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MN·m torque calibration for nacelle test benches using transfer standards

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ABSTRACT
To verify all technical aspects of wind turbines, more and more nacelle test benches have come into operation. One crucial parameter is the initiated torque in the nacelles, which amounts to several MN·m. So far, no traceable calibration to national standards has been performed in such test benches. The paper will show calibration possibilities which already exist and also show future prospects.

Section: RESEARCH PAPER

Keywords: torque calibration; transfer standard; nacelle test bench

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1. INTRODUCTION

The portion of renewable energies for electricity production is rising dramatically. For instance, last year the fraction of renewable energies in Germany was 32.5 %. The portion of energy which was produced by wind energy was thereby 44.3 %, based on all renewable energies. The German government will increase the share of renewable energy in power generation to 40 to 45 % by 2025. From this development it is clear that wind energy is likely to provide the greatest contribution to this planned expansion. Associated with this is a significant increase in the performance of the wind generators. This will lead to individual wind turbines more powerful in height, in wing span as well as in the provided electrical power, as seen in Figure 1, taken from [1].

Of course, reliable energy production from wind turbines will strongly depend upon their technical reliability. For that reason, several nacelle test benches have been established in the past. One crucial parameter for such a nacelle is the torque load which is initiated in the field according to the strength of the wind field.

In nacelle test benches, instead of using wind power, a special motor is used to create the torque. Often an additional device is located between the motor and the nacelle to create axial forces as well as parasitic bending forces and moments onto the drive train.

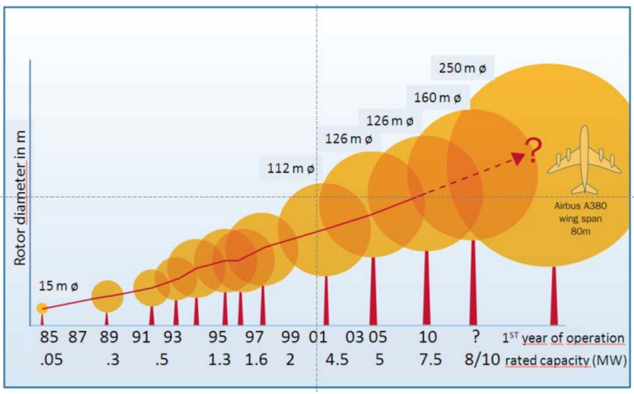

Figure 1. Development of the size of wind turbines.

One of the most important parameters of such test benches is the torque which is initiated in the nacelle. So far, no traceable calibration to national standards has been performed in such test benches. The paper will show calibration possibilities which already exist and also show future prospects.

The torque M is directly related to the electrical power P_{el} and depends on the revolution speed n, respectively of the frequency f.

$$M = \frac{P_{el}}{2\pi \cdot n}, \quad f = \frac{n}{60}. \tag{1}$$

It should be noted that the relationship between f and n in (1) is for the case that the revolution speed is given in rounds per minute, rpm.

Table 1 shows an example of two points of operation.

As shown in (1), the torque can be determined by an electrical power measurement. Nevertheless, this kind of measurement results in relative uncertainties of several percent; that is why a more precise mechanical measurement of the torque is necessary.

Special torque transducers were built to measure the torque in the drive train. Unfortunately, not all of these transducers are calibrated in the MN·m range due to the lack of a calibration facility. Sometimes they are calibrated partially and extrapolated, e.g. via finite element calculations, to the nominal torque [2]-[4].

The paper is organised like this that in Chapter 2 an existing standard torque calibration machine will be described where traceable calibrations up to 1.1 MN·m can be performed. In Chapter 3 a novel 5 MN·m torque transducer and his calibration according the existing standard DIN 51309 with the described machine from Chapter 2 will be introduced. In addition a proposal will be made how one could extrapolate calibration data to a non measurable range. In Chapter 4 a new calibration machine will be introduced which is able to calibrate torques up to 20 MN·m.

2. ABOUT THE TRACEABLE CALIBRATION OF TORQUE

According to the definition of the torque $\vec{M}$, traceability can be realized via a lever arm l on which a force $\vec{F}$ which is acting perpendicular, in the simplest case, is the gravitational force $m \cdot g_{loc}$, whereby m is the mass and g_{loc} is the gravitational constant.

$$\begin{aligned} \vec{M} &= \vec{r} \times \vec{F} \\ M &= r \cdot F \cdot \sin\left(\vec{r}, \vec{F}\right) = m \cdot g_{loc} \cdot l, \quad r = l \end{aligned} . \tag{2}$$

Based on this principle, there are torque calibration machines, which, for the force initiation, use mass stacks which can be varied in such a way that various torque steps can be applied. Often the masses are coupled to the lever arm by means of thin metal bands (e.g. 20 to 30 µm) to get a very precise contact point for the deadweight force. Several aspects of machine design and related measurements can be found in [6]-[12].

Unfortunately, this principle cannot be further used by very high torques which are in the MN·m range. In these cases, one can apply a system where the torque is created by an actor lever system and measured by a second force lever system [7]. The principle is illustrated in Figure 2 where the levers are indicated in red. Between the two levers the torque transducer is mounted indicated in yellow in Figure 2. This principle is used, for example, by the PTB 1.1 MN·m Standard Calibration Machine [7], see Figure 3. On the measuring side, which is the upper traverse in Figures 2 and 3, the lever is connected at both ends with force transducers. In this way, the torque is traced by the length of the lever arm and the measured forces of the calibrated force transducers.

Table 1. Examples of the relation of electrical power and torque.

Electrical Power MW	Revolution Speed rpm	Frequency Hz	Torque MN·m
5	14	0.23	3.4
10	9	0.15	10.6

In the machine, two different pairs of force transducer can be used, one (120 kN) for a lower range up to 220 kNm and one pair (550 kN) for the upper range up to 1.1 MN·m. In the range up to 220 kNm one obtains a relative uncertainty of the torque of $1.0 \cdot 10^{-3}$, whereby in the upper range one gets $0.8 \cdot 10^{-3}$.

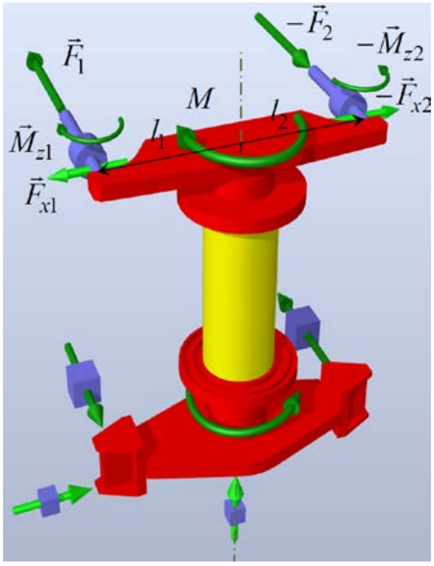

Figure 2. Working principle of the double lever arm system of the 1.1 MN·m Torque Calibration Machine.

Figure 3. Standard Torque Calibration Machine for nominal torques up to 1.1 MN·m.

The torque itself is created by two mechanical spindles which are driven by a motor, as main drives which are located between the two lower platforms, see Figures 2 and 3. In Figure 3 the blue boxes indicate gears, whereby the small boxes represent manually gears and the bigger boxes motor driven gears.

In addition, there is a secondary drive to define the horizontal position (left) and to reduce the cross force (F_{x1}, F_{x2}) and the bending moment (M_{z1}, M_{z2}). To compensate for the vertical force F_z generated by the transducer weight and the lower lever arm, a hand-operated drive unit (under the lower lever arm) can be used. Spring elements (indicated by the blue cylindrical elements in Figure 3) are connected to the measuring lever to measure the parasitic mechanical components in the contact area between force transducer and lever arm. With the aid of these spring elements, all parasitic components can be minimized during a calibration procedure. Last but not least, a reference torque transducer is mounted in the lower part of the machine (below the red flange) which is, in addition, equipped with measuring bridges for bending forces and moments. This transducer offers additional possibilities to check the adjusted torque and the alignment of the whole measuring axis.

The uncertainty of the torque which is provided by the machine mainly depends on the lengths l_1 and l_2 of the double lever arm, on the measured force values F_1 and F_2 at both ends of the lever arm and on the remaining parasitic moments M_{z1} and M_{z2} which are due to not fully compensated bending components measured on the spring elements that are connected with the force transducers.

The model for the uncertainty evaluation of the provided torque is:

$$M = F_1 \cdot l_1 - F_2 \cdot l_2 + M_{z1} + M_{z2} \,. \quad (3)$$

The length of the lever arm was measured with a special coordinate measuring arm within an accuracy of Δl = 100 µm. The force transducers can be calibrated in the PTB 1 MN Force Standard Machine. The calibration of the transducers is repeated in a period of two years. Thereby, a relative measuring uncertainty of better than $1.0 \cdot 10^{-4}$ can be achieved. Nevertheless, in the uncertainty budget, a more conservative value of $1.0 \cdot 10^{-3}$ was taken. For technical reasons, the lever arm cannot be dismounted every two years. Therefore, random deformation measurements using laser interferometers are performed to monitor the stability. As seen from Table 2, the main uncertainty contribution results from the calibration of the force transducers. The contribution from the parasitic moments M_{z1} and M_{z2} are very small and could actually be neglected. The chosen distributions are all rectangular because in most of the cases, where values taken from calibration certificates (here F_1, F_2 and l_1, l_2) this distribution is recommended, see also [13]. For the bending moments M_{z1}, M_{z2} also a rectangle distribution is applied to get a more conservative uncertainty. Anyway the rectangle distribution should be applied if no details about a possible distribution of a certain value is known [13], which applies for the case of the bending moment.

3. TORQUE TRANSFER TRANSDUCERS FOR NACELLE TEST BENCH CALIBRATION

In this section, we will show the partial calibration of a 5 MN·m Torque Transfer Transducer and secondly describe a procedure of how to extrapolate torque values if only a partial

Table 2. Uncertainty budget of the 1,1 MNm Standard Calibration Machine.

Parameter	Value	Standard Unvertainty	Distrib.	Sensitivity Coeff.	Uncert.	Index
F_1	500.0	0.289	rect.	1.1	0.32	49.6%
L_1	1.1	$52.5 \cdot 10^{-6}$	rect.	500	0.026	0.3%
F_2	-500.0	0.289	rect.	1.1	0.32	49.6%
L_2	1.1	$52.5 \cdot 10^{-6}$	rect.	500	0.026	0.3%
M_{z1}	0.02	0.0115	rect.	1.0	0.012	0.0%
M_{z2}	0.02	0.0115	rect.	1.0	0.012	0.0%
M	1100.04	0.451				

Result	Value	Expanded Uncertinty	K-Factor	Coverage-Intervall
M	1100.04	0.90	2.00	95% Normal-Dist
		rel: $8.2 \cdot 10^{-4}$		

range was calibrated. This procedure will be illustrated by means of the data of the reference transducer of the 1.1 MNm Calibration Machine.

3.1. Calibration of a 5 MNm Torque Transducer in the partial range up to 1.1 MNm

In order to realize a traceable calibration for nacelle test benches, the EMPIR project "Torque measurement in the MN·m range" was started in October 2015 [5]. One of the objectives of this project is to develop novel traceable calibration methods for torque values in nacelle test benches with the use of transfer standards for the range above 1 MN·m. For the realization of this goal, a commercial torque transducer with a nominal range of 5 MN·m will be used, see Figure 4. During the above-mentioned EMPIR project, an extrapolation procedure for the range above 1.1 MN·m will be developed. In Figure 4, the commercial transducer is depicted together with 2 DMP 41 bridge amplifiers. The transducer is equipped with two independent torque channels, two channels for transverse bending forces, two channels for bending moments and two channels for axial forces. Due to these additional channels, an investigation of multi-component loading on the measurement of torque will be possible. In particular, crosstalk effects in the case of 6-component loading (main torque, 3 directional forces, 2 directional bending torques) will be studied to describe effects

Figure 4. 5 MN·m torque transducer together with two DMP41 bridge amplifiers for the readout of the 8 channels of the transducer.

on the torque measurements which occur in large nacelle test benches. Finally, a calibration procedure for large nacelle test benches will be developed during the EMPIR program. 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. First calibration measurements were performed with the shown 5 MN·m torque transducer in the PTB 1.1 MN·m Standard Calibration Machine above described. Thereby, the procedure according to the German Standard DIN 51309 was applied [14]. Figure 5 shows the calibration procedure according to DIN 51309. The diagram shows the relationship between the applied torques as a function of time. After three preloads (applying the nominal/maximum torque value of the transducer), a certain number of increasing and decreasing torque steps are performed in three mounting positions. Mounting positions means that the transducer is rotated in respect to the axes where the torque acts, thereby often the three mounting positions 0º, 120º and 240º are used. At least 8 torque steps are required to determine a linear or polynomial fit. From the data, several characteristic parameters are derived which are used for the determination of the measurement uncertainty as well as for a classification of the torque transducer. The parameters are indicated in Figure 5 in the calibration procedure. For example the hysteresis will be determined by the difference between the maximum and minimum torque value which were obtained in one certain torque step. Thereby the data from all mounting positions as well as the steps from increasing and decreasing torque will be taken into account.

More details about the indicated parameters of Figure 5 and their use for an uncertainty determination can be found in [14]. One characteristic result of the calibration is the deviation from linearity shown in Figure 6. The curves reflect the relative deviations of the measured values from a fitting straight line; the deviations are related to the measured mean value of the final value. The fitting straight line is defined by the value of its slope; the axis intercept is zero.

The upper diagram in Figure 6 shows the data of the 5 MN·m transducer, the lower diagram the data from the reference transducer, which was simultaneously calibrated. Note the difference in the shape of the two diagrams. The shape of the reference transducer shows the common behaviour where a transducer is used up to his nominal value (end value). In the case of the 5 MN·m, the transducer was only used up to 22 % of its nominal value, which leads then to a curve shape as

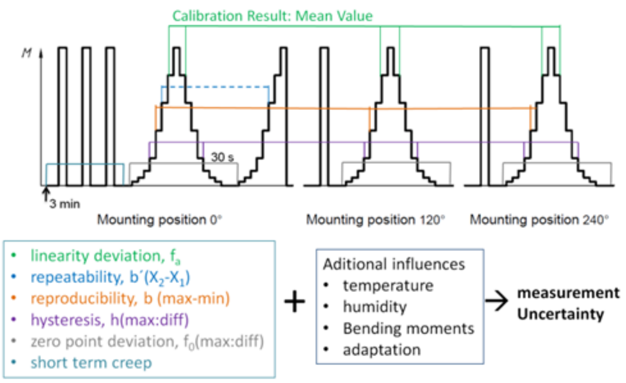

Figure. 5. Calibration procedure according to the German Standard DIN 51309. Indicated are several parameters which will be derived from the calibration data. This parameters as well as other additional influences will be used for an uncertainty determination.

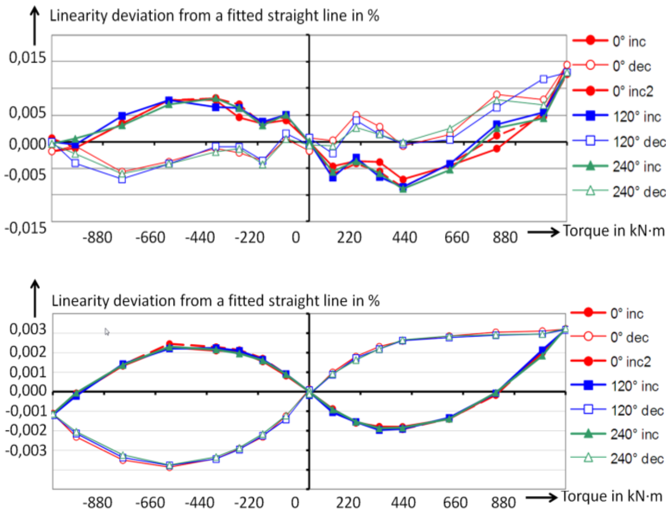

Figure 6. The upper curve is the linearity deviation from a fitted straight line through the origin at zero of the 5 MN·m transducer. The lower curve shows the same behaviour of the 1 MN·m reference transducer .The deviations are related to the measured mean values of the final value.

shown in Figure 6. One of the aims in the mentioned EMPIR-project is to find an extrapolation procedure using the data from the 1.1 MN·m calibration to extrapolate up to 5 MN·m. The significant linearity deviation might be used in this extrapolation procedure.

During the calibration of the 5 MN·m transducer, also partial ranges within the 1.1 MN·m range were measured. This data will also be used to develop an extrapolation procedure. In addition, also the signals from the other six parasitic channels were recorded. The analysis of these data will provide information about the correlations of the torque with the bending forces and moments as well as the axial forces.

3.2. Extrapolation of calibration data measured in a partial range to the full range

In this subsection, a proposal will be made of how the calibration data measured in a partial range has to be extrapolated to the full range. A good starting point for this task is the data of the reference transducer because here, data are available from both a partial range and the full range. This gives us the opportunity to check how precise such an extrapolation will be. In Figure 7, the interpolation deviation of the measurement up to 400 kN·m and the interpolation deviation up to the full range of 1.1 MN·m of the reference transducer are compared. In contrast to Figure 6, all the three different mounting positions were averaged.

As one can be seen from Figure 7, the curves for upward or downward measurement exhibit a sinusoidal behaviour. Due to this, the attempt is made to make a sinusoidal fit of that data. The equation function which was chosen for such a fit is:

$$y = y_0 + A \cdot \sin\left(\pi \cdot \frac{x - x_c}{w}\right) . \tag{4}$$

Thereby, y_0 is the offset, A is the amplitude, x_c is the zero, and w is the period of the sinusoidal function. These parameters are also illustrated in Figure 8, where one can see the sinusoidal fit of the upward row (only increasing torque) of the full-range data of the reference transducer. The uncertainties of the parameters are quite small and lie in the ranges of a few percent.

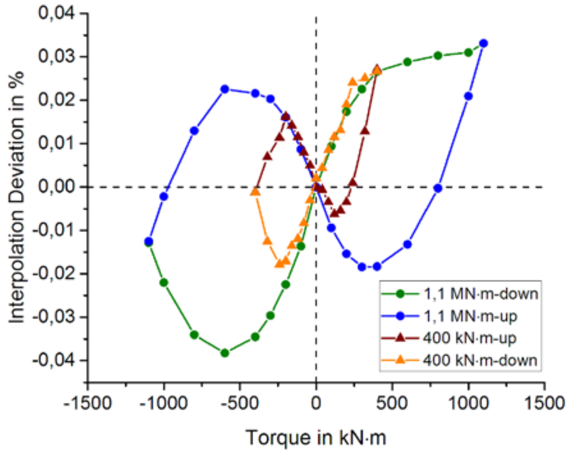

Figure 7. Interpolation deviation relative to the nominal torque of the reference transducer for a partial range up to 400 kN·m and the full range up to 1.1 MN·m. The curves are separated depending on whether the torque increased upwards or downwards.

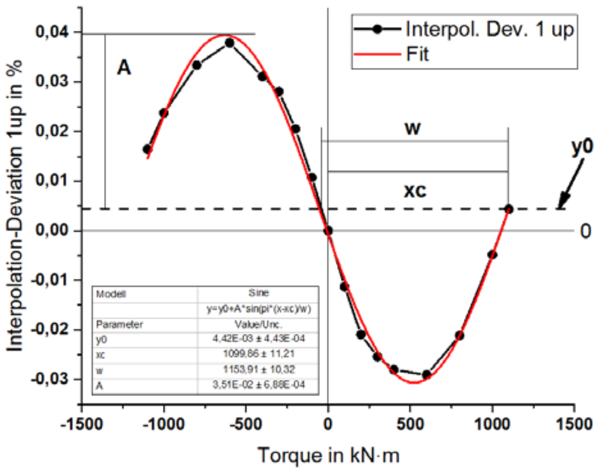

Figure 8. Sinusoidal fit of the interpolation deviation data of the upward torque measurement of the reference transducer in the full range.

The procedure for the extrapolation is now to fit the partial range data and the full range data with a sinusoidal function according to (4). Knowing the fitted parameter, one can then think about a strategy of how to scale the parameters from the partial range function to the full range function. Figure 9 shows the two fits of the partial range data and the full range data of the upward torque measurement. The horizontal, coloured dashed lines are the offsets of the two fitted functions. In view of the fact that the difference between the two offsets (y_0) is very small, one could neglect these for an extrapolation.

The parameters of the fits and their respective uncertainties can be seen in Table 3. Here one can see that the offsets have the largest uncertainty, whereby the zero and the period of the sinusoidal functions have smaller uncertainties. Starting from the parameters of the partial range data, an extrapolated sinusoidal function was calculated which is shown as a dashed curve in Figure 9.

Thereby, the offset y_0 from the partial range was chosen, the parameters x_c and w were scaled with a factor of 1100/400, (which is just the scaling of the measurement range) and the amplitude was calculated by scaling the amplitude of the partial range with the ratio of the amplitudes of the full range to the partial range. Normally one would not know this amplitude ratio, but one could estimate it by measuring several partial ranges. In this way, one would obtain several amplitudes which could be extrapolated linearly to the full measuring range. With the aid of the extrapolated interpolation deviation curve, one can now calculate measuring points which lie outside of the partial range as follows:

Table 3. Fitted parameters of the partial range data and of the full range data with a sinusoidal approximation according to (4).

400 kN·m			
Parameter	Value	Uncertainty	relative Uncertainty %
y_0	2.93E-05	4.72E-06	16.1
x_c	262.53	16.54	6.3
w	300.44	13.93	4.6
A	6.44E-05	6.53E-06	10.1
1.1 MN·m			
y_0	5.74E-05	1.18E-05	20.5
x_c	797.63	20.84	2.6
w	852.99	16.48	1.9
A	3.60E-04	1.79E-05	5.0

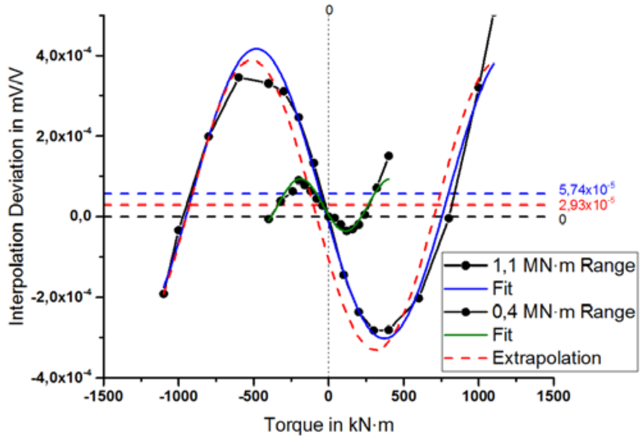

Figure 9. Interpolation deviation of the upward row of the part range and the full range data together with a sinusoidal fit. In addition an extrapolated sinusoidal function (dashed curve) is plotted.

$$y_i^{ex} = m_l \cdot x_i + \Delta y_i^{ex} \,. \tag{5}$$

Thereby, the extrapolated measuring points y_i^{ex} depend from the slope m_l of the linear interpolation in the partial range up to 400 kN·m and on the extrapolated interpolation deviation Δy_i^{ex} which is shown in Figure 9. Last but not least, one can now compare the measuring points calculated according to (5) with the actually measured points in the full range.

As one can be seen from Figure 10 the difference between the actually measured points and the extrapolated ones is mainly below 0.1 %. This difference is smaller or just in the order of the uncertainty of the measured torque in this region. Using the linear interpolation deviation data for an extrapolation procedure seems to be a feasible way. Nevertheless it should be noted that in the actual case of the 5 MN·m transducer this proposed extrapolation procedure will be more uncertain due to the quite scattering data from the partial range, see upper part of Figure 6. Further measurements of different partial ranges could improve the situation.

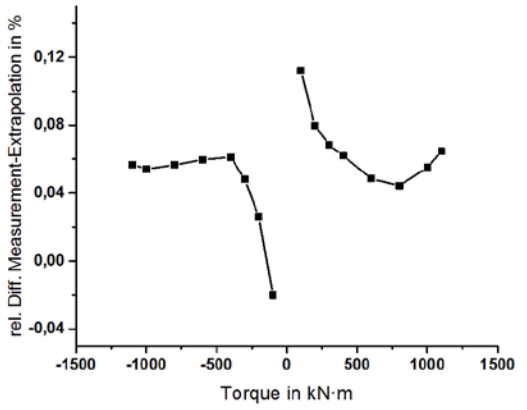

Figure 10. Relative difference between the extrapolated measuring points and the measured points in the full range up to 1.1 MN·m. The difference is given in percent relative to the measured points.

4. DEVELOPMENT OF A TORQUE CALIBRATION MACHINE FOR A RANGE OF UP TO 20 MN·m

To extend the torque calibration range above 1.1 MN·m, a complete new calibration machine will be built at PTB. This machine will be part of a Wind Competence Center which is funded by the German Federal Ministry for Economic Affairs and Energy. This center also includes, besides the new torque calibration machine, a big coordinate measuring machine and a wind channel for the calibration of LIDAR systems. The coordinate measuring machine should be able, e.g., to geometrically measure the gear parts of the nacelles. The capacity will be sufficient for gearwheels with a diameter of up to 3 m. To realize this new center, two new buildings will be built on the PTB site: one for the coordinate measuring machine and the LIDAR system, and one especially for the new torque calibration machine.

The new torque calibration machine (see Figure 11) will be designed in a first stage for torques of up to 5 MN·m, and in a second stage up to 20 MN·m. Similar to the 1.1 MN·m calibration machine, the operation principle will also be based on two lever systems: one actor lever and a measuring lever. On the actor lever, the forces will be created by two 1.2 MN servo-hydraulic cylinders. The lever has a length of 6 m. In addition, also bending moments and axial forces can be applied by a pair of horizontally aligned servo-cylinders. Last but not least, the servo cylinders will also be able to operate dynamically in a frequency range of up to 3 Hz. For that reason, the foundation of the machine is mounted on air springs. Each spring can be individually adjusted in pressure to achieve optimal damping and to avoid resonance frequencies. The measuring lever system includes a pair of force transducers to measure the main force component of the torque and several spring elements for the detection of parasitic bending forces and moments. The base as well as the frame of the machine is designed already for 20 MN·m. By upgrading the machine with 3.6 MN hydraulic cylinders for the generation of the torque an extension to 20 MN·m will be realized.

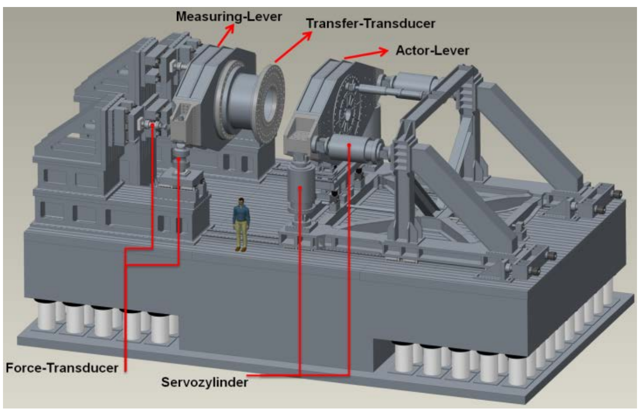

Figure 11. Design of a new standard torque calibration machine for torques up to 20 MN·m.

5. CONCLUSIONS

To increase the reliability of wind turbines, extensive technical tests are performed in nacelle test benches. One important aspect of these tests is the torque in the MN·m range, which is initiated in the nacelle. Traceable torque calibration in the MN·m range can so far only be realized by the 1.1 MN·m Standard Calibration Machine at PTB. One solution for a traceable torque calibration of nacelles is to use transfer torque transducers which are calibrated in special standard calibration machines which are traced to the SI. Currently, a calibration of up to 1.1 MN·m of such a transducers was realized. For the above-mentioned torques, special extrapolation procedures have to be developed. One possibility could be to use in this extrapolation the knowledge of the characteristic sinusoidal shape of the interpolation deviation. To overcome the lack of calibration range, a new machine will be installed insight the PTB´s new Wind Competence Center. This machine will be able to calibrate torques of up to 5 MN·m in a first stage and up to 20 MN·m in a second stage.

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