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Measurement uncertainty estimation of a novel torque transducer for wind turbine test benches

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Abstract. This paper covers the measurement uncertainty estimation of a novel 5 MN·m torque transducer based on the Force-Lever principle for wind turbine test benches. The motivation of this novel transducer is to provide a satisfying accuracy in torque measurement above 1.1 MNm. Therefore the estimation of the measurement uncertainty is significant to evaluate the design. At the beginning the design is shortly introduced. Afterwards, the design is investigated under operational conditions (e.g. torque, gravity, rotational speed and multiaxial loads) by using FE simulations to determine the deformation and the parasitic loads. Finally, the measurement uncertainty is determined based on these FE simulations according to the type B evaluation of the GUM [1], including metrological aspects (e.g. linearity deviation and hysteresis). Additionally, the share in the measurement uncertainty is examined to indicate further starting points for improvements of the design. It can be shown that the novel torque transducer provides a high potential to significantly improve the measurement uncertainty in the MNm range towards existing torque measurement methods.

1. Introduction
A precise measurement of torque in the MN·m range is becoming a more important issue with the expanding wind industry. For example, to evaluate the behaviour of wind turbine on test benches, a precise torque measurement up to 20 MN·m under rotation (depended on the size of the wind turbine) is required. Interviews with industry representative reveal, that a measurement uncertainty between 0.5 % and 1 % referred to the measured value should be aimed. Current existing torque measurement methods for such high torque values like determination of torque by measuring of the

- electrical power and rotational speed,
- twist angle of the main shaft [2] or
- strain by means of flange transducers

only provide an uncertainty between 2 % and 5 % [3]. This high uncertainty for torque measurement in the MN·m range is dependent on the fact that the largest torque calibration machine, located at the German National Metrology Institute (PTB), is only capable of providing a traceable torque calibration up to 1.1 MN·m [4]. To face this issue a concept of a novel torque transducer is developed

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[5], within the project “Torque measurement in MN·m range” – funded by European Association of National Metrology Institutes (EURAMET) and European Union (EU) – the wind turbine test bench operators and National Metrology Institutes, under support of industry partners (e.g. HBM Measurement Technology). The novel torque transducer for torque measurement up to 5 MN·m is based on the Force-Lever principle using a commercial 2.5 MN force transducer. To investigate the potential of the design, various FEM simulations were carried out to determine the capability of the design to measure torque precisely. The objective of this paper provides a closer look on the simulative determination and the estimation of the measurement uncertainty. The subject of the simulative investigation are the loads cases, which represents operational conditions like multiaxial loads, temperature change and rotational speed. In addition, the share in the measurement uncertainty, due to the operational conditions is evaluated.

2. Design of the 5 MN·m Force-lever system

The design of the torque transducer consists of four main parts: input flange, connection rod, bearing system and output flange, see Figure 1. Torque is applied to the input flange, which is connected over the force levers and the connection rod to the output flange. Consequently, under torque load the force levers pull on their corresponding connection rods. These connection rod comprises a 2.5 MN force transducer and adjustment elements. The task of the adjustment elements (rod end and fine thread) is to minimise the parasitic loads during measurement and to ensure a non-overdetermined assembly. In addition, the output flange is mounted with an adjusted roller bearing arrangement on the input flange to offer additional protection against parasitic loads and ensure a coaxial position between the flanges. Consequently, a rotational relative motion between the flanges is ensured. Details to the design process can be taken out of [5].

![Figure 1. Design of the 5 MN·m torque sensor based on the Force-Lever principle.](image)

3. Estimation of the measurement uncertainty

The estimation of the measurement uncertainty for the entire system is performed according to the "Guide to the Expression of Uncertainty in Measurement" GUM [1]. Therefore, a mathematical model (Figure 2) of the torque transducer was developed. To determine the measurement uncertainty the influence of operational conditions on the parameters of these mathematical model must be investigated:

- Deviation in the measured force: \( d_{F_{\text{Para}}} \)
- Deviation of the effective distance: \( dl \)
- Amount of the parasitic loads on the force transducer: \( d_{F_{\text{Trans}}} \)
The deviation in the measured force and the effective distance affect the measured torque directly. On the other hand, the parasitic loads at the force transducer influence the accuracy of the force measurement. Consequently, the parasitic loads influence the torque determination indirectly. To determine the change in these parameters a static FE model of the entire design has been developed. The model is build up by using state of the art modelling methods [6] [7], considering flanges and force lever geometry as well as stiffness and kinematic behaviour of the bearing system and connection rods. The bearing rolling bodies (as spring) and backlash of the bearings are implemented in the model too.

3.1. Investigation of the influence of operational conditions on the measurement uncertainty

Operational conditions are consisting of the load cases shown in Figure 3. Thereby should be mentioned that the load cases Gravity, Radial force and Bending moment were performed under different rotational orientations to ensure that the worst event is considered.

![Figure 3. Load cases to predict the influence of operational conditions](image)

The deviation of the measured force and effective distance, due to these operational conditions are shown in Table 1. Additionally, the measurement uncertainty of the force transducer is considered as also an uncertainty in the initial distance (Δl_initial). The investigation of resulting parasitic loads (e.g. lateral force, bending moments) at the force transducer lead to a measurement uncertainty of the force transducer of ±2.87 kN. This includes the influence of these parasitic loads, temperature change as also the metrology characteristics like e.g. linearity, hysteresis and repeatability. The estimation of the measurement uncertainty for the entire system is performed by using the type B evaluation of GUM [1]. Therefore, the mathematical model of the torque transducer is used. For all uncertainty component the probability density function is assumed to be a uniform distribution. With the uniform distribution the standard uncertainty of each uncertainty component is calculated.

![Table 1. Deviation of measured force and effective distance of each force transducer, due to the operational conditions.](table)

3.2. Estimation of the Expanded Measurement Uncertainty

Afterwards the combined uncertainty is calculated out of the standard uncertainties of the uncertainty components in respect to the mathematical model and the law of propagation of uncertainty. By taking a coverage probability of 95% into account the expanded measurement uncertainty sums up to 31.62 kN⋅m or 0.63 % for a measuring range up to 5 MN-m. This is within the required measurement uncertainty of the industry, which is between 0.5 % and 1 % referred to the measured value. A closer
look on the share in the measurement uncertainty of the torque transducer shows that further improvements of the design should focus on reducing the influence of bending moments and radial forces (see Figure 4). To face this problem the overhang arrangement of the bearing in the design could be changed to a double-sided bearing arrangement to resist a higher tiling moment.

![Figure 4. Share in the measurement uncertainty, due to the operational conditions](image)

4. Conclusion
This paper shows that the introduced design of a torque transducer based on the Force-Lever principle can reach a measurement uncertainty of 0.63 % (coverage probability of 95 %). This is within the required measurement uncertainty of the industry, which lies between 0.5 % and 1 % referred to the measured value. Consequently, the torque traceability could be increased significantly in comparison to current torque measurement methods, which show a measurement uncertainty between 3 % and 5 %. Thus, the introduced torque transducer offers a high potential to increase the torque measurement certainty in the MN·m range. The paper shows also the best starting points for further design improvements.

Major disadvantage of the introduced design is that it cannot be traceably calibrated as a whole system according to metrological standards. The developed FE models, which are used for the entire system calibration, should be validated and enhanced to ensure accurate specification of the measurement uncertainty.

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