IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received April 30, 2019, accepted May 20, 2019, date of publication May 31, 2019, date of current version June 18, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2920261

A Metrological Characterization Approximation for the New Torque Measurement System in Wind Turbines Test Benches

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This work was supported by EURAMET (European Association of National Metrology Institutes) through the project EMPIR 14IND14: Torque Measurements in the MN· m Range, and by EIDUNED (Escuela Internacional de Doctorado de la Universidad Nacional de Educación a Distancia). The EMPIR initiative is co-founded by the research and innovation program Horizon 2020 of the European Union and the Participating States of the EMPIR.

ABSTRACT This paper presents the new transfer standard for torque measurements in the MN·m range and its metrological characterization through FEM analyses. Current methods used for torque measurements in such measuring range are not traceable to international standards; this situation has a deep impact in several industries, being especially important in wind energy generation. In order to improve the quality of torque measurements during wind turbine tests, the "EMPIR 14IND14—torque measurements in the MN·m range," a new European funded project has been launched. This project aims to develop new transfer standards for obtaining accurate, reliable, and traceable torque measurements in the facilities used for testing wind turbine's performance. Within this project, CEM (Spanish Center of Metrology) has designed a new transfer standard for torque measurements named "force lever system." Modeling and simulation technologies have been used not only for designing and testing the proposed system but also for enabling the estimation of its future associated uncertainty even before it is being manufactured. The results have proven that the expected metrological behavior of the designed system will ameliorate the accuracy of current measuring methods while ensuring torque measurements' traceability. The improvement of the torque measurements' reliability will make it possible to better diagnose its behavior and to improve wind energy generation efficiency.

INDEX TERMS Metrology, nacelle, test bench, torque measurement, uncertainty, wind turbine.

I. INTRODUCTION

In the last few years, new techniques and developments have helped to enlarge wind energy generation industry capacities. Bigger and more efficient turbines have been developed, reaching up to the operating range of 20 MW. And they are even expected to increase their size and capacity in the following years, as anticipated by the European Wind Energy Association (EWEA) [1].

Wind turbines are usually tested in Nacelle Test Benches, in which their performance is checked through the analyses of several parameters: rotational speed, torque, etc. Torque measurement is especially significant for diagnosing wind turbines, as it is directly associated to the final power they produce. Unfortunately, notwithstanding its importance, current methods for torque measurements have high associated uncertainties. As it was anticipated by Beaho [2], indirect torque measuring methods, as those employed in Nacelle Test Benches, have higher associated uncertainties due to the effect of tolerances and the later required calculations and mechanical models.

Moreover, Foyer and Kock [3] studied several alternatives which are currently being used for measuring torque in nacelle test benches, concluding that all of them had several drawbacks, including poor accuracy values, and that none of the currently being used is able to measure torque in the MN·m range ensuring its traceability to international standards. When analyzing field calibrations, Borraccino *et al.* [4] explained the importance of ensuring traceability of the measuring systems as it has a direct impact in power performance assessment.

The parameters checked within nacelle test benches (including torque as one of the main variables) are also

The associate editor coordinating the review of this manuscript and approving it for publication was Amedeo Andreotti.

employed for control and test management purposes. Until now, several approaches had aimed to improve the reliability of drive control within nacelle test benches. For example, employing HIL (Hardware in the loop) setups as described in Helmedag *et al.* [5], where several measurements of different parameters are simulated and checked during operation. Other investigations include several different strands all along the drive in the test bench in order to better control the generated torque, as the research described by Behrens *et al.* [6]. However, none of the measuring devices included within these approaches can provide sufficiently accurate, traceable measurements.

The new EMPIR 14IND14 project, "Torque in the MN·m" [7], aims to provide solutions for wind energy generation industry, improving the quality of torque measuring systems. There are several investigations within this project [8], in order to study the characteristics and technical necessities for executing torque measurements in the MN·m range: possible measuring technologies, calibration methods, procedures to be developed, etc. One of the main goals of the project was to develop new transfer standards with higher associated accuracies than current methods and capable to ensure torque traceability.

CEM (Spanish Center of Metrology), in collaboration with other NMI's (National Metrology Institutes), has developed a new transfer standard for torque measurements in the MN·m range, named Force Lever System (FLS). This new system will provide torque measurements by means of force and length measurements instead of employing traditional torque transducers, which are only traceable up to 1.1 MN·m [9].

Given that this new system has never been applied for torque measurements in such a big operating range, several studies and models were needed in order to evaluate its performance.

The investigation, hereinafter described, employs FEM analyses for diagnosing the proposed design, not only from the mechanical point of view, but also from a metrological perspective. FEM is a quite widespread tool in engineering, employed for testing the mechanical behavior of structures, assemblies or parts. The novelty included within this research is the use FEM tools in order to obtain an approximation of the metrological characterization of the designed system.

Generally, when designing a new measuring system, it is not possible to check in advance the results obtained during real functioning, being necessary to test it after being fully developed and manufactured. By means of further analyses [10], in which different operating conditions were emulated, and different influences considered, it was possible to obtain information on the lever length and force measurements that can be expected and their possible variations. Those variations can be considered as uncertainty contributions and employed for estimating the relative associated uncertainty of the new transfer standard.

Based on the results from these studies, it was possible to anticipate the metrological characterization of the proposed system. As the system has not yet been manufactured, modifications to the original design can still be made, making it possible to improve its final accuracy while reducing final verification costs.

The proposed new transfer standard will provide more accurate information about nacelle's generated torque and power output. The present research aims to fully study the measuring components within the system, employing innovative simulations and analyses for evaluating their performance and make it possible to develop an approximation of their future variations and final behavior.

A better information about the operating conditions within the test bench will lead to a better turbine diagnose. Consequently, energy losses and inefficiencies could be precisely detected and reduced, eventually ameliorating wind energy generation systems.

II. PROPOSED FORCE LEVER SYSTEM

The proposed transfer standard is based in the working principle of force lever systems. This kind of systems are used for static drive tests. A lever arm is mounted in a drive which is generating a certain torque load. The lever arm is fixed on its end by a load cell connected to a fix foundation.

The measurement of the torque generated by the drive is obtained as the product of the force measured by the force transducer and the calibrated length of the lever arm (1).

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

The force lever system will be installed within the nacelle test bench drive chain. A nacelle test bench emulates field conditions of includes a main drive, which generates a rotational movement (emulating the rotation that the wind creates on the wind turbine) all along the test bench [11]. It also includes a hydraulic system, named "Load Application System", which is normally mounted within test benches in order to generate lateral and axial forces as well as bending moments [12]. This system resembles the effect of lateral and gusty winds, which have a big impact on the survivability of wind turbines. These parasitic loads, which are normally directly transmitted to the nacelle to be tested, will also be withstood by the force lever system (Figure 1).

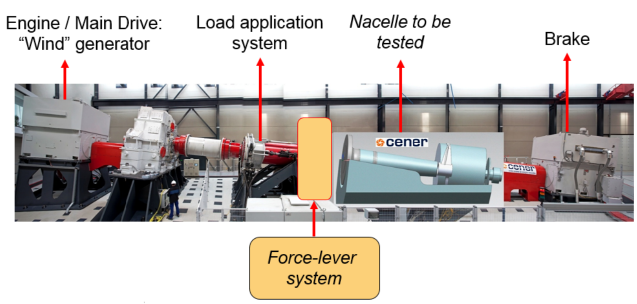

FIGURE 1. Drive chain of a nacelle test bench (Source: CEM and CENER).

Consequently, the force lever system was designed with flanged ends in order to be mounted within the drive chain, ensuring the rotational movement (Figure 2).

FIGURE 2. CEM's force lever system.

The proposed design dimensions (2-4) must fit the available structure of the test bench.

$$Weight = 100\ kN \tag{2}$$

$$Widht = 1\ m \tag{3}$$

$$Diameter = 2\ m \tag{4}$$

One of the flanged ends includes four built-in lever arms, their length calibrated. On the other end, some supports are mounted. These supports will be used to place force transducers. The lever arm and the force transducers will be in contact during operation, ensuring torque transmission (Figure 3). An inner support with mounted roller bearings is included in order to ensure system stability and reduce the effect of lateral efforts on the force transducers while transmitting them downstream the drive chain.

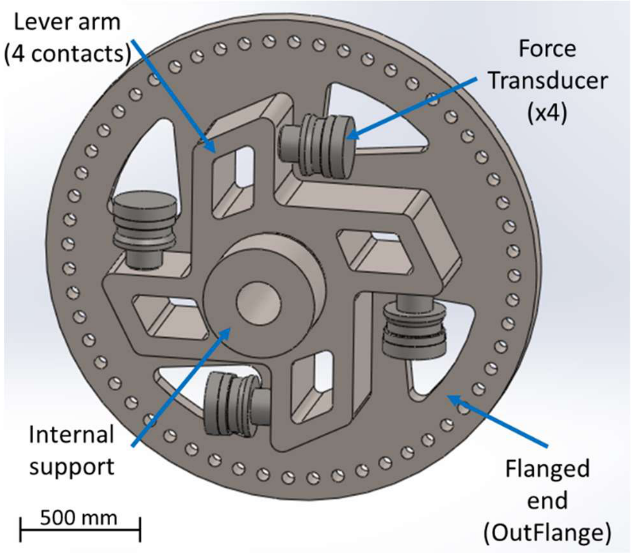

FIGURE 3. Detail of the contact between the lever arm and the force transducers.

III. SPECIFIC CONDITIONS FOR THE APPLICATION OF THE SYSTEM

As it has been briefly explained in section I, this investigation ultimately aims to estimate the metrological properties of the system. The present article focuses on the use of FEM for estimating the metrological characterization of the system. Further information and descriptions about the design and its performance evaluation, as well as the working principle of the force lever system can be found in [13].

The metrological characterization of a system must determine the attributes of the device, including the approximation of its expected performance and its associated uncertainty. Therefore, this research included two different types of study.

Firstly, the reliability of the system was tested, checking the maximum stresses and deformations that appear under the different simple loads that appear during basic tests. Once the preliminary design of the force lever system was developed, these studies were tested for different materials in order to select the more suitable one and to characterize its behavior.

Then, in order to fully determine the behavior of the system under different scenarios, further FEM analyses were carried out. In these simulations different influences were applied in order to define the fluctuations of the torque measurements. To that end, the main components for torque measurements evaluation, force transducers and lever arm length, were studied and their associated parameters evaluated. The software employed for this Finite Element Analyses was Solidworks 2013.

From the results obtained it will be possible to develop a later estimation of the force lever system associated uncertainty, obtaining an approximation of its metrological properties.

Having determine system's performance and it is associated uncertainty, it would be possible to have an estimation its metrological characterization of the proposed torque transfer standard.

A. SIMULATION CONDITIONS: CONSIDERED INFLUENCES AND INPUT PARAMETERS

Nacelle test benches owners participating in the project shared their experience on the operating and environmental conditions at their facilities. From the information gathered from different facilities, four different influences were decided to be study in detail.

In order to study the variations due to each influence, a basic case was simulated as well. In this basic case only pure torque load was applied to the system. Then, each influence study included the pure torque load as well as the typical input parameters for that influence (loads, temperature variations, etc.).

1) PARASITIC LOADS

Although the target torque to be supported by the force lever system is supposed to be 5 MN·m, it was decided that all the FEM simulations within the research would assume an input torque of 6.5 MN·m, so that possible overloads up to 20% of the nominal load could be withstood by the system.

As explained before, the drive chain includes a Load Application System, which generates lateral and axial loads (Thrust), as well as bending moments (Pitch and Yaw effect).

Their typical values are showed in table 1 (where "x" stands for the rotation axis of the wind turbine and "y" for the vertical axis).

TABLE 1. Typical parasitic loads provided by nacelle test bench owners.

Load	Description	Value
$F_{x,y,z}$	Axial and Lateral Loads: Thrust and Radial forces	100 kN
$M_{y,z}$	Bending moments: Yaw and Pitch moment	100 kN·m
M_x	Input torque	6.5 MN·m

However, their actual value during operation has an associated uncertainty [14]. Therefore, these parasitic loads are expected to have a big impact on the force measurements. In normal applications, force transducers work in a static, well aligned calibration processes, were the load is applied without lateral effects. The parasitic loads will generate lateral loads on the force transducer that must be studied.

2) CENTRIFUGAL FORCE AND GRAVITY

Both, gravity and rotational speed are always present during nacelle test bench operation. In comparison to other external influences, their effect is not as high, although it exists and must be considered. Their input parameters are the gravity (in order to evaluate the effect of the weight of the complete system) and the maximum rotational speed (n) that could be reached during a test (5-6).

$$g = 100 \frac{m}{s^2} \tag{5}$$

$$n = 25\ rpm \tag{6}$$

3) TEMPERATURE

Three different temperatures were considered: minimum, maximum and operation temperature (Table 2).

TABLE 2. Typical temperatures provided by nacelle test bench owners.

Parameter	Value (K)
Minimum Temp.	278.15 K
Maximum Temp.	313.15 K
Ideal Operation Temp.	297.15 K
Operation Temp. considering deviations during test	303.15 K

Minimum and maximum temperature were both studied as critical cases. Temperature conditions varies a lot depending on the location of the nacelle test bench facility and the season in which the calibration is being developed. Several facilities and locations were considered; from those, the critical cases (minimum and maximum temperatures) were studied in order to find the worst scenario.

Nevertheless, these critical cases were only applied to the lever arm variation study, as this element is more sensitive to suffer deformations due to temperature, that directly affects the length measurement.

For testing the effect of the temperature on the force transducer, it is only necessary to study the variation during a single complete calibration. Force transducers are tared at the beginning of the calibration process, their original "zero signal" measured. Variation of the temperature during a single calibration test are not as high as the considered when studying maximum and minimum temperatures. Therefore, an operation temperature variation parameter was defined as well, being it +/− 5 K variation from the temperature set in the original pure torque simulation case (in this case, 297.15 K). The final considered operation temperature (T_{op}) for the force transducers analyses was 303.15 K.

B. DETAILED STUDY OF THE MAIN COMPONENTS OF TORQUE MEASUREMENTS

The two main components of the new transfer standard are the force transducers and the lever arms. Detailed studies of their properties were carried out in order to better estimate their behavior. The aim of these detailed investigations was to analyze and reduce when the variations that might appear during operation of the two main components of the torque measurements: reaction force on the force transducers and variation of the originally calibrated length of the lever arms.

Prior to the individual study of components, a preliminary study was carried out, in which the complete system was analyzed under different load combinations (considering different senses and directions). There were significant variations of the resultant stresses (using von Mises stress criteria, measured in N/m^2), although not as important variations in deformation (measured in mm). The combination that caused maximum stresses ("S" in Figure 4) was chosen as the critical load case and was used in later analyses all along the research.

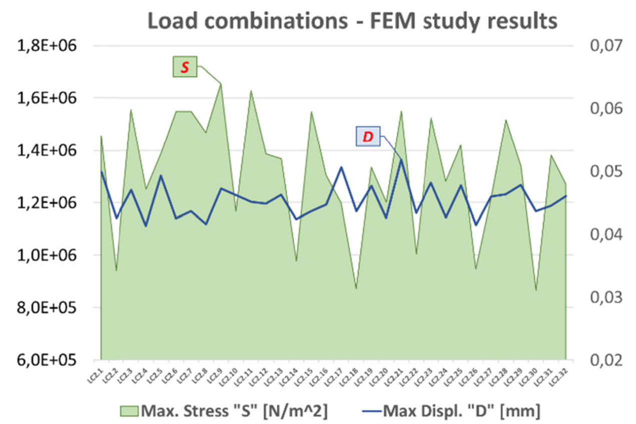

FIGURE 4. Determination of the critical load case [13].

1) LEVER ARM DESIGN AND IMPROVEMENT

One of the objectives of the simulation studies was to improve the design in order to reduce the influences that may affect the system during operation. For instance, gravity and rotational speed are always present and have an effect over the force lever system due to its own weight and geometry. In order to reduce their influence, which might increase the system's associated uncertainty, an iterative re-designing process was carried out, in order to reduce the total weight of the system.

During this process, the lever arm part was modified several times (Figure 5): hollowed areas, depth decreased, etc. A detailed discussion about this iterative improvement process was described by Lorente et al. in [15].

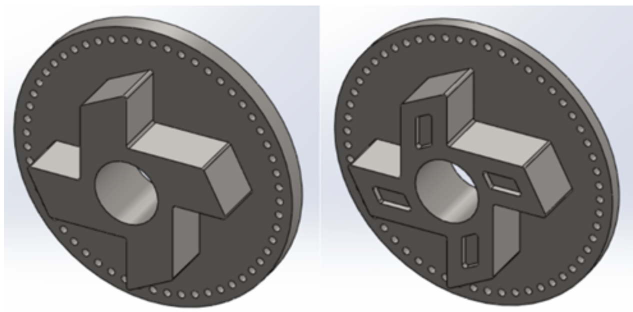

FIGURE 5. **Examples of the improvements and modifications of the design of the lever arm.**

However, these modifications should not affect the stiffness of the system, so that the total variation of the length was not too high. Therefore, an iterative process was carried out, in order to check the lever arm performance after each modification.

The FEM analyses carried out assumed that one face of the arm had a fixed support (where the flanged surface is), while the input torque (generated in the nacelle test bench) was applied in the opposite side of the lever arm.

In order to evaluate the behavior of the lever arm two criteria were studied: von Mises stress and maximum displacement of the lever arm. Von Mises stress was check in order to ensure the stiffness of the lever arm and to study regions were stresses accumulated, in order to reinforce those areas. The maximum displacement was a decisive factor to be studied, as it affects the total length of the lever arm, which, as shown in (1), is one of the main components of torque calculation. Figure 6 shows the percentage of weight that was been reduced and the variation of the lever arm length caused by the new configuration.

For the final design of the lever arm (Case 24, Figure 6), a weight reduction of 38% was achieved and the maximum displacement obtained was lower than 0.3 mm, which considering the total distance of the lever arm, is a relative variation smaller than 0.05%, which is an acceptable value.

2) FORCE TRANSDUCER MEASUREMENTS EVALUATION

Force transducers are commercial elements which do not require any design improvement or modification. Their final characterization depends on additional items (data acquisition systems, signal processing, filters, etc.) which cannot be modeled. However, their mechanical behavior can be simulated and analyzed in order to estimate accuracy of the

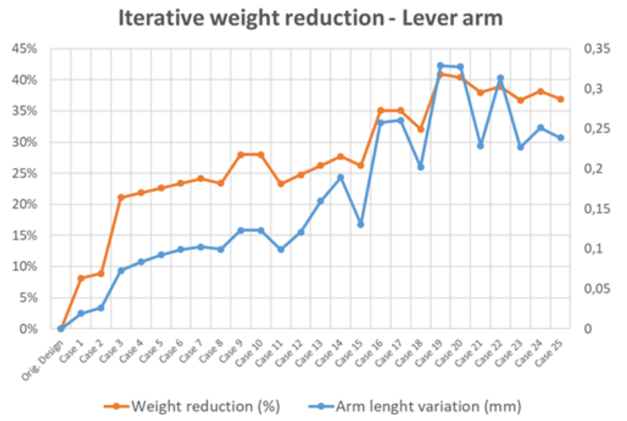

FIGURE 6. **Variation of the lever arm length during the weight reduction process.**

TABLE 3. **Contact force between force transducers and lever arm.**

Contact Type	Contact force
Bonded contact	2.5332 kN
No penetration contact	2.5264 kN
Ideal contact	*2.675 kN*

proposed transfer standard. For that purpose, the force suffered by the force transducers during operation is the main variable to be studied.

The torque generated by the main drive of the nacelle test bench is transmitted all along the force lever system through the contact between the lever arm and the force transducers. Therefore, the reaction force that appears in the contact area between the lever arms and the transducers is measured by the force transducers and can be used for calculating the total torque measurement.

First, the theoretical force value was calculated. The lever arm as designed has an original length of 607.5 mm. The theoretical force that should be appearing in the force transducer for an input torque of 6.5 MN·m is 2.675 MN, as obtained in (7).

$$F = \frac{M}{4 \cdot l} = 2.675\ MN \tag{7}$$

One of the tools provided within the finite element software is contact/reaction/connector forces. By means of this tool it is possible to analyze the force measurement that can be expected during real operation (Figure 5). However, for it to be reliable, it is needed to specify the type of contact between force transducer and lever arm. Therefore, a contact study was necessary to validate the force reaction at the transducer; big deviations from real measured forces might introduce significant increments on the final estimation of the uncertainty of the system (Table 3).

Regular contacts are declared as "Bonded contact", where all parts are supposed to be fixed connected to each other, as if a single part was being analyzed. When this configuration (which is established by the software by default) is chosen, the contact force is not as high as theoretically expected: only

2.228 MN are applied to each individual transducer, which produces a total torque output of only 5.735 MN·m.

Other possible contact type was ''No penetration contact'' in which the assembled parts are considered as individual parts that interact with each other, without penetration. This definition seemed more realistic. When applied to the contact area between transducer and lever arm, the obtained contact force was 2.526 MN, with a total torque output of 6.416 MN·m.

For obtaining the real torque output it is needed to also consider the parasitic bending moments that appear at each force transducers (Figure 7). However, even adding the parasitic bending moments effect, it became clear that ''No penetration contact'' was the more realistic option to be used.

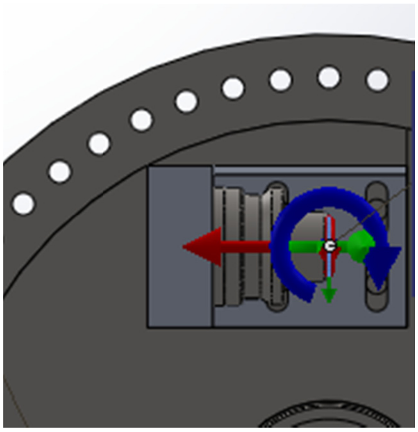

FIGURE 7. Contact force results for each of the force transducers: Red arrows indicate the reaction force at the transducer, while the blue arrow stands for the residual bending moment.

Once the contact type was defined, the complete study of the system and the possible influences that may appear was carried out. In this study, parasitic bending moments were also considered in order to fully characterize the metrological performance of the system.

Further details about the individual studies of the main components involved in the torque measurement were included by Lorente et al. in [15].

IV. ASSOCIATED UNCERTAINTY ESTIMATION MODEL

From the results of the influence study, it was possible to check the variation of the main components of the force lever system. The different variations will be used for estimating the uncertainty contributions to the torque measurement in next stages of this research, and therefore, an uncertainty budget can be created. In order to get to know the main parameters to be analyzed for the future estimation of the uncertainty budget a preliminary uncertainty estimation model is proposed.

A. UNCERTAINTY ESTIMATION MODEL

Ideal torque measurement is obtained as explained in (1). However, during real operations several losses may appear due to materials deformations, friction, heat, etc. One of the losses that can be evaluated are the local bending moments that appear at each force transducer (colored in blue in figure 7), caused by the configuration of the system, its dynamic behavior and the effect of parasitic loads.

Therefore, the equation used for estimating the torque measurements is as shown in (8). Its associated uncertainty (9) is estimated according to the ''Guide to the Expression of Uncertainty in Measurement'' GUM [16].

$$M = \sum\nolimits_{i=1}^{n} F_{loc_i} \cdot l_i + \sum\nolimits_{i=1}^{n} M_{loc_i} \tag{8}$$

$$u^2(M) = n \cdot l^2 \cdot u^2(F_{loc}) + n \cdot F_{loc}^2 \cdot u^2(l) + n \cdot u^2(M_{loc}) \tag{9}$$

where:

- M is the torque measurement
- n is the number of transducers
- l_i is the lever arm length at each individual lever. Again, for simplification, one value is used.
- $M_{loc\,i}$ is the average local bending moment that appears in the force transducers contact surface during operation in the same direction as the total output torque.
- $F_{loc\,i}$ is the average reaction force at the four transducers
- $u(M)$ is the estimated uncertainty for the torque measurement
- $u(F_{loc\,i})$ is the estimated uncertainty for the force measurement.
- $u(l)$ is the estimated uncertainty for the lever arm.
- $u(M_{loc\,i})$ is the estimated uncertainty for the local bending moment.

The uncertainties of the main components of torque calculation (lever arm length, bending moments and force measurements), will be evaluated separately. For each of them, the variation of their original values regarding the effect of the different influences will be studied. Those variations will be considered as uncertainty contributions.

The local variations at each lever arm and force transducers will be initially treated as non-correlated uncertainties. This preliminary research aims to provide a simple uncertainty estimation which will make it possible to validate the proposed system as a torque transfer standard and to compare it with other measuring systems. Additionally, correlation will be included in further calculations of the associated uncertainty estimation.

B. VALIDATION OF THE MODEL'S COHERENCE

As specified in (8), the final torque measurement can be obtained as the addition of each the torque generated at each individual transducer (each reaction force multiplied by the lever arm length, plus the local bending moment). After running the simulations, it was noticed that, given the angular distribution of the transducers, during operation some of them suffered additional compression efforts while others were elongated; moreover, residual bending moments were also different at each transducer. As consequence, for evaluating the uncertainty it was needed to include and average the reaction forces and local bending moments at each individual transducer in order to include all the different stresses having place in the different components. Therefore, an alternative method for evaluating the torque measurement was proposed (10), where the individual value for force and local bending moments are averaged and added.

$$M_{ave} = n \cdot \left(\bar{F_{loc}} \cdot l + \bar{M_{loc}}\right) \tag{10}$$

A comparison between both methods - by developing equations 8 and 10 - was made, in order to validate the use of the average values.

$$M = \sum_{i=1}^{n} F_{loc_i} \cdot l_i + \sum_{i=1}^{n} M_{loc_i} = (F1+F2+F3+F4) \cdot l + (M1+M2+M3+M4) \tag{11}$$

$$M_{ave} = n \cdot \left(\bar{F_{loc}} \cdot l + \bar{M_{loc}}\right) = (F1+F2+F3+F4) \cdot l + (M1+M2+M3+M4) \tag{12}$$

The results from developing (8) and (10) are shown in (11) and (12). It has been proven that both methods are valid and lead to the same expression; therefore, the average calculation approach (10) was acceptable.

V. RESULTS

A. CHARACTERIZATION OF THE LEVER ARM LENGTH

As it has been introduced in section III, force transducers are commercial components and his metrological characterization should be completed through a traditional calibration. However, the lever arm within the proposed force lever system is a custom-made component, whose length, once calibrated, can only suffer variations due to the influences generated during operation. For that reason, an independent study of the lever arm was carried out, in order to determine the variations of the length caused by the different influences.

The considered influences were those described in section III [15]. The pure torque load was considered as a basic case. At each study, the effect of each influence was studied separately (Figure 8).

The results showed that the modifications made to the lever arm helped reducing the effect of the gravity and centrifugal force, which can be neglected in comparison to the other influences.

The bigger variations are caused by the additional loads and the thermal expansions caused by the critical temperatures.

Nevertheless, the maximum displacement is not very different from the one caused by the pure torque load, so it can be concluded that none of the considered influences has a deep impact on the final lever arm length.

Once the lever arm has proven to withstand the different loads when studied separately, it was mounted in the complete force lever system. Once included, the complete force lever system was studied considering the different influences

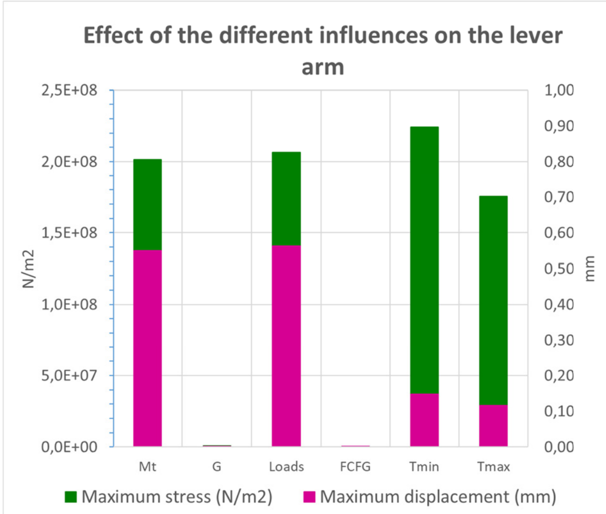

FIGURE 8. Lever arm variation studies.

in combination with the pure torque load (which is always present during operation).

B. COMPLETE FORCE LEVER SYSTEM METROLOGICAL CHARACTERIZATION

Once the lever arm proved to be valid, the complete proposed transfer standard was evaluated. The simulations aimed to emulate the real operating conditions, where pure torque load is affected by the different influences. Therefore, each individual influence is applied to the system combined with the pure torque load.

As established in the uncertainty estimation model, described in section IV, three different measurements are employed for obtaining the total torque measurement: lever arm length, contact force and local bending moments in the transducers.

The effect of the different influences on each measurement were analyzed.

1) LEVER ARM LENGTH VARIATION (WITHIN THE COMPLETE LEVER SYSTEM)

Variations of the lever arm had already been studied independently; their results shown in the previous section. However, the total effect of the influences once the lever arm is assembled were necessary to be calculated (Figure 9).

The maximum stresses (von Mises parameter) and the maximum displacements (related to the lever arm length variation) were analyzed (Table 4). The variations under each considered influences will be considered as input uncertainty contributions for the final lever arm length (Table 5).

By comparing the results from table 4 and table 5 it can be seen that, when combined with the pure torque load, the bigger variations appear under the effect of the maximum temperature case (M_{t}, $T_{\max}$), instead of being caused by the additional loads (M_{t}, *Loads*).

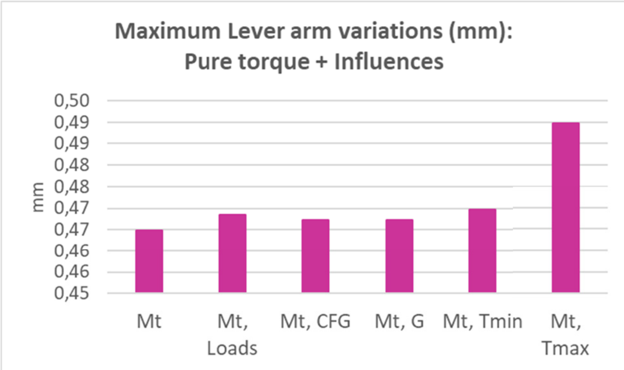

FIGURE 9. Lever arm length variation studies (when mounted within the complete force lever system).

TABLE 4. Study of influences on the lever arm (individual studies).

Considered influences	Short name	Maximum stress (N/m2)	Maximum displacement (mm)
Basic Case: Only pure torque load	Mt	2,02E+08	0,54970
Gravity	G	6,94E+05	0,00149
Loads	Loads	2,07E+08	0,56251
Centrifugal Force	F_{CFG}	4,79E+04	0,00007
Minimum Temperature (278,15 K)	Tmin	2,24E+08	0,14828
Maximum Temperature (303,15 K)	Tmax	1,76E+08	0,11621

TABLE 5. Study of influences on the lever arm (operating conditions).

Considered influences	Short name	Maximum displacement (mm)
Basic Case: Only pure torque load	Mt	0,54970
Torque and Gravity	Mt, Loads	0,00149
Torque and additional Loads	Mt, CFG	0,56251
Torque and Centrifugal Force	Mt, G	0,00007
Torque and Minimum Temperature (278,15 K)	Mt, Tmin	0,14828
Torque and Maximum Temperature (303,15 K)	Mt, Tmax	0,11621

Despite this increase, the total variations are still quite low when compared to the total length (607,5 mm). The relative variations under the different influences are then lower than 1%. These results confirm the stiffness of the final lever arm design.

2) FORCE AND LOCAL BENDING MOMENTS VARIATIONS

The variations of the contact force and local bending moments that appears in the transducers were evaluated (Figure 10). Those variations will be used as input uncertainty

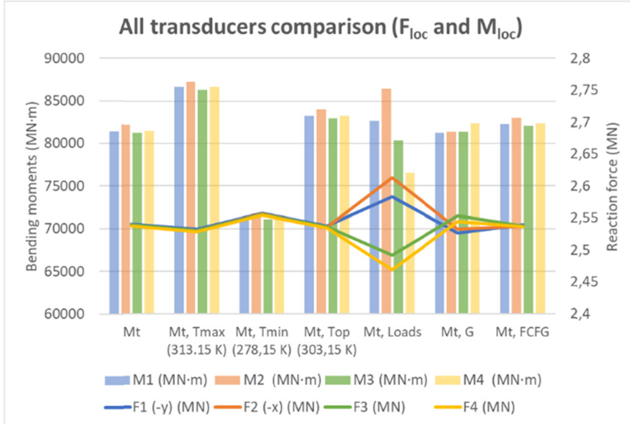

FIGURE 10. Local reaction forces and bending moments for each of the force transducers.

contributions in order to estimate the relative associated uncertainty of the proposed system.

In order to calculate the variations under the considered influences the data from all the different transducers was studied and compared. In Figure 10 the local forces (F1, F2, F3 and F4) and bending moments (M1, M2, M3 and M4) at each force transducer are studied for each different case study, so that the effect of the different influences can be compared.

As expected, the bigger variations appear in the case were the parasitic loads (as well as the pure torque Mt, which is always included) are applied (M_t, *Loads*). Given the distribution of the force transducers (four transducers, each one positioned 90° rotated respect the previous transducer), it is clear that the parasitic loads affect the whole system (13-15), causing an additional compression in the force transducers 1 and 2 and an opposite effort (elongation) in the area were transducers 3 and 4 are located.

$$F_{TRD1,2} \cong 2.56MN \tag{13}$$

$$F_{TRD3,4} \cong 2.49MN \tag{14}$$

$$F_{TRD3,4} < F_{Theoretical} < F_{TRD1,2} \tag{15}$$

As established in the uncertainty model, adding the local bending moments is necessary for obtaining the torque measured at each individual transducer (8). By averaging the results, the additional elongation and compression are compensated, and the total torque measurement is very close to the theoretical value (10, 12). An example of this averaged calculation, for the pure torque load case (M_t), can be seen in table 6.

Given that the input torque was 6.5 MN·m, and the final measured torque is 6.4969 MN·m (Table 6), the mechanical losses within the system are lower than 0.05%. This first result shows that the proposed design for the force lever system will withstand the loads while transmitting them. Moreover, it is possible to assess the torque measurements that the system will provide even before being manufactured.

Another interesting result is the temperature effect: while other influences (gravity - M_t, G, centrifugal force - M_t,

TABLE 6. Example: Total torque measured by the force lever system for the pure torque load case (M_t).

Transducer	Measured Force (F_{loc}) (MN)	Local Bending moment (M_{loc}) (N·m)	Local Measured Torque (MN·m) F_{loc} x l+M_{loc}
1	2,5409	81451	1,6250
2	2,539	82253	1,6247
3	2,5392	81272	1,6238
4	2,538	81490	1,6233
Total Measured Torque			6,4969

F_{CFG}) have very similar results to the basic case (M_t, where only pure torque load is applied), temperature studies have especially big variations on the bending moments at each force transducer. This might be due to the sensibility of force transducers materials to temperature variations. In addition, a single force transducer has very small dimensions in comparison with the complete force lever system. Therefore, the reaction forces, caused by the interaction with the lever arm, do not differ so much, while the bending moments increased due to the force transducer material and dimensions. Nevertheless, as it has been explained, maximum and minimum temperatures (M_t, T_{max} and M_t, T_{min}) are only considered for lever arm length variations, while operation temperature (T_{op}) is considered for force and bending moment's variations evaluation, emulating real operating conditions. Therefore, the impact of the temperature variation in the force and bending moments contributions are smaller than in the maximum and minimum temperature studies carried out for analyzing the lever arm length.

C. RELATIVE ASSOCIATED UNCERTAINTY ESTIMATION

In order to estimate what might be the bigger uncertainty contributions, the relative differences with the original pure torque case (M_t) were studied (Figure 11). The original pure torque case is considered to be the ideal case; then, each influence is added in separate simulation studies. In this way, the difference between each simulation results and the original pure torque case will be used for obtaining the uncertainty contribution due to each influence.

The figure below shows the effect of the 4 scenarios:

- M_t, T_{op} includes the pure torque load as well as the operation temperature.

- M_t, *Loads* includes the pure torque load as well as the parasitical loads.

- M_t, G includes the pure torque load as well as the gravity effect.

- M_t, F_{CFG} includes the pure torque load as well as the centrifugal force.

As explained before, the parasitic loads have an impact on the system, slightly increasing the total reaction force in the transducers. However, after averaging the four different reaction forces, the final force measurement variation is not as high, while the bending moment's variation is still remarkable. In the case of the temperature influence, bigger variations appeared in the force measurements, respect to the original pure torque case.

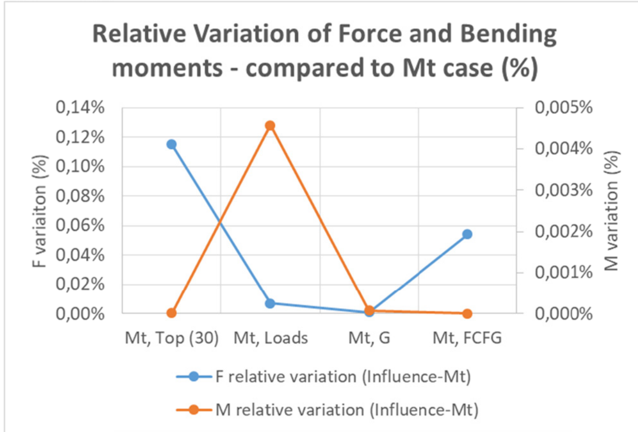

FIGURE 11. Variation of force and bending moment average values due to the different influences.

Regarding the relative deviations, none of the variations due to the considered influences is bigger than 0.14%. Therefore, the total expected uncertainty for the whole system was expected to be low.

As explained in section IV, the three different components of the torque measurement (lever arm length, reaction force and local bending moments) have its own associated uncertainty. Those uncertainties are calculated separately, considering external input data (calibration certificates, information from data sheets, etc.) and the results from the FEM analyses, where the variations of each component due to all the considered influences where studied. Examples of the uncertainty calculations for each measurement element can be seen in Figures 12, 13 and 14.

Lever arm lenght (*l*)- Uncertainty estimation			
Nº	**Input magnitude (m)**		**Contribution**
0	Calibration	0,607500	**0,00057735**
1	Mt	0,000465	**0,00004649**
2	Mt, Loads	0,000004	**0,00000350**
3	…		
A.	**Lever length *l* (mm)**	**0,6079649 +/-**	**0,000581**
		Relative Value	**0,096%**

FIGURE 12. Contributions for the Lever arm length (*l*) associated uncertainty estimation (extract) and final estimated value and uncertainty.

Once the three torque measurement components have been calculated and their associate uncertainties estimated, total measured torque is obtained. Each individual component is considered as an uncertainty contribution for the torque measurement. The final estimated relative uncertainty for the torque measurement is 0.149 % (Figure 15).

Nº	Input magnitude (MN)		Contribution
	Measured Force (F_{loc}) - Uncertainty estimation		
0	Calibration	0,000254	**0,00014661**
1	Effect of Parasitical Forces (TRD Data sheet)	0,000762	**0,00043982**
2	Effect of temperature deviation (TRD Data sheet)	0,000254	**0,00014661**
3	Mt, Loads	0,000175	**0,00017500**
4	…		

B. Measured force F_{loc} (m)	**2,539275**	**+/-**	**0,0022383**
	Relative Value		0,088%

FIGURE 13. Contributions for the measured force (F_{loc}) associated uncertainty (extract) and final estimated value and uncertainty.

Nº	Input magnitude (MN·m)		Contribution
	Local bending moments (M_{loc}) - Uncertainty estimation		
0	Calibration	0,000408	**0,00023561**
1	Effect of temperature deviation (TRD Data sheet)	0,000082	**0,00004712**
2	Mt, Loads	0,000110	**0,00011000**
3	…		

C. Local Bending moment M_{loc} (m)	**0,0816165**	**+/-**	**0,0013526**
	Relative Value		1,657%

FIGURE 14. Contributions for the local bending moment (M_{loc}) associated uncertainty (extract) and final estimated value and uncertainty.

Torque Uncertainty Estimation

Nº	Input magnitude			Standard uncertainty
	Component	Measured Value	Uncertainty contribution	
A	**Length (l)**	0,607965	0,000581	**0,00058101**
B	**Force (F_{loc})**	2,539275	0,002238	**0,00223834**
C	**Bending moment (M_{loc})**	0,081617	0,001353	**0,00135257**

FIGURE 15. Torque relative associated uncertainty estimation.

Compared to methods that are currently being used in nacelle test benches for measuring torque, which have an associated uncertainty not lower than 3%, the new transfer standard proposed by CEM will surely improve turbine diagnose, thanks to a more accurate and traceable torque measuring system.

This uncertainty value is an estimation based on the mechanical analyses of the new torque transfer standard. After manufacturing and mounting the system a complete characterization will be needed. Additional contributions (as those considered in traditional calibrations, such us repeatability, hysteresis, etc.) and non-mechanical influences (signals, filters, etc.) should be included in the final uncertainty budget for the proposed system.

VI. CONCLUSIONS

The described new transfer standard designed by CEM has proven to be a reliable method for torque measuring in nacelle test benches. Regular FEM analyses have satisfactorily tested system's feasibility and performance.

By means of the detailed FEM analyses, it has been possible to estimate possible variations of the torque measurements obtained by the new transfer standard. These innovative studies have enabled the possibility of approximating the metrological characterization the new transfer standard.

The results of the FEM studies can be used to estimate the effect of different influences on the proposed force lever system, anticipating its behavior and making it possible to modify the original design in order to reduce or minimize the relative associated uncertainty of the system. By including all these improvements in the design, before it being manufactured, it will be possible to reduce later verification costs.

The analyses of the relative deviations have shown that the Force Lever System associated uncertainty is much lower than the uncertainty of the methods currently being used in the industry. As a consequence, the proposed system has proven to be a good alternative for obtaining traceable and accurate torque measurements in the MN·m range.

Further investigations will employ the results here described in order to precisely estimate the system's associated uncertainty, including more complex calculations and contributions (e.g. correlation). Furthermore, the proposed system employs traditional force transducers, which, unlike torque transducers, are possible to be calibrated in the required operating range. Consequently, the proposed method will ensure the traceability of torque measurements in the MN·m range.

Hence, the new transfer standard has been proven to be a reliable and traceable system for torque measurements, having its metrological characterization estimated before having it manufactured. By employing the proposed system in nacelle test benches, it will be possible to have more accurate information about nacelle's generated torque and power output. Consequently, energy losses and inefficiencies could be precisely detected and reduced. Increasing the quality of torque measurements will ultimately improve wind energy generation.

ACKNOWLEDGMENT

The authors would like to give a special acknowledge to Ph.D. Javier Carro for his important task and teaching in the field of Metrology, In memoriam. They also want to thank EIDUNED and the EMPIR initiative for supporting this research.

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