Messunsicherheit des Drehmomentes in multi-MW Windenergieanlagen Prüfständen

Torque measurement uncertainty in multi-MW nacelle test benches

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Contents

1 Abstract ................................................................................................................................. 2
2 Introduction .......................................................................................................................... 2
3 MN·m Torque Measurement in Nacelle Test Benches ......................................... 3
   3.1 General structure and components of nacelle test benches ......................... 3
   3.2 MN·m torque measurement methods ................................................................. 4
   3.3 Influences on MN·m torque measurement uncertainty ............................... 4
4 5 MN·m Research Torque Transducer ................................................................. 5
5 Simulative Characterisation of the 5 MN·m Torque Transducer ...................... 6
   5.1 Selection of Model Fidelity ..................................................................................... 6
   5.2 FE Simulation of Sensor Model Separately ..................................................... 7
   5.3 FE Simulation of 1.1 MN·m PTB Calibration Machine .................................. 8
6 Comparison between Simulation and Measurement Results ......................... 9
7 Determination of Parasitic Loads on 4 MW RWTH Nacelle Test Bench ...... 11
   7.1 FE Simulation of 4 MW CWD Nacelle Test Bench .................................... 11
   7.2 Influence of Parasitic Loads on MN·m Torque uncertainty ...................... 12
8 Conclusions ...................................................................................................................... 12
9 Acknowledgements .......................................................................................................... 13
10 Bibliography ..................................................................................................................... 13
1 Abstract

This paper covers a simulative method for the determination of parasitic loads, such as forces and bending moments, on multi-MW nacelle test benches during MN·m torque measurement. One part of this method is the approach to the simulative characterisation of the MN·m torque transducers, which are based on strain gauge measurement. Another part includes recommendations for the structural Finite Element Modeling (FEM) of the multi-MW nacelle test benches.

After a short summary of the main components of the nacelle test bench as well as the existing torque measurement and their calibration methods, the FEM model of the 5 MN·m research transducer will be introduced. The description of the proper element type and mesh density selection as well as the determination of the structural properties of the research transducer will be presented. The FEM model will be validated by measurement results on the calibration machine up to 1.1 MN·m. For this purpose, the paper also compiles the FEM simulation of the calibration machine. In the next step the validated model of the 5 MN·m research transducer will be implemented into FEM model of the 4 MW RWTH nacelle test bench. Consequently it will be possible to determine the parasitic loads and deformations by simulation. The paper is concluded by the discussion and quantification of the influences of the parasitic loads on the MN·m torque measurement uncertainty in multi-MW nacelle test benches.

2 Introduction

Torque, beside temperature, rotational speed and electrical as well as mechanical power, is one of the most important state variables during the operation of the multi-MW nacelle test benches. Torque measurement is inevitable for the determination of the mechanical power, local loads as well as the behavior of the entire drive train and controller under critical load cases. Especially the determination of the drive train efficiency requires extremely precise torque measurement within 0.2 %, according to the latest surveys among gearbox and wind turbine manufacturers. Only under such low uncertainty the average energy production and subsequent profit gain can be estimated properly.

Nowadays typical input torque in the multi-MW nacelle test benches lies in the MN·m range. Using the example of the 4 MW RWTH nacelle test bench, the maximum input torque is 3.4 MN·m. The existing torque measurement methods for such high torque (see chapter 3.2) reach an uncertainty between 2 % and 5 % and do not fulfill the requirements by the wind turbine industry. This can be attributed to the fact that the largest torque calibration machine, located at the German National Metrology Institute (PTB) in Braunschweig, can ensure traceable calibration according to metrological standards only up to 1.1 MN·m. In addition, the influence of the parasitic loads which are generated due to assembly, structural deformation of the nacelle test bench and device under test
(DUT) under operating loads as well as gravity and centrifugal forces is not known sufficiently. The main objective of this paper is to quantify the influence of these parasitic forces and bending moments on the torque measurement uncertainty in the multi-MW nacelle test benches with the example of the 4 MW RWTH nacelle test bench. This objective is also one of the subtasks in the current project “Torque measurement in the MN·m range” – funded by the European Union (EU) and the European Association of National Metrology Institutes (EURAMET). The project delivers results to the present paper.

3 MN·m Torque Measurement in Nacelle Test Benches

For the determination of the parasitic loads it is fundamental to understand the general structure of the multi-MW nacelle test benches. For the discussion of the influence of the parasitic loads on torque measurement uncertainty it is necessary to summarise the existing torque measurement and calibration methods and the general influences on torque measurement uncertainty. For this purpose, section 3 compiles these aspects.

3.1 General structure and components of nacelle test benches

The general structure and main components of the nacelle test bench are shown in Figure 1. The prime mover is responsible for torque application. The load application system (LAS) generates axial and radial forces as well as bending moments, which are applied to the DUT under simultaneous rotation of the main shaft.

![Figure 1: 4 MW RWTH nacelle test bench – main components [RAV15]](image)

Between prime mover and LAS there is almost pure torque load situation. In addition, this location usually contains compensating coupling (e.g. bow tooth coupling) to compensate for assembly misalignments of the main shaft and to minimise parasitic loads acting on the bearing system of the direct drive. Due to this fact this location is well-suited for the deployment of MN·m torque transducers.
Between LAS and DUT there is a 6-degree of freedom (DoF) load situation during operation. The connection between LAS and DUT is rigid. This location can be used to mount a reference torque transducer and to calibrate the entire drive train of the nacelle test bench.

3.2 MN·m torque measurement methods

MN·m torque in nacelle test benches can be measured on different locations, see Figure 2, and by various methods, such as measurement of

1. electrical power and rotational speed followed by a calculation of the torque
2. strain by strain gauges applied on the flange transducer
3. action force and lever arm length followed by a calculation of the torque
4. twist angle by incremental rotary encoder on two locations [AVA14]
5. torque on high-speed shaft followed by a calculation of the MN·m torque according to gearbox ratio and the efficiency.

The existing MN·m torque measurement methods reach an uncertainty between 2 % and 5 %. This level of uncertainty originates from the uncertainty in determination of material properties such as elastic modulus and Poisson’s ratio (in practice up to 10 % [CBR10]). Without traceable calibration, the material properties are in turn necessary for the simulative definition of the characteristic curve of the torque transducer (correlation between input torque and output mV/V signal).

3.3 Influences on MN·m torque measurement uncertainty

Beside the above mentioned material properties, the further influence parameters that define the MN·m torque uncertainty are compiled in Table 1. General influences on torque measurement uncertainty can be found in [VDI26]. Almost all of the introduced metrological and ambient influence parameters are quantified during the calibration process. However, the quantitative determination of the influence of parasitic loads on MN·m torque uncertainty can only be done under the investigation of the nacelle test
bench structure. Section 7 introduces a possible approach to determine parasitic loads by FEM simulation.

| Mechanical Parameters | • Parasitic load due to assembly, deformation, gravity, centrifugal forces
|                       | • Rotational speed, dynamic torque, vibrations
|                       | • Additional axial and radial forces as well as bending moments
|                       | • Material properties (flaws, elastic modulus, Poisson's ratio)
| Metrological Parameters | • Transducer linearity, reproducibility, repeatability, remanence, reversibility, zero signal
|                       | • Signal transmission and supply voltage uncertainty
| Ambient Parameters | • Temperature (air and main shaft), air humidity, atmospheric pressure
|                       | • Interferences and electromagnetic emissions (e. g. motor, converter)

Table 1: Influences on the MN·m torque measurement in nacelle test benches

4 5 MN·m Research Torque Transducer

5 MN·m research transducer, see Figure 3, is supplied by HBM Technology Ltd. and comprises two full Wheatstone bridges for the torque measurement.

Figure 3: 5 MN·m research transducer from HBM Technology Ltd.

Within the scope of the project, the research transducer has been calibrated by PTB [DPE2005] under static torque according to DIN 51309 [DIN51]. The maximum relative torque measurement uncertainty (coverage factor of 2) for clockwise and anti-clockwise torque up to 1.1 MN·m has been determined to 0.15 %.
5 Simulative Characterisation of the 5 MN·m Torque Transducer

This section describes the method for the structural characterisation of the 5 MN·m research transducer by simulation. The result of this method is a FEM model which is capable of determining the parasitic loads as well as the precise strain and stress distribution of the area that contains strain gauges. The calculated strain values are used in section 6 for the validation of the model by the measurement results of the calibration process on the 1.1 MN·m PTB calibration machine.

5.1 Selection of Model Fidelity

By using FEM for the simulative characterization, different element dimensions, element shapes, numbers of nodes, integration types as well as mesh strategies are available. The optimal selection of these FEM parameters depends on the required fidelity and information, load situation, stress and strain state, material properties and geometry as well as type of analysis.

To choose optimal FEM parameters, a convergence study on a simplified 5 MN·m torque transducer structure has been carried out. The reference value for this convergence study was the analytically calculated stress in a hollow cylinder under a dominating torque load. The results of the convergence study have shown that the three dimensional quadratic (containing middle nodes) hexahedron elements with full integration are the optimal selection for further investigations (deviation from reference value less than 0.001 %). It could be shown that the quadratic tetrahedron elements can be best used for the discretization of complex regions (e. g. bore, fillets) of the transducer, see Figure 4a.

<table>
<thead>
<tr>
<th>1 ELEMENT TYPE</th>
<th>2 MESH DENSITY</th>
<th>3 MESH STRATEGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meshing of Complex Geometry</td>
<td>Elements over Thickness</td>
<td>Deviation Reference</td>
</tr>
<tr>
<td>Meshing of Strain Gauge Area</td>
<td>2</td>
<td>1.41 %</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.16 %</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.10 %</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.10 %</td>
</tr>
</tbody>
</table>

Figure 4: Selected model fidelity: a) element type b) mesh density c) mesh strategy
After the element selection, the convergence study on the real transducer geometry for the optimal mesh density and strategy has been carried out. During the convergence study six different mesh densities were evaluated regarding the optimal stress and strain distribution as well as the computational effort. The results have shown that four elements over the cylinder area of the transducer are sufficient, see Figure 4b.

Finally hybrid meshing with hexahedron and tetrahedron elements was selected to save computational time and be capable to mesh complex geometrical areas, see Figure 4c. To reduce the computational time possible simplifications of the transducer geometry have been reviewed. It has shown that the lifting points, several chamfers and fillets as well as the flange cover, which protects the strain gauges from dirt and particles, can be neglected.

5.2 FE Simulation of Sensor Model Separately

The structural FEM simulation of the 5 MN·m torque transducer was executed according to the selected model fidelity. The following points have been investigated:

- axial, radial and bending stiffness of the transducer,
- stress and strain distribution as well as direction of the principle strains under torque and gravity load and
- influence of thickness of adhesive layer on the strain value in the strain gauge.

The manufacturer’s specification on the value of the transducer stiffness was confirmed with a deviation of less than 1 %. Figure 5 shows exemplarily the first principle strain values in the area where the strain gauges are located. The red curve shows an uneven trend of the strain in the model which considers detailed transducer geometry and contains four cable bores. The blue trend corresponds to the simplified model without cable bores.

![Graph showing strain values](image)

**Figure 5**: Negative principle strain value in strain gauge area along the circumference

According to Figure 5, the red curve can be divided into two sections: Section A is influenced by the cable bores. Here the deviation of the strain trend to simplified model is up
to 1%. Section B starts at a considerable distance from the cable bores, thus the strain deviation is small and negligible. For the simulative investigation of the transducer uncertainty, strain deviations in range of 1% and asymmetry in strain distribution can influence the results. Thus it is necessary to consider real transducer geometry. It could be shown that introduced FEM model can cope with such investigations.

5.3 FE Simulation of 1.1 MN·m PTB Calibration Machine

The FEM model of the research torque transducer has been validated by calibration measurements. For this purpose the FEM model of the 1.1 MN·m PTB calibration machine with the integrated research transducer has been modeled.

Figure 6 shows the main components and the FEM model of the calibration machine.

![Figure 6: 1.1 MN·m PTB calibration machine](image)

The FEM model considers the entire drive train of the calibration machine (without its main frame) as well as the bolt connections and bolt preload forces (90% of the yield stress) between research transducer, adapter flange and reaction lever, see Figure 6c. The input torque is applied by means of two forces at the drive lever. The reaction lever is fixed at the end of the lever arms. At this points it is possible to determine the reaction forces and bending moments, hence evaluate the applicability of the FEM model.

The introduced model has been deployed to determine the following:

- correlation between input torque and strain value (or mV/V signal by using Wheatstone Bridge Law) for the comparison with calibration results as well as
- influence of the gravity force and bolt connection on strain value.

Figure 7 shows the comparison between an FEM models

- without bolt connection (blue curve),
- with modeled contact boundaries and even bolt preload forces, which lies in the range of 90% of the yield stress (red curve) as well as
• with modeled contact boundaries and uneven bolt preload forces, which lies between the range of 80 % and 120 % of the yield stress (green curve).

It can be shown that the bolt preload generates positive strain in the range of approximately 15 μm/m in the strain gauges area, which corresponds to 10 % of the strain value under 1.1 MN·m. This effect can be seen in Figure 7 as an offset between red and blue curve. In addition, the bolt preload influences the symmetry of the strain in the strain gauges area, see Figure 7 green curve. Furthermore the bolt preload influences the zero signal of the research transducer.

![Figure 7: FEM strain distribution of research transducer under 1.1 MN·m torque during calibration procedure](image)

It can be concluded that the modeling of the bolt connection has significant influence on the strain distribution in the research transducer and cannot be neglected.

6 Comparison between Simulation and Measurement Results

The FEM model of the research transducer has been validated by the measurement results of the calibration procedure. For this purpose, the μm/m strain values of the strain gauge area have been converted to mV/V signal according to the Wheatstone Bridge Law. To ensure comparability, the simulation results were additionally adjusted under consideration of metrological uncertainties, e.g. transverse sensitivity, linearity error, repeatability error, reproducibility error and strain gauge alignment error (overall relative expanded uncertainty 0.1 %, coverage factor of 2).

Figure 8 shows the comparison between simulation and measurement. For this comparison two different simulation approaches have been used: first, models with varying material properties and without strain gauge and adhesive layer (blue and red curve); second, a model includes the strain gauge and adhesive layer (yellow curve). The first approach should explain the sensitivity of the strain values to the material property. The second explains the transfer of the strain from the transducer body to the strain gauge.
The measurement results are nearly linear, see Figure 8 black curve. Because of the unknown material properties, the first simulation approach under variation of the elastic modulus $E$ between 195 GPa and 215 GPa as well as of the Poisson's ratio $v$ between 0.27 and 0.3 has been carried out, see blue and red curves in Figure 8. The maximum deviation between measurement and first simulation approach (red curve), with reference to each measurement value, is 3.32 %. The maximum deviation is constant due to the linearity of the FEM model.

In addition, the effective thickness of the adhesive layer and strain gauge dimensions (thickness of the grid and of the backing) are not known. Within the second simulation approach, the sensitivity analysis for the investigation of these effects has shown that the variation of the thickness of the

- adhesive layer $a$ between 50 μm and 75 μm (single error 0.92 %) and of the
- grid thickness $b$ between 3 μm and 3.5 μm (single error 0.81 %) as well as of the
- backing thickness $c$ between 40 μm and 45 μm (single error 0.29 %)

can lead to an uncertainty error up to 2 %. These results qualitatively confirm the statements in [KHO87] and [HDA10]. Under consideration of this fact the maximum deviation between measurement (black curve) and optimised simulation (yellow curve, $a = 75 \, \mu m$, $b = 3.5 \, \mu m$, $c = 45 \, \mu m$) is 1.32 %. The maximum deviation is constant due to the linearity of the FEM model.

![Figure 8: Comparison mV/V signal between simulation and measurement — arithmetically averaged research torque transducer signal under clockwise torque](image)

The deviation between measurement and simulation can be attributed to the assumption of the material properties (elastic modulus and Poisson’s ratio) and the assumed strain gauge parameters (thickness of adhesive layer, grid and backing). The validated FEM model can be used to determine the strain distribution in the strain gauge area as well as to determine the parasitic loads during the torque measurement.
7 Determination of Parasitic Loads on 4 MW RWTH Nacelle Test Bench

This section describes the possible approach for the determination of the parasitic loads due to assembly, gravity and torque load. For this purpose the validated FEM model of the research transducer has been integrated into the FEM model of 4 MW RWTH nacelle test bench. The following section introduces the FEM of the nacelle test bench, quantifies the determined parasitic loads and their influence on the torque measurement.

7.1 FE Simulation of 4 MW CWD Nacelle Test Bench

The general structure of FEM model of the 4 MW RWTH nacelle test bench is shown in Figure 9a. The FEM model comprises the main shaft and the load application disk of the test bench, research torque transducer, supporting structure as well as the structural components of the 2.75 MW nacelle (3 point suspension). The research transducer is mounted on the nacelle flange and the load application disc via bolt connection. The foundation bolts of the supporting structure are also considered in the FEM model. The stiffness of the gear tooth coupling was calculated analytically according to the state-of-the-art methods and was implemented to the FEM model. To determine the displacement of the nacelle main shaft the stiffness and kinematic behavior of the nacelle main bearing system have been implemented into the FEM model. The approach for modelling the nacelle main bearing system and test bench structure has been executed according to [SKO15]. Figure 9b shows exemplarily the displacement of the entire nacelle test bench under multiaxial load situation.

![Figure 9: FEM model of the 4 MW RWTH nacelle test bench: a) general structure, b) deformation and stress distribution under multiaxial load](image)

The FEM model introduced above will be validated by measurements and has been used to determine the following:

- strain and stress distribution of the research torque transducer,
- parasitic loads (forces and bending moments, temperature distribution) during torque measurement and
- displacement of the main shaft.
7.2 Influence of Parasitic Loads on MN·m Torque uncertainty

Three different causes of parasitic loads were evaluated: bolt preload (M100 until 90% of yield stress), gravity force and deformation under pure torque load of 2.7 MN·m. Table 2 compiles the parasitic loads that were determined by simulation.

<table>
<thead>
<tr>
<th>Cause</th>
<th>Axial Force</th>
<th>Radial Force</th>
<th>Bending Moments</th>
</tr>
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<tr>
<td>Bolt Preload</td>
<td>630 kN</td>
<td>~ 0 kN</td>
<td>~ 0 kN·m</td>
</tr>
<tr>
<td>Gravity Force</td>
<td>~ 0 kN</td>
<td>134 kN</td>
<td>~ 73 kN·m</td>
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Table 2: Quantitative values of parasitic loads on the example of 4 MW RWTH nacelle test bench

The influence of the determined parasitic loads, see Table 2, on torque measurement uncertainty has been determined by the state of the art according to the manufacturer specification [HBM16], [GBE16], see Equation 1. Equation 1 is based on experimental investigations of the manufacturer and describes the correlation between parasitic loads $L_{para}$ and absolute uncertainty $u_{para}$ in case of the rectangle distribution of uncertainty. Thereby $L_{perm}$ is the permissible load and $T_{nom}$ is the nominal torque.

$$u_{para} = 0.58 \cdot \frac{L_{para}}{L_{perm}} \cdot T_{nom} \cdot 0.30\%$$

Eq. 1

Under consideration of the determined parasitic loads, the overall $u_{para}$ is 2.22 kN·m. Finally the corresponding extended torque measurement uncertainty is 0.09 % (coverage factor of 2).

8 Conclusions

The introduced method for the simulation of MN torque transducers can be used for the determination of the stress and strain distribution in the strain gauges area. Furthermore it is sufficient for the quantification of the parasitic loads in nacelle test benches. It is important to know precise material parameters to produce feasible simulation results. In the next project step the simulative method will be additionally validated on the kN·m transducer under consideration of the precise determined material properties.

It showed that it is necessary to consider the real geometry of the torque transducer. Every simplification of the geometry should be evaluated by simulation. The best finite elements for the determination of the strain are quadratic hexahedron elements with full integration. The bolt preload has significant influence on the symmetry of the strain distribution in strain gauges area. In addition, it influences the zero value of the torque transducer.

It could be shown that the single extended torque measurement uncertainty, caused by parasitic loads due to the bolt preload and gravity load in nacelle test bench, lies in the range of 0.09 %. This value nearly corresponds with linearity and hysteresis value of MN·m torque transducers. The parasitic loads are influenced mostly by the bolt preload.
In the next project steps the influence of other parasitic effects in the nacelle test benches, such as temperature distribution, rotation, deformation and misalignments, will be investigated. In addition, it is intended to validate and if necessary to improve the Equation 1, which shows correlation between parasitic loads and caused absolute uncertainty.

9 Acknowledgements

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10 Bibliography

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