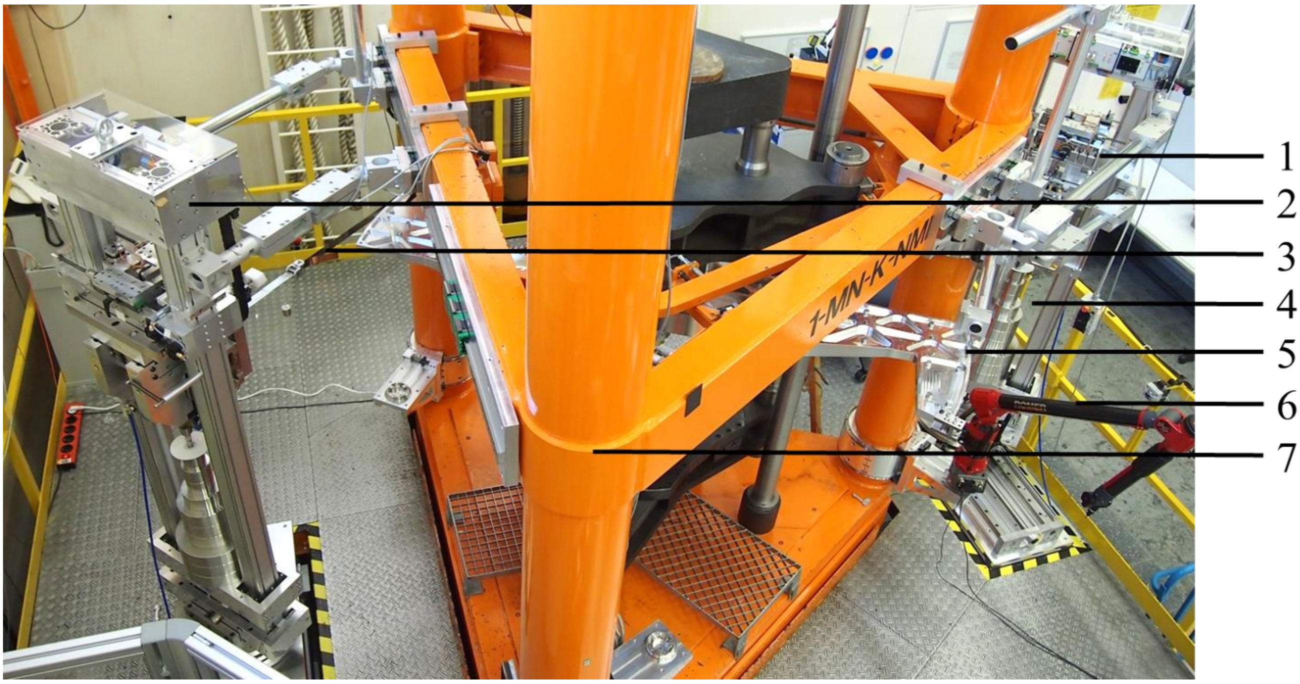

Figure 1: Multi-component measuring facility from above: 1 − mass stack A; 2 − mass stack B; 3 − metallic band for force application onto the lever; 4 − masses; 5 − two-armed lever; 6 − coordinate measuring device, mounted onto a column support; 7 − 1 MN FSM

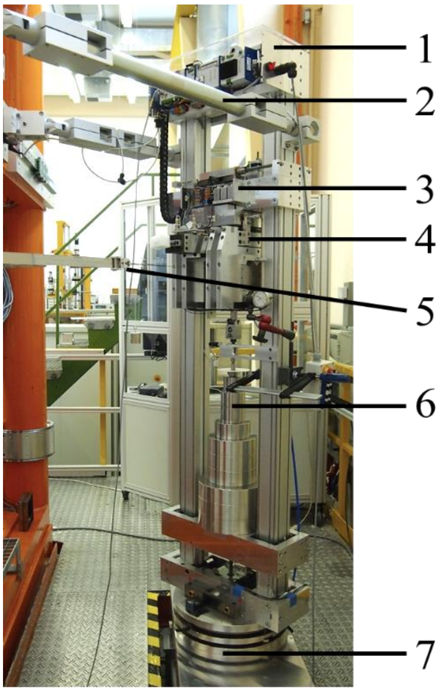

Figure 2: Mass stack B. Both mass stacks exhibit an identical design: 1 − SPS control; 2 − Support elements resting against the frame of the 1 MN FMS; 3 − block with step motors for the displacement and tilting of the air-bearing head; 4 − air-bearing head with integrated rotor for force diversion; 5 − metallic band and coupling element for force application; 6 − masses; 7 − rotational and linear table for position displacement of the mass stack

3. MEASUREMENT UNCERTAINTY BUDGET

A specific measurement uncertainty budget for the additional facility is presented. It includes a model, Figure 3, taking physical and geometric influence factors into account. This includes different factors, among other things, environmental influences, geometric characteristics, or the influence of the mass stacks. The influence of different influence factors on the measurement uncertainty and on the signal stability (e.g. friction inside the air bearing) have been investigated. In this case of application, also the realignment process of the mass stacks, the flatness errors of adaption parts and angular deviations must be taken into account. The model therefore encompasses a consideration of the system according to the vectorial components of $\boldsymbol{M}$ (1) and the analysis of the influence factors on the measurement uncertainty. In the coordinate system used, M_z is the torque, l_y is the lever length, and F_x is the applied force. The ideal case thus consists in the lever and the force vector lying in the xy-plane and being oriented orthogonal to each other. An additional axial force F_z can be applied onto the system by the 1 MN FSM.

Tab. 1 shows identified factors and their percentage weighting for the load steps 20 N·m and 2000 N·m. Identical measurement uncertainty budgets has been established for each load step. According to the physical model, the measurement uncertainty ($k = 2$) for the minimum load step 20 N·m is $5.9 \cdot 10^{-5}$ and $4.2 \cdot 10^{-5}$ for the maximum load step 2000 N·m.

$$\vec{M} = \vec{F} \times \vec{l} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \times \begin{bmatrix} l_x \\ l_y \\ l_z \end{bmatrix} = \begin{bmatrix} F_y l_z - F_z l_y \\ F_z l_x - F_x l_z \\ F_x l_y - F_y l_x \end{bmatrix} = \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} \quad (1)$$

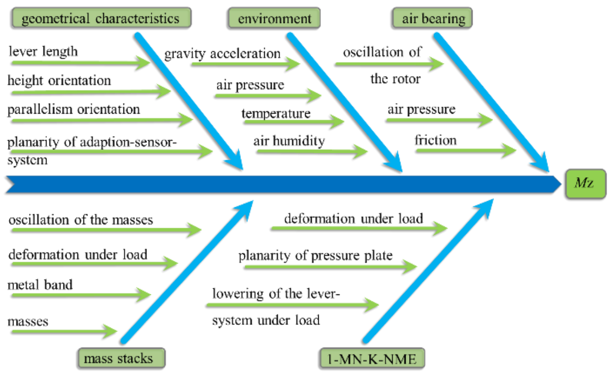

Figure 3: Overview of the acting influence factors in the form of an Ishikawa diagram for M_z

3.1. Local gravitational acceleration

The local gravitational acceleration at the measuring station was determined by the Institute for Earth Measurement (IfE), Hannover, as being 9.812524 ms^{-2} with an expanded measurement uncertainty (k = 2) of 10 µms^{-2}.

3.2. Density and masses of the weight

The density of the material used for the cylindrical weights can be indicated as 7979.7 kgm^{-3} ± 2.0 kgm^{-3} (k = 2). The uncertainty components (k = 2) lie for all masses in a range < 5·10^{-6} kg and are computed separately for each load step. The contribution to the measurement uncertainty budget never exceeds 1.33 %.

3.3. Environment

For the determination of the acting gravitational force, a buoyancy correction (2) was applied. The measuring facility is located in an air-conditioned hall. Changes in the ambient conditions are minimum. The actual values for the air pressure, the humidity and the temperature are acquired to compute the MUB. Their influence on the MUB, however, lies in a range < 0.01 %. The ambient parameters from Tab. 1 for the MUB are the humidity: 42 % ± 5 %, the temperature: 21 °C ± 0.1 C°, and the ambient pressure: 1003.4 hPa ± 2 hPa.

$$F_x = m_m \cdot g_{loc} \cdot \left(1 - \frac{0{,}348 \cdot p_L - 0{,}009 \cdot h_L \cdot e^{0{,}06 \cdot T_L}}{(273{,}15 + T_L) \cdot \rho_m}\right) \qquad (2)$$

3.4. Lever length and thermal expansion

A two-armed lever is used. A specified value of 999.92 mm applies to both sides. The length of the whole lever was calibrated at PTB's Coordinate Metrology Division; the result obtained was: 1999.8822 mm ± 0.028 mm (k = 2). When calculating the total length, also the half of the thickness of the metallic bands for force application must be taken into account. The thickness is 0.08 mm ± 0.001 mm.

Table 1: Measurement uncertainty budget for the load steps 20 N·m and 2000 N·m

Influence quantities	Index of MUB	
	20 N·m 5.9·10^{-5}	2000 N·m 4.2·10^{-5}
Gravitational acceleration	0.05 %	0.12 %
Ambient pressure	< 0.01 %	< 0.01 %
Air humidity	< 0.01 %	< 0.01 %
Temperature	4.92 %	9.73 %
Weight of the masses	1.36 %	0.413 %
Metallic bands overlap	< 0.01 %	< 0.01 %
Lever length	45.24 %	89.53 %
Air bearing friction	48.31 %	< 0.01 %
Metallic band thickness	0.06 %	0.11 %
Height discrepancy	< 0.01 %	< 0.01 %
Parallelism error	0.04 %	0.07 %
Angular error of the pressure plate	< 0.01 %	< 0.01 %
Angular error of the adaption/sensor system	< 0.01 %	< 0.01 %

The measurement uncertainty of the determination of the lever length represents the largest contribution to the MUB for M_z. Due to the geometrical dimension of the lever, this uncertainty cannot be further reduced with the existing coordinate measuring machines.

The lever is made of an aluminum alloy. The thermal expansion for this alloy is 2·10^{-2} K^{-1}. Accordingly, temperature fluctuations of 0.1 C° have an influence of 4.92 % on the MUB. The lever will later be replaced by another lever made of a temperature-stable INVAR alloy.

3.5. Friction of the air bearings

The air bearings do not provide absolutely friction-free force diversion. The influence of the friction inside the air bearing on the torque signal must therefore be investigated [5]. For this investigation, additional weight having a defined mass were applied. The weights are selected in such a way that, with the measuring chain used, a change in signal of practically exactly 1 digit is expected. Figure 4 shows the expected change in signal for additional weights of different mass. The measurements were repeated at all load steps and yielded the same result. A change of 1 digit, however, also corresponds to the signal stability of the measuring amplifier, the influence has, thus, been estimated as being 2 digits. This corresponds to a maximum torque proportion of 3.1·10^{-4} N·m. The contribution to the MUB is constant across the load steps. The percentage contribution to the MUB for small load steps, 48.3%, is therefore the largest.

3.6. Influence of torsion under load

Loading the system with a torque leads to a torsion of the adaption/sensor system. Torsion, in turn, leads to a reduction of the length of the metallic band between the lever and the unwinding point at the air bearing. The difference represents the overlapping of the metallic band on the side of the force generation F_x and, as an additional mass, it contributes accordingly to the torque M_z. The proportion directly depends on the load step. The differential length is determined by means of a laser sensor as being to 10 µm. The change in mass is determined by means of the band thickness 0.08 mm ± 0.001 mm, height 30 mm ± 0.1 mm and density 7850 kgm^{-3} ± 20 kgm^{-3} and it is taken into account for the torque calculation. The contribution to the MUB is < 0.01%.

4. GEOMETRICAL CHARACTERISTICS

To calculate the MUB and the disturbing quantities, the orientation as well as the geometric deviation from the optimal orientation must be detected. Parallelism differences, angular deviations, tilts of the lever and height differences are part of these deviations.

A coordinate measuring device acquires the geometric characteristics. By scanning any given point, the coordinate measuring device, with the aid of various angular encoders, computes the spatial position in relation to the machine coordinate system. The quality of a measurement depends on the measurement process, on the user, on individual errors of the angular encoders as well as on the computation performed by the coordinate measuring device. We have assumed that the accumulation of the individual errors follows a Gaussian distribution. The hypothesis was checked – and confirmed – by repeated measurements and by means of a Shapiro-Wilk test [6] for the individual measurement processes.

Sine and cosine functions must be used to calculate the MUB according to (1). The problem is that the sensitivity coefficient often tends to be zero at small angles. For this reason, an upper estimation is used for the influence [7].

4.1. Deviation in parallelism orientation

For an ideal couple, both metallic bands must be exactly parallel to each other. Measurement points for the coordinate measuring device on the lever and on the air bearing serve as reference points to determine the angle. The uncertainty across the measurement process was estimated by averaging with ($k = 2$) 0.02°. Together with the fine adjustment of the angular orientation, a parallelism error of 0.072° is obtained.

4.2. Deviation in height orientation

For the ideal orientation, the height of the force application point at the lever must be in agreement with the band unwinding point at the air bearing. Reference points are used for the height orientation of the system; with 45 µm ($k = 2$) for the contribution throughout the measurement process. The stability of the height is given by differential

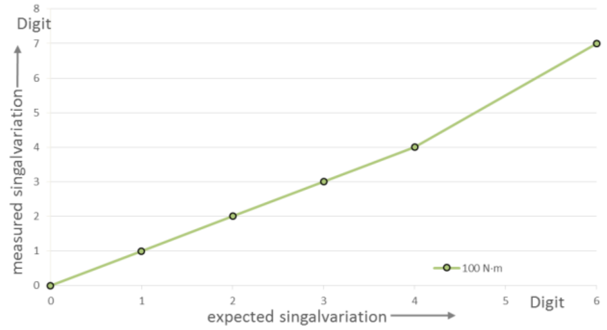

Figure 4: Deviation of the measured torque from the applied torque in relation to the load step.

height measurements with a laser sensor at the end of the lever and by the displacement of the air bearing via a step motor. The signal threshold level for the adjustment was laid down as being 100 µm. If the signal threshold level and the contributions due to the uncertainties of differential height measurements and of the displacement by means of the step motor, then one obtains a total contribution of 186 µm. A reduction of the signal threshold level considerably reduces the uncertainty; however, the effort for the adjustment control then increases tremendously. A one-sided height difference of 186 µm, related to a band length of 1440 mm, corresponds, at 1000 N, to a negligible change in torque of $8.3 \cdot 10^{-6}$ N·m.

When loading with the 1 MN FSM with F_z, the adaptor/sensor/lever set-up lowers itself. This is due to elongations in the 1 MN adjustment control and compression of the adapter/sensor system. For 500 kN this lowering amounts to ~ 2.6 mm. This height difference to the air bearing is corrected automatically by the adjustment control when the load is changed. The orientation therefore remains stable, even under an F_z load, in a range of 186 µm.

4.3. Deviation in planarity of the pressure plate, adaptation and sensor

The lever's tilt in relation to the ideal xy-plane depends on the orientation of the adaptor/sensor system. The adaptor parts are mechanical components to mounting the sensors at the multi-component facility. Deviations lead to angular errors and, thus, to a tilt of the lever. The standard reference is the pressure plate of the 1 MN FMS. Averaging over different measurement series provides an estimate of the flatness. This can be specified as 0° ± 0.0178°. The angle refers to a tilt of the plane in relation to the ideal xy-plane. Correspondingly, an angular deviation 0° ± 0.0178° also applies to the lever.

In addition, the flatness errors accumulate due to the adaption parts, the sensor and their installation. The resulting angular error depends on the quality of the components and must therefore be determined separately for each adaptor/sensor system. In the case of the MUB described in Tab. 1, an angular error 0.18° ± 0.0201° can be stated. The MUB does not take the orientation of the angular error into account. The error is upper estimated by considering it as being constant for all directions.

According to the calibration results obtained by the Coordinate Metrology Division, the deflection of the lever due to its dead weight can be neglected.

5. DISTURBING QUANTITIES

The quantities considered as disturbing quantities are the shearing force F_y, an additional axial force F_z and the bending moments M_x and M_y. A nominal value 0 is the goal for all disturbing quantities. Deviations of the geometric orientation (essentially), however, result in an uncertainty for the nominal value; this applies to each quantity.

The computation is carried out separately for each torque load step and must be calculated anew for each adaptor/sensor system. For the system to which also Tab. 1 applies, at 2000 N·m, 0 N·m ± 0.4 N·m is obtained for M_x and 3.49 N·m ± 1.01 N·m for M_y. The deviation from the nominal value for M_y is due to the acting force F_x and to an effective lever length l_z as a result of the lever's tilt. Due to adaption parts with smaller flatness errors, it is possible to reduce the lever's tilt as well as the resulting bending moments significantly. Tab. 2 shows the percentage contribution of the significant influence quantities on the uncertainty of M_y and M_x. The influence quantities that are not mentioned there, see Tab. 1, have a negligibly small influence on the MUB amounting to < 0.0001 %.

The disturbing quantities F_y and F_z were also computed from the geometric deviations. At the maximum load step 2000 N·m, one obtains for the system 0 N ± 2.6 N for F_y and 0 N ± 0.3 N for F_z.

Disturbing quantities may cause the characteristic curve of a sensor to shift. The signal crosstalk as a function of these quantities is often difficult to describe [8]. With little technical effort, it is possible to use the measuring device asynchronously in order to, for example, estimate the sensitivity of a sensor to a certain disturbing quantity.

Table 2: Significant influences on the MUB of M_x and M_y for the 2000 N·m load step

Influence quantities	Index of MUB	
	M_x / 0.4 N·m	M_y / 1.01 N·m
Height discrepancy	99.97 %	< 0.01 %
Parallelism error	0.02 %	< 0.01 %
Angular error of the pressure plate	< 0.01 %	43.98 %
Angular error of the adaption sensor	< 0.01 %	56.02 %

5. CONCLUSIONS

The relative measurement uncertainty ($k = 2$) of the 1 N FSM is about $2 \cdot 10^{-5}$. The model provides an expanded relative measurement uncertainty for the additional measuring facility for torque generation of $5.9 \cdot 10^{-5}$ at 20 N·m and of $4.2 \cdot 10^{-5}$ for the maximum load 2000 N·m. Comparison measurements with different torque reference transducers have shown very good repeatability; the reproducibility, however, is within a range of $< 3 \cdot 10^{-4}$. The $< 1 \cdot 10^{-4}$ goal has, thus, not been achieved yet. Correspondingly, the measuring device is not yet listed in the catalogue of measuring facilities and PTB's Quality Management System. There is, however, no reason why this measuring device should not be used for research purposes. For example, investigations on industrial multi-component sensors will be beginning shortly for which measurement uncertainties of $< 1 \cdot 10^{-3}$ are sufficient.

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