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PRINCIPLE AND DESIGN OF A 5 MN·M TORQUE STANDARD MACHINE

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Abstract: This paper describes the design and working principle of a new multicomponent torque standard machine with a torque range of 5 MN·m. The design was in particular optimized to reduce the influences of parasitical components on the main torque component.

Keywords: torque standard machine, 5 MN·m, multicomponent

1. INTRODUCTION

Wind energy is one of the most important energy sources for the future. The mechanical power is proportional to the torque, which is in the range of up to 5 MN·m for most wind energy systems. This moment can be measured in test benches (nacelle test stands) with torque transducers; for optimal measurement results, these torque transducers should be calibrated, preferably in a torque standard machine.

The torque standard machine with the currently largest measuring range reaches torques of up to 1.1 MN·m [1]. A larger torque standard machine with a measuring range of 5 MN·m and a relative uncertainty of < 0.5 % (k = 2) is therefore being developed at PTB.

In addition to the torque, forces and bending moments are also introduced when testing wind turbines at test benches. For the investigation and calibration of these components, the torque standard machine allows the torque to be combined with other quantities.

Quantity	Nominal load	Uncertainty
Torque M_z	5 MN·m	< 0.5% (k = 2)
Bending moment M_y	3 MN·m	< 1% (k = 2)
Bending moment M_x	2 MN·m	< 1% (k = 2)
Axial force F_z	1 MN	< 1% (k = 2)
Shearing force F_y	1 MN	< 1% (k = 2)

For dynamic investigations, it is possible to superimpose an additional dynamic moment of 600 kN·m in a frequency range up to 3 Hz onto the static moment.

Since the torque range in the field of wind energy will keep on increasing, this machine design allows a future extension of the measuring range up to 20 MN·m.
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2. PRINCIPLE OF THE CALIBRATION MACHINE

The new torque standard machine operates according to the reference principle. The moments and forces are generated and measured separately (i.e. in different places). The forces and moments are generated on the actuator side via hydraulic cylinders and then transmitted onto the measuring side via the EUT. These two entities are kept apart in order to prevent unknown friction torques from occurring in the plain bearing joints of the hydraulic cylinders [2] and to avoid temperature influences and angle deviations between the force vector and the lever. The measuring device itself is realized with a horizontal torque axis. The torque M_z is measured by means of a force lever system. Besides the torque, the bending moments M_x, M_y and the forces F_z, F_x and F_y can also be measured. All moments are measured via force couples with very rigid force transducers. Figure 1 below shows a schematic representation of the measuring device with the configuration of the test sections for the measurement of the respective components.

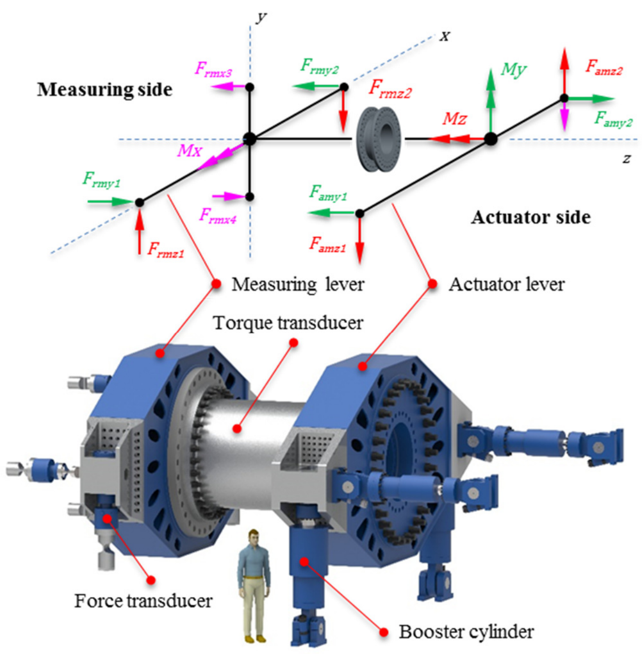

Figure 1: Principle of the torque standard machine

Besides the measurement uncertainty contributions of the reference measuring parts, a number of other influences prevail which have to be taken into account in the design. In the following, we will deal in more detail with some of the basic mechanical influences and how to avoid them. The elastic deformations of the force transducers, levers and machine frames cause bending moments, torques and shearing forces to occur which lead to an error inherent in the system in the form of by-passes when the actual moment is being determined. Reducing these influences is necessary, not only with regard to the reference moment, but also for the cross-talk with the force measuring parts of the machine. These influences are partly reduced via the design by using flexible springs. Together with the force transducers, the flexible springs form a sensible combination which represents a measurement chain. Figure 2 shows a simulation of the whole measuring side and of the interaction between the machine frame, the measuring levers, the force transducers and the flexible springs. The red areas show the total maximum Deformations of 0,8 mm.

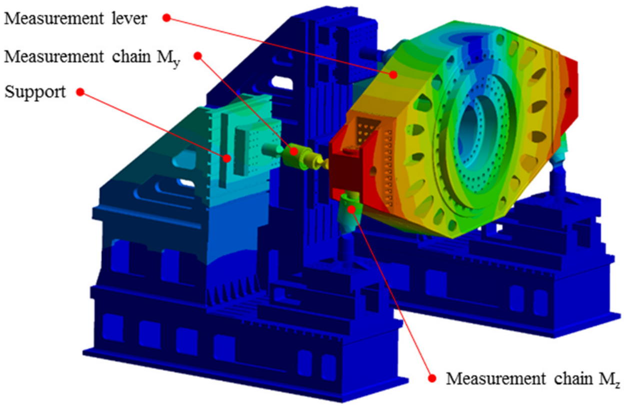

Figure 2: Measuring side: Lever and frame loaded with a 5 MN·m torque moment and a 3 MN·m bending moment

Besides, the fact that the machine is in a horizontal position also contributes to reducing by-passes since, during the measurement of the torque M_z, all parts of the frame which lie within the force flow exhibit high tensile stiffness and compressive rigidity as well as small deformations in the y-direction due to the fact that they are directly anchored in the foundation. As a result, the restoring forces occurring at the measuring chains of the other degrees of freedom are low.

For the measuring chains used to measure the bending moments, a solution was selected which allows the machine's frames to be arranged with high supporting stiffness and, at the same time, exerts only small influences on the applied torque. A larger lever arm induces larger shearing forces; however, it also enables the use of measuring chains with lower nominal loads and more resilient joints. Thus, due to the measuring chains which are arranged in pairs, it is possible to achieve a small uncertainty even in the case of the bending moments.
When designing the measuring chains, the objective was to create a balanced tuning of the flexible springs between the resilience and the tensile stiffness and an optimal spacing of the bending joints. This was achieved, among other things, by the fact that the forces and moments were determined at the contacts between the components when optimizing the measuring chains by means of FEM simulation on the sub-model of the complete assembly (Figure 3). Figure 4 represents all the occurring by-passes.

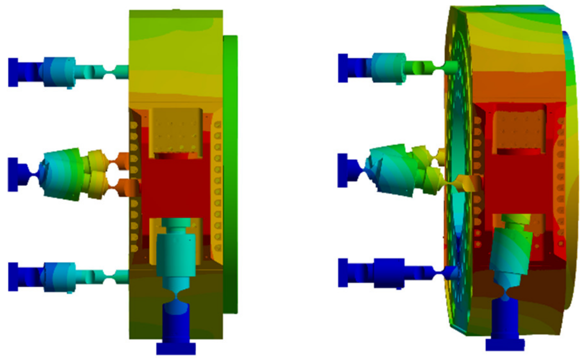

Figure 3: Lever loaded with a torque moment and combined with a bending moment

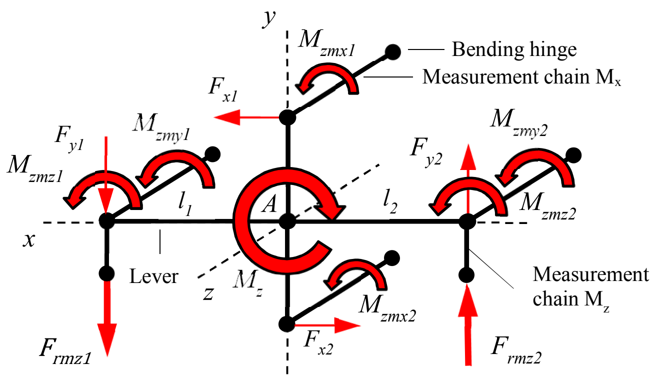

Figure 4: Mechanical influences considered for the main torque moment M_z

$$M_Z = F_{rmz1} \cdot l_1 + F_{rmz2} \cdot l_2 + \sum_{i=2}^{6} M_i = \sum_{i=1}^{6} M_i \qquad (1)$$

Taking these influence quantities into account, the applied moment M_z can be calculated as follows according to equation (1). In the current state, the individual systematic influences have been reduced to the values listed in Table 2. Thus, the total error due to systematic influences amounts to less than 0.2 %. Since the by-passes can only be reduced up to a certain extent, the flexible springs are equipped with strain-gauge applications in order to measure the remaining bending moments, torques and shearing forces.

Symbol	Designation
M_z	Moment to be determined
M_{zr}	Reference moment from reference force $F_{rmz1,2}$
$M_{zmz1,2}$	Bending moment throughout measuring chain M_z
$M_{zmy1,2}$	By-pass throughout measuring chain M_y
$M_{zmx1,2}$	By-pass throughout measuring chain M_x
$M_{zFy1,2}$	Moment from force by-pass $F_{y1,2}$
$M_{zFx1,2}$	Moment from force by-pass $F_{x1,2}$
$F_{rmz1,2}$	Reference force torque M_{rz}
$F_{y1,2}$	Force by-pass throughout measuring chain M_y
$F_{x1,2}$	Force by-pass throughout measuring chain M_x
M_i	Individual moments in Table 2
$l_{1,2}$	Lever arm lengths

Table 1: Designations of quantities

i	Systematic influences	Partial moment	Fraction
1	$M_{zr\ 1,2}$	4.991 MN·m	99.82 %
2	$M_{zmz1,2}$	281 N·m	0.006 %
3	$M_{zmy\ 1,2}$	361 N·m	0.007 %
4	$M_{zmx1,2}$	327 N·m	0.007 %
5	$M_{zFy1,2}$	6634 N·m	0.133 %
6	$M_{zFx1,2}$	1524 N·m	0.03 %

Table 2: Results of the FEM simulation

The measuring lever was dimensioned to have a length of 6 m. The lever arm length was planned taking the preload of the lever and of the EUT into account in such a way that force transducers with a nominal load of 1.5 MN can be used and calibrated in a deadweight machine. For future torques of up to 11 MN·m, force transducers can be calibrated in the 2 MN force standard machine and up to 20 MN·m in the 5 MN force standard machine. In the 1 MN force standard machine, the flexible springs are calibrated by means of an additional device with axial force combined with shearing forces, bending moments and torques [3]. The lever arm will be calibrated using a laser tracker while still assembled. During the calibration, the spacing of the flexible springs, which transmit the forces to the lever arm, and the position vectors of the measuring chains are determined. The laser tracker will tested at a specially developed reference wall of PTB [4].

3. DETAILS OF THE TORQUE MACHINE

Figure 5 below shows the design as it is at present. The machine has dimensions of 17 m in length by 9 m in width. The total mass amounts to 1650 t. The horizontal position of the machine creates similar conditions for the calibration of the transducer to when it is fitted in nacelle test stands. Moreover, this position contributes to the safe and fast fitting of the torque transducers. The machine essentially consists of three components: the machine foundation, the measuring side and the actuator side. The parts of the machine are dimensioned in such a way that the measuring range can later be extended. An extension is effected by changing the booster cylinder and the force transducers.

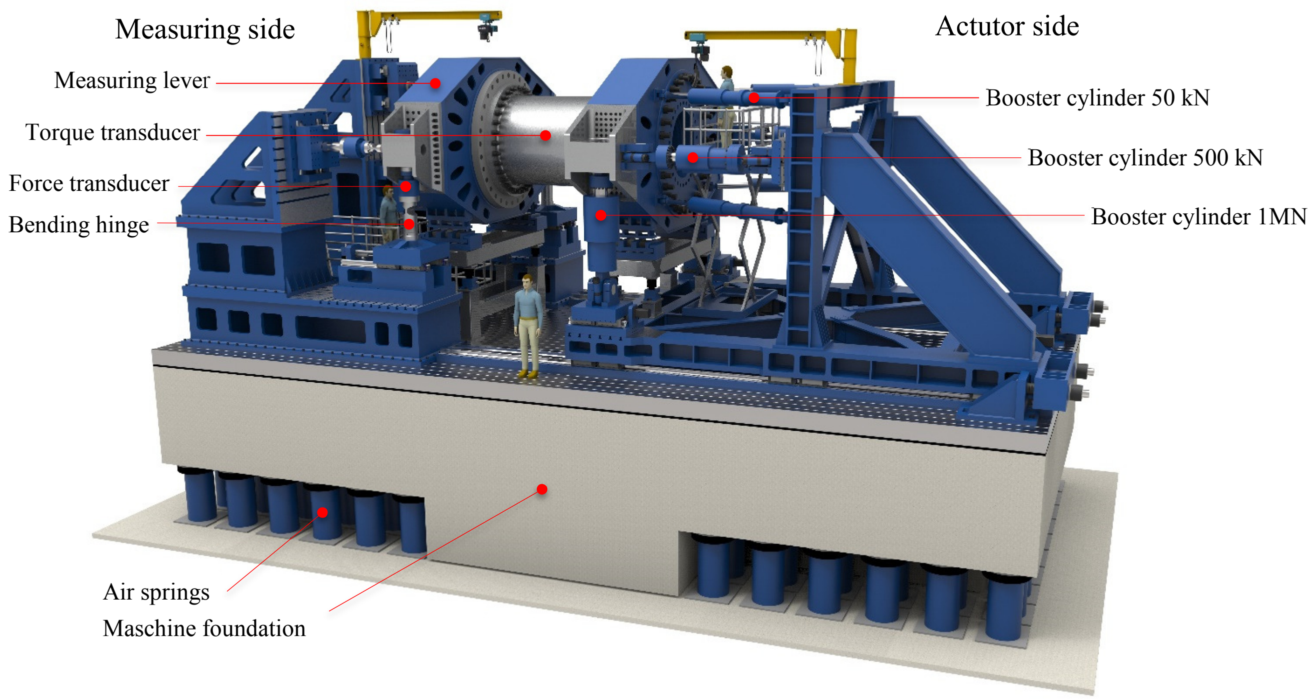

Figure 5: 5 MN·m torque standard machine

3.1 Machine foundation

The machine's foundation performs the active vibration isolation and represents part of the machine's frame. It achieves very high stiffness. This is an advantage for the adjustment and calibration, since the machine may not exhibit any substantial creep phenomena after the load has been applied. The resonance frequency of the foundation can be adapted to the excitation frequency. With its 60 air springs, the foundation can be positioned horizontally. The machine's foundation has a T-nut field which enables the precise orientation of the machine's components.

3.2 Measurement side

The three machine frames on the measuring side serve as the lever suspension. They are also equipped with T-nuts which enable the precise orientation of the test sections in the x-direction. A tensile force is applied hydraulically to the test sections by means of variably supported thrust bearings via spherical caps. The thrust bearings allow the orientation of the test sections in the y-direction. In this way, it is possible to achieve a state which is fundamentally free of tensile forces. Via a lift table, the lever can be oriented in all degrees of freedom and in alignment with the linear stage of the actuator side while it is being fitted and before tensile forces are applied to the test sections. The lift table also absorbs the load of the lever when the test sections have to be replaced for recalibration or when modifying the measuring range. To extend the measuring range, the test sections can be replaced in any increments.

3.3 Actuator side

The whole hydraulic system is supported by the actuator frame. The vertical hydraulic cylinders generate the torque M_z, the horizontal cylinders generate the bending moment M_y and the force F_z. Two additional small cylinders cater for the orientation of the lever during the fitting and for the compensation of parasitic forces and moments. Via a stiff rail guide, the actuator frame can be shifted around on wheels, and the appropriate fitting frame for the EUT can be adjusted to a maximum length of 3 m. The advantage of this feature is that the levers and the cylinders remain in a precise, defined default orientation. This also considerably reduces the setup times. The normal forces are deviated into the foundation via the linear stages. The shearing forces are deviated into the foundation via stiff sliding bolts which are tensed after the actuator frame has been aligned with the T-nut field. When the facility is idle, another lift table acts as a support for the actuator lever.
The measuring and the actuator levers were designed in such a way that they are highly flexible when it comes to the adaption of the EUTs. For example, it is possible to hydraulically tense the transducers via bolts through the lever (Figure 6). This is an advantage, especially in the case of large and short transducers or of flange reference circles that are close to each other. Also, the adapters can be designed so as to be short, compact, flexible and inexpensive. At present, five reference circles of up to 2 600 mm in diameter are available.

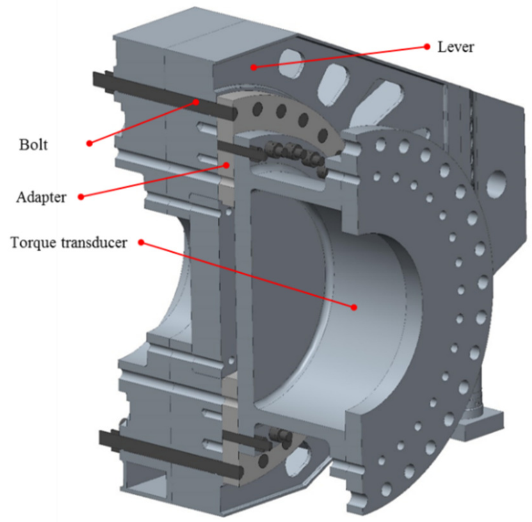

Figure 6: Assembly of the transducer with the lever

4. CURRENT STATUS AND OUTLOOK

The machine described here is currently being constructed. At present, the development is focused on optimizing the adjustment on the measuring side. Hereby, other variants of the measuring side are being developed, analyzed and compared. Completion of the machine is planned for 2019 with its commissioning envisaged in 2020. Upon completion, a first series of comparison measurements will be carried out with PTB's new 5 MN·m transducer against the 1.1 MN·m torque standard machine. As mentioned previously, it will later be possible to upgrade the machine to reach a torque of 20 MN·m. Bending moments M_y of 5 MN·m would then also be possible.

ACKNOWLEDGEMENT

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