Simulation Method for the Characterisation of the Torque Transducers in MN·m range

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Abstract. MN·m torque measurement in wind turbine test benches and in the field is influenced by specific system-dependent parameters (e.g. rotational speed, multi-axial operation loads or deformation). Each of these parameters have a share in the torque measurement uncertainty budget. FEM simulation of the torque transducers provides a flexible and time-efficient method for the quantification of these influences. This paper describes a method for the characterisation of the torque transducers (body and strain gauges) by FEM simulation. The main focus is to give the recommendation for the selection of the FEM parameters (e.g. element type, mesh density), modelling of the strain gauges and connection between strain gauges and transducer body as well as for determination of material properties. The introduced simulation method is exemplarily deployed and validated on a self-designed 4 kN·m torque transducer and can be adapted on the MN·m torque transducers. The validation and measurement investigations have been executed on a 4 kN·m torque test rig under different temperatures (20°C, 40°C, 60°C), strain gauge adhesives (cyanoacrylate, methacrylate, epoxy resin) and various torque steps. The compiled results are a part of the EU and EURAMET funded project “Torque measurement in the MN·m range” [1].

1. Motivation and Objective
Precise MN·m torque measurement is essential for the high quality of the measurement results on multi-MW wind turbine test benches as well as in the field operation. Furthermore, MN·m torque measurement is necessary for the

- determination of the wind turbine efficiency and estimation of the annual energy yield,
- condition monitoring, optimization of the control system as well as
- characterisation of the drive train behavior under critical operation modes [2].

Torque transducers, based on the strain gauges (SG), are commonly deployed for the above mentioned tasks. Nowadays, it is not possible to calibrate this transducers above 1.1 MN·m [3]. In addition, the system dependent influences on torque measurement such as

- deformation and friction of the drive train, specific gravity forces and rotational speed,
- multi-axial operation loads as well as temperature distribution and
- assembly misalignments in the drive train

are not investigated sufficiently [4]. Consequently, the MN·m torque transducers have an unsatisfactory measurement uncertainty in the range of 5 % referred to the measured value [5].

The evaluation of the above mentioned influences and cross-talk effects on torque measurement could lead to a better understanding and simultaneously can contribute to the reduction of the torque uncertainty budget. Besides the experimental techniques, simulation is a mighty tool for such investigations. Especially Finite Element Method (FEM) simulation is a flexible and time efficient possibility for qualitative or quantitative determination of the above mentioned influences. By means of FEM it is possible to calculate the deformation and stress distribution of the MN·m torque transducers and SG and subsequently derive the mV/V output signal according the bridge circuit. This gives an opportunity to investigate the influence on torque measurement under various operation conditions and finally to calculate the share of each influence on the measurement uncertainty more precisely. In the next step, the measurement uncertainty can be optimised by modifying the transducer body design, assembly parameters or strain gauge (SG) geometry and wiring. Furthermore, simulative characterisation of the MN·m transducer can be used to enhance the existing extrapolation methods and describe the behavior above the highest possible calibration range of 1.1 MN·m. Finally, several scientific investigations show that the deviation between the measured and simulated torque signal can be up to 15 % [4],[6]. This can be mainly contributed to the unknown and fluctuating
material parameters (Young modulus and Poisson’s ratio) of the transducers body and
unknown parameters of the application process of the SG (SG adhesive properties and position
as well as alignment of the SG).
Consequently, there is a need for the improvement and verification of the mentioned simulative
methods.
The objective of this paper is to provide a method for the characterisation of the torque transducer
body and of the SG by FEM simulation. The simulation of the electrical wiring of the strain gauges is
executed via MATLAB Simulink. This paper discusses the main challenges of the FEM modelling such
as
- selection of the FEM parameters (e.g. element type, mesh density, boundary conditions),
- simulation methods of the strain gauges, adhesive connection between SG and transducer body,
- and selection of the material properties and post-processing techniques.
Finally, this paper intends to confirm the suitability of the FEM simulation as a tool for the modeling
of the torque transducers and to show the high influence of the material properties and SG application
parameters on simulation of the torque transducers.

2. Self-built 4 kN·m torque transducer
A self-built 4 kN·m torque transducer is used for the investigations and validation of the simulative
method, see Figure 1a). The usage of a self-built transducer allows to determine the Young’s modulus
of the transducer body and use it as input parameter for the simulation. In addition, it is possible to
control the applications process of the strain gauges. Consequently, the SG factor k, wiring circuit and
adhesive are also known.

An SG application device has been used to assure reproducible application process of the SG, see
Figure 1b). Furthermore, five different Wheatstone full bridges have been applied to investigate the
influence of the adhesive, application pressure and temperature on the torque signal, see Figure 1c).

The test pieces for the determination of the Young’s modulus have been taken in lateral and
longitudinal direction from the wrought material of the 4 kN·m transducer body. In total, five test pieces
were examined. The Young’s modulus has been determined 15 times for each of the test piece non-
destructively by a tensile test. The results show that the Young’s modulus varies in the range between
201.3 GPa and 215.8 GPa (scattering of 10.5 %) by the expanded measurement uncertainty (k=2, GUM
Method A) of the measurement of 1.3 %. The deviation of 10.5 % between the test pieces can be
explained by the material flaws and inhomogeneities [7].

3. FEM modelling
3.1. Element type and Mesh density selection
A state of the art FEM solver provides about 500 types of element formulations for the different
materials, structures, load and strain states, required fidelity and analysis type. To choose an optimal
element type for specific problem, it is necessary to execute a convergence study for the variables of
interest (e.g. strain, stress, displacement) [8]. In case of the strain in the torque transducers (hollow shaft
flange), the convergence study revealed that full-integrated hexahedral elements with quadratic
formulation are optimum. In addition, it could be shown that one hundredth of the hollow shaft diameter
is the best element size for modelling of the transducer body considering the accuracy and
computational time. In this case, the deviation (strain value) between FEM and the analytical model of
the hollow shaft is less than 2·10^{-4} % and is negligible.

3.2. Strain Gauge (SG) modelling
Five different methods for simulation of the strain gauges (SG) have been compared during the
sensitivity analysis according to specific comparison criteria, see Figure 2. The modelling of the SG as
multi-spring element is the best discretisation method for the torque transducers because of the acceptable modelling effort, low computational and post-processing time and applicability on non-homogeneous strain fields. This method leads to a small deviation (mV/V torque transducer signal) between FEM and the analytical model of the hollow shaft under torque load in the range of $1.3 \times 10^{-2}$ %. The backing and encapsulation as well as adhesive thickness are not considered by the multi-spring method because the effect of these parameters is considered by the strain gauge factor $k$ during the calculation of the torque transducer signal.

3.3. Material properties selection
The sensitivity analysis for the material parameters (Young’s modulus $E$ and Poisson’s ratio $\nu$) have shown that Young’s modulus has a much bigger influence on the torque transducer signal than the Poisson’s ratio. The increase of the Young modulus by 10.5 % leads to a decrease of the torque transducer signal of 10 %. A similar increase of the Poisson’s ratio leads to an increase of the torque transducer signal of only 2.2 %. Consequently, the Young modulus value of the transducer body has been determined by measurement, see Subsection 2. Poisson’s ratio has been implemented to the simulation model according the manufacturer specification.

4. Measurement Set-Up
Measurement studies and validation of simulation have been executed on the 4 kN·m test rig (test rig) under static torque steps, see Figure 3 a). The torque steps are applied by a hydraulic stepper motor. Furthermore, the test rig comprises bellows shaft to avoid additional parasitic loads on the 4 kN·m torque transducer due to the assembly process and shaft misalignment. Finally, there is a calibrated reference torque transducer HBM TB1A (expanded measurement uncertainty ($k = 2$) of 0.08 %) which is used as a “transfer standard”. 4 kN·m torque transducer is tempered by a climatic machine, see Figure 3 b). Measurement program is based on the approaches like in EURAMET, DIN 51309, VDI 2639 and can be seen in Figure 3 c).

5. Measurement Results and Validation of the Simulation Method
5.1. Measurement results
The expanded measurement uncertainty ($k = 2$) of the torque bridges have been determined to be 0.36 % under consideration of the characteristic values of 4 kN·m torque transducer and accuracy of the measurement system. In addition, the measurements have revealed that the lines of best fit of all five
torque bridges have small deviations among each other of maximum 0.4 %. Consequently, the application pressure and type of the adhesive have no significant influence on the torque signals. Furthermore, the signals of the cyanoacrylate and epoxy resin bridges have shown no difference between the measurement under 20 °C and 60 °C as well as negligible creep. In comparison, signals of the methacrylate bridge have a maximum difference of 0.7 % between the measurement under 20 °C and 60 °C. This could be attributed to the fact that this kind of adhesive has a maximum application temperature of 60 °C and that near this temperature value the adhesive shows highly non-linear behaviour.

5.2. Validation of the simulation method

The Figure 4 shows the comparison between the measurements (cyanoacrylate) and the simulation method. The grey area, which is limited by a blue and red fit curve, represents the range of the simulated torque signal depended on the variation of the possible material properties. Black fit curve stands for the measurement results of the cyanoacrylate bridge under normal application pressure of 1.275 bar and 20 °C. The minimum deviation between mean values of this measurement and the simulation is 1.3 %.

![Figure 4. Comparison between simulation and measurement results](image)

6. Summary

The introduced simulation method of the torque transducers has a small deviation (minimal of about 1.3 %) from the measurement results and is applicable for the determination of the system dependent influences on the torque measurement in wind turbine test benches and in the field. The best FEM element type for the modelling is the fully-integrated hexahedral element with quadratic formulation. Furthermore, five different modeling strategies for the strain gauges (SG) have been introduced. Considering the SG as multi-spring is the optimum for the modelling of the shaft transducers. The measurement results revealed that the application pressure and type of the adhesive have only a minor influence on the torque signal. The Young’s modulus of the transducer body has a great influence on the simulation results and can vary, also for small transducers (<100 mm shaft diameter), in the range of 10 %. The introduced simulation method can be used for the determination of the influence of the parasitic loads (rotational speed, gravity, centrifugal loads, multi-axial loads) on the torque measurement. Additional, it can contribute to a better characterisation of the torque transducers and thus enhance the estimation of the measurement uncertainty. Finally, the simulation method is universal and can be adapted for MN·m torque transducers.

References

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