IMEKO 24th TC3, 14th TC5, 6th TC16 and 5th TC22 International Conference
11 – 13 October 2022, Cavtat-Dubrovnik, Croatia

FINAL DESIGN OF PTB’S 5 MN·m TORQUE STANDARD MACHINE WITH POSSIBLE FUTURE EXTENSION TO 20 MN·m

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Abstract:

This paper describes the final design of the new 5 MN·m torque standard machine which is currently under installation at PTB in Germany. The machine can generate additional components for multi-component investigations and it is capable of applying - to a certain degree - dynamic torques. In the future, it can be extended to a maximum torque capacity of 20 MN·m.

Keywords: torque standard machine; large torque; torque for wind energy; torque calibration

1. INTRODUCTION

Recent years have seen the power capacity of wind turbines installed offshore increase from about 5 MW to as much as 10 MW (correlating to a torque of 5 to 10 MN·m at a typical rotational speed of 10 rpm), with the future trend pointing to larger turbines that by 2027 will be capable of generating up to 15 MW. For the testing of nacelles on test benches, traceability is therefore essential with respect to mechanical power and hence to torque measurement, which represents one of the largest uncertainty contributions when determining efficiency. To address this need, PTB has developed a new torque standard machine with a capacity of 5 MN·m that can be optionally extended to 20 MN·m. An initial design of the machine was presented in [1], but the machine has undergone further optimization over the past years. This work is now finished and will be described in this paper.

2. DESCRIPTION OF WORK

The final design of this torque standard machine – the world’s largest – is shown in Figure 1. The pictured machine is already extended for the final range of up to 20 MN·m, with two 3.5 MN cylinders acting on the lever system and four 400 kN cylinders for generating bending moments and axial forces. The first step was to design the machine for the 5 MN·m torque range, as is will be described in more detail below. For this 5 MN·m range the machine is operated with two 1.2 MN cylinders that generate torque up to 5 MN·m and four 100 kN cylinders for generating the bending moments and axial forces. The possible ranges and expected relative expanded uncertainties of this configuration are shown in Table 1. The machine was designed entirely by PTB. The large components are manufactured according to PTB specifications by external companies and assembled at PTB by in-house staff. Measurement components are manufactured in PTB workshops.

3. MACHINE DESIGN

The torque standard machine described here is a reference machine that is able to produce not only torque but also bending moments and axial and shear forces. These forces and moments can be arbitrarily combined in line with the capacity of the hydraulic cylinders, and are initiated via servohydraulic cylinders mounted on the machine’s actuator lever arm. The generated torque is then transferred via the device under test (DUT) to the measuring side and measured with the reference measuring system connected to the measuring lever.

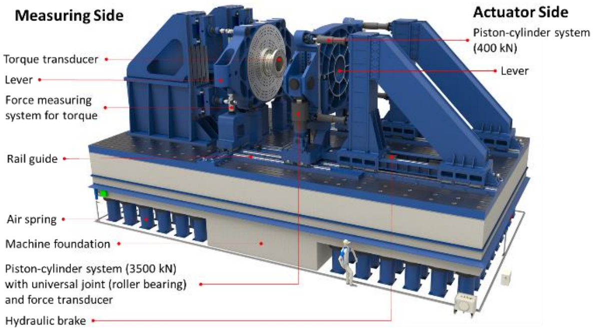

Figure 1: Design of the 5 MN·m torque standard machine with optional extension to 20 MN·m

Table 1: Quantities and their uncertainties.

Quantity	Range	Uncertainty
Torque M_z	5 MN·m	< 0.5 % ($k = 2$)
Bending moment My	900 kN·m	< 1 % ($k = 2$)
Bending moment M_x	600 kN·m	< 1 % ($k = 2$)
Axial force F_z	400 kN	< 1 % ($k = 2$)
Shear force Fy	(2.4 MN)	< 1 % ($k = 2$)

The reaction forces initiated by the torque excitation are absorbed by the foundation, which itself is mounted on 65 air springs. These provide active damping in the case of a dynamic torque excitation by the hydraulic cylinders. The foundation is in addition responsible for regulating the position and level. The eigenfrequency of the air springs can be adjusted in a range of 0.85 Hz to 1.4 Hz by means of an additional air reservoir. The foundation is 17 m long, 9 m wide, and weighs 1650 t. On its surface is mounted a T-slot field with a flatness of 0.125 mm. This field is needed to ensure the exact mounting and positioning of the machine frame. While the measuring side is rigidly connected to the foundation, the actuator side can be shifted using a linear guide unit. This allows the mounting space for the DUT to be adjusted as required.

4. MEASURING SIDE

The primary feature on the measuring side is the reference measuring system. As seen in Figure 2, it consists of mechanically decoupled force transducers and the measuring lever. Elastic deformations result in force and moment shunts, which are the origin of the systematic errors illustrated in Figure 3.

For the decoupling of the shunts, flexure hinges are used that are coupled with the force transducers to form the measuring strings (MSs). These strings not only reduce the shear force shunts but also reduce the cross talk of the reference measuring system. The MSs have been mutually adjusted such as to exhibit maximum stiffness for the primary quantities (e.g., torque) and minimum stiffness for the other degrees of freedom.

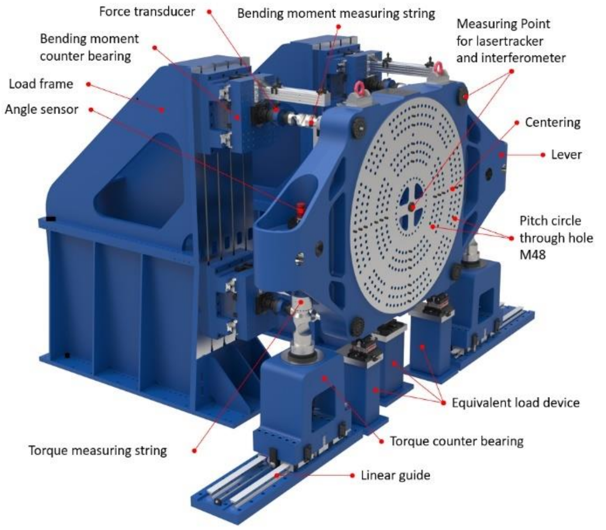

Figure 2: Measuring side for the 5 MN·m operation mode

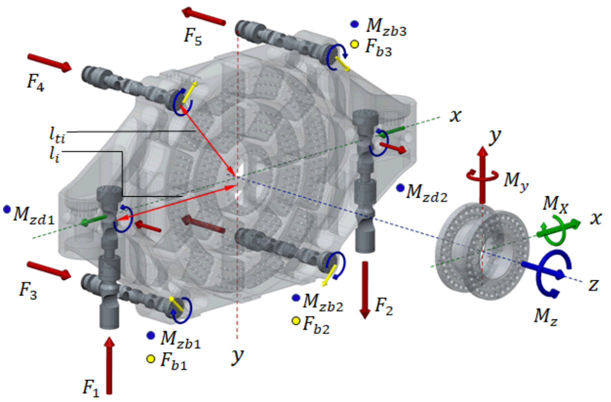

Figure 3: Multicomponent force reference measurement system connected to the lever on the measurement side

The torque, M_z, is measured via two vertical torque MSs. For force measurement, very stiff shear force transducers with a nominal force of 1.2 MN are used. These transducers are calibrated in the PTB 2 MN Deadweight Force Standard Machine, which has a relative uncertainty of $2 \cdot 10^{-5}$ (k=2). The force transducers further have strain gauges for use in measuring bending moments. The bending moments, M_x, M_y, and the axial force, F_z, are measured through four horizontal MSs with a nominal force of 500 kN each.

The reference torque can be calculated by the equation shown here, which factors in the shear force shunts as well as other influences like the angles between the MSs and the lever

$$M_z = \sum_{1}^{i=2} \cos(\alpha_i) \cdot \cos(\beta_i) \cdot F_i \cdot l_i (1 + \alpha_{St} \cdot \Delta T) + \sum_{1}^{i=2} M_{zd,i} + \sum_{3}^{i=6} M_{zb,i} + \sum_{3}^{i=6} F_{b,i} \cdot r_{t,i} \,. \quad (1)$$

Table 2: Description of the forces and moments indicated in Figure 3.

Symbol	Description
M_z	Main torque
$M_{zd,i}$	Bending moment shunt - MS 1-2
$M_{zb,i}$	Torque moment shunt - MS 3-6
$F_{b,i}$	Force shunt through MS 3-6
F_i	Reference force of MS 1-2
l_i	Lever length
r_i	Lever arm of the tangential force
α_i β_i	Angles of the force vector MS 1-2
α_{St}	Linear expansion coefficient

The measuring lever is a casting produced of nodular graphite cast iron (GJS 500-7).

Through topological optimization of the lever while maintaining the required high stiffness, it was possible to reduce the total weight to the current 30.2 t. The result is the overall measuring system depicted in Figure 4.

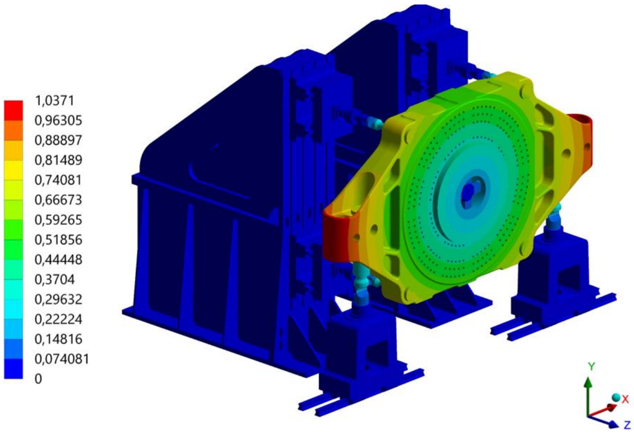

Figure 4: Deformation in mm of the whole measuring system at 5 MN·m torque

For the characterization of the shunts, the stiffnesses of all MSs are determined. For this purpose, a special test bench was developed [2]. During normal operation, an absolute measuring tilt sensor (Zeromatic 2/2) and an interferometer measure continuously and under load both the position and the position change of the lever around the x- and z-axes (see Figure 5). Combining these results with the known stiffnesses of the MSs allow the force and moment shunts to be determined.

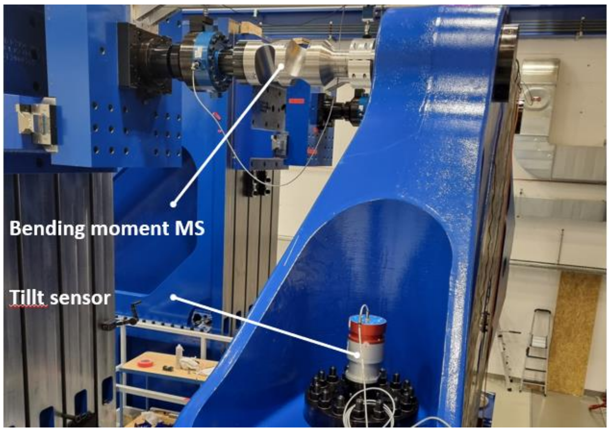

Figure 5: MS for bending moment and the tilt sensor

To ensure that the MSs are in perfect perpendicular alignment to the measuring lever surface, the bending moment counter bearings can be adjusted in the x- and y-directions using a laser tracker system and the resulting angles measured.

To extend the measuring range of the torque, the measuring lever has two positions for the inclusion of different MSs for measuring the main torque in different torque ranges, see Figure 6. The different positions then realize a lever length of 5 m and 6 m, respectively. This feature will allow torques of 10, 15 and 20 MN·m to be measured by simply applying the right MS with the necessary lever length.

The torque counter bearing can be moved via a linear guiding unit, controlled by a position measuring system, to the position of the needed MS and then fixed in place by a hydraulic locking system.

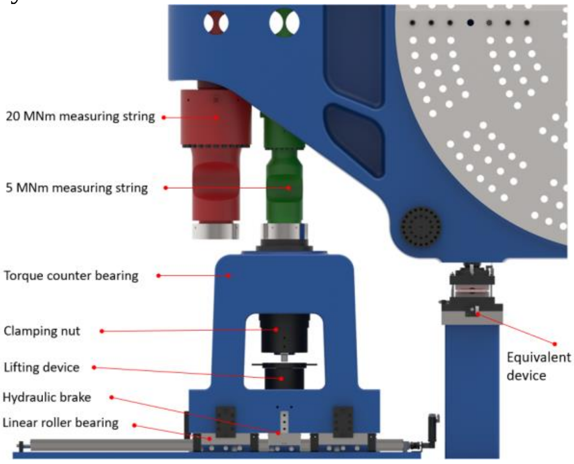

Figure 6: The two MSs for different torque ranges

This system makes it easy to change the measuring range within a relatively short time. Finally, the MS is fixed in place by a clamping nut on the torque counter bearing.

A substitute load system equipped with levelling elements and an integrated position measuring system can hold the whole lever during the change of the measuring range. This system guarantees that the lever returns to its original position after the change of the measuring range.

5. ACTUATOR SIDE

The creation of the forces and moments is realized through servohydraulic cylinders equipped with force transducers to control the real forces. The actuator lever is made of the same nodular graphite cast iron (GJS 500-7) as the measuring lever and has a total weight of 32 t. Two vertically arranged servohydraulic cylinders, each with a nominal force of 1.2 MN, form a force pair in the y-direction and generate the main torque. The connection of the servocylinders to the actuator lever is realized by two 6 t cardan joints equipped with spherical roller bearings. Four servocylinders arranged horizontally in the z-direction and having a nominal force of 100 kN can be used to produce bending moments, axial forces and shear forces. The servocylinders are supported on the actuator frame and transfer the forces to the foundation. The positioning of the actuator lever during the mounting of the DUT and the compensation of the shear forces are realized by means of two additional servohydraulic cylinders arranged in the x-direction.

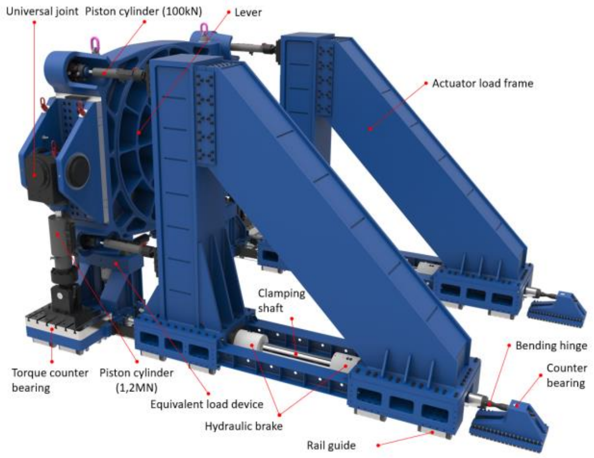

Figure 7: Actuator side for the 5 MN·m range

A substitute load system holds the actuator lever if no DUT is mounted or if the entire machine is switched off. This substitute system further includes an integrated fall protection facility consisting of a hydraulic cylinder and a fastening unit. When the servohydraulics are switched off, this mechanism is extended and clamped to ensure that the weight of the DUT is supported.

The actuator frame and the torque counter bearings are firmly connected to one another and can be moved by means of two separate spindle drives onto special rails cars. In this way, the whole actuator frame is supported by 28 such cars, which travel along two parallel guide rails. Each of the cars can be loaded with 2 MN.

Once the mounting space for the DUT has been established and the DUT itself is rigidly braced by the two levers, the locking unit of the actuator lever guiding system can be activated and the entire setup clamped. The complete actuator side is then supported via the clamp shaft and the counter bearing by the foundation. Figure 7 shows a drawing of the complete actuator side.

6. ADAPTATION OF THE DUT

For the mounting of the torque transducers, both the measuring lever and the actuator lever have through-holes for M48 clamping bolts with identical geometries on both lever arms (see Table 2). For the mounting of transducers provided by customers, adapters with threaded holes matching the geometries given in Table 3 are required. The minimum length of the DUT with adapter is 1550 mm.

Table 3: Mounting pitch circles on both levers with their appropriate boreholes.

Adapter – Threads for transducer			
Circle	**Diameter**	**Number of threads**	**Thread**
1	900 mm	30	M36
2	1100 mm	32	M64
3	1450 mm	40	M48
Lever – Holes for adapter			
Circle	**Diameter**	**Number of holes**	**Thread**
1	900 mm	30	M36
2	1450 mm	32	M48
3	1725 mm	40	M48
4	2000 mm	48	M48
5	2575 mm	60	M48
6	2850 mm	60	M48
7	3125 mm	72	M48

For the mounting of the PTB 5 MN·m transfer torque transducer, a special adapter made of nodular graphite cast iron (GJS 500-7) was manufactured (see Figure 8). This first allround adapter has an additional 1450 mm circle with M48 through-holes where future customer devices can be mounted. This pitch circle is intended exclusively for the mounting of transducers that will be excited by not more then 5 MN·m. Starting from this circle, separate steel disks can be used to adapt for transducers with smaller measuring ranges.

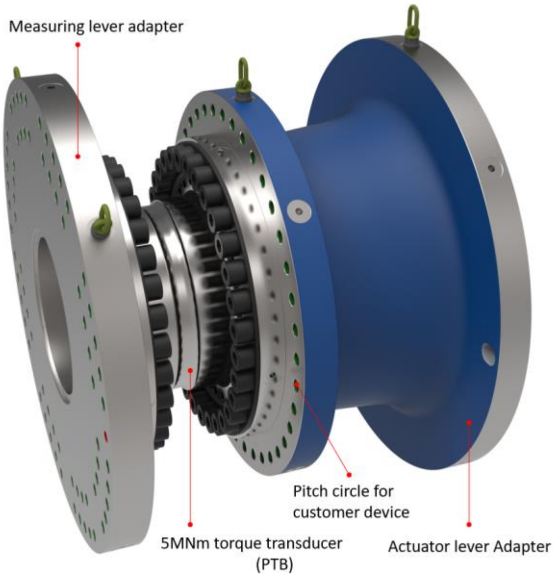

Figure 8: Adaptation of the PTB 5 MN·m transducer

7. CONCLUSION

The new PTB 5 MN·m standard torque machine with optional extension up to 20 MN·m. The new torque reference machine is based on a two-lever system, with one lever creating torque via piston cylinders (actuator side) and another lever equipped with a reference measuring system that can measure all initiated forces and moments (measuring side). In addition to the main torque, the machine can also create and measure bending moments, shear forces and axial forces and as such is able to calibrate a multicomponent transducer system.

The manufacturing of the machine components is nearly finished and the machine is now almost completely set up at PTB's Competence Center for Wind Energy (CCW) in Euler Building II. The hydraulics will be installed in the coming months and machine testing and operation is scheduled to begin in late 2022.

8. REFERENCES

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