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Development of a New 400 kN·m Torque Calibration Machine

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Abstract – This paper describes the development of a torque calibration machine, based on a reference system, with a measurement range up to 400 kN·m and a target expanded relative measurement uncertainty of 0.1 %. Several factors that have to be considered as contributing to the uncertainty of measurement are discussed. The paper deals with multi-disc couplings, reference transducers and other mechanical components that are used to implement this calibration system.

Keywords: calibration machine, large torque, measurement uncertainty

1. INTRODUCTION AND PRINCIPLE OF THE CALIBRATION MACHINE

Torque measurements and calibrations over 20 kN·m are increasingly coming into focus. Precision measurements are necessary to determine efficiency, which is, for example, essential to meet the strict environmental regulations for marine diesel engines. Very few calibration systems covering this area are available worldwide. HBM has recently put into operation a new 400 kN·m torque calibration machine based on the reference principle. The challenge here was to cover a wide range of transducer capacities and to work on a reference system which takes up little space. As a reference transducer for these tasks, two modified torque transducers (T10FH/150 kN·m and T10FH/400 kN·m by Hottinger Baldwin Messtechnik) were chosen. The control unit and mechanics were supplied by the company Inova.

The calibration machine is placed on an appropriate vibration decoupled base plate. The base structure consists of a base frame with two side-mounted columns on which a crosshead can be guided and clamped (Fig. 1). In the basic framework, there are two linear actuators (Fig. 2) that are applied to the left and right of the lever arm and generate the torque using the principle of a force couple. To introduce the torque into the test specimen quick connectors are used. These connectors (toothed disk adapters, Fig. 3) are placed between the reference transducer and the test specimen (Fig. 4) on both sides of the measurement setup (Fig. 5). The complete measuring train is connected with multi-disc couplings to the frame on the top and the bottom. The calibration machine has a weight-compensation system which ensures that the weight of the complete measuring train is compensated for and thus the multi-disc couplings are placed in a neutral vertical position. The residual axial load does not affect the measurement result.

The torque is generated by two linear drives which act on a lever mounted in the base frame. They work in the same direction, both in tension and compression and thus generate clockwise (cw) and counter-clockwise (ccw) torque. A force transducer is mounted between each of the load acting parts on the lever arm and the linear drives. The signal of these sensors is only used to monitor the balance of forces while the reference transducer is exclusively used to measure the actual torque.

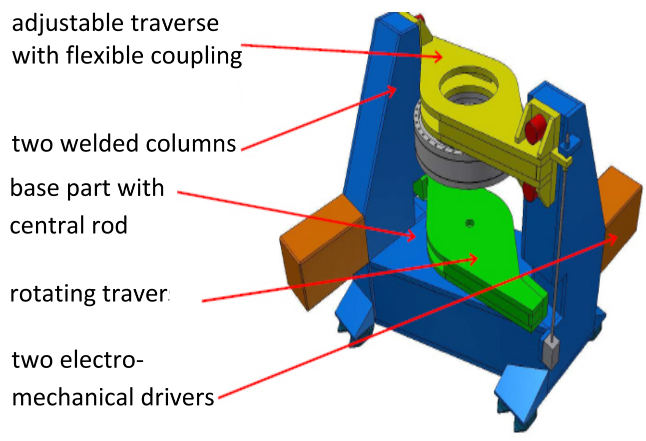

Fig.1: 400 kN·m Torque Calibration Machine with its main parts

2. DETAILS OF THE CONSTRUCTION

2.1. Weight-compensation system

A pneumatic bellow can move the clutch up from the end stop via a load cage. A U2B/50 kN load cell from HBM is used for measuring the total weight. A pair of axial thrust bearings with misalignment capability is used to prevent side load. The compensated mass is automatically measured, before a measuring series is started.

2.2. Multi-disc couplings

The multi-disc couplings allow a maximum bending deformation of 2°. With the maximum torque of 400 kN·m being applied, the bending deformation is 0.5°. The axial travel is max. ± 10 mm and restricted by end stops. The axial stiffness is 190 N/mm.

2.3. Electromechanical drives

As drive, a brushless servomotor with harmonic gear box is used. A backlash ball screw with nuts is used for precise control. An HBM force transducer (U5/200 kN) is used to control the drives. The speed control is realized by a precise belt gear system (Fig. 2).

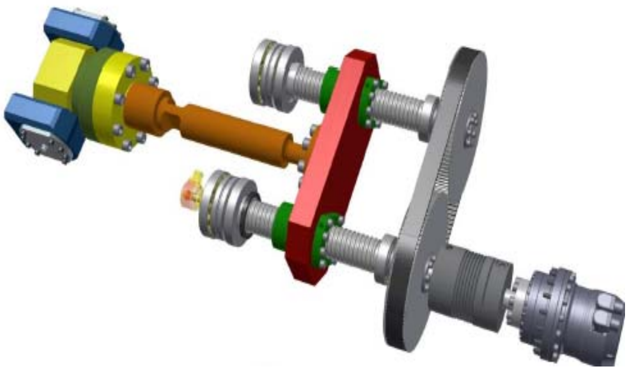

Fig.2: Electromechanical drives

2.4. Toothed disk adapter

To guarantee quick and easy assembly of the test specimen it was decided to use a toothed disk adapter. The teeth are not paired, so that each clutch fits to any other (Fig. 3). The fixing between the specimen and the calibration machine, is realised with 12 x M10 screws with a screw torque of only 62 N·m.

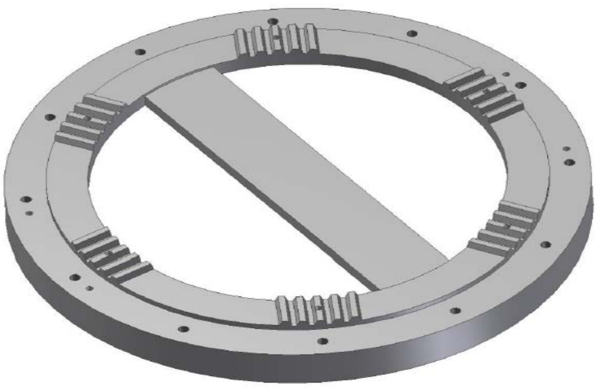

Fig.3: Toothed disk adapter

To quickly secure the adapter, hydraulic clamping cylinders are used, which automatically close and open before starting or at the end of the fully automated calibration process. Thus, it is easily possible to rotate the specimen by 0, 120 and 240 degrees according to DIN 51309 (Fig. 4).

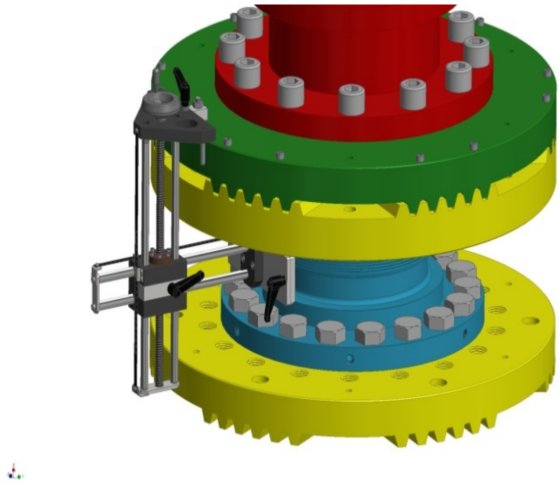

Fig.4. The test specimen (blue) mounted between the toothed adapters (yellow)

2.5. Complete setup of the Measuring train

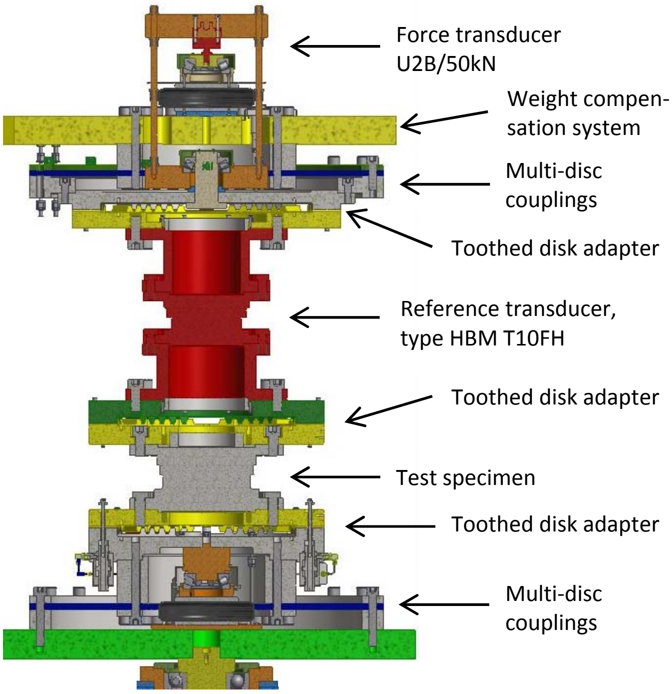

Fig.5: Complete measuring train

3. INVESTIGATION OF THE TORQUE CALIBRATION MACHINE AND MEASUREMENT UNCERTAINTY CALCULATION

3.1. Testing of the influence of bending moment and axial load

The requirement was to prove that the calibration machine compensates all axial loads before each measurement run. During this test an additional load of 250 kg was induced in the measurement train, 200 kg in the direction of measurement and 50 kg to create a bending moment on the multi-disc couplings at the upper crosshead was induced (Fig. 6). The described test setup allowed measurements with clockwise and counter-clockwise torque.

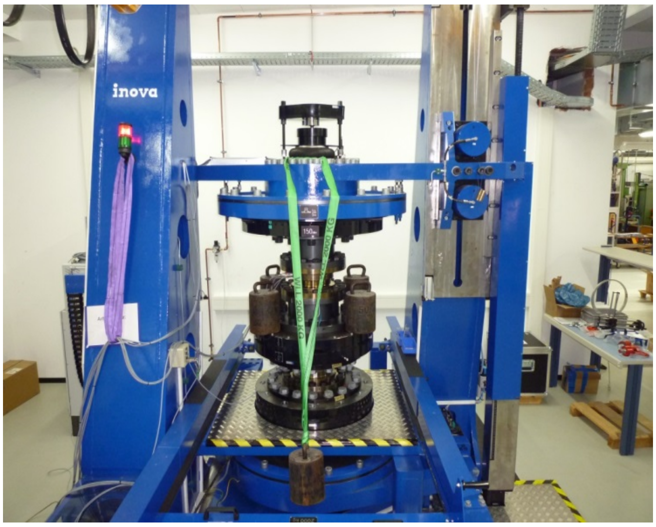

Fig.6: Test setup with 250 kg additional load

The comparison of these results with the results of measurements undertaken without any additional axial load is shown in figure 7. The maximum deviation resulting from the applied bending moment and axial load is 0.004 % at the lowest measuring step (Fig. 7). As a result the influence of bending moment and axial load is negligible compared with the target measurement uncertainty of 0.1 %.

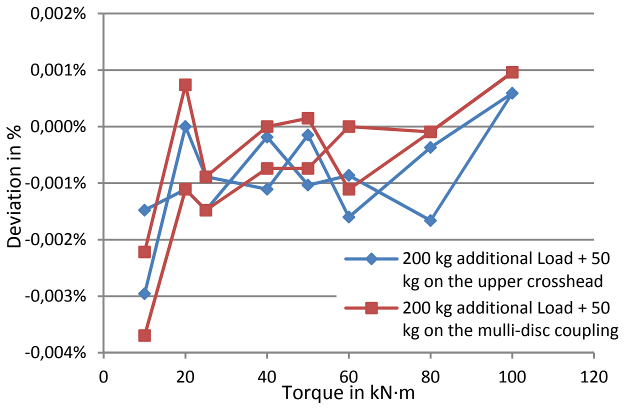

Fig.7: Influence of the axial load (clockwise)

3.2. Checking of the control mode using calibration sequence according to DIN 51309

To check the control mode of the system, the measured data of a second torque measuring bridge installed on the transfer transducer are used. The target was to check how fine the torque step could be tuned independently of the controller and to investigate the control behavior (Figs. 8 and 9). The specification of the control is a maximum overshoot of 1% at each load level, as well as keeping the load with the active controller constant with a maximum deviation of 0.01%.

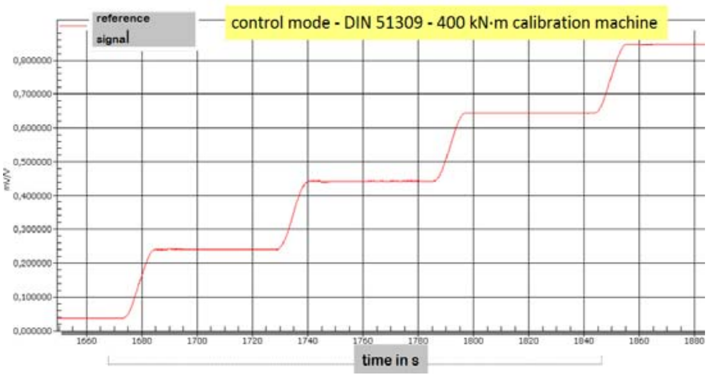

Fig.8: Clockwise load steps in mV/V according to DIN 51309

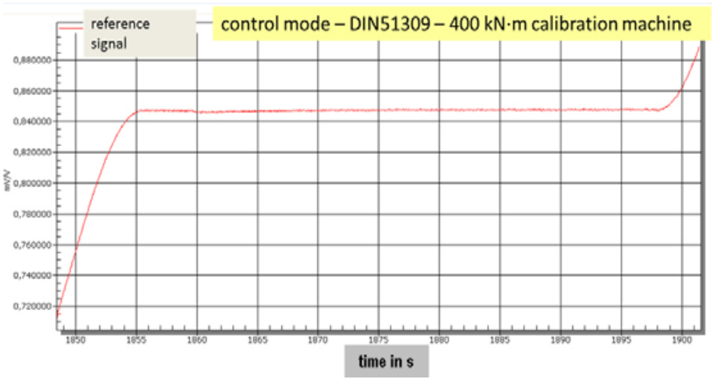

Fig.9: Signal in mV/V during a measuring step (30 s)

3.3. Comparison of calibration results using transfer transducer at HBM and at PTB (DIN 51309 calibration)

Two special HBM torque transducers type T10FH with 400 kN·m and 150 kN·m capacity as well as an additional HBM TB2/25 kN·m are used as transfer transducers. All three transducers were calibrated at PTB according to DIN 51309. The calibration results obtained both by PTB (in the 1.1 MN·m calibration machine) and by HBM were compared. All measurements were taken with a DMP41 (HBM measuring amplifier) [3] [4] [5] at 5 V / 225 Hz with a filter of 0.1 Hz Bessel and an indication resolution of 0.00001 mV/V. Deviations of the measured values from the PTB data are shown in Fig. 10.

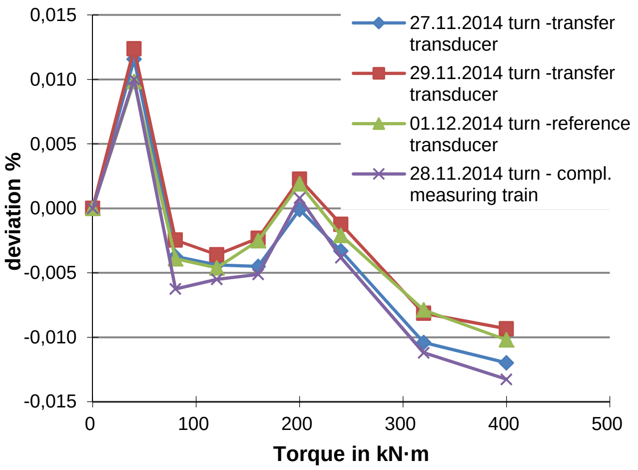

Fig 10: Comparison between the 400 kN·m reference transducer calibration (ccw) at HBM and PTB (01.04.2014)

The measurement results of the 150 kN·m and 20 kN·m measurement are not shown, however they were of the same high quality. Measurements with the transfer transducer installed in different mounting positions and measurements with complete rotation of the measurement train (transfer and reference transducer simultaneously rotated) showed also no significant changes in the calibration result. Thus, there is a very good reproducibility and stability of the transfer transducer and a good alignment of the calibration machine.

3.4. Measurement uncertainty calculation

The following factors should be taken into account when calculating the measurement uncertainty:

Stability of the reference transducer: w_L
Repeatability of the load: w_b
Influence of the amplifier: w_V
Regression uncertainty: w_R
Hysteresis calculation: w_h
Reference transducer: w_{Ref}
Influence of temperature on the output signal (TK_C): w_{TC}
Influence of temperature on the zero signal (TK_0): w_{T0}

The relative standard measurement uncertainty w can then be calculated according to (1):

$$w = \sqrt{w_L^2 + w_b^2 + w_V^2 + w_R^2 + w_h^2 + w_{Ref}^2 + w_{TC}^2 + w_{T0}^2} \qquad (1)$$

The expanded ($k = 2$) relative uncertainty W of the calibration result is given by:

$$W = 2 \cdot w \qquad (2)$$

In the case of comparison measurements, the E_n value [2] is calculated from (3)

$$E_n = \frac{X_{Lab} - X_{Ref}}{\sqrt{U_{Lab}^2 + U_{Ref}^2}} \qquad (3)$$

Results of these calculations are shown in Tab. 1 and 2.

Table 1: Results of E_n calculations in the 400 kN·m range (cw)

Load	U_{Ref}	U_{Lab}	U_{Ref}	U_{Lab}	X_{ref}	X_{lab}	E_n
in kN·m	%	%	mV/V	mV/V	mV/V	mV/V	
40	0.1	0.1	0.000201	0.000201	0.201187	0.201145	-0.147
80	0.1	0.1	0.000402	0.000402	0.402261	0.402283	0.039
120	0.08	0.1	0.000483	0.000603	0.603465	0.603438	-0.035
160	0.08	0.1	0.000644	0.000805	0.804647	0.804617	-0.029
200	0.08	0.1	0.000805	0.001006	1.005886	1.005830	-0.043
240	0.08	0.1	0.000966	0.001207	1.207180	1.207090	-0.058
320	0.08	0.1	0.001288	0.001610	1.609910	1.609732	-0.086
400	0.08	0.1	0.001610	0.002013	2.012733	2.012626	-0.041
320	0.08	0.1	0.001288	0.001610	1.610244	1.610076	-0.082
240	0.08	0.1	0.000966	0.001208	1.207738	1.207621	-0.076
200	0.08	0.1	0.000805	0.001006	1.006497	1.006402	-0.074
160	0.08	0.1	0.000644	0.000805	0.805199	0.805156	-0.042
120	0.08	0.1	0.000483	0.000604	0.603939	0.603900	-0.050
80	0.1	0.1	0.000403	0.000403	0.402669	0.402627	-0.072
40	0.1	0.1	0.000201	0.000201	0.201354	0.201338	-0.057

Table 2: Results of E_n calculations in the 400 kN·m range (ccw)

Load	U_{Ref}	U_{Lab}	U_{Ref}	U_{Lab}	X_{ref}	X_{lab}	E_n
in kN·m	%	%	mV/V	mV/V	mV/V	mV/V	
-40	0.1	0.1	-0.000201	-0.000201	-0.201092	-0.201109	-0.061
-80	0.1	0.1	-0.000402	-0.000402	-0.402248	-0.402221	0.048
-120	0.08	0.1	-0.000483	-0.000603	-0.603387	-0.603361	0.033
-160	0.08	0.1	-0.000644	-0.000805	-0.804544	-0.804532	0.011
-200	0.08	0.1	-0.000805	-0.001006	-1.005732	-1.005737	-0.004
-240	0.08	0.1	-0.000966	-0.001207	-1.207032	-1.206984	0.031
-320	0.08	0.1	-0.001288	-0.001610	-1.609754	-1.609576	0.086
-400	0.08	0.1	-0.001610	-0.002012	-2.012586	-2.012338	0.096
-320	0.08	0.1	-0.001288	-0.001610	-1.610038	-1.609872	0.080
-240	0.08	0.1	-0.000966	-0.001207	-1.207619	-1.207449	0.110
-200	0.08	0.1	-0.000805	-0.001006	-1.006393	-1.006241	0.118
-160	0.08	0.1	-0.000644	-0.000805	-0.805158	-0.805020	0.134
-120	0.08	0.1	-0.000483	-0.000604	-0.603892	-0.603804	0.114
-80	0.1	0.1	-0.000403	-0.000403	-0.402598	-0.402559	0.068
-40	0.1	0.1	-0.000201	-0.000201	-0.201290	-0.201293	-0.012

3.5. E_n Comparison with a PTB calibration

For the final verification of the new HBM calibration machine the calibration results (according to DIN51309) of a standard torque transducer were compared with the calibration of the same sensor at PTB. Figure 11 shows the E_n-values according to equation (3) for clockwise and counter-clockwise torque. The results prove once again the excellent comparability of the calibration results.

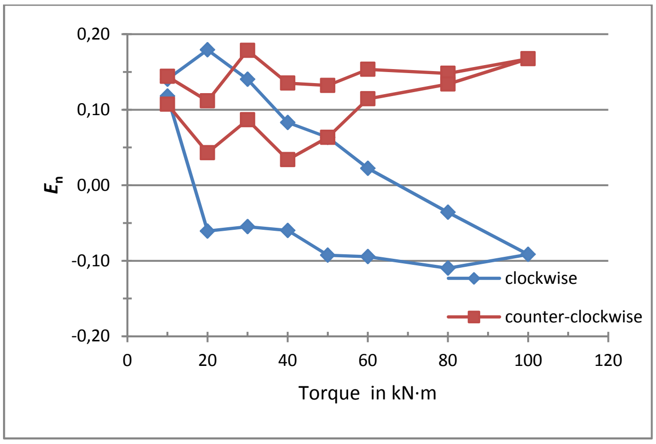

Fig 11: E_n comparison of a calibration (DIN 51309) with the data by PTB

4. CONCLUSIONS

The described calibration machine based on the reference system is unique in its design and remarkable for its ability to calibrate up to 400 kN·m. The stability of each load step results from a constantly active control. Axial forces as well as bending moments are compensated for by a multi-disc coupling.

The machine works automatically and opens up many possibilities for further investigations and calibrations. Due to the two precision reference transducers, a measurement uncertainty of 0.1 % could be achieved. The main contribution to the uncertainty results from the PTB calibration of the reference transducers. The best uncertainty of the 1.1 MN·m torque standard machine to which the new 400 kN·m machine is traced back is 0.08 %, so that the additional uncertainty of the described 400 kN·m machine is only 0.02%.

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