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Methodology for managing traceability in the measurement of torque in wind generators

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Abstract

The research described within this paper has aimed to develop new methods for determining torque in an accurate, traceable way. The proposed methods must suit the operating conditions on nacelle test benches, which are facilities where wind turbines are tested. The operating conditions in these facilities are quite different from the standard machines used to calibrate torque. Normal torque calibrations are performed in static standard machines, while nacelles are tested under rotation. As a consequence, the new proposed methods must operate under dynamic conditions. Therefore, different approaches have been studied, each of them based on different techniques: small scale investigations, new torque transfer standards, etc. All these studies aimed to estimate the performance of the new methods and their associated uncertainties. This article specially describes the force lever system, a new torque transfer standard developed within this research. This new system will not only ensure torque traceability by means of direct mechanical measurements, but also will provide a new way of obtaining torque measurements with a much lower uncertainty than current employed methods.

Keywords: wind turbine; torque; transfer standard; nacelle; test bench;

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1. Introduction

Wind power generation techniques have made great strides in recent years, with new wind turbines being able to produce power in the range of MW. In order to ensure power generation efficiency, wind turbines are normally tested in facilities named Nacelle Test benches. In these facilities, the main parameters that define their performance are studied in detail through several tests.

One of the most important parameters is torque, as it is employed for estimating the generated power during operation [1]. As we can see in (1), the electrical generated power (P_{el}) is directly related with torque (M) and also related with rotational speed (n). In the last few years, manufacturing capabilities and advances in the wind power industry have enable the enlargement of wind turbines, having nacelles capable of operating in the range up to 20 MN·m. p

$$M = \frac{P_{el}}{2 \cdot \pi \cdot n} \tag{1}$$

However, due to this high operating range and their special test conditions, it is not possible to employ traditional torque measuring systems. Normal torque calibrations are performed in static standard machines, while nacelles are tested under rotation. Moreover, there are no available commercial torque transducers for this operating range.

Therefore, alternative torque measuring systems are employed in nacelle test benches for controlling the generated torque. Unfortunately, none of the methods proposed is traceable to the primary torque standards and they have relative associated uncertainties which are too high, between 2 and 5 % [2].

The new project, "EMPIR 14IND14: Torque in the MN·m" aims to provide new measuring methods and torque transfer standards which can be used to improve the quality of torque measurements in order to have a better characterization of wind turbines performance. A better diagnose of wind turbines will ultimately lead to a better wind power generation efficiency.

In this article, the different researches within this project are described. Two main approaches were developed: extrapolation of calibrated measurements obtained in a smaller range with a traditional torque transducer, and direct traceable measurements obtained through a new developed torque transfer standard, named force lever system.

The first approach, carried out by PTB collaborators at their torque laboratory, consisted of an experimental study, where a multi-MN·m torque transducer was calibrated up to a certain range, and then an extrapolation method was developed to characterize the transducer to its nominal capacity.

The second approach, which is the main discussion within this article, related to the development of this new torque transfer standard, having proposed a new design which has also been tested through FE simulation. The novelty of the proposed force lever system is that it enables direct mechanical torque measurements, employing the definition of torque in order to measure it. By means of length and force measurements, both traceable to their primary standards, it is possible to determine accurate torque measurements in the range of MN·m.

2. Extrapolation method: an alternative employing traditional torque transducers

The idea within this approach was to employ a high operating range (multi-MN) torque transducer. This torque transducer was to be mounted in the test bench and employed for calibrating it. But firstly, it was needed to characterize its behaviour and estimate its relative associated uncertainty.

The selected transducer was a 5 MN·m hollow shaft type torque transducer. Additionally, supplementary gauge bridges where used to detect axial forces (up to 30 MN), lateral forces (up to 8 MN) and bending moments (up to 3 MN·m).

So far, torque primary standards do only reach a range of 1.1 MN·m (the largest torque standard machine is located at PTB's) [3]. Therefore the 5 MN·m torque transducer was only possible to be calibrated up to 1.1.MN·m. For the rest of the range, two methods were attempted: a simulation of its behaviour employing FEM tools, and a numerical extrapolation based on the results obtained in the partial range calibration. Further descriptions of this process can be found in [4].

Once the 5 MN·m transducer was characterized, it was employed in a nacelle test bench facility in Aachen. There, in collaboration with RWTH, a calibration procedure up to 5 MN·m was developed. Apart from having a new transfer standard for the required range, it was needed to create a calibration procedure to be used in nacelle test benches.

Calibrations to be made in this kind of benches must face a number of special conditions. One of the most important one is the rotation of the system during operation. The obtained torque measurements may suffer of several influences while operating under rotation, which are never present in traditional static calibrations. Therefore, the new calibration procedure considers the special operating conditions of this facilities [5].

3. Force lever system: a new torque transfer standard

3.1. Proposed system

Although the proposed extrapolation method could be a solution which can employ traditional torque transducers, its performance and accuracy highly depends on extrapolation. In this research, the main goal was to develop a new torque transfer standard that could measure torque and ensure its traceability in the whole considered range.

Given that torque (M) is defined as a force (F) applied at the end of a body of known length (l) (2), a new working principle was employed: force lever systems.

$$M = F \cdot l \tag{2}$$

This working principle is widely used in several industrial applications, such as drive testing facilities, and it is able to measure applied at one edge of a body of known length (usually known as lever arm) by multiplying its length and the force measured by a force transducer connected on the other edge (Fig. 1).

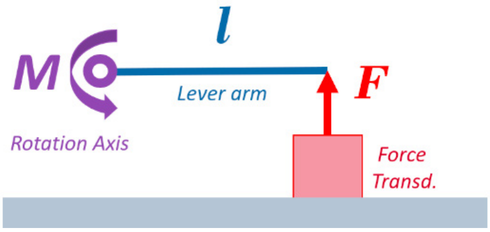

Fig. 1. Force lever system working principle.

However, as it happened with traditional torque transducers, current force lever system (as used in industry) are conceived to work in a static mode, in contrast to the rotational operating conditions of nacelle test benches.

Therefore, it was needed to adapt the traditional concept to a new designed force lever system (FLS). The proposed system was to be mounted in the nacelle test bench drive chain, where it should be able to withstand the rotation of the system, as well as the possible parasitical loads that appear in the driving chain.

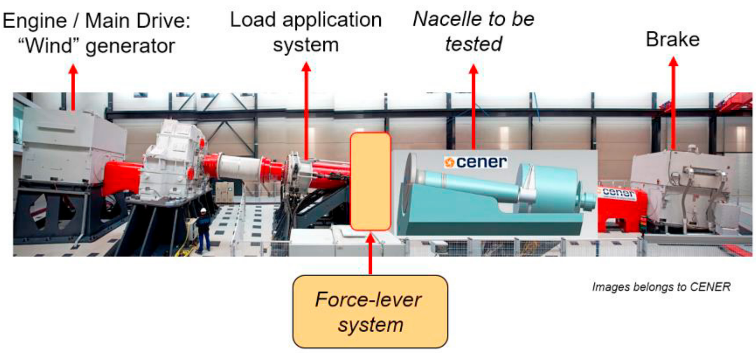

Fig. 2. Nacelle Test Bench and position of LAS and FLS.

When emulating field conditions, some lateral and gusty wind may appear. In order to replicate them, a Load Application System (LAS) is included within nacelle test benches (Fig. 2). Even the minimum loads generated by this system can affect the torque measurement to be obtained by the proposed FLS.

Then the system to be designed required to be stiff enough to withstand the additional loads, work under rotation and at the same time being able to measure torque. So it was decided that all the components of the system will be contained within two flanged ends for its connection to the test bench (Fig. 3).

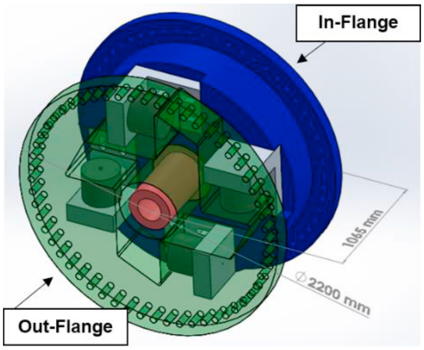

Fig. 3. Proposed force lever system.

In one end of the system there are housings to locate 4 force transducers. In the other flanged end there is an in-built lever arm, which has 4 different ends, one per each force transducer. When the test begins, and the system starts to rotate, the transducers are in contact with the lever arm. By means of this contact, they transmit the motion of the in-flange to the out-flange, ensuring the transmission of torque downstream the drive chain. The force detected by the transducers multiplied by the length of the lever arm are employed to obtain the measurement of the torque generated in the nacelle test bench.

3.2. FEM analyses for evaluating the Force Lever System

FE simulations is a widespread tool in engineering for analysing and verifying the structural resistance and the mechanical properties of a new design. That was in fact one of the main goals of this research: to demonstrate the reliability of the proposed system.

However, another important target was to evaluate its metrological characteristics, in order to estimate its relative associated uncertainty and make it possible to compare it to the indirect methods currently being used in nacelle test benches. In order to do this evaluation, several influences that could affect the system were considered (Table 1).

Table 1. Considered influences.

Influence	Description	Influence name, parameter value
Lateral loads	Parasitical loads caused by the assembly process or by the LAS. Their values are provided by nacelle test benches owners	Axial/radial forces: $F_{x,y,z}$= 100 kN Bending moments: $M_{y,z}$ = 100 kN·m
Centrifugal force	Due to the inertia of the system when under rotation a centrifugal force may appear. It is defined by the rotational speed (rpm)	F_{cga}, n=25 rpm
Gravity	Given the big dimensions of the proposed system, its own weight combined with the rotational motion can have an influence on the final torque measurements. It is related to gravity.	G, g= 9.81 m/s^2
Temperature (min, max)	Thermal expansion or contraction can cause variations of the lever arm length and affect the measurements taken by force transducers. Both, maximum and minimum values should be considered when designing, although only operational temperature is considered when estimating systems behaviour during calibration	$Tmin$ = 278.15 K $Tmax$ = 313.15 K Top = 303.15 K

In order to analyse its mechanical and metrological properties, two different studies where made:

- Lever arm optimization and evaluation

The lever arm length is one of the main components in the torque measurement. Moreover, this component must withstand the loads generated in the test bench, as well as other influences. All those influences may affect the length of the lever arm, causing deformations that could increase or decrease the originally calibrated length [6].

As seen in table 1, two of the possible influences are gravity and the centrifugal force. Both of them are related to systems weight. Therefore, one of the goals of the lever arm analyses was to reduce the weight of the original design, without detriment to its stiffness. If the weigh was reduced while lever arm length variation remains as low as possible, then its metrological behaviour could be improved.

So an iterative improvement process was carried out, in which several modifications were made to the lever arm (Fig. 4). For each design modification the lever arm was tested through FEM analyses in order to ensure that its stiffness and length were valid.

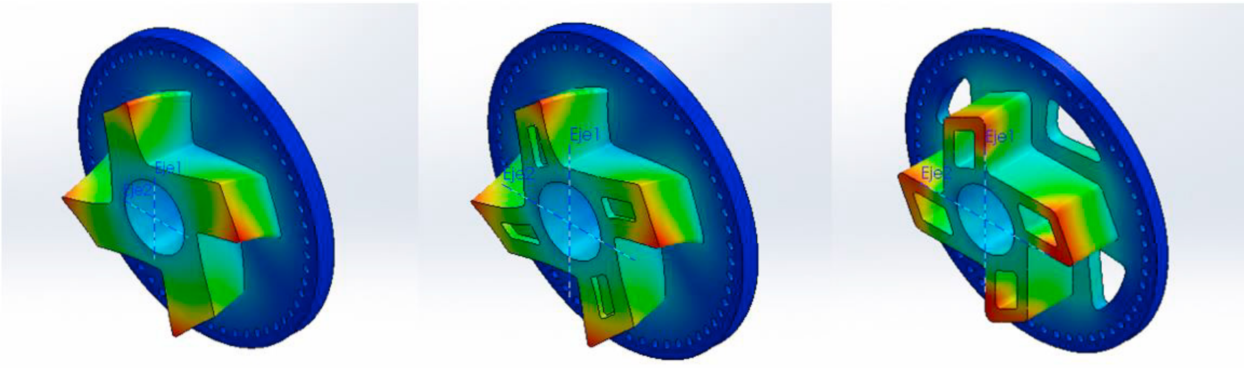

Fig. 4. Lever arm improvements (from original concept to the final design).

More than 26 iterations were tested. For each of them, von Mises tension, maximum displacements and total weight were studied. The objective was to minimize the total mass of the lever arm while minimizing the internal tensions and displacements. The initial weight was reduced from 6644.62 kg to 4108.93 kg, so that the final optimized design had 38% less mass. After each iteration, due to the reduction of material the von Mises Tension and maximum displacements increased slightly. However, the maximum von Mises tension values for the final design ($2.07x10^8$ Pa) was satisfactory, as it were much lower than the maximum admissible tension (maximum admissible tension was 70% of the elastic limit: 7.35x108 Pa)

After the final version of the lever arm was obtained, the effect of the different influences was tested to check its viability and the effect on the lever arm length in detail [7]. However, the study of the influences is more relevant when applied to the whole system, so a new research was started.

- Complete force lever system evaluation

The complete system was updated with the new optimized lever arm and other minor improvements (reduction of weight in some parts, reinforcements in the transducer supports, etc.) (Fig. 5).

Fig. 5. Final design of the force lever system.

Then the considered influences where applied to the system in order to check the variations of the reaction forces (Fig. 7) and the lever arm length (Fig. 6) compared to the case where only pure torque load was applied.

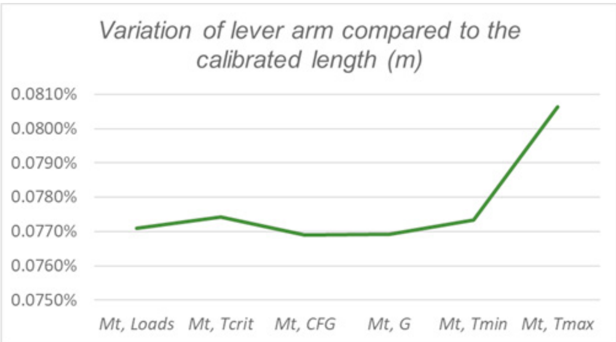

Figure 6. Variation of the lever length

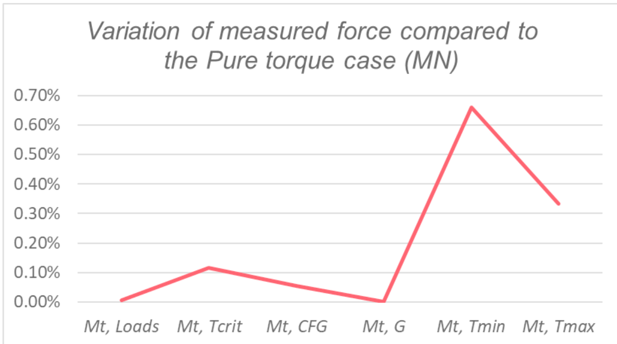

Figure 7. Variation of the measured force

The different influences acronyms are:

- *Mt, Loads*: combination of pure torque load (*Mt*) and the parasitical loads of the system (*Loads*)
- *Mt, Tcrit*: combination of pure torque load (*Mt*) and the critical (operational) temperature (*Tcrit*)
- *Mt, CFG*: combination of pure torque load (*Mt*) and the centrifugal force (*CFG*)
- *Mt, G*: combination of pure torque load (*Mt*) and gravity (*G*)
- *Mt, Tmin*: combination of pure torque load (*Mt*) and the minimal temperature (*Tmin*)
- *Mt, Tmax*: combination of pure torque load (*Mt*) and the maximum temperature (*Tmax*)

All the influences (represented in the X axis, e.g.: *Mt, G* represents the combination of the pure torque load case combined with the effect of gravity) have a certain effect on the two components involved in torque measurements. The bigger effects appear for temperature and parasitical loads influences. Gravity and centrifugal force have a minor impact (lower than 0.1% for both components). Then it can be concluded that the optimization process made it possible to reduce the effect of several influences in the final torque measurement.

4. Conclusions

All these variations will be introduced as contributions for estimating the force lever system relative associated uncertainty. Regarding the results obtained, the design has been optimized so that the variations are kept minimum, so that the total expected uncertainty is expected to be lower than 0.2 %. Such a low value for uncertainty validates the proposed lever system as a novel, yet reliable alternative to indirect methods currently being used in test benches.

In addition, the optimization process applied to the lever arm component permitted to reduce the effect of some influences, such us gravity and centrifugal force. As a consequence, those influences have a minor impact on the final torque measurement and its uncertainty.

The proposed system has proved to be a satisfactory alternative to other methods: its final associated uncertainty is much lower than the uncertainties associated to current methods being used in nacelle test benches (0.2 % for the new system, 2-5% for current methods). Moreover, the proposed system is able to measure torque as defined in the International System of units (by means of force and length measurements). Consequently, the proposed system will provide accurate torque measurements while ensuring their traceability to primary standards.

By means of the new transfer standard described in this article and the calibration procedure that was developed within the EMPIR project it would be possible to improve wind turbine diagnose. Torque measurements with better quality will facilitate identifying mechanical and electrical losses, eventually improving wind power generation efficiency.

5. Acknowledgements

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6. References

[1] C. Schlegel, H. Kahmann, and R. Kumme, MN·m torque calibration for nacelle test benches using transfer standards, ACTA IMEKO, 5 (4), (2016).
[2] G. Beaho, Measurement and traceability of torque on large mechanical drives, Sensor+Test, (2015).
[3] D. Peschel, D. Mauersberger, D. Schwind, and U. Kolwinski, The new 1.1 MN·m torque standard machine of the PTB Braunschweig/Germany, IMEKO, (2005).
[4] P. Weidinger, C. Schlegel, G. Foyer, and R. Kumme, Characterisation of a 5 MN·m torque transducer by combining traditional calibration and finite element method simulations, Sensor, (2017).
[5] 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., 1037, (2018).
[6] R. M. Lorente-Pedreille, M. N. Medina-Martín, M. A. Sáenz-Nuño, and M. A. Sebastián, Torque traceability for nacelle's test benches: a design proposal, IMEKO, (2017).
[7] R. M. Lorente-Pedreille, M. N. Medina-Martín, M. A. Saenz-Nuño, and M. A. Sebastián, Study of influences in CEM's new transfer standard for torque measurements in the MN·m range, IMEKO World Congr. XXII, (2018).