# FINAL PUBLISHABLE REPORT

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# 1 Overview

The overall aim of this project was to provide traceability for torque measurements in the MN·m range for nacelle test benches. Such a development supports the wind energy industry by significantly improving testing conditions. Within the framework of this project, existing nacelle test benches were reviewed, multi component effects of superimposed forces and bending moments were investigated and novel traceable calibration methods were developed.

# 2 Need

In the last few decades, the combination of climate change and the increase in electricity consumption led to a general demand for more renewable energy. The EU Directive “2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources” is a direct consequence of this general demand. It requests the countries of the European Union to set overall national targets for the use of renewable energy sources. One of the main pillars in the new energy mix in most countries is onshore and offshore wind energy. To improve the technical development of wind turbines as well as their cost-effectiveness, several large test benches have been constructed to supply full scale testing facilities.

These new test benches can be used to test full nacelles (the upper part of a wind power station) under conditions that are similar to the field. Current nacelles have a power rating of around 3 MW (onshore) and 6 MW (offshore) and even 20 MW machines are thought to be possible (source: EU-Project Upwind). Therefore, the test benches have to apply torque loads in the multi-MN·m range. The measurement of this torque load is needed for the steady control of the torque loading system and also for the determination of the efficiency of entire nacelles or single components that are tested on the test bench.

The operators of the above-mentioned test benches could not measure torque loads very precisely. The main reason for this was that they were not traceable to a torque standard. The largest torque standard worldwide, at PTB in Germany, covers a maximum torque of 1.1 MN·m while the largest nacelle test bench could exert up to 18 MN·m. The traceability of torque measurements is important in order to be able to reliably verify the quality of the measurements. Another problem was the occurrence of other mechanical loads, such as longitudinal and lateral forces and bending moments, on the test benches which simulate the real wind conditions. The effect of these loads on the torque measurement was mostly unknown. Last but not least, all test benches differ from each other depending on their focus of testing (functionality, efficiency …) but also their power ratings range from 1 – 20 MW. This variation made universal approaches very difficult.

# 3 Objectives

To provide precise and traceable torque measurements to nacelle test bench operators the specific scientific and technological objectives of the project were to:

1. Review existing nacelle test benches and their boundary conditions. The review will include the range of loads that can be applied and the dimensions of the test bench, as well as existing methods of torque measurement and calibration and the levels of uncertainty achieved.
2. Develop novel traceable calibration methods for torque values in nacelle test benches in the form of transfer standards for the range above 1 MN·m. In order to enable the multi-use of transfer standards a unified approach for several nacelle test benches will be applied. Two different approaches will be used in the project: a commercial torque transducer will be used with an extrapolation procedure for the MN m range and a force lever system will be designed to directly reach the MN·m range.
3. Investigate the effect of multi-component loading on the measurement of torque. In particular, cross-talk effects, in the case of 6-component loading (3 directional forces, 2 directional bending, torque), will be studied to describe effects on the torque measurements which occur in large nacelle test benches.
4. Develop a calibration procedure for large nacelle test benches. The calibration procedure will enable the traceability of torque loads up to 20 MN·m and will include an uncertainty model that considers crosstalk effects.

5. Engage with industries that utilise the MN·m range for torque measurements to facilitate the take up of the technology and measurement infrastructure developed by the project, to support the development of new, innovative products, thereby enhancing the competitiveness of European industry.

# 4 Results

## 4.1 Overview of existing nacelle test benches

The development of a traceable torque calibration procedure for the nacelle test benches (NTBs) as well as development of novel torque measurement methods requires knowledge of NTB properties. Specific NTB properties are for instance the general structure of the NTB, range of operation loads, dimensions, testing conditions such as temperature, and furthermore torque measurement and calibration methods. By knowing the NTB properties it is possible to derive requirements for torque measurement and calibration procedures. These requirements represent the main input for the development of the calibration procedure (see Chapter 4.4) and innovative torque measurement methods based on force lever systems (see Chapter 4.2.2).

A questionnaire was prepared to gather required information about NTBs. This questionnaire has been filled in by nacelle test bench operators and project partners. The questionnaire's results can be divided into three main parts: structure, load characteristics and torque measurement in NTBs. The results on each part are presented in the following.

*Structure of the nacelle test benches (NTBs)*

The conventional NTB comprises a prime mover for torque generation, a non-torque load application system for the generation of external forces and bending moments and an artificial grid (not shown in the figure e.g. converter, transformer), see Figure 1. A device under test (DUT) is mounted on the NTB for testing.

The torque generation can be realised either by a high-speed motor in combination with a downstream gearbox or a low-speed direct drive. The generation of external forces and bending moments is realised with hydraulic actuators. Similar to real wind turbines, the inclination angle of NTB varies between 4° and 6°. In most cases, the mounting of the DUT to the NTB is realised with adapters and bolt connections. By deploying different adapters and a translational adjustment of the DUT, various DUTs with specific dimensions can be integrated into one NTB. For the integration of the DUT into the NTB, the testing facilities are equipped with heavy load cranes providing a load capacity in the range of 100 tons to 300 tons. Therefore, the modern nacelles, e.g. 5 MW power class with dimensions of 6.5 m height, 6.5 m width and 17 m length and total mass of 290 tons, can be lifted and integrated into test benches.

*Load characteristics of the nacelle test benches (NTBs)*

In the last two years, several NTBs have been put into operation. The main characteristics of an NTB are nominal power, applicable torque, forces, bending moments and load emulation capabilities. The nominal power of the existing NTBs is in the range of 1 MW to 18 MW. In comparison, the actual average nominal power of deployed onshore wind turbines is 2 - 3 MW and of offshore wind turbines is 3 – 8 MW. NTBs are constructed to cope with the high dynamic growth of the power class on the wind turbine market. In addition, the current overload capacities of NTBs are necessary to test the DUT under extreme conditions (e.g. gust, emergency shut down, fault ride through). Most NTBs can generate torque under simultaneously acting bending moments, radial forces and thrust in all 6 degrees of freedom. As a result, a realistic consideration of the influence of the wind field and its respective forces and moments on the DUT during the test procedure is ensured. Using the example of the 4 MW RWTH NTB, it is possible to apply 3.4 MN·m torque under maximum bending moments of about 7 MN·m, 3.3 MN radial forces and 4 MN thrust.

Some of the existing NTBs provide an opportunity to emulate a real electrical grid to simulate fault ride through scenarios or to process numerical wind fields for the calculation of the input loads and thus to operate the nacelle in the "hardware in the loop" mode. Only under these test conditions, the evaluation of functionality of the entire nacelle and controller behavior under dynamic and non-linear conditions delivers highly accurate results.

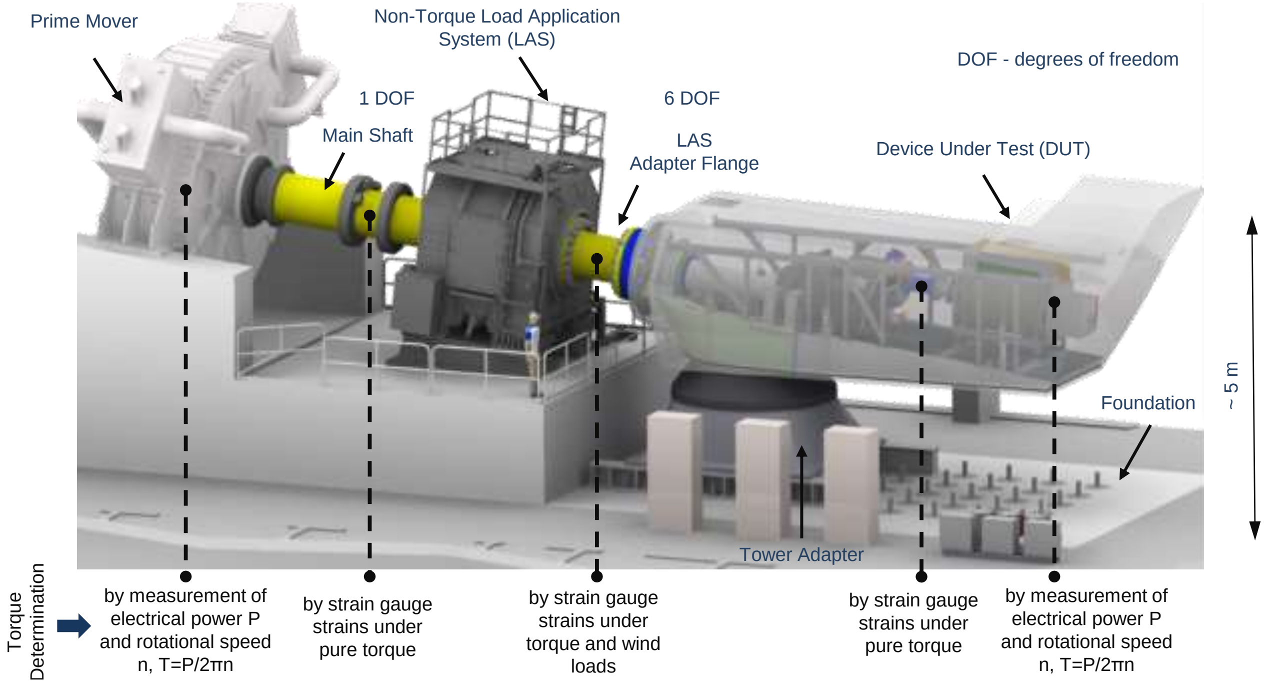



**Figure 1 Structure of an NTB and torque determination methods using the example of the 4 MW RWTH NTB.**

*Torque measurement in nacelle test benches (NTBs)*

The torque measurement in NTBs is carried out under rotation. The torque can be determined by:

- measurement of the electrical power and the rotational speed followed by a calculation of the torque and
- using strain gauge technology (flange transducer or force lever system). see Figure 1

The uncertainty of the MN·m torque measurement achieved with these options is between 2 % and 5 % with respect to the measured value. This can be attributed to the lack of torque standards above 1.1 MN·m and calibration methods for NTBs as well as to the unknown system-dependent influences on the torque measurement. Consequently, the MN·m torque measurement performed in NTBs is not traceable. Moreover, the currently high measurement uncertainty does not meet requirements of industry and research facilities, which are in the range of 0.5 % for MN·m torque measurement with respect to the measured value. A precise torque measurement is crucial for the quantification of the input power and the efficiency of subsystems (e.g. main bearing, gearbox and generator) and the entire drive train of the nacelle. Furthermore, the measured torque is used for the investigation of the impact of the critical operation modes, such as start-up or emergency shut-down, on the local loads and the behaviour of the entire drive train. This way, the torque measurement accuracy defines the resulting quality of the investigations on the NTB.

**Key output:** In order to develop traceable torque measurement and calibration procedures for nacelle test benches (NTB) it is indispensable to determine the boundary conditions as a first step. Results of a questionnaire survey gave an overview of 10 NTBs. This input has been analysed, specific setups and characteristics of NTBs have been determined and used in the following steps of the project e.g. design of force lever systems (Chapter 4.2.2) and development of a calibration procedure (Chapter 4.4). Furthermore, the most required measurement uncertainty for torque measurement in NTBs turned out to be 0.5 %. The first objective aiming at a review of existing technology has been fulfilled.

## 4.2 Novel traceable calibration methods

Driven by the up-scaling of nacelles to multi-megawatt power ratings, the need for precise torque measurement in nacelle test benches above the current limit of 1.1 MN·m arose. To solve this issue, among other things a torque transfer standard (TTS) in the range above 1.1 MN·m up to 5 MN·m is to be established. In general, a transfer standard is a measurement gauge bearing a defined relation between a physical quantity, which is here torque, and the unit of measurement, which is mV/V for all measurement instruments using strain gauges. Within this project two different approaches for TTSs were pursued: (i) the characterisation of a commercially available torque transducer with the help of a newly developed extrapolation method (Chapter 4.2.1) and (ii) the design of a force lever system, which is able to directly reach the MN·m range (Chapter 4.2.2).

### 4.2.1 Extrapolation

An overview about appropriate and commercially available torque transducers revealed that not even the transducer with the largest measurement capacity of 400 kN·m is sufficient for a torque calibration in NTBs. Consequently, a customised torque transducer with a measurement capability up to 5 MN·m was needed to meet the requirements for becoming a TTS to calibrate NTBs. This torque transducer, however, cannot be calibrated over its full measurement range due to a lack of torque standard machines (TSMs) and, therefore, a traceability above 1.1 MN·m is not given. To overcome this issue, an extrapolation method based on a partial range calibration was developed.

For this extrapolation method, two different approaches were investigated: (i) a simulative approach based on a Finite Element Method (FEM) model and (ii) a simple mathematical method using partial range calibration data to predict the regression curve and the measurement uncertainty for the full measurement range.

*Simulative approach*

For the simulative approach, two FEM-models (see Figure 2) of the deformation body and the strain gauges of the 5 MN·m torque transducer were generated. In the first model, the strain gauges were represented by multi-spring elements[1]. For the second model, shell elements with a thickness of 0.025 mm and a zero-stiffness were used. To avoid changes of the bonded contact between the strain gauge and the deformation body by penetration of the contact, the pure penalty algorithm for the contact was deployed[2]. For both models, a strain transmission from the deformation body into the measuring grid of 100 % was assumed. During the simulations it was found that the Young's Modulus influences the simulation result significantly. Moreover, the determination of the Young's Modulus is fraught with a rather high uncertainty and deviation.

**Figure 2 5 MN·m torque transfer standard and meshed FEM-model of it depicting the occurring strains.**

To validate the FEM-models, the 5 MN·m transducer was partially calibrated up to 22 % of its measurement range using PTB's 1.1 MN·m TSM with an expanded relative measurement uncertainty ($k$ = 2) of $8 \cdot 10^{-4}$ %. Based on the calibration data, the FEM-models were adjusted in terms of the smallest achievable deviation between measured and simulated torque values by means of varying the Young's Modulus (model I) or by introducing a linear calibration factor that considers all possible influences (model II).

Due to the linear simulation approach, the characteristic non-linearities of torque transducers are not mapped in the simulation, neither can a measurement uncertainty be calculated based on linear simulation data.

*Mathematical approach*

To counter this, a mathematical method to predict the transducer's sensitivity and its measurement uncertainty based on partial range calibrations of the same transducer was developed. To validate this mathematical approach, several partial (20 %, 50 %, and 80 %) and full range (100 %) measurements using a very well-known transducer of high quality were performed. To this end, a shaft type torque transducer with a measuring capacity of 20 kN·m was chosen. The Raute Precision Oy TT1 features an uninterrupted history and very

[1] Kock S, Jacobs G, Bosse D, Strangfeld F. Simulation Method for the Characterisation of the Torque Transducers in MN · m range. In: *IMEKO World Congress Proceedings.*; 2018.
[2] Weidinger P, Schlegel C, Foyer G. Characterisation of a 5 MN · m Torque Transducer by Combining Traditional Calibration and Finite Element Method Simulations. In: *SENSOR 2017*.

stable characteristics, e.g. small creep and hysteresis. For the data acquisition, high precision carrier frequency amplifiers were deployed.

Since the metrological properties vary depending not only on the applied torque steps but also on the maximum torque load and the deployed TSM, partial and full range calibration data was gathered on different TSMs:

At PTB the measurements were performed on a *dead-weight TSM* with a horizontal measuring axis and a torque capacity ranging from 100 N·m up to 20 kN·m. As common for a *dead-weight TSM*, the load is generated by precisely determined mass stacks in a known gravitational field of the Earth acting on a lever arm of well-defined length. Several special designs, such as a counter drive to ensure the horizontal position of the lever arm, and, therefore, the same effective lever length for calculating the applied torque as well as an air bearing to minimise the influence of friction in the bearing on the effective torque, allow for an expanded relative uncertainty ($k$ = 2) of $2 \cdot 10^{-5}$ %.

At VTT a *reference TSM* using a multiphase motor to generate torque and a serially connected high ratio gearbox to enable a more precise adjustment was deployed. Its measurement range starts at 200 N·m and is steplessly increasable up to 20 kN·m with an expanded relative measurement uncertainty ($k$ = 2) of $5 \cdot 10^{-4}$ % depending on the reference transducer's uncertainty. Here, the measurement axis is vertical and the reference transducer and the transducer to be calibrated are mounted above each other.[3] A synchronous data acquisition of the reference transducer and the transducer to be calibrated was ensured.

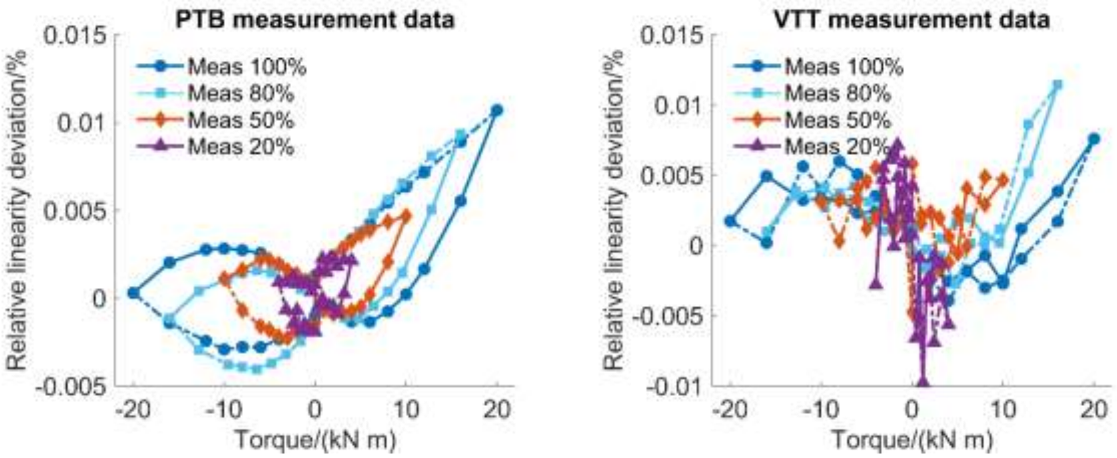
All partial and full range measurements were performed stepwise increasingly and decreasingly according to DIN 51309 starting at the smallest measurement range (20 %) to minimise the hysteresis effect of larger torque loads on the sensitivity in the smaller range. The evaluation of the measurements follows DIN 51309 as well, where the data set for each of the 0°, 120° and 240° mounting positions is tared separately.

Before an extrapolation method can be developed, it is of great importance to analyse the alterations between the various load ranges. Theoretically, the relation between the output signal $S$ and the applied torque $M$ is linear and, consequently, the relative sensitivity of the transducer per load step is linear as well. From practical experience it is known that slight non-linearities occur in the coherence between signal and applied torque. These non-linearities can be calculated for each load step by subtracting a linear regression curve fitted through the measurement data and the origin (0/0) from the tared measurement signals. As shown in Figure 3, the non-linearities are highly dependent on the deployed TSM and vary for the different calibration ranges.[4]

Based on a test-extrapolation, it was decided on extrapolating the tared measurement data for each mounting position separately and calculating the associated measurement uncertainty rather than simply extrapolating the calibration result including the measurement uncertainty. In order to extrapolate the zeroed measurement data, every curve must be fitted cubically and separately for each mounting position and for clockwise and anti-clockwise torque load.

The extrapolated data sets are then evaluated according to DIN 51309 case I, where only the increasing load steps are considered. Advantageous for this method is the possibility to calculate the reproducibility and the repeatability, as well as the interpolation deviation, which all contribute to the measurement uncertainty.

[3] Pusa A, Röske D, Sachs M. Comparison measurements of MIKES-Raute 20 kN·m torque reference device with the PTB. In: *IMEKO TC 3 Proceedings.*; 2005.
[4] Weidinger P, Foyer G, Ala-Hiiro J, Schlegel C, Kumme R. Investigations towards extrapolation approaches for torque transducer characteristics. In: *IMEKO World Congress*.; 2018.




**(a)** **(b)**

**Figure 3 Characteristic relative linearity deviation curve of a 20 kN·m torque transducer calibrated in several partial ranges and the full measurement range on (a) a *dead-weight torque standard machine (TSM)* at PTB and (b) on a *reference TSM* at VTT.**

As expected, the measurement uncertainty based on a cubic evaluation (case I) for the cubically extrapolated data based on the 20 % measurement data gathered on both the *dead-weight* (Figure 4c) and the *reference TSM* (Figure 4d) increases for the predicted range. In general, the expanded measurement uncertainty for the predicted range based on the 20 % measurement data is relatively high. Since it is only a prognosticated behaviour, these relatively high uncertainties are acceptable. For the linearly extrapolated data sets, however, the predicted measurement uncertainty based on a linear evaluation (case I) is lower than for the true measurement data, which is not plausible. This phenomenon is caused by the small interpolation deviation and the very good repeatability and reproducibility for the linearly extrapolated data due to the missing non-linearities, which contribute all to the overall measurement uncertainty. When using the cubic extrapolation approach, the uncertainty of the TSM on which the data was gathered on as well as the uncertainty of the extrapolation approach are considered in the predicted measurement uncertainty.

For the calibration of the torque measurement in the NTB of RWTH Aachen, as described in 4.4.4, a measurement uncertainty of the TTS for clockwise torque up to 1.5 MN·m is required, where increasing and decreasing torque is combined linearly (case II). Due to the small non-linearities of ≤ 0.05 % and the very small hysteresis of ≤ 0.05 %, the combination of increasing and decreasing load steps is suitable and simplifies the application. The relative expanded measurement uncertainty of the 5 MN·m TTS determined by calibration amounts to $8.7 \cdot 10^{-4}$ % for clockwise torque with a linear regression curve through increasing and decreasing load steps (case II). As for the later calibration measurements needed, the relative expanded measurement uncertainty for torque load up to 1.5 MN·m was calculated using the cubic extrapolation approach for case II. This extrapolated uncertainty adds up to $9.6 \cdot 10^{-4}$ %. Using the same approach, the predicted uncertainty of the TTS for 5 MN·m is $10.03 \cdot 10^{-4}$ %.

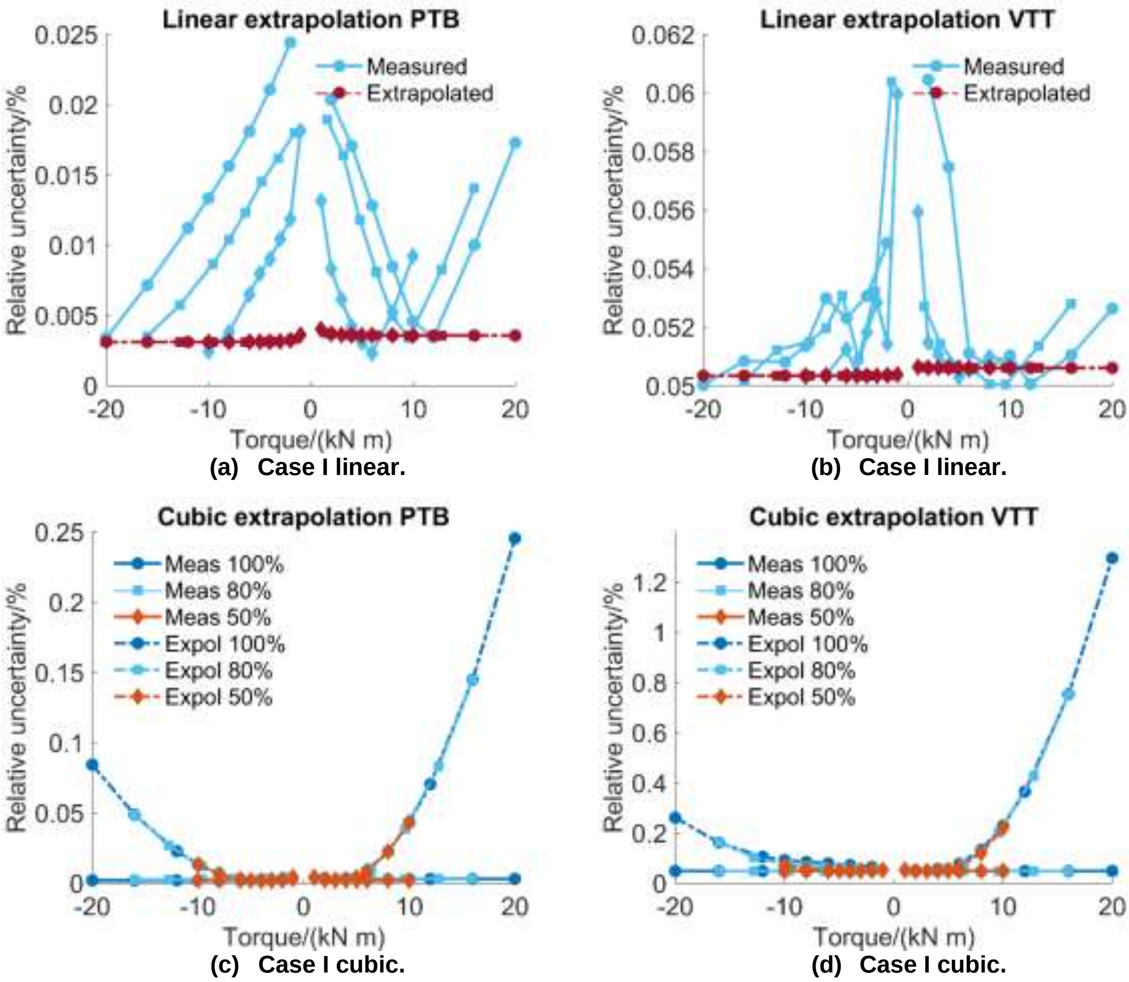



**Figure 4 Expanded (*k* = 2) relative measurement uncertainties for linearly and cubically extrapolated data up to 50 %, 80 % and 100 % based on 20 % measurement data gathered on different TSMs.**

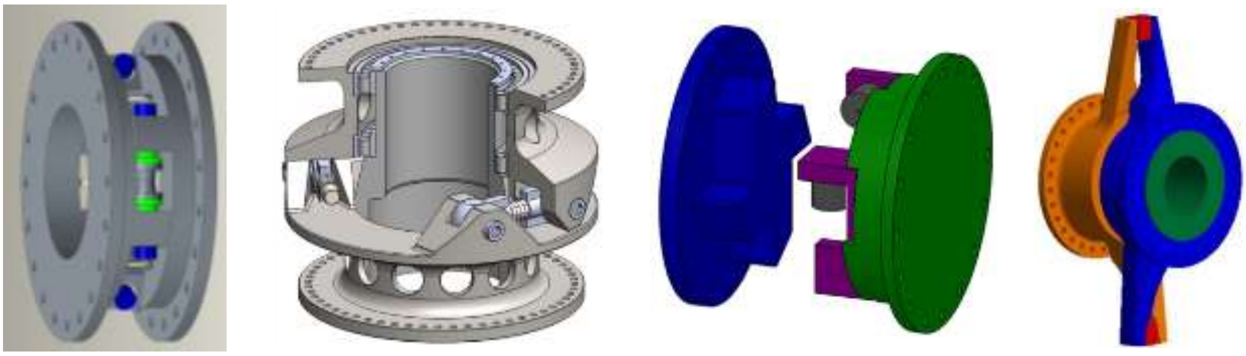
### 4.2.2 Force lever systems

At the moment the torque measurement accuracy in the existing nacelle test benches does not fulfil the requirements of national metrology institutes (see also Chapter 4.1) and should be enhanced. Moreover, traditional torque transducers are only traceable up to 1.1 MN·m. A new concept for a torque transfer standard has been developed, based on force lever system's working principle. This type of system includes force transducers, which can be traced to deadweight force machines to ensure the lowest possible uncertainty.

Four different force lever systems were developed. Although their configuration and characteristics are different, their functionality is based on the same principle: several transducers are mounted within the system, connected to a lever arm of known length; torque measurements are obtained by means of the product of the measured reaction force at the transducers and the lever length.

*Preliminary force lever system designs*

Initially, four project partners (PTB, VTT, CEM and RWTH) proposed several design ideas to evaluate and discuss them and eventually choose four options as the preliminary designs to be fully developed all along the project lifetime. These preliminary designs are shown in Figure 5.

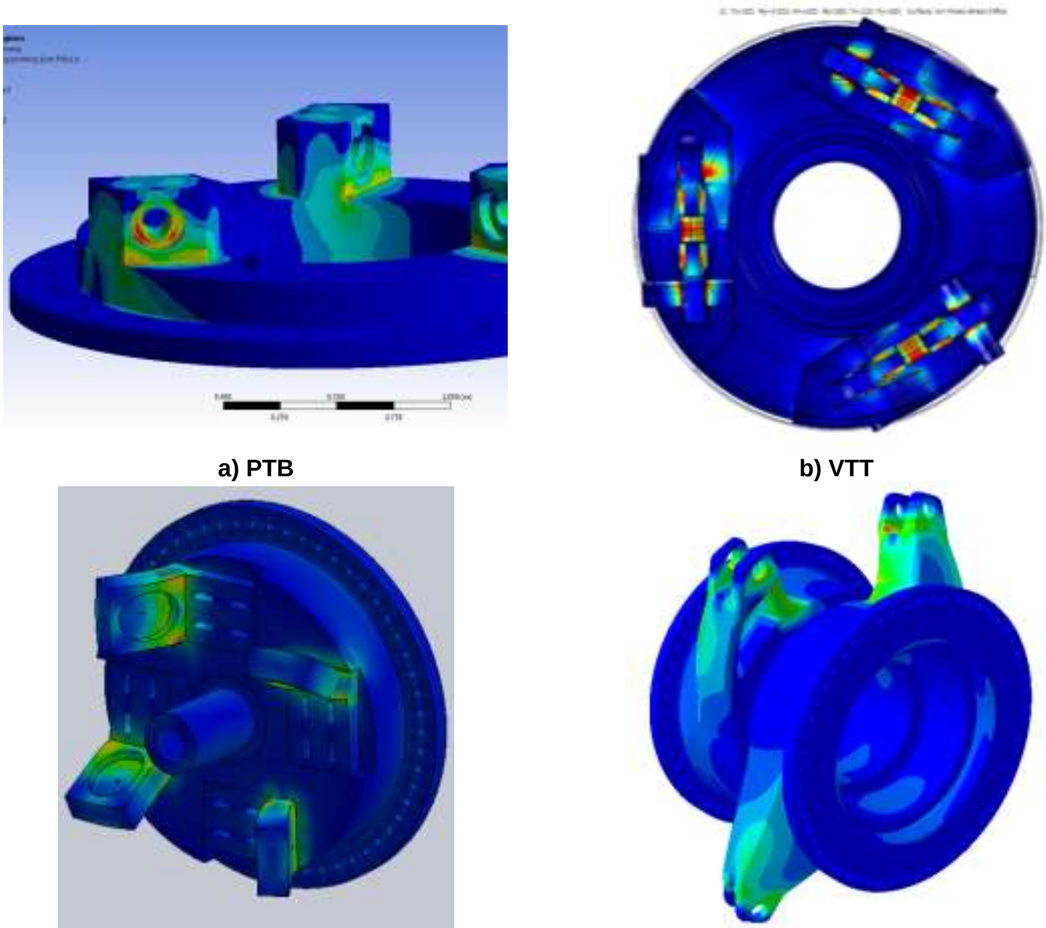


a) PTB b) VTT c) CEM d) RWTH

**Figure 5 Preliminary designs chosen for the development in the project.**

All the preliminary designs were tested using FEM simulations, to check their performance and viability (Figure 6). The loading conditions and a selection of materials were discussed and agreed upon in advance to the simulation also based on the findings from the overview of NTBs (see Chapter 4.1).

Through several simulations, the stiffness and reliability of the designs were tested. The main parameter to be studied in this initial study was the maximum von Mises stress, which ensured that the proposed design was able to withstand the loads applied by NTBs during operation. Maximum displacement and deformation were considered as well, as the variation of some crucial dimensions (e.g. lever arm length) were vital for torque measurements calculation.

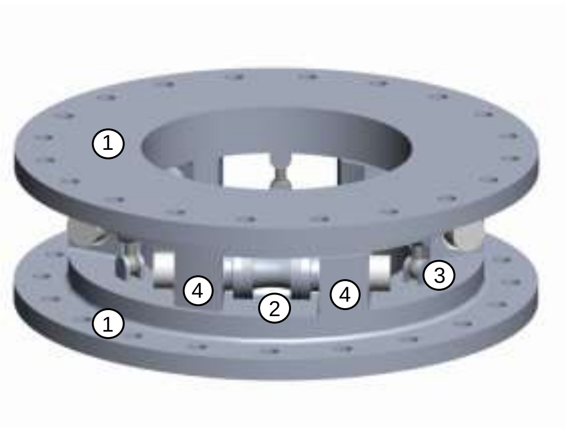


a) PTB b) VTT c) CEM d) RWTH

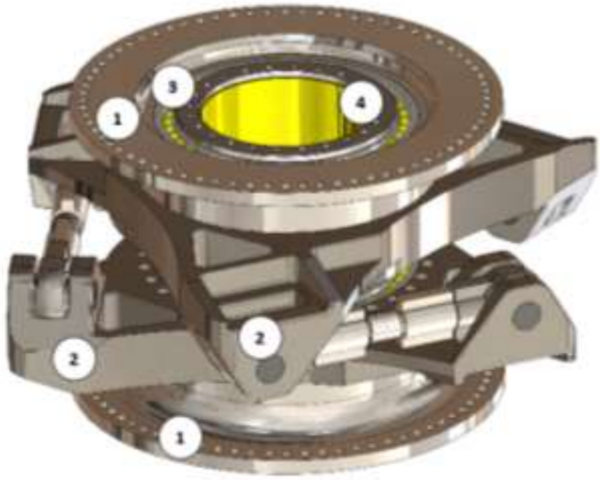
**Figure 6 Preliminary FEM analyses of the different designs.**

*Complete force lever system: design and FEM analyses*

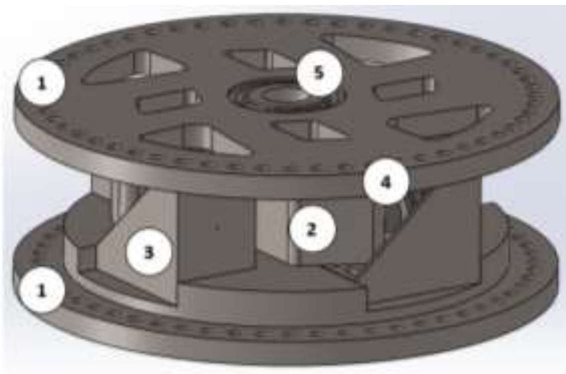
The main components of the force lever system, that are force transducers and lever arm, were studied separately. Each participant carried out a study of the requirements for the force transducers to be included in their systems; then the more suitable commercial options were selected and included within the models. Lever arms were improved, their performances tested and their behaviour under different influences were studied. The improved components were included in the complete force lever system and the remaining components updated (Figure 7).



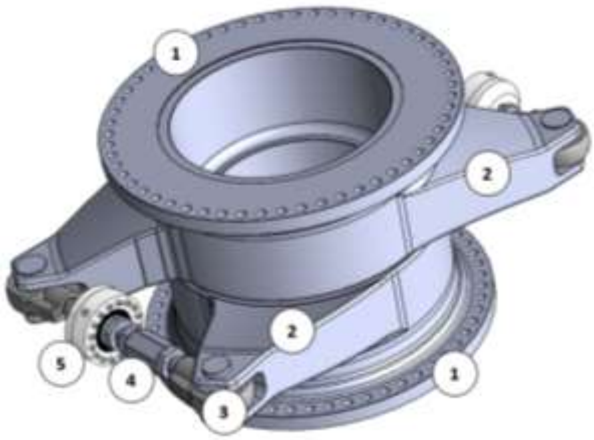

**a) PTB: 1 – lever plate, 2 – transducer with bolted connection, 3 – connection rod, 4 – counter bearing**



**b) VTT: 1 – connection flanges, 2 – lever arms, 3 – angular contact bearings, 4 – support axle**



**c) CEM: 1 – connection flanges, 2 – lever arm, 3 – transducer's supports, 4 – force transducer, 5 – inner support and roller bearing**

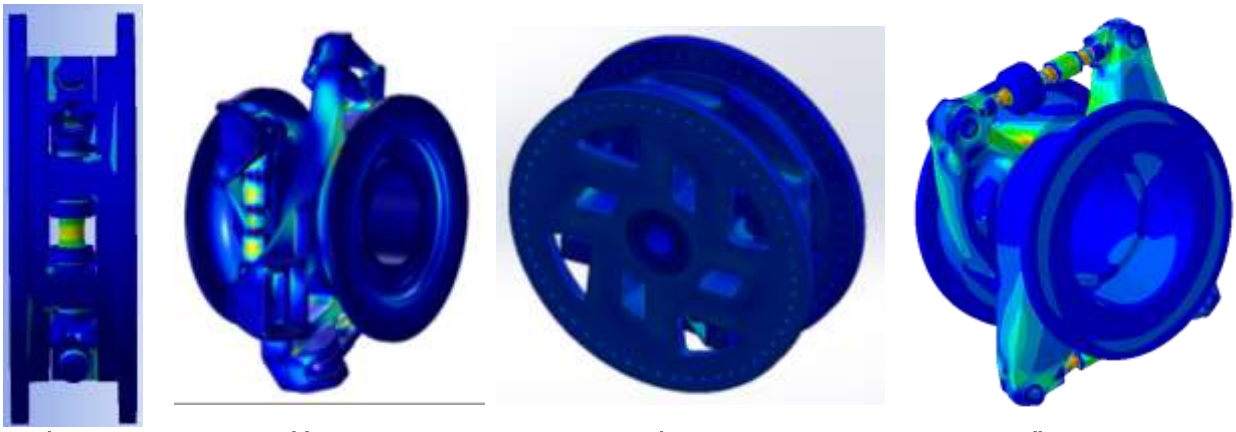


**d) RWTH: 1 – connection flanges, 2 – lever arms, 3 – connection rod (joint head), 4 – fine thread, 5 – force transducer**

**Figure 7 Final force lever systems.**

The performance of all systems was tested through several FEM analyses (Figure 8). In order to carry out the analyses, input information was required and provided by nacelle test benches operators participating in the project (RWTH, FhG, and CENER). Literature was studied: a review of the existing force-lever system in other industries, as well as the torque measuring techniques in different NMI's was done. All this information was used to elaborate the preliminary design of the different force lever systems. Additionally, the nacelle test operating conditions were obtained from the information and characteristics described in Chapter 4.1.

Although maximum stresses and deformations were considered, the more relevant parameters to be studied in the FEM analyses were those directly related to torque measurement calculation: reaction force at the transducers (as well as residual bending moments that may appear) and variation of lever arm length. In the case of the reaction force studies, it became clear that due to systems configuration, residual bending moments appeared at each transducer (coloured in blue in Figure 9). Therefore, for each simulation, both, forces and bending moments, were studied. This was especially the case for the simulations used for a measurement uncertainty estimation which is described in the following section.



a) PTB b) VTT c) CEM d) RWTH

**Figure 8 FEM studies of the four complete FLS depicting a stress analysis of the system or part of the system.**

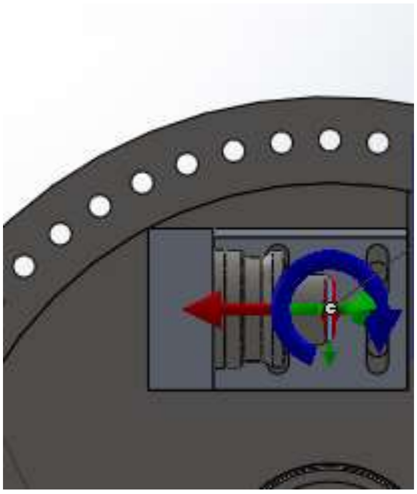


**Figure 9 Example of the reaction forces and bending moments at each force transducer for CEMs force lever design: red arrows indicate the reaction force in the transducers, while the blue arrow shows the direction of the residual bending moments.**

*Measurement uncertainty of the force lever systems*

Additional simulations were carried out in order to determine the different influences that may affect the system during operation. Four different influences were studied as well as the base case, where only pure torque load was considered:

- Parasitical loads (100 kN for axial and lateral forces, 100 kN·m for bending moments)
- Maximum, minimum and operation temperature (40°C, 5°C, 30°C)
- Centrifugal force (25 rpm)
- Gravity

For each simulation, the local reaction forces and bending moments and the lever arm length were analysed and employed as input contributions to an estimation of the associated uncertainty of the system based on the mathematical model described in Equations 1 and 2 where $M$ is the overall torque, $F_{\text{loc}i}$ is the local force at transducer $i$, $M_{\text{loc}i}$ is the local bending moment at transducer $I$, $n$ is the number of force transducers in the system and $l_i$ is the distance of transducer $i$ from the centre of rotation.

$$M = F \cdot l \tag{1}$$

$$M = \sum_{i=1}^{n} F_{\mathrm{loc}_i} \cdot l_i + \sum_{i=1}^{n} M_{\mathrm{loc}_i} \tag{2}$$

From the results of the influence study, together with external input information (e.g. transducers data sheet, calibration certificates, etc.) an uncertainty budget was developed jointly. As mentioned, this uncertainty budget did consider variations of the measured force transducer and lever length; additionally, residual local moments at the transducers were also studied. From the combined study of these three components, the estimation of each force lever system associated uncertainty was obtained.

An exemplary measurement uncertainty calculation is given in Table 1. Using this method, it was found that a measurement uncertainty of less than 1 % is achievable with three out of four designed systems. It is very probable that issues in the simulations led to the higher uncertainty in the last system. As some systematic errors have not been addressed the results have to be interpreted carefully but it is assumed that the overall measurement capabilities of force lever systems as designed within the project can improve the current situation of torque measurement in NTBs.

**Table 1 Example of a measurement uncertainty budget for a force lever system with four force transducers.**

| **Input magnitude** | | **Original contribution** | **Distrib. type** | **Standard uncertainty** | **Sensitivity Coef.** | **Contribution (MN·m)** | **%** |
|---|---|---|---|---|---|---|---|
| Length (*l*) | 0.607965 m | 0.000581 m | Normal | 0.000581 m | 2.53928 MN | 0.001475 | 37.2 |
| Force ($F_{loc}$) | 2.539275 MN | 0.002238 MN | Normal | 0.002238 MN | 0.60797 m | 0.001361 | 31.6 |
| Bending moment ($M_{loc}$) | 0.081617 MN·m | 0.001353 MN·m | Normal | 0.001353 MN·m | 1 | 0.001353 | 31.2 |

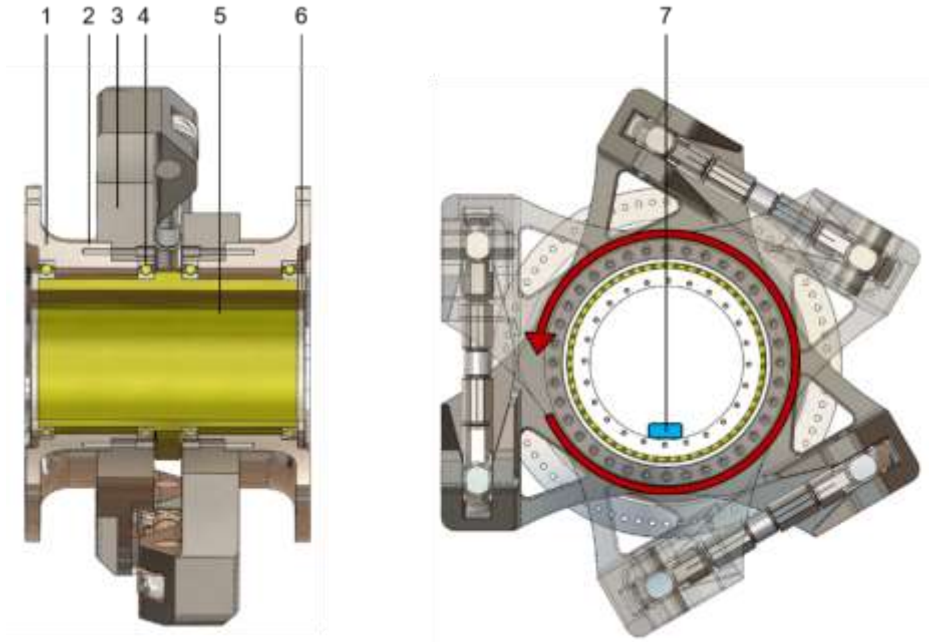
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Torque (*M*)** | **6.5016 MN·m** | **+/-** | **0.0097** | **(rel. val.: 0.149%)** | Combined uncertainty (MN·m) | 0.0048 | |
| | | | | | Expanded uncertainty (MN·m) | 0.0097 | k=2 |

*Upscaled force lever systems*

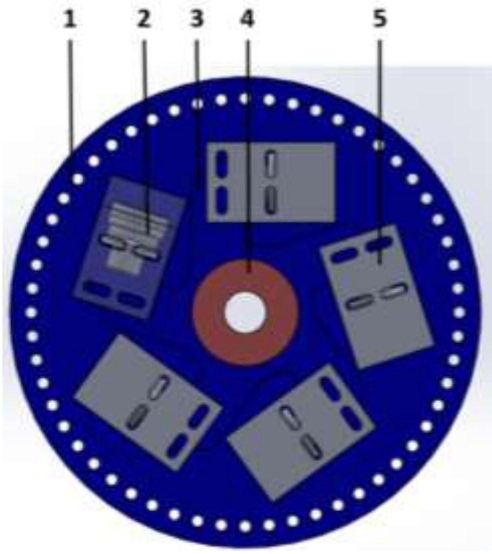
In order to enlarge torque measurement capabilities even above 5 MN·m, VTT, CEM and RWTH upscaled their force lever systems. VTT and RWTH systems (Figure 10, a and c) were upscaled up to 20 MN·m, while CEM's force lever system (Figure 10, b) was upscaled to 15 MN·m.

The feasibility of the upscaled systems was tested and their performance studied through FEM analyses. As in the preliminary design evaluation process, the main parameter to be studied for the upscaled force lever systems was the maximum von Mises stress, which ensured that the proposed design was able to withstand the loads applied by the test bench during operation.

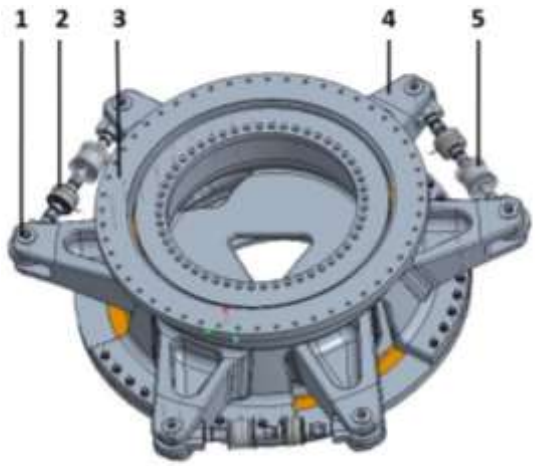
All the proposed upscaled systems have proven their feasibility and are expected to have similar metrological characteristics as the original force lever systems. Additional FEM studies are needed in order to analyse the study of the different influences and the behaviour of the upscaled force lever system during operation.




a) VTT: 1 – Adapter flanges, 2 – bolt connection, 3 – lever arms, 4 – angular contact ball bearings, 5 – support axle, 6 – supporting flanges, 7 – additional weight




**b) CEM: : 1 – Adapter flange, 2 – force transducer, 3 – additional lever arms, 4 – inner support and ball bearings, 5 – force transducer support**




**c) RWTH: : 1 – Rod connection, 2 – force transducer, 3 – Adapter Flange and special roller bearing in O-arrangement, 4 – additional lever arms, 5 – hydraulic adjusting system**

**Figure 10 Upscaled force lever systems.**

**Key output:** Two different approaches were used to enable traceability for torque in the MN·m range:

(I) Using FEM-simulations and measurements in the kN·m range, an extrapolation method was developed. This is solely based on partial range measurements as several effects could not be accounted for in the simulations. It was possible to establish an extrapolation method which is based on standard calibration measurements also giving a measurement uncertainty for the predicted transducer behaviour of 1.003 % for 5 MN·m.

(II) Four force lever systems have been designed with different layouts. The systems were investigated on their measuring capabilities, strength and deformations. It turned out that systems of this kind can enable traceability of torque measurements in the MN·m range even for more than 20 MN·m. Furthermore, a measurement uncertainty estimation was performed which has shown a good metrological performance of the systems leading to an improvement of the torque measurement precision compared to the status quo.

Overall, it was discovered that both investigated methods can provide traceability for torque in the MN·m range. The objective was fulfilled.

## 4.3 Multi-component effects

NTB do not only induce torque loads but also all other mechanical components leading to a six degrees of freedom (6DoF) loading situation. To analyse the influences of the additional load components on the torque measurement, investigations in the kN·m range had to be used as there are no calibration capabilities for MN·m-multi-component transducer. Furthermore, multi-component transducers for the multi-MN·m torque range were designed with optimal features for the use in NTBs.

*Multi-component calibration procedure for the kN·m range*

Multi-component effects can only be studied with torque transducers that are equipped at least with one measuring bridge for at least one additional component. A survey about existing torque transducers with additional component measuring capabilities was undertaken and it was found that there are several different transducers available at the participating partner institutes (PTB, VTT and CMI). Most of them are torque transducers with additional measuring bridges for two bending moment components. One transducer at CMI has these bridges and a bridge for the axial force component. Another transducer at PTB consists of two single transducers for force and torque. It can measure these two components only but not bending moments. There is also a so-called force vector sensor available at PTB which can measure all six force and moment components, but the force is the main quantity. At VTT, there is a transducer available that is equipped with two bridges for each of the two bending moment components. Finally, PTB has two multi-component transducers with the capability of measuring all force and moment components. The 5 MN·m torque transducer (see Figure 2) is too large and heavy for studying multi-component effects, but the 2 kN·m is well suited and was selected for the further investigations. VTT also selected a transducer with a torque capacity of 2 kN·m, it is the one with the two bridges for each of the two bending moment components. CMI selected a 1 kN·m transducer with one bridge for each of the two bending moment components. All these transducers have a shaft-type deformation body. Unfortunately, there was no other type of transducer available. An advantage of the selected specimens is that they all have ø 50 mm × 82 mm cylindrical shaft ends for adaptation. The transducers are shown in Figure 11.

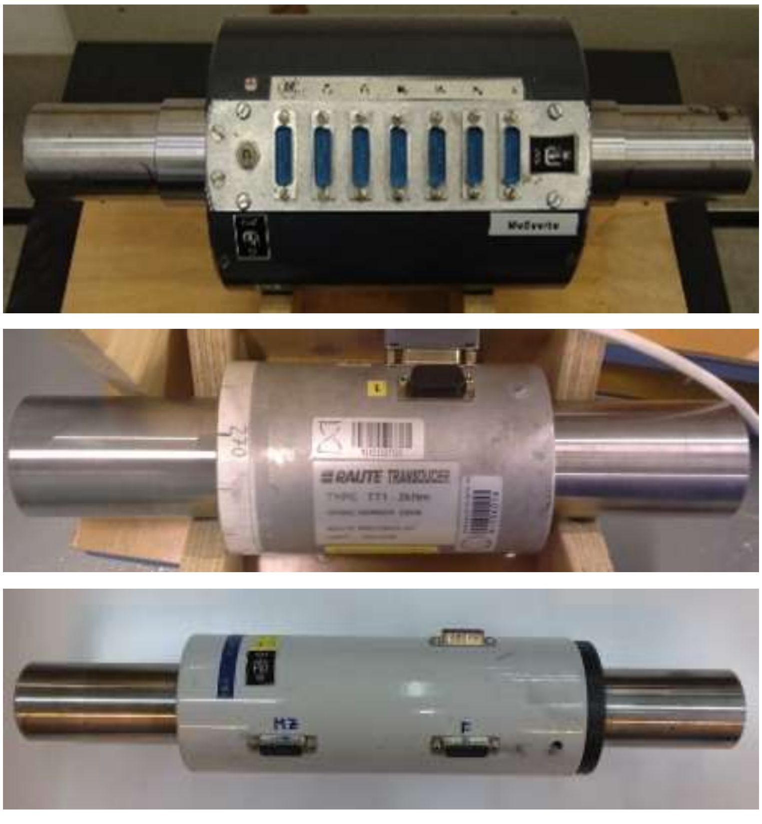



**Figure 11 Selected multi-component transducers (top: PTB MKA 2 kN·m, middle: VTT TT1 2 kN·m, bottom: CMI ETI 1 kN·m).**

To realise a complete multi-component calibration, different TSMs and additional equipment were necessary. The torque channels of all selected transducers were calibrated in a TSM of the participating NMI using the calibration guideline EURAMET cg-14. The machines used for these measurements are shown in Figure 12.

**Figure 12 Torque standard machines used for calibrating the torque channel (top left: PTB 20 kN·m, top right: PTB 1 kN·m, bottom left: VTT 2 kN·m, bottom right: CMI 1 kN·m).**

The calibrations of the other force and moment vector components were carried out with a specially designed and manufactured lever-mass-system. It is shown in Figure 13. It consists of a lever with well-defined force introduction points at distances of 360 mm, 400 mm, 450 mm, 514.3 mm, 600 mm, 720 mm, and 800 mm, mounting adaptations for ø 50 mm, and a set of two calibrated hangers with calibrated weights. The nominal loads that can be generated are: force (one side) 150 N, force (two sides) 300 N, moment 120 N·m.

**Figure 13 Lever-mass-system mounted on top of the PTB MKA 2 kN·m.**

The lever arm lengths (the distances of the force introduction point to the centre) were calibrated and correction factors were applied to account for the deviations due to manufacturing and temperature variations. The following calibration procedure was agreed upon:

Torque $M_z$

- according to EURAMET cg-14
- in horizontal setup of the transducer and mounting position 0°:
  - three pre-loadings
  - one series with incremental and decremental torque steps
  - one repeated series with only incremental torque steps
- in mounting positions 120° and 240°
  - one pre-loading
  - one series with incremental and decremental torque steps

Axial force $F_z$, bending moment $M_x$, $M_y$

- in vertical setup of the transducer and in mounting position 0° (double side masses for force and single side masses for bending moments):
  - three pre-loadings
  - one series with incremental and decremental torque steps
  - one repeated series with only incremental torque steps

Cross force $F_x$, $F_y$

- in horizontal setup of the transducer and in mounting position 0°:
  - three pre-loadings
  - one series with incremental and decremental torque steps
  - one repeated series with only incremental torque steps
- repetition of these measurements with the transducer turned by 180° around the vertical axis

The signals from all available channels must be recorded in each measurement.

The results were used to calculate the sensitivity matrices, one example is given in Table 2.

**Table 2 Example of a sensitivity matrix, values in (mV/V)/N, resp. (mV/V)/(N·m).**

| **Signals => in mV/V** | $S(F_x)$ | $S(F_y)$ | $S(F_z)$ | $S(M_x)$ | $S(M_y)$ | $S(M_z)$ |
|---|---|---|---|---|---|---|
| $F_x$ in N | **1.03E-05** | -5.75E-08 | 3.64E-07 | 2.48E-06 | -1.56E-05 | 4.26E-08 |
| $F_y$ in N | -1.15E-07 | **1.08E-05** | 7.81E-08 | -1.52E-05 | -4.47E-06 | -3.19E-08 |
| $F_z$ in N | -7.06E-08 | 1.04E-07 | **-4.31E-06** | 6.87E-08 | -1.46E-07 | -6.97E-08 |
| $M_x$ in N·m | 8.35E-07 | -2.73E-07 | -3.93E-06 | **8.44E-04** | -7.53E-06 | -5.68E-07 |
| $M_y$ in N·m | 5.85E-08 | 8.05E-07 | 1.45E-08 | -6.42E-06 | **8.32E-04** | 2.82E-07 |
| $M_z$ in N·m | 1.13E-08 | -5.05E-08 | 3.59E-07 | -2.78E-07 | 4.98E-06 | **7.90E-04** |

To compare the quality of multi-component transducers with different capacities, performance indicators were found in the literature and discussed.

*Simulation models for kN·m multi-component torque transducers*

In a next step, two multi-component torque transducers were studied theoretically, one by PTB and RWTH, the other one by VTT. The aim was to compare the results of numerical and analytical models with the measured data. For this purpose, FE models of the PTB's MKA 2 kN·m and VTT's TT1 2 kN·m, see Figure 14, were generated and the simulated signals were calculated using COMSOL or Abaqus. For simple geometries like cylindrical shafts it is possible to calculate the strains caused by the different load components based on the theory of elasticity. This allows the measurement bridge signals to be calculated too when it is known where on the surface the strain gauges are placed.

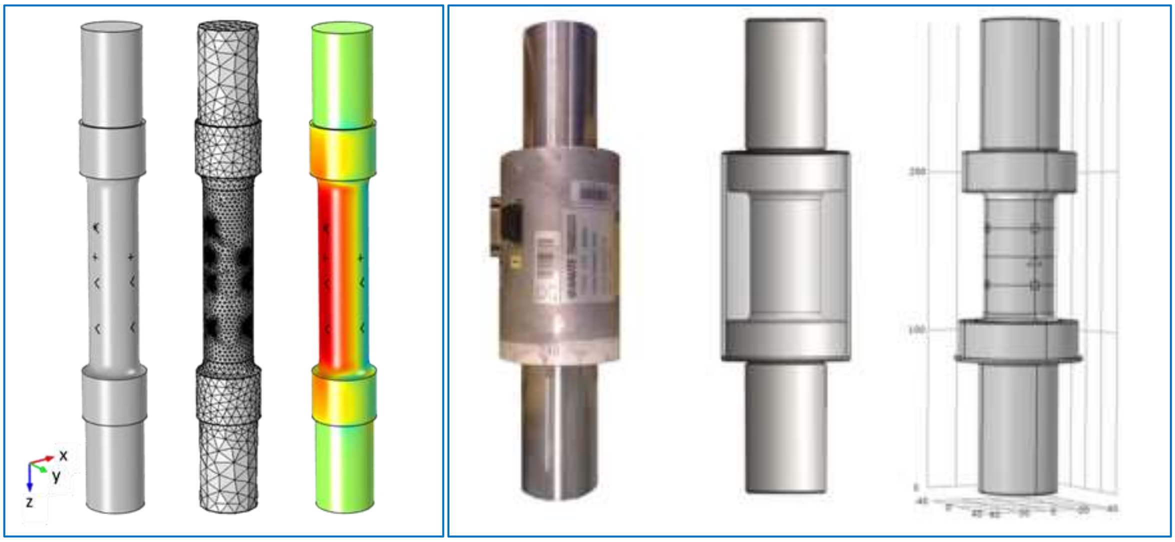



**Figure 14 Left: PTB's FE model of PTB's MKA 2 kN·m, Right: FE model of VTT's TT1 2 kN·m.**

In the result, it was possible to reproduce the behaviour of a MCTT for the main components (no crosstalk) in the range of < 6 %. For crosstalk behaviour, the results are not as reliable. This can be caused by several influences which are only relevant for very small values:

- Manufacturing tolerances of the transducer
- Minor deviations of the material parameters
- Minor Deviations in the ideal positioning of the strain gauges
- Convergence limit, Mesh size and type, non-linearity of the FE-models.

For the focus of this study, the torque measurement, all investigations show very small influences by other mechanical components on the torque signal. Only for very large loads, the result is noticeably affected. Therefore, it is advised to perform measurements where the requirements for the torque precision are very high with no or low additional loads.

*Design for MN·m multi-component torque transducers*

In a last step, the partner institutes performed design studies to find out basic principles for the development of multi-component torque transducers in the MN·m range with low crosstalk. One study was done by PTB and was based on the concept of a multilayer spoked wheel transducer, see Figure 15. The values of the geometrical parameters were optimised to get a lower crosstalk and a better self-compensation of the measuring bridges against the other components. An example of calculated strains in an improved model is given in Figure 16.

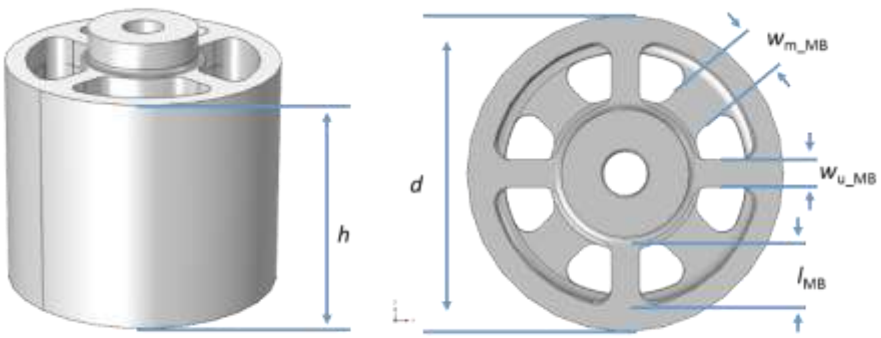



**Figure 15 PTB's design study of a multi-component torque transducer.**

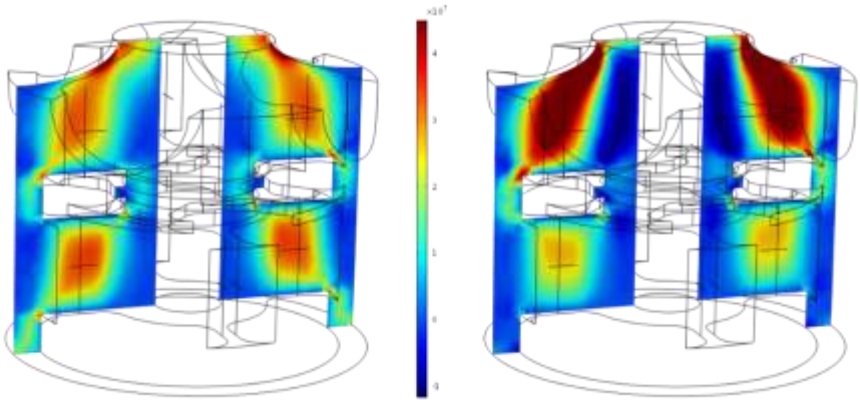


**Figure 16 Example of calculated strains for an improved version of the transducer from Figure 15.**

The second study was performed by RWTH and was executed according to the design methodology of the VDI 2221 guideline. It divides the design process into four different steps: (i) classification of the task, (ii) conceptual design, (iii) embodiment design and (iv) detail design (only the first three steps were performed). The main requirements were the following:

- Measuring body preferably in one piece
- Integration in the drive train with flanges
- Preferably rotationally symmetric measuring elements
- Measurement ranges for each degree of freedom (DOF) individually designable
  - Axial force 1.5 MN
  - Lateral force 2 MN
  - Bending 5 MN·m
  - Torque 5 MN·m

To achieve a precise measuring for all DOF, an individual design of the measurement components was necessary (see Figure 17). Besides this, the crosstalk between one load component and a different measurement component had to be minimised. In the conceptual design step various principles were developed to solve single sub-functions, which when combined can solve the main function “Measurement of all six DOF”. With these design principles, different design concepts were generated and compared according to VDI 2225 guideline. The most suitable design concept was then selected for further investigations.

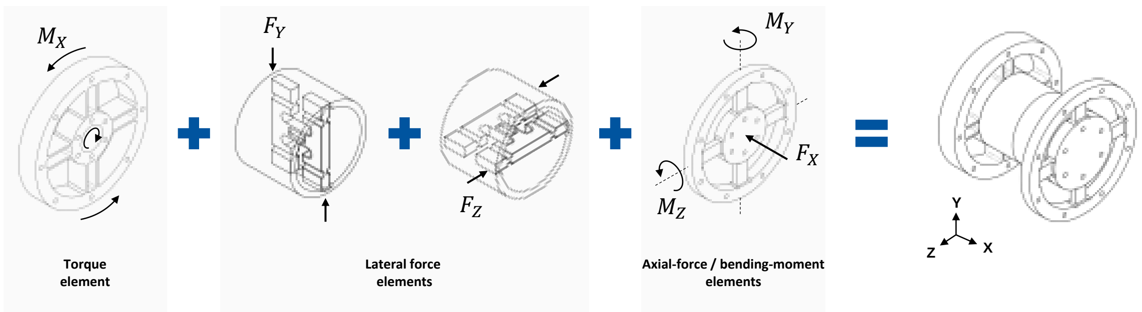



**Figure 17 RWTH’s design concept of a multi-component torque transducer.**

For the optimised design of the transducer, the measurement uncertainty was estimated considering the uncertainty of the load, linearity and hysteresis, repeatability and temperature influences as well as the crosstalk. Based on a rough estimation from the simulation results, the total expanded relative uncertainty was 0.22 % for each of the components. A problem of multi-component torque transducers with MN·m capacities is the heavy weight and the large dimensions.

**Key output:** Two different approaches were used to investigate the crosstalk effect on torque measurements. First, a small-scale study was performed to develop and validate a calibration procedure for multi-component transducers using a lever-mass-system. Based on the results, numerical models of the transducers were established to further investigate the transducer behaviour under multi-component loading. Second, a design study for a 5 MN·m multi-component torque transducer was undertaken. Two different designs were developed which focus on meeting the requirements of nacelle test benches. The objective to further investigate the multi-component effect on torque measurement was fulfilled.

## 4.4 Calibration procedure for nacelle test benches

In order to trace torque measurement in nacelle test benches (NTBs) to national torque standards, not only a torque transfer standard (TTS, see also Chapter 4.2), but also a practical calibration procedure is required. Before starting the development of a calibration procedure, the main influencing factors in NTBs had to be determined to account for them during the measurements. Therefore, pre-investigations using FEM studies were performed (Chapter 4.4.1). Afterwards, a calibration procedure for torque under rotation was developed considering the input from the industrial survey about existing NTBs (see Chapter 4.1) and the pre-investigations. The development of the calibration procedure was divided into the following steps: preparatory operations (Chapter 4.4.2), development (Chapter 4.4.3) and performance (Chapter 4.4.4). Subsequently, the obtained data was analysed (Chapter 4.4.5) and a calibration result determined (Chapter 4.4.6).

The same test setup was used for all steps of the process. It is depicted in Figure 18 including the NTB of RWTH Aachen at the Center for Wind Power Drives (CWD) as well as the 5 MN·m TTS presented in Chapter 4.2.1.

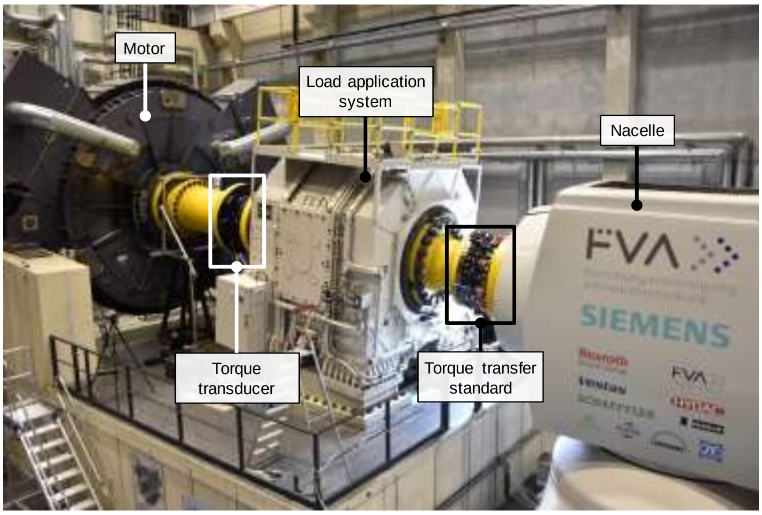



**Figure 18 Setup to perform the calibration measurements on the NTB of CWD Aachen including the torque transducer of the NTB and the reference torque transducer in form of the TTS with adequate adapters.**

### 4.4.1 Pre-investigations – simulations

The existing NTBs have specific system-dependent influences, which can affect torque calibration and torque measurement under normal NTB operation. These system-dependent influences in NTBs are:

- Parasitic loads due to assembly misalignments and control of the load application system (forces and moments in the range of kN and kN·m),
- Deformations, temperature distribution and rotational speed of the drive train,
- Gravitational forces as well as friction of the load application system (LAS) and
- Multi-component operation loads (forces and moments in the range of MN and MN·m)[5].

The above-mentioned system-dependent influences cause additional loads which in turn can lead to crosstalk during torque measurement. Thereby, the undesired crosstalk itself is the difference between the torque signal under pure torque load and the torque signal under torque and additional loads. The crosstalk is caused by additional strains in the strain gauges. Furthermore, the crosstalk depends on the geometry of the transducer body, the uniformity of the strain distribution, the strain gauge circuit, the type of the additional load and the strain gauge factor *k*.

[5] Kock S, Jacobs G, Bosse D, Weidinger P. Torque measurement uncertainty in multi-MW nacelle test benches. In: *Conference for Wind Power Drives Proceedings*. Aachen, Germany; 2017

The additional loads have been quantified in the project by an FEM simulation model of the entire NTB at CWD (RWTH Aachen) which was also used in the subsequent tests. The loads are listed in Table 3. The multi-axial operation loads are the highest additional loads. Other system-dependent influences generate smaller parasitic loads in the kN and kN·m range. During the torque application, no additional multi-axial operation loads were applied. In this case, the TTS and NTB torque transducer are loaded with torque and parasitic loads. Some of the system-dependent influence, such as bolt pre-load or weight force is only relevant for the zero-signal of the transducer, can be tared.

**Table 3 Additional loads caused by system-dependent influences in the NTB of RWTH.**

| System-dependent Influences | Additional Loads | | |
|---|---|---|---|
| | Axial Force | Radial Force | Bending Moment |
| Multi-axial operation loads (2,75 MW wind turbine) | 500 kN | 590 kN | 1500 kN·m |
| Self-aligning couplings of NTB | 290 kN | 36 kN | 9 kN |
| Control system of the load application unit | 100 kN | 100 kN | 100 kN·m |
| Centrifugal load (rotational speed) | 0,5 kN | 3 kN | ~ 0 kN·m |
| Deformation of the system | ~ 0 kN | ~ 0 kN | ~ 0 kN·m |
| Assembly process (bolt preload, relevant for zero-signal) | 630 kN | ~ 0 kN | ~ 0 kN·m |
| Gravity load (relevant for zero-signal) | ~ 0 kN | 134 kN | ~ 73 kN·m |

In the frame of the project, the influence of additional loads (see Table 3) on the torque measurement have been investigated. The simulation results are compiled in Figure 19. This figure shows the influence of additional operation loads (bending moment, radial and axial forces) on the torque signal, while a torque load of 1500 kN·m is applied simultaneously. The FEM investigations have been executed under the assumption of ideal strain gauges with a constant strain gauge factor *k*, a constant temperature and without gravitational as well as centrifugal force. The simulation model is linear. The bending moment $M_y$ = 1500 kN·m generates the highest crosstalk of 292 N·m. The axial force $F_x$ = 500 kN leads to a crosstalk of 119 N·m and the radial forces $F_y/F_z$ = 590 kN to 79 N·m. The investigated 5 MN·m research torque transducer is more sensitive to bending moments. This can be attributed to the fact that the bending moment leads to a more unequal strain distribution in the transducer than axial and radial forces. According to the simulation, the highest crosstalk due to the additional operation loads under 1500 kN·m torque is 0.02 %. This is much lower than the envisioned measurement uncertainty and it was, therefore, decided to not use any corrections for the influence of the multi-axial load operation conditions during the torque calibration.

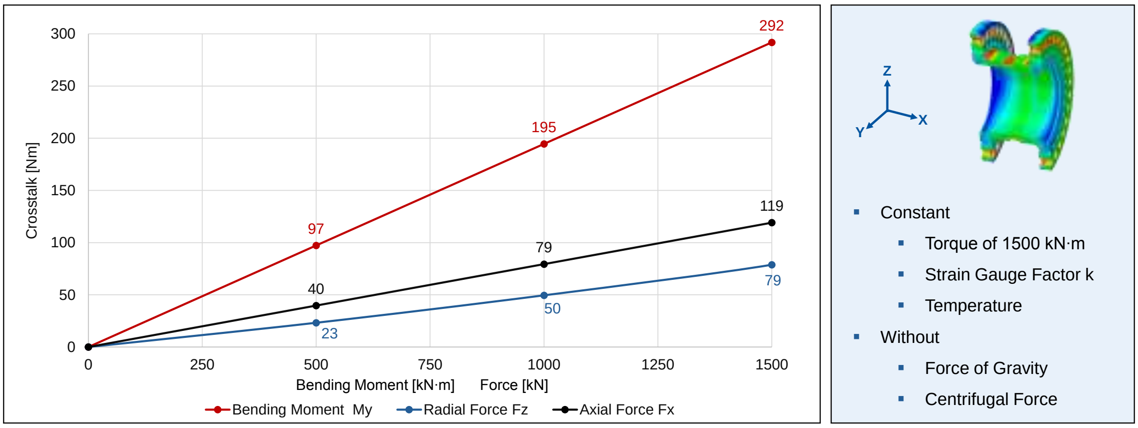



**Figure 19 Influence of additional operation loads on the torque signal (determined by simulation).**

*General effect of system-dependent influences on torque measurement*

The presented simulation and measurement results have been used to quantify the contribution of system-dependent influences on the torque measurement uncertainty budget in NTBs for the calibrated torque transducer, which is located between the load application system and the DUT. For the calculation of the torque measurement uncertainty, the values of the additional loads, see Table 3, have been considered. It was assumed that the nacelle operates under rotational speed of 17.5 rpm and under torque of 1500 kN·m. Furthermore, it was assumed that the temperature of the torque transducer increases by 5 K.

The expanded measurement uncertainty ($k$ = 2) for the mentioned case is 0.153 %. The highest contribution to the measurement uncertainty budget are the measurement uncertainty of the TTS (76 %). The additional multi-axial operation loads contribute to the uncertainty with 16 %. The temperature distribution (5 %) and the control effect of the LAS (3 %) have a smaller influence. It was therefore concluded that the TTS can be used for the calibration of the NTB without any further correcting measures.

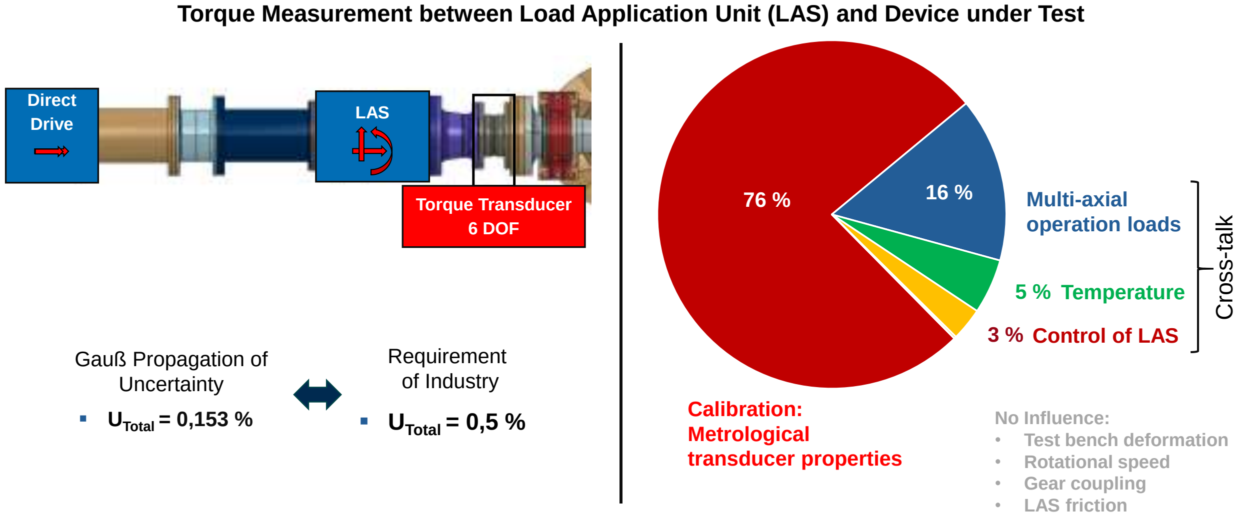



**Figure 20 Contribution of system-dependent influences in an NTB to the measurement uncertainty budget.**

4.4.2 Preparatory operations and preliminary tests

As not all influences in NTBs on the torque measurement can be studied simulative, several pre-tests as well as means to monitor the conditions during the measurements had to be considered. These are discussed in the following.

Besides the challenge of calibrating torque at the relevant place using a TTS and adequate adapters, the difficulty of measuring under rotation had to be faced. To allow for measuring under rotation and, at the same time, monitoring the effective loads on the TTS, a special telemetry system was deployed. Because of the autarkic data acquisition system (DAQ) of the TTS, a timewise synchronisation of the two independent data sets had to be performed. This was realised by an ideal square-wave signal with a voltage of $\hat{u} = \pm 5$ V and a frequency of $f_{sync}$ = 0.2 Hz, which was recorded by both DAQs and used in a post-processing to synchronise the data sets.

For a torque calibration under rotation, it is not sufficient to investigate only torque $M$ and rotational speed $n$, but to monitor the ambient conditions in form of temperature $\vartheta$ and humidity $H$ as well. Before starting a calibration measurement, it was ensured that all electrical and mechanical components were heated up to stable conditions by operating the NTB at nominal speed $n_{nom}$ and nominal torque $M_{nom}$.

Before starting the calibration measurements, the behaviour of the NTB and the TTS regarding mounting conditions, constraint forces, and temperature were analysed in several tests. Moreover, to minimise time-effects after the first mounting of the TTS as part of the NTB drive train, the NTB was operated in several modes with different combinations of rotational speed, torque, and additional multi-component loads. The boundary conditions of the NTB have been set in a way to prevent an overloading of the TTS. Furthermore, another pre-test gave some indication of the negative influence of emergency brakes on the torque signal. The knowledge obtained during the test measurements was transferred to the development of the calibration procedure.

As not all influences on the torque measurement could be analysed in the nacelle test bench within the project, a researcher mobility grant (RMG) of EMPIR was used to additionally perform small-scale measurements. These measurements on a 1 kN·m torque transducer on a reference torque standard focused on the effects of filter settings and altered load cycles on the torque measurements. The RMG study showed that very low filter settings have to be avoided to prevent a falsification of measurement data. Furthermore, a hysteresis effect due to altered load cycles was observed that has to be accounted for in the calibration of the torque transducer.

4.4.3 Development of the calibration procedure

A calibration procedure should always be as close to the intended operation mode as possible. To this end, it is important to get an overview of the devices tested on the NTB. For the calibration, a nacelle, which was representative for the operating point of the NTB regarding the range of torque and rotational speed, was installed on the NTB, because only then a torque generation is possible.

Of great importance for any calibration is the zero signal, which is used to eradicate the signal offset caused by tension due to the assembly in all measurement data of each following load cycle. Due to the horizontally aligned NTB drive train and, consequently, the torque transducers, a signal in only one position would be highly influenced by dead-weight effects and misalignments, which have to be averaged out. This issue can be overcome by two possibilities developed within the development of the calibration procedure: (i) a static zero signal determination with static measurements equally allocated over one full rotation and (ii) a zero signal determination under constant rotation with minimum rotational speed.

For the static zero signal determination, the zero-torque signal was measured over incrementally rotated positions relative to the main axis of the drive train. The number of distinct positions per full revolution depends on the measurement system of the transducers deployed. Because of the usage of the typical strain gauge principle with a 90° strain gauge distribution, 3·120° or 4·90° measurements are sufficient, while for force lever systems 6·60° measurements should be gathered. Here, all increments were tested.

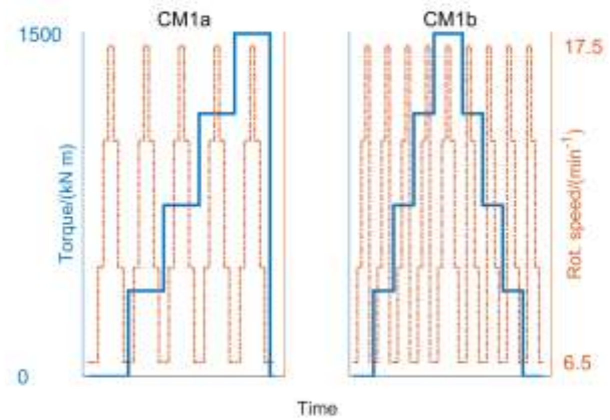
This kind of zero signal determination, however, was very time-consuming, which is the reason why a rotational zero signal determination was performed before each load cycle. The rotational zero signal is acquired at minimum rotational speed and no torque load applied, and it is averaged over six full rotations. The friction influence during this measurement can be reduced by switching on the nacelle's generator and its control system, which act as an additional motor to compensate friction torque in this setup. For the calibration of the NTB at RWTH Aachen, solely the rotational zero signal with the entire drive train and the nacelle under test with the torque control switched on was applied.

However, the control of the zero signal can be very difficult and instable, in this case a rotational zero signal determination without the generator or a static zero signal calibration is recommended. Prior to every signal averaging, a dwell time of 20 s in order to attain a stationary state in terms of control and rotational effects was observed.

Most nacelles and other DUTs have a device specific operating point, which have to be partly mapped in the calibration by applying different combinations of torque and rotational speed (eigenfrequencies must be omitted). To do so, so-called *characterisation maps* were developed based on [6]. The measurement points of a *characterisation map* represent the typical operating range of the NTB depending on the commonly tested devices. It is to be pointed out, that the *characterisation map* is limited by the DUT being installed during the calibration measurements. To investigate the influence of rotational speed on the torque measurement, there are two different categories of *characterisation maps*: the torque being fixed periodically while the rotational speed is altered stepwise (Figure 21) and vice versa. For a statistical evaluation of the calibration, each *characterisation map* is to be repeated twice or each load step is to be passed four times.

A similar approach was also used for the multi-component load tests: One or two additional loads have been applied with and without torque load to investigate the crosstalk of the additional loads on the torque measurements. An example of this is given in Figure 22.

[6] Brüge A, Pfeiffer H. A standard for rotatory power measurement. 2018:paper draft (unpublished).



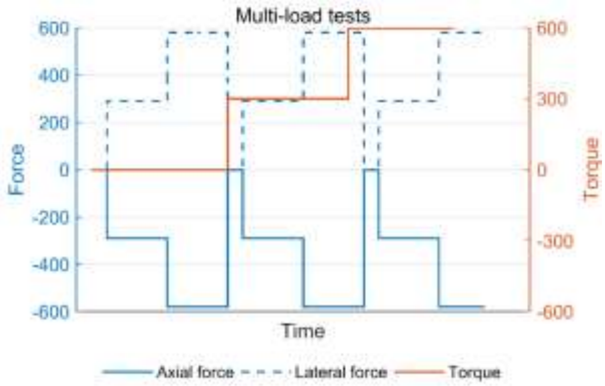




**Figure 21 Schematic principle of the characterisation maps to calibrate torque depending on rotational speed.**

**Figure 22 Schematic principle for investigating the crosstalk effect on the torque signal caused by additional loads.**

4.4.4 Performance of the calibration measurements[7]

Within a three-week field campaign at RWTH Aachen, a torque calibration of an NTB was performed for the first time based on the aforementioned calibration procedure developed. The NTB at RWTH Aachen is a 4 MW test bench (Figure 18) with a direct motor, an LAS to simulate wind loads in form of multi-component loads, and a torque transducer with a capacity of $M_{nom}$ = 2.7 MN m. The torque transducer is located between the direct motor and the LAS to protect it from the high simulated wind loads at the rotor hub flange. In order to generate torque, a 2.75 MW nacelle from the *Forschungsgemeinschaft Antriebstechnik e. V.* (FVA) with a maximum torque load of $M_{max}$ = 1.5 MN m and a minimum constant rotational speed under load of $n_{min}$ = 6.5 min$^{-1}$ was installed. Using specially designed adapters, the TTS was mounted directly at the rotor hub flange of the nacelle, where the input torque to the nacelle is intended to be measured. Here, the nacelle is part of a research project and, therefore, full access to its control system was provided. Due to this, a closed loop control of the setup was realisable.

Moreover, a DAQ with a sampling frequency of $f_{sample}$ = 1200 Hz and a 180 Hz Bessel Filter was employed to record the rotational speed *n*, which was measured by an incremental encoder, and the torque *M*, which was measured by the NTB torque transducer. The DAQ was realised permanently without any triggers in order to allow the torque and rotational speed acceleration ramps between the different load steps to be monitored.

*5 MN·m torque transfer standard (TTS)*

The 5 MN·m TTS was characterised in a previous step of the project (see Chapter 4.2.1) and was installed in the NTB of RWTH Aachen (see Figure 18). For a rotating application of the TTS, a self-sufficient DAQ with a wireless data transmission was developed. The DAQ consists of a very precise amplifier (Quantum MX238B) that has a 225 Hz carrier frequency for the torque bridges, two additional amplifiers (Quantum MX430B) that have a 600 Hz carrier frequency for the additional bridges, and a battery that functions as an independent power supply while under rotation. It is very important that the data gathered is accessible within a narrow time frame while the measurements are being performed. This was ensured by means of two wireless access points and a computer communicating via WLAN. To avoid imbalances and force/torque shunt, the components of the DAQ are symmetrically distributed around the TTS's flange (Figure 23). To gain a resolution of 1° per revolution for a maximum rotational speed of 25 min$^{-1}$, the sampling frequency must be $f_{sample}$ = 150 Hz. In addition, a Bessel filter with a frequency of 50 Hz was used for the TTS.

[7] Weidinger P, Foyer G, Kock S, Gnauert J, Kumme R. Development of a torque calibration procedure under rotation for nacelle test benches. In: *The Science of Making Torque from Wind*.; 2018.

**Figure 23 360° view of the torque transfer standard with a 5 MN m measuring range equipped with a data acquisition system and a telemetry system to transmit the acquired measurement data.**

### 4.4.5 Data analysis

*Zero point determination*[7]

Two different zero point determinations have been performed during the tests: static and rotational (see Chapter 4.4.3). For the static zero point determination during post-processing, the torque signal was averaged over 30 s with a prior dwell time of 20 s for each position. Subsequently, the averaged torque signals per position were averaged again to get an overall zero point. In order to consider the influence of the transducers' dead-weights, distinct relative positions (e.g. 12·30°, 6·60°, and 4·90°) were tested and the same order of magnitude found for the torque signal of both transducers (TTS and NTB transducer). This is a good indication that the same additional influences, such as system oscillations and noise, act on both transducers.

For the rotational zero point determination under permanent rotation, the NTB was operated with a low rotational speed of $n_{min}$ = 6.5 min$^{-1}$, and the torque signal was averaged over six full rotations using $n$ and the measuring time to calculate full rotations. Prior to the averaging, the dwell time was observed. The procedure can also be incorporated into the general test routine of a new nacelle implementation to get a reliable zero point. Due to the fact that the nacelle torque control system starts when the generator is switched on, thereby changing the torque signal (Figure 24), the generator was switched on for the zero point determination. This zero signal was used to tare the rest of the torque signals in post processing. A similar procedure is recommended for other test benches as well.

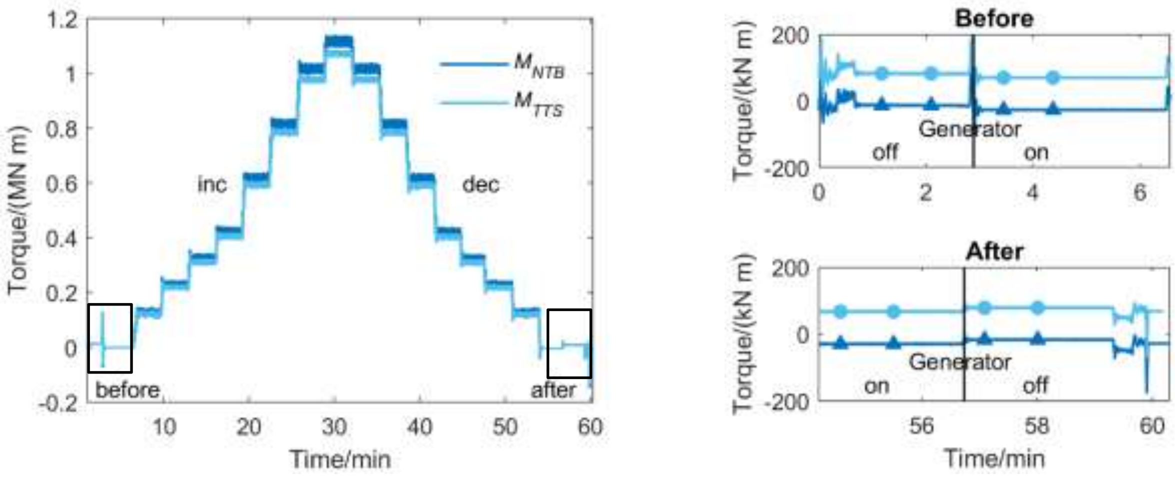



**Figure 24 Example of a stepwise increase and decrease of the torque load at $n$ = 6.5 min$^{-1}$ with the rotational zero point determination before and after each load cycle with generator switched off and on.** [7]

*Characteristic maps*[7]

After the two data sets have been synchronised, the sequences to be analysed for each measurement are defined. Within these sequences, which follow a dwell time of 20 s after reaching a stable torque signal, the torque signal is averaged over six full rotations (see description in Chapter 4.4.3). As an example, the data processed for a *characteristic map* of type CM1a (cf. Figure 21) is presented in Figure 25. The torque signals $M_{NTB}$ and $M_{TTS}$ acquired for the NTB transducer and the TTS are plotted over time. While these signals refer to the ordinate on the left, the ordinate on the right is for the rotational speed *n*. The visual distance between the torque signals is due to the raw data not being tared.

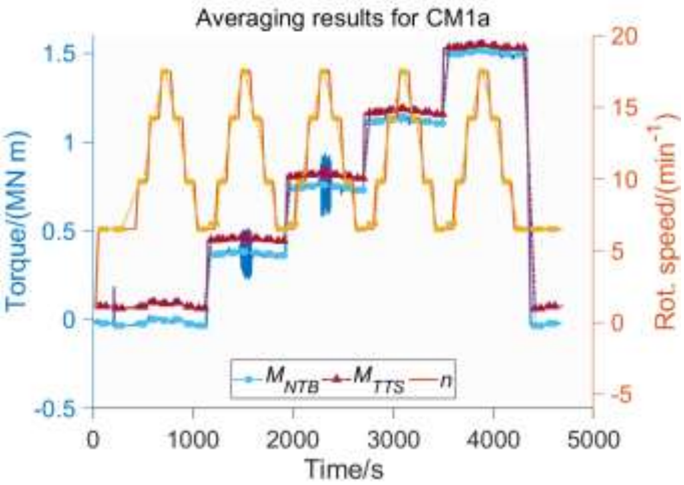
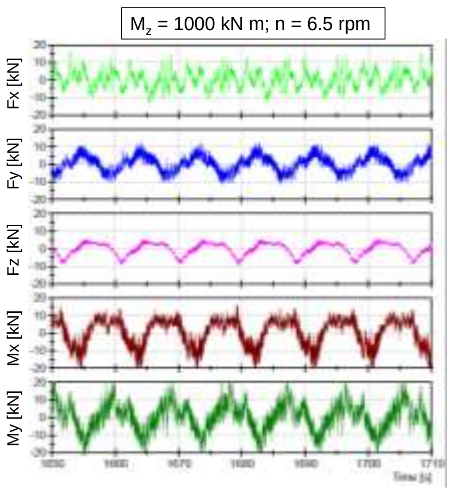



**Figure 25 Measurement data of CM1a *characteristic map*, including averaged signals and marked analysing sequences.** [7]

*Crosstalk effects during torque calibration*

The assembly process and the integration of the nacelle into the test bench is challenging, because of the nacelle's big masses and dimensions (see Chapter 4.1). Even an accurate assembly leads to an axis misalignment between the main shaft of the test bench and the hub of the nacelle. This axis misalignment can be in the range of up to 0.5 mm and generates parasitic loads (forces and bending moments) during rotation. The control system of the LAS tries to control the parasitic loads to zero. An ideal adjustment of the parasitic loads to zero is not possible, because of the inaccuracy of the control system. Because of this fact the application of pure torque load during the calibration is not feasible. Figure 26 shows the acquired data of the LAS over time for the parasitic loads at a load step of $n$ = 6.5 min$^{-1}$ and $M$ = 1000 kN·m. The periodic behaviour of the parasitic loads demonstrates the correlation of the parasitic loads and the revolution of the main shaft of the NTB, which in turn confirms the high influence of the axis misalignment on the parasitic loads. According to Figure 26, the maximum parasitic forces reach up to 17 kN and the maximum parasitic moments rise up to 26 kN m. In case of higher rotational speeds, the parasitic loads can reach up to 100 kN and 100 kN·m, see Table 3. These values are small in comparison to the nominal operating loads of multi-MW nacelles. As the data of the torque transducers is averaged over an integer number of rotations, periodic effects are assumed to be neglectable. Other effects caused by the LAS are randomly distributed. Such effects can be considered in the measurement uncertainty budget by the repeatability contribution.




| | Average | St. Dev. | Min | Max |
|---|---|---|---|---|
| $F_{x,LAS}$ [kN] | 0.4 | 5.0 | -13.5 | 16.7 |
| $F_{y,LAS}$ [kN] | 0.3 | 4.6 | -12.5 | 13.4 |
| $F_{z,LAS}$ [kN] | -0.3 | 3.6 | -9.7 | 5.8 |
| $M_{x,LAS}$ [kN m] | 0.5 | 7.6 | -22.8 | 16.6 |
| $M_{y,LAS}$ [kN m] | 0.4 | 7.9 | -22.6 | 26.1 |

**Figure 26 Parasitic loads during the calibration at a torque step of 1000 kN·m and a rotational speed of 6.5 min$^{-1}$.**

### 4.4.6 Calibration results

The calibration results for the NTB calibration basically consist of an indication deviation between the two torque signals from the TTS and the NTB, the measurement uncertainty of this indication deviation and a discussion of the multi-load tests with additional mechanical loads. All three are described in the following.

*Indication deviation of torque signals*

For the torque calibration in test benches, the calibration result is adapted to the calibration result in ISO 7500-1 and consists of (i) the relative indication deviation and (ii) the measurement uncertainty for the indication deviation.

Figure 27 shows the calculated relative indication deviation between the torque measured by the TTS ($M_{TTS}$) and the torque measured by the NTB transducer ($M_{NTB}$). A deviation of about 4 % was found, which also depends on the load direction (increasing or decreasing load). It is also visible that the repeatability between the different tests is relatively good. Figure 28 depicts the relative indication deviation for a set of combined *characterisation maps*. No differentiation was made between the directions of loading as they were different for the *characterisation maps*. The indication deviation here is slightly larger than 4 %.

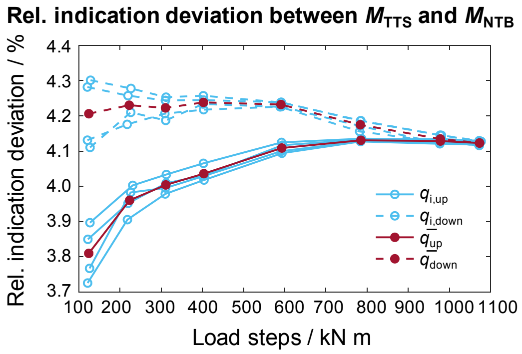



**Figure 27 Calibration result of the static torque calibration under constant rotation of 6.5 min$^{-1}$ in form of the relative indication deviation between the reference torque signal measured by the TTS and the torque signal to be calibrated, which was measured by the torque transducer in the NTB.**

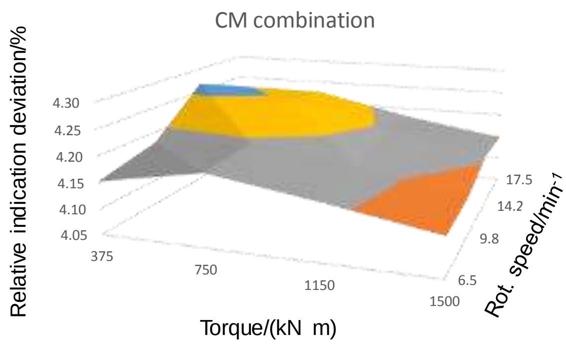



**Figure 28 Visualisation of the relative indication deviation depending on torque and rotational speed applied for a combination of all *characterisation maps* (CM).**

*Measurement uncertainty of the torque calibration*

The measurement uncertainty itself consists of the following uncertainty contributions: (i) the resolution, (ii) the repeatability, and (iii) the torque transfer standard. It can be calculated using the following equation:

$$U = k \cdot u_c = k \cdot \sqrt{\sum_{i=1}^{n} u_i^2} = k \cdot \sqrt{u_{\text{res}}^2 + u_{\text{rep}}^2 + u_{\text{std}}^2} \quad (3)$$

The measurement uncertainty is an absolute measurement uncertainty of the relative indication deviation, which is represented in the unit %. The absolute measurement uncertainty has the same unit as its reference value, consequently the unit of the absolute measurement uncertainty is %. It is recommended to use a coverage factor of $k = 2$. In certain cases, $k$ can also be calculated based on the number of effective degrees of freedom as stated in the Guide to the Uncertainty in Measurement (GUM).

The absolute expanded measurement uncertainty ($k = 2$) for the NTB of RWTH Aachen amounts to $U \leq 0.161\%$ for a relative indication deviation of ≈ 4% under constant rotation.

*Multi-component effects on the torque results*

The measurement investigations on the 4 MW RWTH Aachen NTB have shown that the change of the torque signal (crosstalk) due to additional loads is superimposed by friction in the drive train, pre-tension of the drive train and the control effect of the DUT torque. The highest contribution to the change of the torque signal has friction in the drive train, see Figure 29. The friction increases with higher multi-axial loads. The influence of crosstalk on torque measurement is small in comparison to the measurement uncertainty of the TTS.

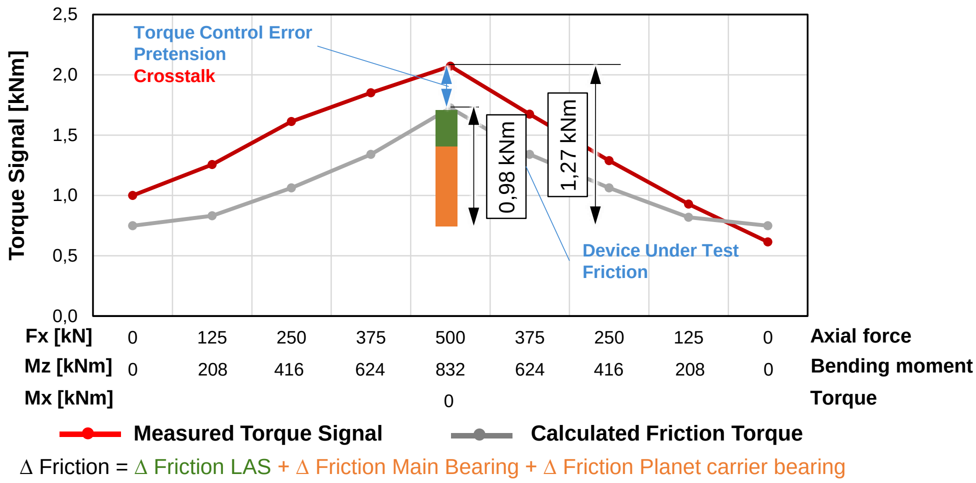



**Figure 29 Contribution to the change of the torque signal due to additional multi-axial operation loads.**[8]

The determination of crosstalk in the measurements is possible by subtracting the friction of the DUT, the control error of the DUT torque and the pre-tension of the drive train from the torque signal under additional loads. Figure 30 shows the crosstalk values due to a bending moment determined by measurement. In total, nine measurements have been processed to achieve statistical confidence. The bending moment has been increased from 0 kN·m to 1500 kN·m. The crosstalk increases nonlinear with a higher bending moment. The measured crosstalk under highest bending moment amounts to 300 N·m and 350 N·m. The simulation results are linear and fit only approximately the measurement results. For this reason, the simulation can be used to estimate the crosstalk and to characterise or optimise torque transducer designs.

It can be concluded that in case high additional loads occur, a correction of the torque results using simulations or detailed data analysis has to be performed. As this was not the case during the torque calibration performed at RWTH Aachen, the data was not corrected.

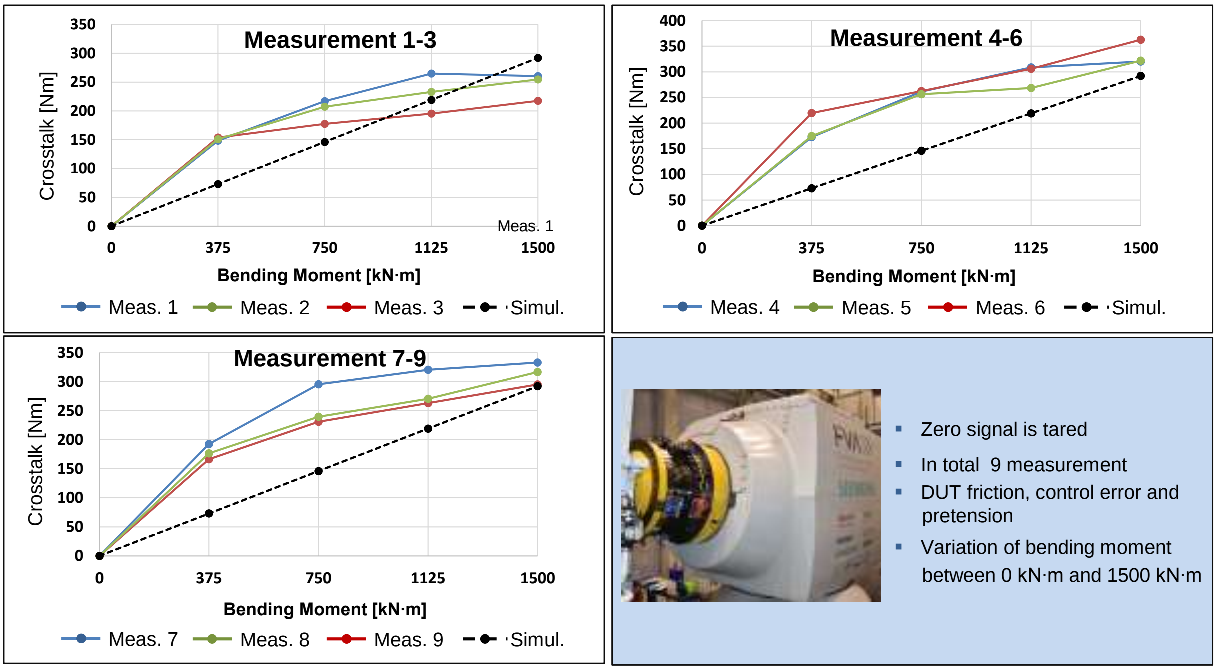



**Figure 30 Measurement results - crosstalk caused by bending moment.**

**Key output:** Based on pre-investigative simulations, tests and the survey described in Chapter 4.1, a calibration procedure for torque measurements in nacelle test benches has been developed and tested at

[8] Kock S, Jacobs G, Bosse D, Sharma A. Friction as a major uncertainty factor on torque measurement in wind turbine test benches. *J Phys Conf Ser*. 2018;1037.

RWTH Aachen. The results have been analysed, discussed and a measurement uncertainty calculation was proposed taking account of the small control effects of a load application system. Larger multi-component loads have found to have an effect that is not negligible and has to be corrected using simulations or data analysis. Overall, the objective has been fulfilled.

# 5 Impact

The project outputs have been disseminated in several ways: through communication with stakeholders, scientific publications and presentations on conferences, participation in standardisation meetings as well as web-based information including press releases.

The communication with stakeholders was one of the most important tools also during the project, as they are the direct end-users. Therefore, several stakeholder meetings have been held including a meeting following the Conference for Wind Power Drives in March 2017 in Aachen, a web meeting presenting the calibration procedure in April 2018 and a final meeting in August 2018 in Braunschweig. Furthermore, a newsletter was created at the beginning of the project. Four issues all together have been written summarising current outputs of each of the project's phases. They have been sent to the stakeholders and project partners as well as posted on the project website.

The scientific output of the project was mainly disseminated through conference presentations and publications in the proceedings. 18 presentations, in many cases made in collaboration between at least two project partners, have been given on national and international conferences.

*Impact on industrial and other user communities*

Two project results that are the most interesting for industry are the two torque transfer standards which were the focus of Objective 2: the 5 MN·m torque transducer was calibrated within the project up to 1.1 MN·m. With the help of the extrapolation method and further measurements it was characterised up to its full range of 5 MN·m. Moreover, it was already tested in the nacelle test bench in the Center for Wind Power Drives. It now represents an adequate torque transfer standard that can be requested at PTB and can be used for other calibrations up to 5 MN·m. With such measuring range, it is, up to this day, the largest of its kind worldwide.

The second transfer standard is the force lever system which has only been designed within the project and not, yet, constructed, however it gives the possibility to be used up to 20 MN·m. With the four design options, it provides the stakeholders with an opportunity to improve their torque measurements. A patent application has been filed by three project partners for the general design of the force lever system.

*Impact on the metrology and scientific communities*

The project outputs were introduced to the scientific community through conference presentations. The latest and largest impact in this regard was achieved at the IMEKO World Congress in September 2018 in Belfast where a special session dedicated to the project was held, giving the opportunity to present the whole project to an international scientific audience. The session included the overview of the project and five scientific presentations which all focused on the development of new torque transfer standards. One of the publications had also been chosen there for the György Striker Junior Paper Award.

Moreover, a workshop presenting most of the project results was held within the 2018 EURAMET TC-M meeting in Dublin. Thus, the national metrology institutes in Europe working in the area of calibration of mechanical quantities could be reached and informed about the findings of the project.

With three doctoral students involved in the project, it is expected that doctoral theses will be published on the topic in the following years. The three rough topics covering results from Objective 2 (transfer standards) and Objective 4 (calibration procedure) are: (i) Metrological characterisation of a torque transfer standard for a traceable calibration of nacelle test benches; (ii) Force lever systems and their suitability as a new torque transfer standard and (iii) Torque measurement uncertainty budget of MN·m torque measurement in nacelle test benches.

*Impact on relevant standards*

As there is no standard dealing with the torque calibration in nacelle test benches, the project consortium were attending similar standardisation body meetings. This included EURAMET TC-M (calibration on the European level), ISO TC 164 (mechanical testing) and IEA Task 35 (testing of nacelles). Rather than submitting a new standard to one of these groups, a good practice guide was written. This includes all information on how and why to calibrate torque measurement in nacelle test benches. Furthermore, it describes how to evaluate the results and gives examples on how to integrate them in the test bench's measurement process. This guide can later be used as a template for a new standard if the community of test bench operators decides to produce one. The document already takes into account many specific requirements of different facilities and constitutes an ideal starting point for future standardisation work.

*Longer-term economic, social and environmental impacts*

Achieving traceability for torque measurements in the MN·m range will create impact by improving the accuracy and precision of torque measurements in nacelle test benches. Traceable torque measurements will provide a more solid basis for the development and optimisation of drive trains or entire wind power stations. These measurements will simplify the certification process and enhance the quality of the certification for entire systems or components. In addition, better testing of mechanical components will result in the whole power station being more reliable with less downtime due to mechanical failures, which would decrease economic losses. These advances will also create impact as it lowers the risk for single wind turbine or entire wind park projects making them more likely to receive funding. By improving wind power stations, the energy change which is an important European goal can also be brought further.

# 6 List of publications


[1] C. Schlegel, H. Kahmann, and R. Kumme, "MN · m torque calibration for nacelle test benches using transfer standards," *ACTA IMEKO*, vol. 5, no. 4, pp. 12–18, 2016. http://dx.doi.org/10.21014/acta_imeko.v5i4.414

[2] S. Kock, G. Jacobs, D. Bosse, and P. Weidinger, "Torque measurement uncertainty in multi-MW nacelle test benches," in *Conference for Wind Power Drives Proceedings*, 2017. http://dx.doi.org/10.18154/RWTH-2017-02946

[3] R. M. Lorente, N. Medina, M. A. Sáenz, and M. Á. Sebastián, "Torque Traceability for Nacelle's Test Benches: a Design Proposal," in *23rd IMEKO TC3*, 2017. http://www.imeko.org/publications/tc3-2017/IMEKO-TC3-2017-004.pdf

[4] G. Foyer and S. Kock, "Measurement Uncertainty Evaluation of Torque Measurements in Nacelle Test Benches," in *23rd TC3 IMEKO*, 2017. https://www.imeko.org/publications/tc3-2017/IMEKO-TC3-2017-010.pdf

[5] C. Schlegel, H. Kahmann, P. Weidinger, and R. Kumme, "New Perspectives for MN·m Torque Measurement at PTB," in *23rd IMEKO TC3*, 2017. http://www.imeko.org/publications/tc3-2017/IMEKO-TC3-2017-045.pdf

[6] P. Weidinger, G. Foyer, S. Kock, J. Gnauert, and R. Kumme, "Development of a torque calibration procedure under rotation for nacelle test benches," *J. Phys. Conf. Ser.*, vol. 1037, no. 5, 2018. http://dx.doi.org/10.1088/1742-6596/1037/5/052030

[7] S. Kock, G. Jacobs, D. Bosse, and F. Strangfeld, "Simulation Method for the Characterisation of the Torque Transducers in MN · m range," in *IMEKO World Congress*, 2018. http://www.imeko2018.org/abstracts/IMEKO18-241.PDF

[8] R. M. Lorente and N. Medina, "Study of influneces in CEM's new transfer standard for torque measurements in the MNm range," in *IMEKO World Congress*, 2018. http://www.imeko2018.org/abstracts/IMEKO18-454.PDF

[9] G. Foyer and H. Kahmann, "A finite element analysis of effects on force lever systems under nacelle test bench conditions," in *IMEKO World Congress*, 2018. http://www.imeko2018.org/abstracts/IMEKO18-195.PDF

[10] P. Weidinger, G. Foyer, J. Ala-Hiiro, C. Schlegel, and R. Kumme, "Investigations towards extrapolation approaches for torque transducer characteristics," in *IMEKO World Congress*, 2018. http://www.imeko2018.org/abstracts/IMEKO18-667.PDF

[11] J. Gnauert, G. Jacobs, S. Kock, and D. Bosse, "Measurement uncertainty estimation of novel torque transducer for wind turbine test benches," in *IMEKO World Congress*, 2018. http://www.imeko2018.org/abstracts/IMEKO18-575.PDF

[12] G. Foyer, S. Kock, and P. Weidinger, "Influences in nacelle test benches , their effect on the

measurement uncertainty and consequences for a calibration," *ACTA IMEKO* (submitted).

[13] P. Weidinger, G. Foyer, S. Kock, J. Gnauert, and R. Kumme, "Calibration of torque measurement under constant rotation in a wind turbine test bench," *JSSS Conf. Ser.* (submitted).