IMEKO 23rd TC3, 13th TC5 and 4th TC22 International Conference
30 May to 1 June, 2017, Helsinki, Finland

MEASUREMENT UNCERTAINTY EVALUATION OF TORQUE MEASUREMENTS IN NACELLE TEST BENCHES

G. Foyer, S. Kock

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, gisa.foyer@ptb.de
Center for Wind Power Drives, Aachen, Germany, stefan.kock@cwd.rwth-aachen.de

Abstract: Torque measurement in the MN·m range is important in nacelle test benches, as it constitutes a main value for the efficiency determination of wind turbine drive trains. However, no traceable measurement is possible above 1.1 MN·m. At the moment, alternatives to direct torque measurement in the MN·m range are, therefore, used. Several of these torque measurement methods are presented and discussed in this paper with respect to traceability and measurement uncertainty. As these methods cannot substitute direct measurements fully, recommendations for a calibration procedure are given to enable a calibration of torque measurement using a torque transfer standard.

Keywords: torque measurement, measurement uncertainty, nacelle test bench calibration, wind energy

1. INTRODUCTION

Wind energy is a developing market initiated by a worldwide change towards renewable energies. This is leading to more and also larger wind turbines, which have to be tested prior to their market launch. Several nacelle test benches (NTBs) have been constructed worldwide in the last few years. These NTBs aim at accelerating the testing phase of innovative concepts and enabling an overall system test compared to component testing.

One example of an NTB is shown in Figure 1. It consists of a prime mover, a load application system (LAS) and a device under test (DUT). The prime mover in Figure 1 is an electrical direct drive; other NTBs have a geared drive reducing the speed and increasing the torque between the electrical engine and the DUT. The LAS shown in Figure 1 is not present on all NTBs. Its purpose is the exertion of additional load components (axial and lateral forces as well as bending moments) to the main shaft to simulate the mechanical loads acting on the rotor hub of a nacelle during field operation. A DUT, which is normally a nacelle but can also be a gearbox or a main bearing, is connected to the main shaft of the NTB for testing.

The tests on NTBs generally include torque measurements to determine the input power to the DUT. Depending on the purpose of the measurements, a measurement uncertainty of 0.1 % for the torque measurement is envisioned. However, the nominal torque load on most NTBs is in the multi-MN·m range, e.g. 13 MN·m at the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), 6 MN·m at the Centro National de Energías Renovables (CENER) and 3.4 MN·m at the Center for Wind Power Drives of RWTH Aachen University, whereas the largest torque standard is only able to exert torque loads up to 1.1MN·m [1]. Moreover, the input torque to the DUT should ideally be measured directly at the DUT. This location is subjected to additional mechanical loads if an LAS is present on the NTB. Due to these constraints, NTB operators use different methods to determine the torque that is applied onto the DUT. These measurements are often not traced back to national standards and sometimes this is not even possible. Even if traceability is ensured, the measurement uncertainty for the torque measurement is most likely to be > 0.1 %. However, for most NTBs, no uncertainty budget for the torque measurement exists at all.

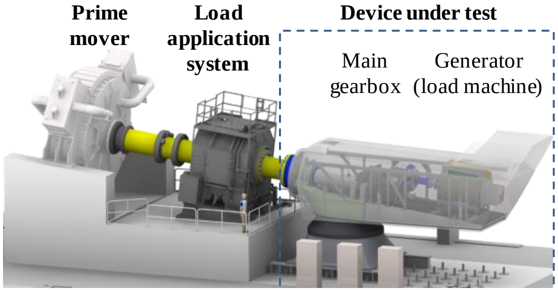

Figure 1 Example of a nacelle test bench: CWD Aachen, 4 MW system test bench (Source: CWD Aachen)

In September 2015, the “Torque measurement in the MN·m range” project started within the framework of the European Metrology Programme for Innovation and Research (EMPIR). It aims at improving the above-mentioned situation by evaluating the current situation and enabling torque traceability up to 5 MN·m [2]. This paper is based on the first outcomes of the project and it describes the different methods of torque measurements on NTBs. The traceability and measurement uncertainty of these methods are discussed to enable an evaluation of the present measurement uncertainty of NTBs, which is otherwise not possible. Based on the discussion, recommendations for a calibration procedure for torque measurements on NTBs using a torque transfer standard (TTS) are given to form the basis for traceable torque measurements in the MN·m range.

2. OVERVIEW OF CURRENT TORQUE MEASUREMENT METHODS ON NTBs

The main objective of torque measurements on NTBs is to determine the torque load the DUT is submitted to. Therefore, a measurement directly between the LAS and the DUT would be preferable. However, this is not possible for all different torque measurements, as they do not tolerate additional mechanical loads or have to be performed at another location. To account for the special requirements for the different torque measurement methods, alternative locations have been chosen. In Figure 2, an overview of the locations for torque measurements on NTBs is given together with the three most common measurement methods based on [3]. In the following, the three methods are described and their location of application is discussed.

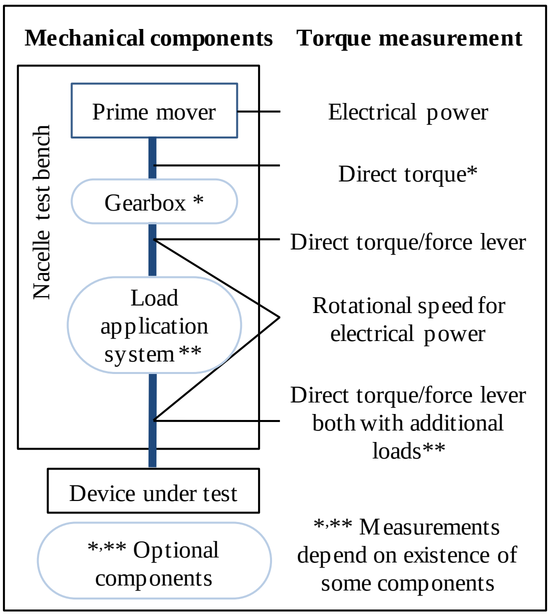

Figure 2 Locations and methods of torque measurements on nacelle test benches

Direct torque measurement: A torque transducer consisting of a deformation body and strain gauges is used. This measurement method is feasible at any position of the main shaft of an NTB (see Figure 2).

Torque loads occurring directly at the DUT are in the multi-MN·m range and, therefore, cannot be traced to any torque standard. Moreover, the effects of the multi-component loading by the LAS cannot be taken into account. A torque measurement between a prime mover and an LAS (without a gearbox) still lacks traceability due to the large torque loads. The only option of traceable measurements using direct torque measurement is to measure the torque load between the prime mover and the gearbox, as this is much smaller than at the DUT (see Figure 3). If this last option is used, the mechanical efficiency of the gearbox η_{gear} has to be considered as an additional effect.

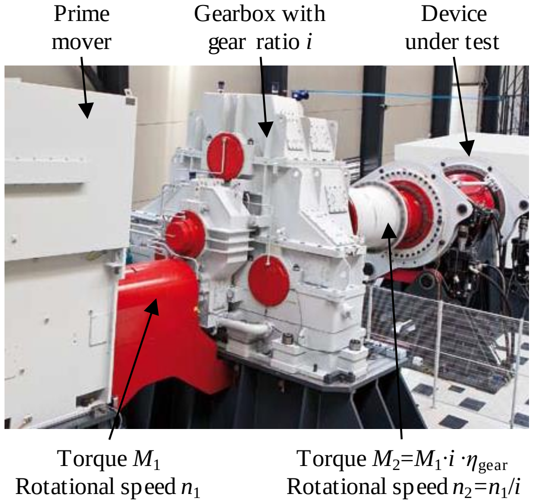

Figure 3 Example of a gearbox in an NTB (source: CENER)

Force lever: A rotating force lever system consists of several force transducers that are connected to the main shaft of the NTB at a certain distance to the centre of rotation. Technically, the same locations as for direct torque measurements are possible for force lever measurements. However, due to the increased measurement uncertainty compared to direct torque measurements, using force lever systems only makes sense at locations where direct torque measurement is not possible, e.g. due to traceability issues for multi-MN·m measurements. These locations are either between the prime mover and the LAS without a gearbox or between the LAS and the DUT. At the second location, the loads from the LAS have to be transmitted by the force lever system as well.

Theoretically, a non-rotating force lever measurement at the prime mover in the form of a reaction force measurement would be possible. However, in practice this is not sensible, as it entails a myriad of other issues from the location of the measurement to the quantification of effects such as torque bypasses and additional mechanical loads.

Electrical power: Torque measurements based on the measurement of electrical power also need the measurement of rotational speed. The electrical power has to be measured as the input to the prime mover. The rotational speed should be measured at the location for which the torque load is calculated: between the LAS and the DUT. This difference in the location of the two components involved in the torque calculation is the main drawback of this method. It entails a temporal shift between the two measured components, which is an issue especially for dynamic test conditions.

Traceability of the above-mentioned methods: Not all of the described methods provide complete traceability for the torque measurement. Direct torque measurement is only traceable up to 1.1 MN·m, which is only sufficient for measurements between the prime mover and the gearbox. All measurements between the LAS and the DUT (direct and force lever measurement) are inflicted with the effect of the additional mechanical loads which cannot sufficiently be considered yet. Hence, these methods are not considered in the following section.

3. INFLUENCES ON MEASUREMENT UNCERTAINTY ON NTBs

As the torque measurement methods on NTBs differ greatly, several different influences on the measurement uncertainty have to be accounted for. In addition, some specific effects are found on all NTBs. An overview of the influences on the torque measurement on NTBs is given in Figure 4. In the following, the NTB-specific effects are discussed as well as the method-dependent influences. Only traceable torque measurement methods that are not inflicted with a large temporal shift due to their location in respect to the DUT are considered. This leaves two methods: the direct torque measurements between the prime mover and the gearbox with torque loads in the kN·m range, and force lever measurements between the prime mover and the LAS without large additional loads, as measurements under these conditions would not be traceable.

General effects: Essentially, the measurements on NTBs are under the same influences as those in reference torque standards using one or several calibrated transducers. However, the effects are sometimes even larger and additional contributions to the measurement uncertainty are found on NTBs. In [4], an overview of the measurement uncertainty in reference torque standards is given. This includes the uncertainty based on *transducer calibration* but also the ambient conditions such as *temperature* and *humidity*, which are often not stable on NTBs. A correction of the torque measurement based on a temperature and humidity measurement should, therefore, be made, which requires investigations of the measuring system under different conditions.

Another NTB-specific effect is the influence of *rotation* on the torque measurement. A detailed analysis of the influence of rotation on the measurement results can be found in [5]. According to this paper, it can be assumed that the rotation effect for torque transducers on an NTB is mostly

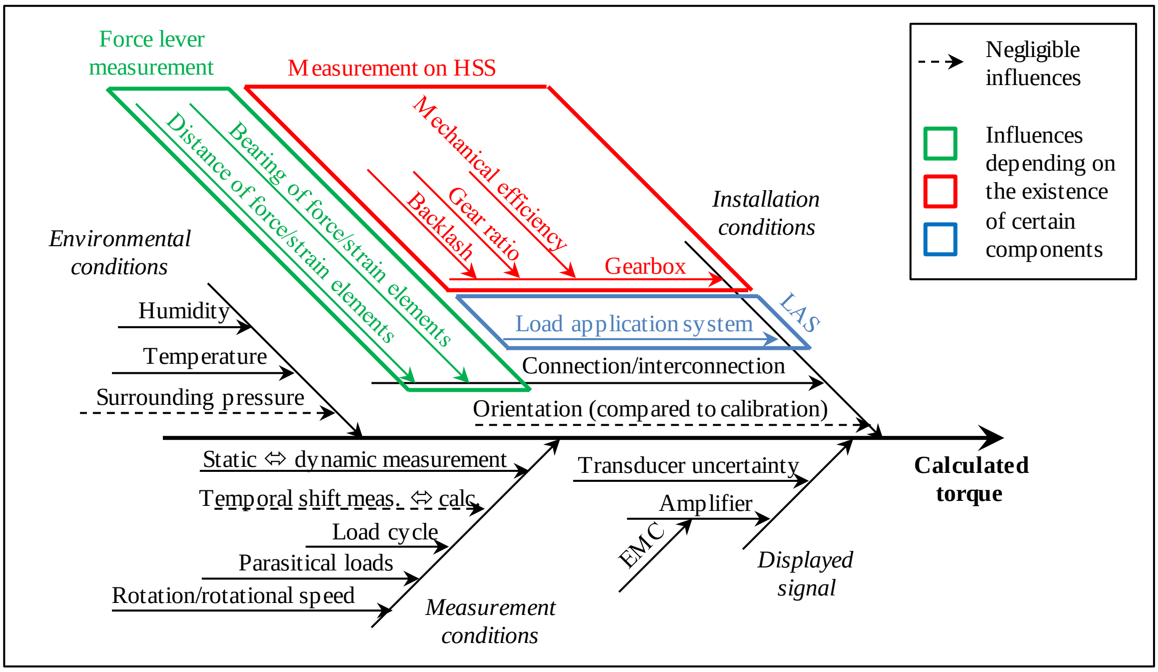

Figure 4 Ishikawa diagram with the influences on current torque measurement methods on nacelle test benches

negligible, as the rotational speed is fairly small. Only for torque transducers between the prime mover and the gearbox can an effect of up to 0.1 % occur due to the much higher rotational speed. An estimation of the effect of rotation on the force lever measurement is performed in [6] and was found to be < 0.1 %.

The effect of *dynamic* mechanical loading compared to a static calibration is extremely difficult to estimate and to take into consideration. As a dynamic calibration is not possible at the moment, dynamic loading has to be minimised.

A further influence that can be observed on all NTBs is the *load cycle* which differs greatly from the standard calibration cycle and which can have an effect on the torque measurement, e.g. by affecting the hysteresis. In general, this effect is relatively small but if it is combined with alternating torques, which occur for example in brake tests, a larger influence on the measurement signal and, thus, on the measurement uncertainty is expected [7]. The calibration of the transducers should, therefore, account for this effect.

The effects of *parasitical loads* and a proposal to consider them are described in [8]. However, this approach is purely empirical and more research is needed to include this effect into an uncertainty budget.

The last general effect is caused by the *amplifier*. This should be chosen according to the targeted uncertainty. However, due to the amount of electrical components of the NTBs, electromagnetic compatibility (*EMC*) is an issue for the measurements. As a consequence, the effect on the amplifier signal should be recorded.

Effect of the LAS: The LAS is responsible for the application of additional static and dynamic wind loads (e.g. thrust, radial forces and bending moments). There are different construction principles of the LAS regarding the load application and the suspension of the NTB main shaft: e.g. load application by several preloaded hydraulic cylinders, see Figure 5, or by a hydraulic hexapod in the form of a Stewart platform (e.g. 10 MW IWES DyNaLab). The suspension of the NTB main shaft can be designed with hydrostatic plain bearings or with roller bearings (e.g. arranged tapered roller bearings). Hydrostatic plain bearings are more expensive, but their use is preferred because of the lower friction torque, lack of stick slip, lower deformation, longer life durability and high reliability.

Even when no additional loads are applied, the LAS is used for stabilisation, leading to power losses and friction torque during rotation along the main shaft. This loss is mainly caused by the NTB main shaft suspension and can be accounted for with an efficiency parameter η_{LAS}, which depends on the design of the LAS, the rotational speed and the torque on the drive train as well as the loads applied by the LAS. Because of the above-mentioned influences, the traceable measurement of the LAS friction torque under different operation conditions is not possible. However, the efficiency parameter η_{LAS} can be estimated by analytical or numerical methods which are based on fluid dynamics. In the case of suspension with roller bearings, the bearing manufacturer provides analytical calculation methods for the estimation of friction torque. In the case of hydrostatic plain bearings, the calculation methods are based on the description of the Hagen-Poiseuille flow and the corresponding drop of the pressure in the plain bearing. For both suspension methods of the NTB main shaft, the load-dependent parameters – such as the temperature and viscosity of the oil as well as lubricant thickness, local pressure and the entire system friction coefficient – are estimated roughly. As a consequence, the estimation of η_{LAS} requires close consultation between the NTB operator and the LAS manufacturer.

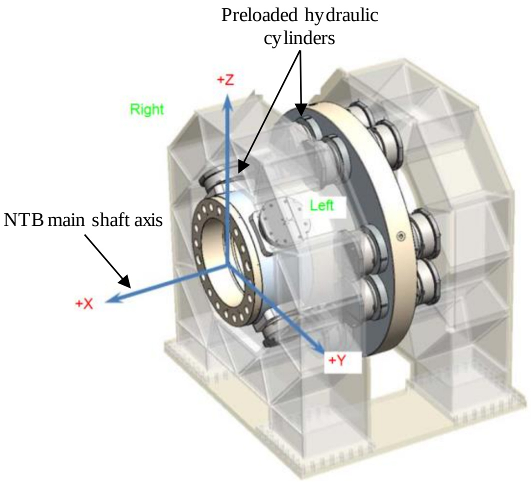

Figure 5 Load application system at CWD Aachen (source: MTS Systems Corporation)

Gearbox: To determine the torque load at another part of the drive train, e.g. right at the DUT, the effect of the gearbox has to be considered. For a measurement between the prime mover and the gearbox, this can be expressed in the following equation:

$$M = M_T \cdot i \cdot \eta_{\mathrm{gear}} \qquad (1)$$

with:
M = input torque for DUT
M_{T} = torque measured at transducer between the prime mover and the gearbox
i = gear ratio
η_{gear} = mechanical efficiency of the gearbox

The gear ratio i is a parameter that is determined by the layout of the gearbox. As this is a fixed constant, apart from small variations due to imprecision in the manufacturing process, the uncertainty of the gear ration i is extremely small. This can be neglected if the measurement values are averaged over an integer number of rotations of the shaft where the measurement is taken and, if possible, even over an integer number of rotations of the shaft for which the torque load is calculated. Ideally, several full rotations of the gearbox are used for the measurement.

The mechanical efficiency of the gearbox η_{gear} is dependent on the load (torque and rotational speed) as well as on the condition of the gearbox (e.g. oil condition and temperature). Therefore, precise information on η_{gear} for the entire load and condition range of the NTB is necessary. Ideally, the measurement uncertainty is provided, too. This is, however, mostly not the case and an uncertainty for η_{gear} has to be assumed based on experience. If a transfer torque transducer for the MN·m range is available, this assumption can be verified.

An example of the measurement uncertainty of a torque measurement caused only by the presence of a gearbox is given in the following.

The assumed input is based on the general information known about NTBs and gearboxes; i is considered to be a constant factor without a measurement uncertainty:

M = 4750 kN·m
M_{T} = 100 kN·m
i = 50
η_{gear} = 0.95
measurement uncertainty of torque transducer:
u_{MT} = 0.1 kN·m (normal distribution)
measurement uncertainty of gearbox efficiency:
u_{η} = 0.02/√3 (rectangular distribution)

The standard measurement uncertainty of the calculated torque is:

$$u_{\text{M}} = \sqrt{u_{\text{MT}}^2 \cdot c_{\text{MT}}^2 + u_{\eta}^2 \cdot c_{\eta}^2}$$

The sensitivity coefficients for the torque transducer and gearbox efficiency are:

$$c_{\text{MT}} = i \cdot \eta_{\text{gear}}$$

$$c_{\eta} = M_{\text{T}} \cdot i$$

$$u_{\text{M}} = \sqrt{\begin{matrix}(4.75\ \text{kN·m})^2 \\ +(57.73\ \text{kN·m})^2\end{matrix}} = 57.93\ \text{kN·m}$$

The expanded relative measurement uncertainty of the calculated torque is:

$$W_{\text{M}}(k = 2) = 2 \cdot \frac{57.93\ \text{kN·m}}{4750\ \text{kN·m}} = 2.4\ \%$$

The standard uncertainty of the mechanical efficiency η_{gear} cannot be determined correctly, so the result cannot be used as an "official" measurement uncertainty. However, the effect of the uncertainty of the mechanical efficiency η_{gear} on the overall result is made clear, as it constitutes the main part of the overall uncertainty.

Force lever measurement: An option to evade the problem of the traceability of direct torque measurements in the MN·m range is to employ a torque transducer consisting of force transducers at a fixed distance to the main rotation axis. The number of force transducers is variable. Equation (2) presents the calculation of the resulting torque assuming equally distanced transducers.

$$M = \sum_{i=0}^{n} \left(F_{\text{T},i} \cdot r_i \cdot \eta_{\text{con}}\right) \qquad (2)$$

with:
M = input torque for DUT
$F_{\text{T},i}$ = force measured at transducers
r_i = distance of force measurement from the main axis
n = number of force transducers used for the measurement
η_{con} = mechanical efficiency of the connection between the force transducers and the main shaft

The measurement uncertainty for force measurement can be based on a calibration. However, the effect of parasitic loads on the force transducer due to alignment errors and deformation under load cannot be sufficiently accounted for. Some recommendations and a mathematical model to determine the additional measurement uncertainty for force measurements in the MN range were given in the EMRP project called "Force traceability in the meganewton range" [9]. The influence of slightly dynamic loading of the force transducers cannot be taken into account at all.

The effect of the distance r on the overall measurement uncertainty is very difficult to estimate as r changes under load. This change Δr is load-dependent, making it a systematic effect which cannot be measured. Moreover, the value of r only decreases under pure torque load if the force transducers are under a tension load. As a correction of this effect is not possible without detailed measurements of r under load, Δr has to be estimated and taken as a direct influence on the overall measurement uncertainty of M according to [10], [11]. Δr is much bigger than the uncertainty of r itself, which can be obtained by a calibration, and it is also bigger than its own uncertainty.

The influence of the connection between the force transducers and the main shaft can be accounted for using a factor η_{con}. This factor can technically be treated similarly to η_{gear}. However, the influence on the force lever system is expected to be much smaller as the effect is only indirect. Moreover, Δr has a much larger influence. Therefore, η_{con} can be considered to be negligible as long as Δr cannot be quantified satisfactorily.

In the following, an example of a calculation of the measurement uncertainty contribution caused by a torque measurement using a force lever system is presented. Similarly to the example of the effect of a gearbox given above, the values given are based on estimations:

M = 4800 kN·m
n = 3
$F_{\mathrm{T1}} = F_{\mathrm{T2}} = F_{\mathrm{T3}}$ = 1600 kN
$r_1 = r_2 = r_3$ = 1 m
η_{con} = 0 (neglected in the example)
measurement uncertainty of distance r:
u_{r} = 0 (neglected in the example)
measurement uncertainty of force transducers:
u_{FT} = 1 kN (normal distribution)
Δr = 0.005 m (systematic error)

The standard measurement uncertainty of the calculated torque is:

$$u_{\mathrm{M}} = \sqrt{3 \cdot u_{\mathrm{FT}}^2 \cdot c_{\mathrm{FT}}^2 + 3 \cdot \Delta r^2 \cdot c_{\mathrm{r}}^2}$$

The sensitivity coefficients for force transducers and the distance from the main axis are:

$$c_{FT} = r$$

$$c_{\mathrm{r}} = F_{\mathrm{T}}$$

$$u_{\mathrm{M}} = \sqrt{\begin{matrix} 3 \cdot (1\ \mathrm{kN{\cdot}m})^2 \\ +3 \cdot (8\ \mathrm{kN{\cdot}m})^2 \end{matrix}} = 24.06\ \mathrm{kN{\cdot}m}$$

The expanded relative measurement uncertainty of the calculated torque is:

$$W_{\mathrm{M}}(k = 2) = 2 \cdot \frac{24.06\ \mathrm{kN{\cdot}m}}{4800\ \mathrm{kN{\cdot}m}} = 1.0\ \%$$

The effect of the change of distance r under load might be overestimated in the example; however, the significance of the effect is clearly shown. For the overall measurement uncertainty, the uncertainties of r itself and of Δr are not considered as they should be comparatively small. Even without these components, the expanded relative uncertainty of M results in $W_{\mathrm{M}}(k{=}2)$ = 1.0 %.

Summary: Most of the influences shown in Figure 4 and their effect on the uncertainty for torque measurements on NTBs can be estimated. The uncertainty is larger than the demanded 0.1 %, due to the variety of influences on the measurement. Moreover, effects derived from an LAS, such as friction and additional loads, are still not accounted for. In summary, it can be stated that a calibration of the torque measurement on NTBs is necessary to obtain better precision of the measurements through improving the estimation of the measurement uncertainty, thus, also improving the efficiency determination of nacelles. For the calibration of an NTB, a TTS in the MN·m range is required. Moreover, a calibration procedure considering all occurring effects on NTBs is necessary. In the subsequent section, the recommendations for such a procedure are summarised.

4. RECOMMENDATIONS FOR FUTURE CALIBRATIONS OF NTBs

Based on the descriptions and discussion of the previous sections, recommendations for a calibration procedure of NTBs are given in the following. The premise for the recommendations is the existence of a calibrated multi-MN·m TTS with additional multi-component measurement capabilities. This TTS is placed directly between the NTB and the DUT (see Figure 2). The basis for the calibration recommendations is provided by EURAMET cg-14 (Guidelines on the calibration of static torque measuring devices) and ISO 7500-1 (Metallic materials - Calibration and verification of static uniaxial testing machines - Part 1: Tension/ compression testing machines - Calibration and verification of the force-measuring system). The following recommendations are made in addition to these two standards:

1. Same-time measurement of NTB torque and TTS signal is necessary; moreover, the rotational speed has to be recorded to determine any influences due to rotation.
2. The torque signals (NTB and TTS) and the rotational speed have to be recorded in an adequate frequency and should be averaged for each load step over at least one turn of the main shaft. The recorded (non-averaged) values can be used to determine any temporal phase shifts between the measurements.
3. The measurement and recording of humidity and temperature values should be ensured during the measurement as close to the TTS and the NTB-torque measurement as possible. Ideally, the temperature gradient on the TTS is measured. All transducer signals should be corrected for changes in the environmental conditions (see [4]). To ensure relatively stable environmental conditions, the NTB should be in operation with the entire set-up prior to the calibration.
4. The repeated installation of the transducer would be helpful but is not necessary due to the averaging over several rotations.
5. The EMC of the TTS should be tested by purposely causing possible interference e.g. test with a TTS in an uninstalled situation prior to installation. Furthermore, EMC for the NTB-torque measurement has to be ensured.
6. The TTS has to be installed onto the NTB right in front of the DUT.
7. All zero signals of the NTB torque measuring device and the TTS have to be determined as an average over differently rotated positions with respect to the measurement axis. The rotation should be performed for the entire main shaft of the NTB without dismounting and mounting of the TTS. Depending on the measurement

method, 6·60° rotations (force lever system) or 3·120° rotations (direct torque measurement) are suitable.

8. In addition to a zero signal without the rotation of the test bench, a zero signal under rotation should be measured. This is possible when the main shaft can rotate freely without a DUT. However, the effect of the different installation conditions should be minimised.
9. Definition of the typical testing range (electrical power and corresponding rotational speed and torque values) of the NTB. The calibration should cover the entire range by repeating the standard calibration with different combinations of torque load and rotational speed. If this is not possible, the calibration has to be performed in the median of the typical testing range.
10. Load steps for the torque calibration should be based on the typical maximum torque loads in the NTB for different DUTs. Several standard calibrations, one for each typical load, should be performed. The increments of the load steps should also represent the typical NTB situation; e.g. if a torque load of 4 – 5 MN·m is typical, more load steps in this range and fewer below 4 MN·m are required.
11. If an LAS is present on the NTB, small variations of parasitical loads (F_z, F_x, F_y, M_y, M_x) are required in an additional calibration. Single components as well as a combination should be used.
12. Additional partial load sequences also including zero crossings should be performed in order to determine the effect of alternate loading and different load cycles.
13. Creep measurements have to be executed to determine the creep of the NTB-torque measurement.
14. All resulting data has to be checked for signs of resonance and/or dynamic loading effects.
15. No class definition should be made. Only an indication of all the determined components is necessary.

5. SUMMARY & OUTLOOK

This paper gives an overview of torque measurement methods on NTBs and the specific influences on measurement uncertainty. It was found that the current measurement methods do not fulfil the envisioned measurement uncertainty. Therefore, a calibration with a TTS is inevitable. Several recommendations for such a calibration have been given.

A number of investigations that are proposed above are planned within the EMPIR project entitled “Torque measurement in the MN·m range” which is also the basis of this paper. Additional tests and research include the calibration of a 5 MN·m TTS with multi-component capabilities up to 1.1 MN·m and an extrapolation to 5 MN·m. Furthermore, the use of this TTS on the 4 MW RWTH nacelle test bench at the Center for Wind Power Drives in Aachen, Germany, is also part of the project. Another focus of the project is the development of a force lever system to be used as a TTS on NTBs.

6. ACKNOWLEGEMENTS

The EMPIR initiative is co-funded by the European Union’s Horizon 2020 research and innovation programme and the EMPIR Participating States. The discussions and input of all the partners in the project as well as of my colleagues are greatly appreciated.

7. REFERENCES

[1] D. Peschel, D. Mauersberger, D. Schwind, and U. Kolwinski, “The New 1.1 MN·m Torque Standard Machine Of The PTB Braunschweig / Germany,” in *19th Conference on Force, Mass and Torque Measurement*, 2005, p. 7.

[2] “Torque measurement in the MN·m range.” [Online]. Available: http://www.ptb.de/emrp/torquemetrology.html.

[3] S. Kock, D. Bosse, N. Eich, G. Foyer, N. Medina, J. M. Quintanilla Crespo, L. Vavrecka, and J. Ala-Hiiro, “Report on existing nacelle test benches and their boundary conditions,” Deliverable in EMPIR 14IND14 Project, unpublished, 2016.

[4] D. Röske, “Messunsicherheiten bei der Drehmomentmessung Mit Referenzmesseinrichtungen,” *Tech. Mess.*, vol. 78, no. 2, pp. 77–87, 2011.

[5] A. Brüge, “Influence of Rotation on Rotary Torque Transducers Calibrated Without Rotation,” in *Proccedings of the IMEKO World Congress*, 1997, no. 1, pp. 1–7.

[6] S. Kock, G. Jacobs, D. Bosse, and J. Gnauert, “Conception of 5 MNm torque transducer for wind turbine test benches,” in *5. Innovation Messtechnik*, 2017, p. (to be published).

[7] D. Röske and D. Peschel, “Investigations Into the Alternating Torque Calibrration of Torque Transducers,” *XIV IMEKO World Congr.*, pp. 1–6, 1997.

[8] G. Wegener and J. Andrae, “Measurement uncertainty of torque measurements with rotating torque transducers in power test stands,” in *Proceedings of IMEKO TC3*, 2005, vol. 40, no. 7–8, pp. 748–755.

[9] “Force traceability within the meganewton range - WP4 Improved traceability.” [Online]. Available: http://www.ptb.de/emrp/2387.html. [Accessed: 13-Oct-2016].

[10] I. H. Lira and W. Wöger, “The evaluation of standard uncertainty in the presence of limited resolution of indicating devices,” *Meas. Sci. Technol.*, 1998.

[11] Joint Committee for Guides in Metrology, “Evaluation of measurement data — Guide to the expression of uncertainty in measurement,” 2008.