Publishable Summary for 14IND14 MNm Torque
Torque measurement in the MN·m range

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.

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.

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.

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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.

Progress beyond the state of the art

Prior to this project, several approaches have been used to solve the problem of the missing traceability for torque measurement in the range above 1 MN·m:

- Torque calculation based on strain gauge measurements
- Low torque (kN·m range) measurement on the high-speed shaft
- Torque calculation from electrical power and rotational speed measurements
- Torque calculation from force and length measurement.

All of these four options have drawbacks: the use of strain gauges lacks accurate knowledge of material properties and dimensions; measurements on different parts of the transmission line (either electric power or high-speed shaft) rely on estimations of friction losses in e.g. gears or engines; the use of the product between force and distance still suffers from unknown uncertainties.

To progress beyond the state of the art, the project first of all had to establish an overview of all boundary conditions (see Objective 1) for torque measurements in nacelle test benches and to discuss the actual uncertainty of the methods that were in use.

Furthermore, new methods had to be developed which enable traceability and enable measurements in the envisioned precision (see Objective 2). Two methods have been investigated during the lifetime of the project: extrapolation of calibration data to a larger measurement range and development of force lever systems. For the force lever systems, influences on the measurement and an estimation of the uncertainty have been studied.

At the beginning of the project, no calibration procedure or appropriate transducer for multi-component measurements were available. The consortium of this project succeeded in developing a calibration procedure and performing a design study on possible transducer layouts.

All previously existent calibration guidelines or standards for torque calibration focused on static calibration under relatively stable laboratory conditions. Within this project, a torque calibration procedure especially for nacelle test benches has been developed (see Objective 4).

Results

Objective 1 – Review of existing nacelle test benches

A survey using a questionnaire was undertaken at the beginning of the project to gather information on the nacelle testing facilities, their torque measurement, additional mechanical loads as well as range of devices under test and aim of testing. An overview of ten very different test benches revealed that the required measurement uncertainty for torque in the MN·m is 0.5 %. Furthermore, existing measurement methods have been discussed and their uncertainty was assumed to be in the range of 2 – 5 %.

The results from the survey were used further in the project. The information on the boundary conditions such as torque measurement range, additional mechanical loads, rotational speed, temperature etc. served as an input for the design of the force lever systems (Objective 2), for the design of multi-component torque transducers (Objective 3) and also for the development of the calibration procedure (Objective 4). Objective 1 was fully achieved, representing an insight into torque measurement in nacelle test benches based on a comprehensive survey.

Objective 2 – Development of torque transfer standards above 1.1 MN·m

Two different approaches were applied to enable traceability for torque in the MN·m range: extrapolation and the design of a force lever system.

As for the extrapolation method, the idea was to use a multi-MN·m torque transducer, in this case a 5 MN·m transducer, calibrate it to the maximum of 1.1 MN·m and apply numerical simulations and other mathematical methods to forecast its behaviour for the range that was not calibrated.

In a first step, the 5 MN·m torque transducer was calibrated in PTB’s 1.1 MN·m torque standard machine. Afterwards, two finite element models have been created to understand the behaviour of the 5 MN·m transducer. Several influences on the measurement were found. This included geometrical characteristics such as bore holes but also the pre-tension with which the bolts, used to fix the transducer in the test bench, are tightened. A further influence was caused by the material characteristics such as Young’s modulus which varies greatly and makes a prediction based on simulations rather complicated. Therefore, it was decided to base the extrapolation method solely on measurements with a smaller torque transducer.

A very stable and well-known 20 kN·m transducer was selected and calibrated in several steps (up to 4 kN·m, 10 kN·m, 16 kN·m and 20 kN·m) and also in two different machines: a dead-weight torque standard machine and a reference standard machine. The resulting data set was then used to study the behaviour of the transducer and to develop a mathematical extrapolation method based on linear and/or cubic extrapolation. This method was also applied to the 5 MN·m torque transducer to predict its behaviour.

The second approach to establish a new torque transfer standard was to design a force lever system. The idea behind this approach is to separate the unit torque into its components force and length which are both precisely measurable.

First, ideas for developing such a system were gathered and afterwards four preliminary designs have been made. The challenges for a real use of the preliminary designs were discussed within the consortium and finally, four designs with commercially available force transducers were created. All of them enable a torque measurement up to at least 5 MN·m also withstanding the additional mechanical loads which occur in test benches as found in Objective 1. These additional loads were the main challenge for the design. They are transmitted either using roller bearings or fixed mechanical components. Some of the designs already address the issue of how to precisely mount the force transducers, using adjustable means of fixing.

Second, numerical studies using finite element models were performed to find out how the force lever systems react to temperature, gravity, rotational speed and mechanical loads. The results from these studies and information on the precision of the force transducers were gathered to estimate the overall measurement uncertainty for the force lever systems. In most cases this was found to be smaller than 1 % and often even smaller than 0.5 %. As this is only a rough estimation based on simulation data, it must be kept in mind that the result is not yet verified by measurement data.

Third, three of the designed force lever systems have been upscaled to 20 MN·m to see whether systems of this size are realisable and can be implemented in a nacelle test bench despite their enormous weight and dimensions and the consequently emerging influences. Especially, the weight of these systems is extremely high, however, compared to the blades of a wind power station, acceptable.

Overall, it was found that both investigated methods can provide traceability for torque in the multi-MN·m range with an uncertainty of less than 1 % and the Objective was therefore achieved.

Objective 3 – Effects of multi-component loading

As it is not possible to study multi-component loads in the MN and MN·m range for all six components (axial force, two lateral forces, two bending moments, torque), due to a lack of machines operating in this range and in more than one dimension, most of the work within this objective focused on the kN·m range.

Three different torque transducers with multi-component measurement (at least bending moments and up to all six components) were used to develop a multi-component calibration procedure which did not exist beforehand. As neither there is a calibration machine for this purpose, a lever-mass loading system was designed. The results of all transducers were compared to evaluate the procedure. It was found to be appropriate to calibrate torque transducers with additional measurement capabilities.

Three finite element models of the transducers were developed. The results of the numerical simulations were compared to analytical calculations as well as the experimental results. The agreement was rather good with a few small exceptions. It was decided that it is possible to use numerical investigations for the design of a MN·m torque transducer with multi-component measurement capabilities.

The knowledge of the small-scale investigations with the multi-component calibration and the numerical simulations was used to design a multi-component torque transducer that could be used in nacelle test benches. The findings from Objective 1 have also been applied to determine the target measurement range for all six components. Finally, two different designs were made focusing on separating the measurement of the six components from each other for a precise measurement in nacelle test benches. These can be refined further and can be used as the basis of transducers in the future.

Overall, more knowledge on the behaviour of multi-component torque transducers has been obtained, a new calibration procedure has been developed and new designs for MN·m multi-component torque transducers have been made based on experimental data and numerical studies. The objective was achieved.

Objective 4 – Torque calibration procedure for nacelle test benches

The project's main objective was to enable traceability for nacelle test benches. Two basic requirements had to be fulfilled to achieve this: a transfer standard and a calibration procedure. The 5 MN·m torque transfer standard was calibrated within Objective 2. Based on the data from Objective 1 and pre-investigative simulations, a calibration procedure was developed for all three test benches that have been represented in the consortium (Center for Wind Power Drives in Aachen, Fraunhofer IWES in Bremerhaven, CENER in Sarriguren). The results from the survey on the other test benches undertaken within Objective 1 have also been considered. The pre-investigative simulations focused on the influence of the system-dependent parameters in the nacelle test benches, e.g. operational loads, rotational speed, gravity and assembly process, and on the uncertainty of the torque measurement.

The calibration procedure is based on existing standards such as the ISO 7500-1 (for material testing machines) and the EURAMET cg-14 (for static torque). It includes the calibration of the torque measured in nacelle test benches under different rotational speeds. The main result is a so-called indication deviation which is the relative deviation of the indicated torque in the test bench from the indication of the 5 MN·m torque transfer standard and describes how accurate the test bench works. The second result is the uncertainty of this deviation. One of the objectives was to also find out how the additional mechanical loads influence the torque measurement (called cross-talk). Additional tests have been performed with load combinations to detect any influences.

The highlight of the project was a three-week testing phase in the Center for Wind Power Drives where the calibration procedure was tested. An indication deviation of about 4 % was determined and an uncertainty of around 0.2 % was calculated. Test bench operators can use this result to correct their torque measurement and reach an uncertainty of 0.2 %. Smaller mechanical loads that always occur in the test benches were taken into account and they did not influence these results. For larger loads, however, a correction of the torque results depending on each test bench has to be performed because it is influenced by its characteristics, e.g. sources of friction and deformation.

By developing the calibration procedure and also successfully testing it in Aachen, Objective 4 was achieved.

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.

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

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[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

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Test Benches," in *23rd TC3 IMEKO*, 2017. https://www.imeko.org/publications/tc3-2017/IMEKO-TC3-2017-010.pdf

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[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

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[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

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[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).

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 September 2015, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Dr. Rolf Kumme, PTB, Tel: +49 531 592 1200 E-mail: rolf.kumme@ptb.de
Project website address: http://www.ptb.de/emrp/torquemetrology.html</td></tr>
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