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~~Traceable~~MN·m Torque Calibration for Nacelle Test Benches ~~in the MN·m Range~~using Transfer Standards

Christian ~~Schlegel~~Schlegel[1], Holger ~~Kahmann~~Kahmann[1], Rolf Kumme[1]

[1] *Physikalisch~~-~~Technische Bundesanstalt, Bundesallee 100, ~~D-~~38116 Braunschweig, ~~Christian.Schlegel@ptb.de, Holger.Kahmann@ptb.de, Rolf.Kumme@ptb.de~~ Germany*

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.

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Corresponding author: Christian Schlegel, e-mail:Christian.Schlegel@ptb.de

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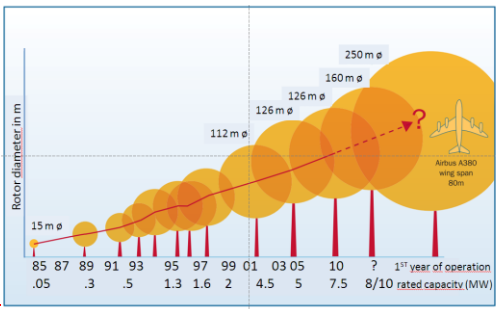
~~I.~~1. INTRODUCTION

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 % ~~in~~by 2025. From this development it is clear that ~~by~~ 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 Fig. 1, taken from [1].

~~It is obvious of~~ Of course~~ that a~~, 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



~~*Fig. 1. Development of the size of wind turbines.*~~

parameter for such a nacelle is the torque load which is initiated in the field according to the strength of the wind field.

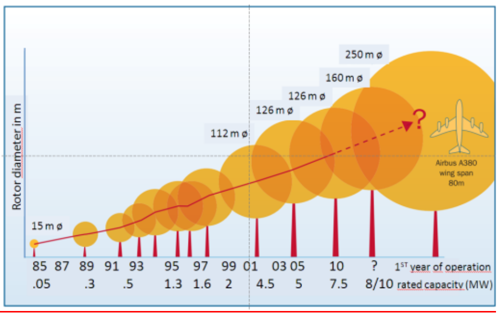


Figure 1. Development of the size of wind turbines.

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.

One of the most important parameters of such test benches is the torque which is initiated in the nacelle. The torque M is directly related to the electrical power P_{el} and depends on the revolution speed n.

$$M = \frac{P_{el}}{2\pi \cdot n} \qquad (1)$$

Table 1 shows an example of two points of operation.
As shown in equation 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.

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

Electrical Power in MW	Revolution Speed in rpm	Torque in MN·m
5	14	3.4
10	9	10.6

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

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.

In the next chapters we will introduce a torque calibration machine which is able to calibrate torques up to 1.1 MN·m. Furthermore we will present a 5 MN·m torque transducer which will be investigated for the application of torque measurement.

~~II.~~2. ABOUT THE TRACEABLE ~~CALIBARTION~~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~~ which –~~, in the simplest case, is the gravitational force $m \cdot g_{loc}$, whereby m is the mass and g_{loc} is the gravitational constant.

$$\vec{M} = \vec{r} \times \vec{F}$$
$$M = r \cdot F \cdot \sin(\vec{r}, \vec{F}) = m \cdot g_{loc} \cdot l, \quad r = l \qquad (2)$$

Based on this principle, there are torque calibration

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machines, which, for the force initiation, use mass stacks which can be varied in such a way that various torque steps can be applied [2]. 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. 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. This principle is used, for example, by the

~~*Fig. 2. The 1.1 MNm Standard Calibration Machine of PTB.*~~

PTB 1.1 MN·m Standard Calibration Machine [3], see Fig. 2. On the measuring side, which is the upper traverse in ~~Fig~~Figs. 2 and 3, the lever is connected at both ends with force transducers. In this way, the torque is traced ~~back~~ by the length of the lever arm and the measured forces of the calibrated force transducers. ~~In the machine, two different pairs force of 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 has a relative uncertainty of the torque of 1.0·10⁻³, whereby in the upper range one obtains 0.8·10⁻³. The torque itself is created by two mechanical spindles as main drives which are located between the two lower platforms, see Fig. 2.~~

Figure 2. Standard Torque Calibration Machine fot nominal torques up to 1,1 MN·m.

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 $0.8 \cdot 10^{-3}$. 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 Figs. 2 and 3.

In addition, there is a secondary drive to define the horizontal position (left) and to reduce the cross force F_x and the bending moment M_z. 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.~~-~~ Connected to the measuring lever are spring elements 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.

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~~The calibration procedure which is used for the transducer under test usually follows German Standard DIN 51309.~~

~~III. TORQUE TRANSFER TRANSDUCER FOR NACELLE TEST BENCH CALIBRATION~~

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

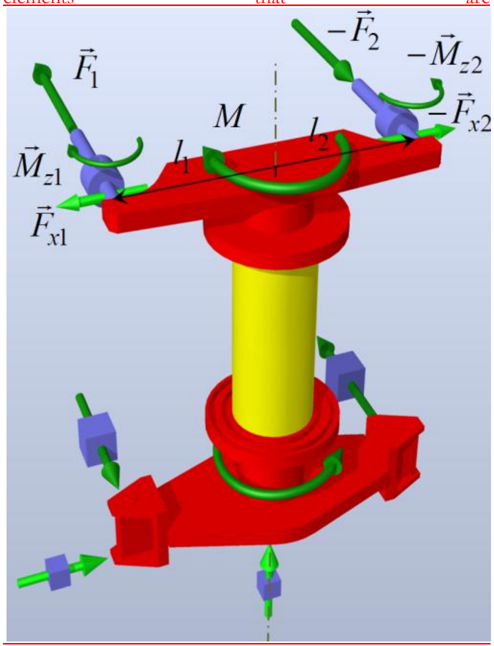

Figure 3. Working principle of the double lever arm system of the 1.1 MN·m Torque Calibration Machine.

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

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

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

Parameter	Value	Standard Uncertainty	Distrib.	Sensitivity Coeff.	Uncert.	Index
F_1	500.0	0.289	rectang.	1.1	0.32	49.6 %
l_1	1.1	$52.5\cdot10^{-6}$	rectang.	500	0.026	0.3 %
F_2	-500.0	0.289	rectang.	1.1	0.32	49.6 %
l_2	1.1	$52.5\cdot10^{-6}$	rectang.	500	0.026	0.3 %
M_{z1}	0.02	0.0115	rectang.	1.0	0.012	0.0 %
M_{z2}	0.02	0.0115	rectang.	1.0	0.012	0.0 %
M	1100.04	0.451				

Result	Value	expanded Unc.	K-Factor	Coverage-Intervall
M	1100.04	0.90	2.00	95%
		rel: $8.2\cdot10^{-4}$		(Normal-Dist.

connected with the force transducers.
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 $1.0\cdot10^{-4}$ can be achieved. Nevertheless, in the uncertainty budget, a more conservative value of $1.0\cdot10^{-3}$ 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.

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 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 [3]. 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 ~~from HBM~~ will be used, see Fig. ~~2.~~ 4. During the above-mentioned EMPIR project, an extrapolation procedure for the range above 1.1 MN·m will be developed.

In Fig. ~~3~~4, the commercial transducer ~~from HBM~~ 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

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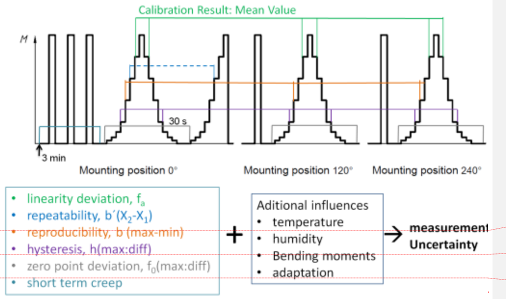
~~*Fig. 3. 5 MN·m torque transducer together with two DMP41 bridge amplifiers for the readout of the 8 channels of the transducer.*~~

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 ~~torque~~torques) will be studied to describe effects 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 ~~cross-talk~~crosstalk effects.

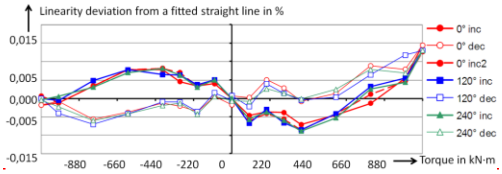
First calibration measurements were performed with the shown 5 MN·m torque transducer in the ~~above described~~ PTB 1.1 MN·m Standard Calibration Machine above described. Thereby, the procedure according to the German Standard DIN 51309 was applied [~~4].~~ 5]. Fig. ~~4~~5 shows the calibration procedure according to DIN 51309. After three preloads, a certain number of upward and downward steps are performed in three mounting positions. At least 8 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 Fig. ~~4.~~5 in the calibration procedure.

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

One characteristic result of the calibration is the deviation from linearity shown in Fig. ~~5~~6. The curves reflect the relative deviations of the measured values from a fithe r straight line; the deviations are related to the measured mean value of the fistr value. The fivalue straight line is defined by the value of its slope; the axis intercept is zero.



~~*Fig. 4. Calibration procedure according to the German Standard DIN 51309. Indicated are several parameters which will be derived from the calibration data.*~~



~~*Fig. 5. Linearity deviation from a fitted straight line through the origin at zero. The deviations are related to the measured mean values of the final value.*~~

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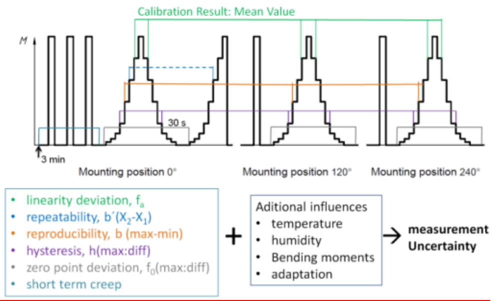

Figure. 5. Calibration procedure according to the German Standard DIN 51309. Indicated are several parameters which will be derived from the calibration data.

The upper diagram in Fig. 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 shown in Fig. 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 ~~measurement campaign~~calibration of the 5 MN·m transducer, also partial ranges ~~in between~~within the 1.1 MN·m range were measured. This data will also be used to develop an extrapolation ~~procedures~~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 ~~from~~with the bending forces and moments as well as the axial ~~force~~forces.

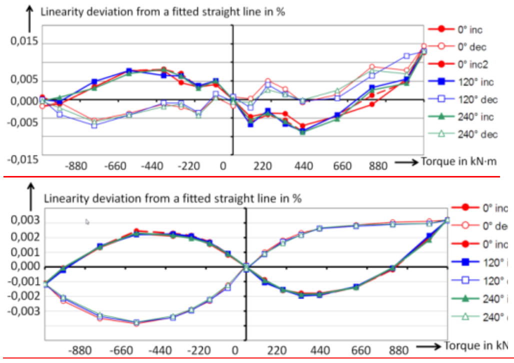

Figure 6. The upper curve is the linearity deviation from a fitted straight line through the origin at zero of the 5 MN·m transducer. The lower curve shows the same behaviour of the 1 MN·m reference transducer .The deviations are related to the measured mean values of the final value.

3.2. ~~IV.~~ 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.

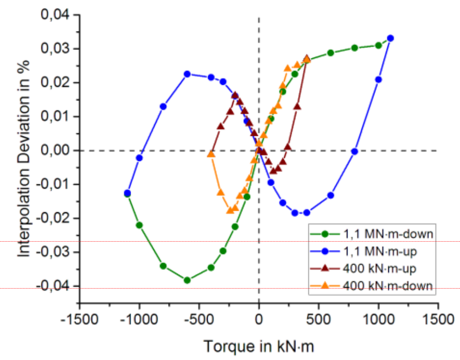

Figure 7. Interpolation deviation relative to the nominal torque of the reference transducer for a partial range up to 400 kN·m and the full range up to 1.1 MN·m. The curves are separated depending on whether the torque increased upwards or downwards.

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.

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The uncertainties of the parameters are quite small and lie in the ranges of a few percent.

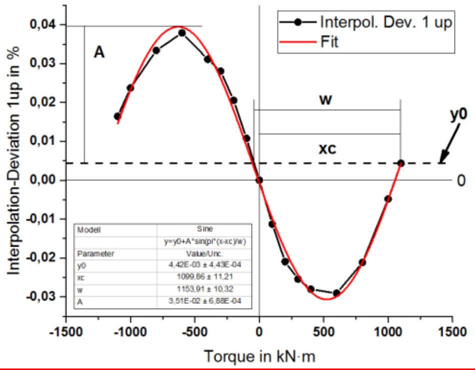

Figure 8. Sinusoidal fit of the interpolation deviation data of the upward torque measurement of the reference transducer in the full range.

The procedure for the extrapolation is now to fit the partial range data and the full range data with a sinusoidal function according to equation 4. Knowing the fitted parameter, one can then think about a strategy of how to scale the parameters from

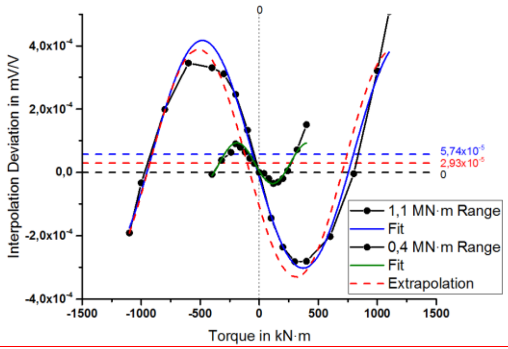

Figure 9. Interpolation deviation of the upward row of the part range and the full range data together with a sinusoidal fit. In addition an extrapolated sinusoidal function (dashed curve) is plotted.

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.

Table 3. Fitted parameters of the partial range data and of thefull range data with a sinusoidal approximation according to equation 4.

400 kN·m			
Parameter	Value	Unc.	rel.Unc. in %
y0	2,93E-05	4,72E-06	16,1
xc	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			
y0	5,74E-05	1,18E-05	20,5
xc	797,63	20,84	2,6
w	852,99	16,48	1,9
A	3,60E-04	1,79E-05	5,0

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:

$$y_i^{ex} = m_l \cdot x_i + \Delta y_i^{ex}$$

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(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 equation 5 with the actually measured points in the full range.

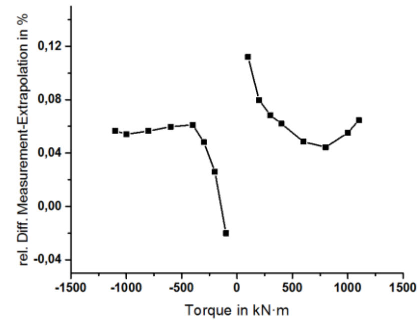


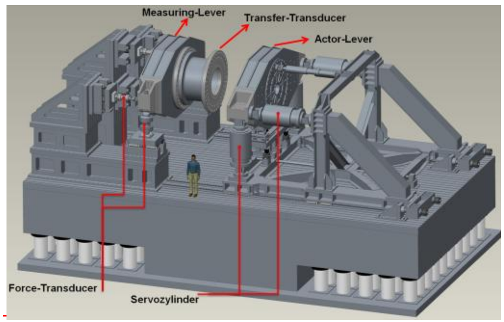
Figure 10. Relative difference between the extrapolated measuring points and the measured points in the full range up to 1.1 MN·m. The difference is given in percent relative to the measured points.

As one can be seen from Figure 10 the difference between the actaully 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.

4. DEVELOPMENT OF A TORQUE CALIBRATION MACHINE FOR A RANGE OF UP TO 20 ~~MN·M~~MEGANEWTONMETER

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 ~~of Economy~~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~~these new center, two new buildings will be built on the PTB site~~,~~: one for the coordinate measuring machine and the LIDAR system, and one ~~speciallyespecially~~especially for the new torque calibration machine.

The new torque calibration machine (see Fig. ~~6~~7) 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



~~*Fig. 6. Design of a new standard torque calibration machine for torques up to 20 MN·m.*~~

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 MN servo-hydraulic cylinders.

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 ~~an~~ 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.

~~IV. CONCLUSION~~

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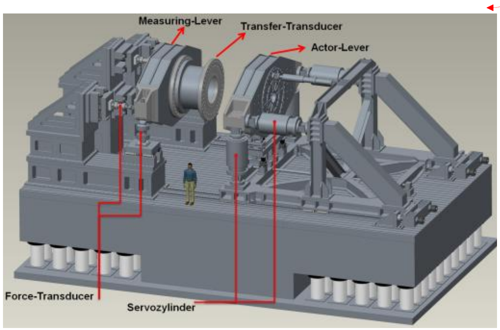

Figure 11. Design of a new standard torque calibration machine for torques up to 20 MN·m.

5. CONCLUSIONS

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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 ~~back~~ to the SI. Currently, a calibration of up to 1.1 MN·m of such a transducers ~~can be~~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 ~~built~~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.

Formatiert: Englisch (Großbritannien)

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