Final report on bilateral force and torque comparison between MIKES and PTB (EURAMET 1278 Project)

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Centre for Metrology MIKES, VTT Technical Research Centre of Finland Ltd

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Abstract

The report gives information on the force and torque comparisons (EURAMET 1278 Project) to demonstrate the calibration and measurement capabilities (CMC) of the MIKES force and torque laboratory. The first part of comparison is a bilateral force and torque comparison between PTB and MIKES for the force in the range from 0.8 kN up to 1000 kN and for the torque in the range from 0.4 N·m up to 20000 N·m. The second part of force comparison is an internal force comparison between three force standard machines of MIKES for the range from 0.2 kN up to 4 kN. The aim of the comparisons was to confirm the CMC of MIKES after relocation and reinstallation of the force and torque standard machines from Lahti to Kajaani.

The results of the participants were found to be in agreement with each other within their claimed uncertainties (k = 2) at almost all compared forces and torques. Therefor additional force and torque comparisons between PTB and MIKES had to be carried out. The overall results of the comparisons are considered to be satisfactory.

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Contents

1. Introduction

In Finland, Lahti Precision Oy acted as designated institute for force and torque until June 2010. The force measurement capability of the laboratory was proved with several comparisons and as well with the Key comparison CCM.F-K1.a and K1.b, where the laboratory worked as Pilot [1]. This activity was moved to MIKES in Kajaani between June 2010 and September 2011. All the standard machines were dismantled in Lahti and reinstalled in Kajaani. Since then MIKES force and torque laboratory has established the force scale in range from 0.002 kN up to 1100 kN with five different FSMs and the torque scale in range from 0.1 N·m up to 20000 N·m with four different TSMs. Four of MIKES FSMs are deadweight FSMs with nominal capacities of 50 N, 1 kN, 20 kN and 100 kN and one is hydraulic amplification FSM with nominal capacity of 1000 kN. Two of MIKES TSMs are lever deadweight TSMs with nominal capacities of 50 N·m and 2 kN·m and two are reference TSMs with nominal capacities of 20 N·m and 20 kN·m. MIKES has also equipment for torque tool calibrations. The Centre for Metrology MIKES has been a part of VTT Technical Research Centre of Finland Ltd since January 2015.

Force and torque laboratory of MIKES (Centre for Metrology MIKES, VTT Technical Research Centre of Finland Ltd is National Metrology Institute of Finland) and force and torque laboratory of PTB (Physikalisch-Technische Bundesanstalt is National Metrology Institute of Germany) carried out a bilateral comparison of force and torque standard machines (FSMs and TSMs) for the force in the range from 0.8 kN up to 1000 kN and for the torque in the range from 0.4 N·m up to 20000 N·m according to EURAMET Project 1278. In addition, MIKES compared its own FMSs for the force in range from 0.2 kN up to 4 kN. This document comprises a report on the comparisons carried out and the results of the bilateral and internal comparisons of force and torque standard machines of MIKES, Finland and PTB, Germany. In this report, “Centre for Metrology MIKES, VTT Technical Research Centre of Finland Ltd” is shortened as “MIKES” and “Physikalisch-Technische Bundesanstalt” is shortened as “PTB”.

At the beginning in 2011, in accordance with EURAMET Project 1278, it was decided that the bilateral force comparison will cover the force range from 0.8 kN up to 1000 kN involving three MIKES FSMs (nominal capacities of 1000 kN, 100 kN and 20 kN) and four PTB FSMs (nominal capacities of 2000 kN, 100 kN, 20 kN and 2 kN).

Also in accordance with EURAMET Project 1278, it was decided that the bilateral torque comparison will cover the torque range from 1 N·m up to 20000 N·m involving three MIKES TSMs (nominal capacities of 20 kN·m, 2 kN·m and 50 N·m) and two PTB TSMs (nominal capacities of 20 kN·m and 1 kN·m).

Both, the bilateral force and torque, comparisons would be carried out during 2011 and 2012. However due to some technical problems with MIKES newly installed FSMs and TSMs, relatively new and inexperienced MIKES laboratory staff and some problems related to MIKES measurement values some additional comparisons for force and torque were carried out during 2013 and 2015. For those same reasons MIKES carried out the internal force comparison between three MIKES FSMs (nominal capacities 100 kN, 20 kN and 1 kN) during 2015 and 2016.

The comparison of force standard machines would be carried out for compressive forces only. The comparison of torque standard machines would be carried out for both, clockwise and anti-clockwise, torques. Several different transducers would be used as transfer standards to carry out the comparisons. However, the same force or torque range would be measured with same transfer standard in both participating laboratories. Both laboratories would use their own high-precision frequency-carrier measuring amplifiers. Comparisons would be carried out with equivalent comparison measurement procedures in appropriate laboratory ambient conditions.

2. Force comparison

2.1 Laboratory standards and measurement methods of the participants

2.1.1 The Force Standard Machines of MIKES

A list of MIKES FSMs used to carry out measurements for the force comparisons is presented in the table 1.

Table 1. MIKES FSMs used in comparisons.

Force standard machine	Force standard machine type	Rel. uncertainty W_{FSM}, (k = 2)
1000 kN	Hydraulic amplification FSM	$1 \cdot 10^{-4}$
100 kN	Deadweight FSM with tara scale	$5 \cdot 10^{-5}$
20 kN	Deadweight FSM with tara scale	$5 \cdot 10^{-5}$
1 kN	Deadweight FSM	$5 \cdot 10^{-5}$

MIKES 1000 kN hydraulic amplification FSM

MIKES 1000 kN hydraulic amplification FSM has a hydraulic amplification ratio of 10. It has three stacks of deadweights with nominal values of 20 kN, 50 kN and 100 kN. Each stack comprises of 11 pieces of deadweights. Each deadweight has a value of 10% of the stack's nominal value. The same deadweights stacks are used in MIKES 100 kN deadweight FSM. Loading of the deadweights is mechanical and machine is controlled by PC. Machine generates compression and tension calibration forces from 20 kN up to 1100 kN. Relative expanded uncertainty of the generated force is $1 \cdot 10^{-4}$ (k = 2).

MIKES 100 kN deadweight FSM

MIKES 100 kN deadweight FSM has three stacks of deadweights with nominal values of 20 kN, 50 kN and 100 kN. Each stack comprises of 11 pieces of deadweights. Each deadweight has a value of 10% of the stack's nominal value. The 20 kN deadweight stack can be used in MIKES 20 kN FSM. Loading of the deadweights is mechanical and machine is controlled by PC. Machine has tare scale system to eliminate the weight of the loading frame. The tare scale system is automatically adjusted. Machine generates compression and tension calibration forces from 2 kN up to 110 kN. Relative expanded uncertainty of the generated force is $5 \cdot 10^{-5}$ (k = 2).

MIKES 20 kN deadweight FSM

MIKES 20 kN deadweight FSM has four stacks of deadweights with nominal values of 2 kN, 5 kN, 10 kN and 20 kN. The 20 kN deadweight stack is the same stack used in MIKES 100 kN FSM and normally it is installed in the 100 kN FSM. Each stack comprises of 11 pieces of deadweights. Each deadweight has a value of 10% of the stack's nominal value. Loading of the deadweights is mechanical. Machine has tare scale system to eliminate the weight of the loading frame. The tare scale system is manually adjusted. Machine generates compression and tension calibration forces from 0.2 kN up to 11 kN. Relative expanded uncertainty of the generated force is $5 \cdot 10^{-5}$ ($k = 2$).

MIKES 1 kN deadweight FSM

MIKES 1 kN deadweight FSM has four stacks of deadweights with nominal values of 0.1 kN, 0.2 kN, 0.5 kN and 1 kN. Each stack comprises of 11 pieces of deadweights. Each deadweight has a value of 10% of the stack's nominal value. The FSM has two loading frames. One frame is used with 0.2 kN, 0.5 kN, and 1 kN deadweight stacks and the other is used with 0.1 kN deadweight stack. Loading of the deadweights is mechanical. Machine generates compressive and tensile calibration forces from 0.01 kN up to 1.1 kN. Relative expanded uncertainty of the generated force is $5 \cdot 10^{-5}$ ($k = 2$).

2.1.2 The Force Standard Machines of PTB

A list of PTB's FSMs used to carry out measurements for the force comparisons is presented in table 2.

Table 2. PTB's FSMs used in comparisons.

Force standard machine	Force standard machine type	Rel. uncertainty W_{FSM}, (k = 2)
2000 kN	Deadweight FSM	$2 \cdot 10^{-5}$
1000 kN	Deadweight FSM	$2 \cdot 10^{-5}$
100 kN	Deadweight FSM	$2 \cdot 10^{-5}$
20 kN	Deadweight FSM	$2 \cdot 10^{-5}$
2 kN	Deadweight FSM	$2 \cdot 10^{-5}$

PTB's 2000 kN deadweight FSM

PTB's 2000 kN deadweight FSM has five stacks of deadweights with nominal values of 100 kN, 200 kN, 200 kN, 500 kN and 1000 kN. Each stack comprises of 10 pieces of deadweights. Each deadweight has a value of 10% of the stack's nominal value. The FSM has a loading frame which has a weight of 50 kN and constitutes the minimum force for comparisons. Each deadweight can be selected to be used for the force generation independently from the other deadweights but usually increasing or decreasing series are realised. The loading of the deadweights on the frame is carried out using hydraulic means. The machine generates compression and tension calibration forces from 50 kN up to 2000 kN. The expanded relative uncertainty of the generated force is $2 \cdot 10^{-5}$ ($k = 2$).

PTB's 1000 kN deadweight FSM

PTB's 1000 kN deadweight FSM has a stacks of 13 deadweights with nominal values of 100 kN (nine pieces), 50 kN (one piece), 20 kN (two pieces) and 10 kN (one piece). The FSM has a loading frame which has a weight of 20 kN and constitutes the minimum force for comparisons. The loading of the deadweights on the frame is carried out using hydraulic means. When the load has to be changed from one value to another, an additional piston-cylinder system generates a substitution force which is measured by means of three force transducers. The machine generates compression and tension calibration forces from 20 kN up to 1000 kN. The expanded relative uncertainty of the generated force is $2 \cdot 10^{-5}$ ($k = 2$).

PTB's 100 kN deadweight FSM

PTB's 100 kN deadweight FSM has a stack of 22 deadweights with nominal values of 10 kN (five pieces), 5 kN (six pieces), 2 kN (seven pieces) and 1 kN (four pieces). The FSM has a loading frame which has a weight of 2 kN and constitutes the minimum force for comparisons. The loading of the deadweights on the frame is carried out using electric means by moving the corresponding crosshead. The deadweights can only be used for the force generation in the order given by their position in the stack. The machine generates compression and tension calibration forces from 2 kN up to 100 kN. The expanded relative uncertainty of the generated force is $2 \cdot 10^{-5}$ ($k = 2$).

PTB's 20 kN deadweight FSM

PTB's 20 kN deadweight FSM has a stack of 23 deadweights with nominal values of 2 kN (five pieces), 1 kN (five pieces), 0.5 kN (six pieces) and 0.25 kN (seven pieces). The FSM has a loading frame which has a weight of 0.25 kN and constitutes the minimum force for comparisons. The loading of the deadweights on the frame is carried out using electric means by moving the corresponding crosshead. The deadweights can only be used for the force generation in the order given by their position in the stack. The machine generates compression and tension calibration forces from 0.25 kN up to 20 kN. The expanded relative uncertainty of the generated force is $2 \cdot 10^{-5}$ ($k = 2$).

PTB's 2 kN deadweight FSM

PTB's 2 kN deadweight FSM has a stack of 20 deadweights with nominal values of 0.2 kN (four pieces), 0.1 kN (seven pieces) and 0.05 kN (nine pieces). The FSM has a loading frame which has a weight of 0.05 kN and constitutes the minimum force for comparisons. The loading of the deadweights on the frame is carried out using electric means by moving the corresponding crosshead. The deadweights can only be used for the force generation in the order given by their position in the stack. The machine generates compression and tension calibration forces from 0.05 kN up to 2 kN. The expanded relative uncertainty of the generated force is $2 \cdot 10^{-5}$ ($k = 2$).

2.1.3 Measurement amplifiers

Both participating laboratories used their own high-precision frequency-carrier measuring amplifiers with the same amplifier settings. Any comparison of used measuring amplifiers was not included in this comparison. A list of used measurement amplifiers is presented in the table 3.

Table 3. Measurement amplifiers used in comparison.

Measurement amplifier			
Manufacturer	Type	Serial number	Owner
HBM	DMP 39	# 146	MIKES
HBM	DMP 40	# 054320095	MIKES
HBM	DMP 40 S2	# 010620004	MIKES
HBM	DMP 41 T6	# 822125801	MIKES
HBM	DMP 40	# 962720026	PTB
HBM	DMP 40	# 033120012	PTB

2.2 Transfer Standards

Several compression force transducers with various capacities were used as force transfer standards for the comparisons. The transducers used for the comparisons are listed in the table 4. The Raute Precision BA3-100kg-C4 and the GTM 5 kN transducers were only used for the MIKES internal force comparison. All of these transducers have 6-wire connection to measuring amplifier. All used transducers are well known and have suitable characteristics for a use as a transfer standard. Most of them have been used for comparisons over several decades. All transducers except one, HBM C12 500 kN, belong to MIKES. The HBM C12 500 kN transducer belongs to PTB.

Table 4. Force transfer standards for the comparisons.

Force transducer			
Manufacturer	Type	Serial number	Capacity
Raute Precision	BA3-100kg-C4	# 22796	1 kN
Raute Precision	BA3-200kg-C4	# 36242	2 kN
GTM	5 kN	# 30681	5 kN
GTM	20 kN	# 00221	20 kN
HBM	C4	# B52769	100 kN
HBM	C4	# C57751	200 kN
HBM	C4	# B79676	500 kN
HBM	C12	# 1	500 kN
HBM	C12	# 1	500 kN
HBM	C4	# 82814	1000 kN

2.3 Organization, chronology and problems during the comparison

All the comparison measurements were carried out between 2012 and 2016. The bilateral force comparison between MIKES and PTB was carried out during 2012 and 2013. The MIKES internal force comparison was carried out during 2015 and 2016. All the measurements for the same force range were carried out according the same measurement procedure.

2.3.1 First set of comparison measurements 2012

The first set of comparison measurements were carried out during 2012. The initial measurements were carried out at MIKES. After the initial measurements the transfer standards were delivered to PTB and measurements at PTB were carried out. Then the transfer standards were delivered back to MIKES and the final measurements were carried out. The measurements included seven different force ranges. Compared forces were from 0.8 kN up to 1000 kN. Each force range was measured with different transfer standard.

The results of the first set of the comparison measurements indicated incorrect function of MIKES 1000 kN hydraulic amplification FSM on a force range from 80 kN up to 200 kN and MIKES 20 kN deadweight FSM on a force range from 0.8 kN up to 2 kN. The most significant problem to cause the incorrect function of the MIKES 1000 kN hydraulic amplification FSM was related to unexpected friction in the working cylinder of the machine. The problem affecting the final accuracy of the MIKES 20 kN deadweight FSM was related to incorrect function of the machine’s tare scale system. The incorrect function of the tare scale system was a result from the small error in the MIKES 20 kN deadweight FSM zero point. The mechanical and electrical zero points had small difference and this was detected after the first set of the comparison measurements. More detailed information about these problems can be found in ref. [2].

2.3.2 Second set of comparison measurements 2013

The second set of comparison measurements were carried out during 2013. Because of the problems during 2012 measurements related to results of the force range from 80 kN up to 200 kN it was decided that additional measurements were needed. The initial measurements were carried out at PTB. After the initial measurements the transfer standards were delivered to MIKES and measurements at MIKES were carried out. Then the transfer standards were delivered back to PTB. These measurements did not include a second measurement at PTB. The measurements included two different force ranges. Compared forces were from 80 kN up to 500 kN. Both of the force ranges were measured with the same transfer standard, PTB’s HBM C12 500 kN.

2.3.3 Third set of comparison measurements 2015 and 2016

The third set of comparison measurements were carried out during 2015 and 2016. Because of the problems during 2012 measurements related to results of the force range from 0.8 N up to 2 kN it was decided that MIKES should carry out an internal force comparison. MIKES 1 kN FSM should be compared to MIKES 20 kN FSM and MIKES 20 kN FSM should be compared to MIKES 100 kN FSM. The initial measurements were in both cases carried out by the FSM with higher nominal force capacity. After the initial measurements the transfer standards were measured again by the FSM with lower nominal force capacity. Results of these measurements were considered as a reference values. The final measurements were carried out by the same FSM which was used in the initial measurements. The measurements included two different force ranges. Compared calibration forces were from 0.2 kN up to 4 kN. Both of the force ranges were measured with different transfer standard.

2.4 Measurement procedures

The comparisons were carried out according to measurement procedure commonly used for comparisons of force standard machines. That meant the measurement of each transfer standard in four (steps of 90°) rotational positions, with two increasing loading series for each position and an additional fifth position (360°) with one increasing and decreasing loading series. In order to stabilize the transfer standard before the first measurement series in rotational position 0º, the force transducers were loaded with a preload equal to each transducer's nominal capacity three times. The selected time delay between the start of the load change (increase or decrease of the load) and reading of the measurement result varied from 150 seconds up to 250 seconds depending on the used transfer standard and FSMs. However, the same time delay for the same transfer standard was applied in both participating laboratories. Selected force ranges and steps for each transfer standards are presented in table 5.

Table 5. Selected force ranges and steps for the transfer standards.

Force transducer				Selected force steps
Manufacturer	Type	Serial number	Capacity	
Raute Precision	BA3-100kg-C4	# 22796	1 kN	0.2 kN …1 kN (step 0.2 kN)
Raute Precision	BA3-200kg-C4	# 36242	2 kN	0.8 kN … 2 kN (step 0.2 kN)
GTM	5 kN	# 30681	5 kN	2 kN and 4 kN
GTM	20 kN	# 00221	20 kN	8 kN … 20 kN (step 2 kN)
HBM	C4	# B52769	100 kN	40 kN … 100 kN (step 10 kN)
HBM	C4	# C57751	200 kN	80 kN … 200 kN (step 20 kN)
HBM	C4	# B79676	500 kN	200 kN … 500 kN (step 50 kN)
HBM	C12	# 1	500 kN	80 kN … 200 kN (step 20 kN)
HBM	C12	# 1	500 kN	200 kN … 500 kN (step 50 kN)
HBM	C4	# 82814	1000 kN	400 kN…1000 kN (step 100 kN)

2.5 Results of the comparison

2.5.1 Measurement results and uncertainties - Bilateral force comparison

Measurement results and uncertainties of the first set of measurements are shortly presented in the tables 7 to 12. Measurement results and uncertainties of the second set of measurements are shortly presented in the tables 13 and 14. The following designations are used in the tables 7 to 14:

$\mathrm{MIKES_A}$ = Mean deflection of initial MIKES measurement calculated as $\overline{X}_r$ in table 6.

$W_{\mathrm{MIKES\ A}}$ = Relative expanded uncertainty (k = 2) of initial MIKES measurement calculated as W in table 6.

$\mathrm{MIKES_B}$ = Mean deflection of final MIKES measurement calculated as $\overline{X}_r$ in table 6.

$W_{\mathrm{MIKES\ B}}$ = Relative expanded uncertainty (k = 2) of final MIKES measurement calculated as W in table 6.

PTB = Mean deflection of PTB measurement calculated as $\overline{X}_r$ in table 6.

W_{PTB} = Relative expanded uncertainty (k = 2) of PTB measurement calculated as W in table 6.

The uncertainties were estimated according to principles laid out in the document "JCGM 100:2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement" [3]. The principal components of the uncertainty budget to be evaluated are in accordance with the document "Calibration Guide EURAMET cg-4 version 2.0 (03/2011) - Uncertainty of Force Measurement" [4]. The relative expanded uncertainties of the measurements are mainly calculated to present that the uncertainty contribution of applied force is the most significant uncertainty contribution. The calculation of relative expanded measurement uncertainties W (k = 2) is presented in the table 6.

Table 6. Calculation of relative expanded uncertainties W (k = 2).

Uncertainty arising from	Equation	Statistical distribution	Rel. uncertainty contribution
Reproducibility from rotational (0º ... 270º) measurement values (*n* = 8) *b*	$b = \frac{1}{\overline{X}_r} \cdot \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X}_r)^2}{(n-1)}}$ $\overline{X}_r = \frac{\sum_{i=1}^{n} X_i}{n}$	Normal distribution	$w_b = \frac{b}{\sqrt{n}}$
Repeatability, from first measurement position *b'* (rel. half width value)	$b' = \frac{1}{2} \cdot \frac{\lvert X_1 - X_2 \rvert}{\overline{X}_{wr}}$ $\overline{X}_{wr} = \frac{X_1 + X_2}{2}$	Rectangular distribution	$w_{b'} = \frac{b'}{\sqrt{3}}$
Resolution of indication *r* (rel. half width value) (*a* = indication step)	$r = \frac{1}{2} \cdot \frac{a}{\overline{X}_r}$	Rectangular distribution	$w_r = \frac{r}{\sqrt{3}}$
Uncertainty of applied force (*k* = 2)	W_{FSM}	Normal distribution	$w_{FSM} = \frac{W_{FSM}}{k}$
Rel. expanded uncertainty of the measurement (*k* = 2)	$W = k \cdot \sqrt{w_b^2 + w_{b'}^2 + 2 \cdot w_r^2 + w_{FSM}^2}$		

Table 7. Measurement results and uncertainties, force range 0.8 kN ... 2 kN, year 2012.

Force kN	MIKES_A mV/V	$W_{\text{MIKES A}}$ (k = 2) %	MIKES_B mV/V	$W_{\text{MIKES B}}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
0.8	0.805015	0.0077	0.804957	0.0056	0.804913	0.0023
1.0	1.006286	0.0071	1.006226	0.0054	1.006179	0.0022
1.2	1.207578	0.0066	1.207513	0.0053	1.207468	0.0021
1.4	1.408886	0.0061	1.408817	0.0052	1.408768	0.0021
1.6	1.610210	0.0058	1.610133	0.0052	1.610083	0.0022
1.8	1.811542	0.0056	1.811458	0.0051	1.811411	0.0021
2.0	2.012883	0.0054	2.012793	0.0051	2.012739	0.0021

Table 8. Measurement results and uncertainties, force range 8 kN ... 20 kN, year 2012.

Force kN	$MIKES_A$ mV/V	$W_{MIKES\ A}$ (k = 2) %	$MIKES_B$ mV/V	$W_{MIKES\ B}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
8	0.800101	0.0051	0.800089	0.0052	0.800067	0.0020
10	1.000181	0.0051	1.000169	0.0052	1.000143	0.0021
12	1.200270	0.0051	1.200257	0.0052	1.200224	0.0021
14	1.400360	0.0051	1.400343	0.0051	1.400311	0.0021
16	1.600450	0.0050	1.600434	0.0051	1.600394	0.0021
18	1.800531	0.0050	1.800513	0.0051	1.800475	0.0021
20	2.000606	0.0050	2.000586	0.0051	2.000548	0.0021

Table 9. Measurement results and uncertainties, force range 40 kN ... 100 kN, year 2012.

Force kN	$MIKES_A$ mV/V	$W_{MIKES\ A}$ (k = 2) %	$MIKES_B$ mV/V	$W_{MIKES\ B}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
40	0.799857	0.0052	0.799825	0.0052	0.799826	0.0024
50	0.999881	0.0052	0.999843	0.0053	0.999839	0.0025
60	1.199908	0.0052	1.199871	0.0052	1.199863	0.0026
70	1.399953	0.0052	1.399915	0.0052	1.399905	0.0025
80	1.600007	0.0052	1.599963	0.0053	1.599955	0.0025
90	1.800076	0.0052	1.800030	0.0053	1.800025	0.0026
100	2.000153	0.0052	2.000103	0.0052	2.000101	0.0025

Table 10. Measurement results and uncertainties, force range 80 kN ... 200 kN, year 2012.

Force kN	$MIKES_A$ mV/V	$W_{MIKES\ A}$ (k = 2) %	$MIKES_B$ mV/V	$W_{MIKES\ B}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
80	0.799443	0.0115	0.799627	0.0103	0.799713	0.0028
100	0.999458	0.0116	0.999646	0.0101	0.999751	0.0031
120	1.199517	0.0115	1.199688	0.0102	1.199808	0.0024
140	1.399590	0.0115	1.399762	0.0100	1.399894	0.0031
160	1.599691	0.0115	1.599852	0.0100	1.599985	0.0026
180	1.799812	0.0116	1.799978	0.0101	1.800117	0.0031
200	1.999955	0.0116	2.000115	0.0101	2.000243	0.0027

Table 11. Measurement results and uncertainties, force range 200 kN ... 500 kN, year 2012.

Force kN	$MIKES_A$ mV/V	$W_{MIKES\ A}$ (k = 2) %	$MIKES_B$ mV/V	$W_{MIKES\ B}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
200	0.800155	0.0102	0.800175	0.0101	0.800193	0.0037
250	1.000159	0.0101	1.000180	0.0101	1.000159	0.0035
300	1.200169	0.0101	1.200186	0.0101	1.200163	0.0026
350	1.400193	0.0102	1.400203	0.0100	1.400180	0.0026
400	1.600219	0.0101	1.600233	0.0100	1.600203	0.0023
450	1.800259	0.0101	1.800275	0.0100	1.800227	0.0028
500	2.000302	0.0101	2.000321	0.0100	2.000327	0.0030

Table 12. Measurement results and uncertainties, force range 400 kN ... 1000 kN, year 2012.

Force kN	$MIKES_A$ mV/V	$W_{MIKES\ A}$ (k = 2) %	$MIKES_B$ mV/V	$W_{MIKES\ B}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
400	0.800270	0.0101	0.800260	0.0105	0.800314	0.0028
500	1.000325	0.0102	1.000337	0.0103	1.000289	0.0026
600	1.200406	0.0101	1.200417	0.0102	1.200365	0.0024
700	1.400472	0.0102	1.400500	0.0101	1.400434	0.0032
800	1.600551	0.0100	1.600577	0.0101	1.600479	0.0022
900	1.800619	0.0100	1.800658	0.0101	1.800537	0.0022
1000	2.000664	0.0101	2.000700	0.0101	2.000581	0.0021

Table 13. Measurement results and uncertainties, force range 80 kN ... 200 kN, year 2013.

Force kN	$MIKES_A$ mV/V	$W_{MIKES\ A}$ (k = 2) %	$MIKES_B$ mV/V	$W_{MIKES\ B}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
80	0.310911	0.0100	-	-	0.310895	0.0021
100	0.388629	0.0101	-	-	0.388614	0.0021
120	0.466351	0.0100	-	-	0.466338	0.0021
140	0.544071	0.0100	-	-	0.544065	0.0021
160	0.621796	0.0100	-	-	0.621792	0.0021
180	0.699524	0.0101	-	-	0.699517	0.0021
200	0.777249	0.0101	-	-	0.777243	0.0021

Table 14. Measurement results and uncertainties, force range 200 kN ... 500 kN, year 2013.

Force kN	MIKES_A mV/V	$W_{\text{MIKES A}}$ (k = 2) %	MIKES_B mV/V	$W_{\text{MIKES B}}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
200	0.777220	0.0101	-	-	0.777230	0.0021
250	0.971532	0.0100	-	-	0.971554	0.0021
300	1.165860	0.0100	-	-	1.165890	0.0021
350	1.360203	0.0100	-	-	1.360230	0.0021
400	1.554557	0.0100	-	-	1.554591	0.0021
450	1.748921	0.0100	-	-	1.748956	0.0021
500	1.943297	0.0100	-	-	1.943337	0.0021

2.5.2 Relative deviations and E_n numbers - Bilateral force comparison

Relative deviations (RD) between MIKES and PTB of the first set of measurements are presented in the tables 15 to 20. Relative deviations (RD) between MIKES and PTB of the second set of measurements are presented in the tables 21 and 22. The relative deviations are calculated according to equation (2). The results of the comparison measurements are evaluated by using the E_n number, given in "ISO/IEC 17043:2010 Conformity assessment - General requirements for proficiency testing", calculated for each measurement point [5]. The E_n numbers express the degree of equivalence between MIKES and the reference laboratory PTB. The relative expanded uncertainties applied for the E_n number calculations are uncertainties of applied forces instead of uncertainties related to measurement results. For the assessment based on E_n numbers the given rule in ISO/IEC 17043:2010 is $|E_n| \leq 1$ indicates "satisfactory" performance and $|E_n| > 1$ indicates "unsatisfactory" performance. The E_n numbers of the first set of measurements are presented in the tables 23 to 28. The E_n numbers of the second set of measurements are presented in the tables 29 and 30. E_n numbers are calculated according to equation (3). The following designations are used in the tables 15 to 30:

$\text{MIKES}_{\text{A-B AVE}}$ = Mean deflection of MIKES measurements calculated according to equation (1).

PTB = Mean deflection of PTB measurement calculated as $\overline{X}_r$ in table 6.

W_{FSM} = Relative expanded uncertainty of applied force (k = 2)

$$MIKES_{A-B\ AVE} = \frac{MIKES_A + MIKES_B}{2} \qquad (1)$$

$$RD = \frac{MIKES_{A-B\ AVE} - PTB}{PTB} \qquad (2)$$

$$E_n = \frac{MIKES_{A-B\ AVE} - PTB}{\sqrt{U^2_{FSM\ MIKES} + U^2_{FSM\ PTB}}} \quad (3)$$

Table 15. Relative deviations between MIKES and PTB, force range 0.8 kN ... 2 kN, year 2012.

Force kN	$MIKES_{A\text{-}B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A\text{-}B\ AVE}$ to PTB %
0.8	0.804986	0.804913	0.0091
1.0	1.006256	1.006179	0.0076
1.2	1.207545	1.207468	0.0064
1.4	1.408852	1.408768	0.0059
1.6	1.610172	1.610083	0.0055
1.8	1.811500	1.811411	0.0049
2.0	2.012838	2.012739	0.0049

Table 16. Relative deviations between MIKES and PTB, force range 8 kN ... 20 kN, year 2012.

Force kN	$MIKES_{A\text{-}B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A\text{-}B\ AVE}$ to PTB %
8	0.800095	0.800067	0.0035
10	1.000175	1.000143	0.0032
12	1.200263	1.200224	0.0033
14	1.400352	1.400311	0.0029
16	1.600442	1.600394	0.0030
18	1.800522	1.800475	0.0026
20	2.000596	2.000548	0.0024

Table 17. Relative deviations between MIKES and PTB, force range 40 kN ... 100 kN, year 2012.

Force kN	$MIKES_{A\text{-}B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A\text{-}B\ AVE}$ to PTB %
40	0.799841	0.799826	0.0019
50	0.999862	0.999839	0.0022
60	1.199889	1.199863	0.0022
70	1.399934	1.399905	0.0021
80	1.599985	1.599955	0.0019
90	1.800053	1.800025	0.0016
100	2.000128	2.000101	0.0014

Table 18. Relative deviations between MIKES and PTB, force range 80 kN ... 200 kN, year 2012.

Force kN	$MIKES_{A\text{-}B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A\text{-}B\ AVE}$ to PTB %
80	0.799535	0.799713	-0.0223
100	0.999552	0.999751	-0.0199
120	1.199602	1.199808	-0.0171
140	1.399676	1.399894	-0.0155
160	1.599771	1.599985	-0.0133
180	1.799895	1.800117	-0.0123
200	2.000035	2.000243	-0.0104

Table 19. Relative deviations between MIKES and PTB, force range 200 kN ... 500 kN, year 2012.

Force kN	$MIKES_{A\text{-}B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A\text{-}B\ AVE}$ to PTB %
200	0.800165	0.800193	-0.0035
250	1.000169	1.000159	0.0011
300	1.200178	1.200163	0.0012
350	1.400198	1.400180	0.0012
400	1.600226	1.600203	0.0015
450	1.800267	1.800227	0.0022
500	2.000312	2.000327	-0.0007

Table 20. Relative deviations between MIKES and PTB, force range 400kN ... 1000 kN, year 2012.

Force kN	$MIKES_{A\text{-}B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A\text{-}B\ AVE}$ to PTB %
400	0.800265	0.800314	-0.0061
500	1.000331	1.000289	0.0042
600	1.200411	1.200365	0.0038
700	1.400486	1.400434	0.0037
800	1.600564	1.600479	0.0053
900	1.800639	1.800537	0.0056
1000	2.000682	2.000581	0.0051

Table 21. Relative deviations between MIKES and PTB, force range 80 kN ... 200 kN, year 2013.

Force kN	$MIKES_{A\text{-}B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A\text{-}B\ AVE}$ to PTB %
80	0.310911	0.310895	0.0051
100	0.388629	0.388614	0.0037
120	0.466351	0.466338	0.0028
140	0.544071	0.544065	0.0012
160	0.621796	0.621792	0.0006
180	0.699524	0.699517	0.0010
200	0.777249	0.777243	0.0008

Table 22. Relative deviations between MIKES and PTB, force range 200 kN ... 500 kN, year 2013.

Force kN	$MIKES_{A\text{-}B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A\text{-}B\ AVE}$ to PTB %
200	0.777220	0.777230	-0.0014
250	0.971532	0.971554	-0.0023
300	1.165860	1.165890	-0.0025
350	1.360203	1.360230	-0.0020
400	1.554557	1.554591	-0.0022
450	1.748921	1.748956	-0.0020
500	1.943297	1.943337	-0.0021

Table 23. E_n numbers of the comparison, force range 0.8 kN ... 2 kN, year 2012.

Force	Relative deviation	W_{FSM} ,(k = 2)		E_n
kN	$MIKES_{A\text{-}B\ AVE}$ to PTB %	MIKES %	PTB %	
0.8	0.0091	0.0050	0.0020	1.69
1.0	0.0076	0.0050	0.0020	1.41
1.2	0.0064	0.0050	0.0020	1.19
1.4	0.0059	0.0050	0.0020	1.10
1.6	0.0055	0.0050	0.0020	1.02
1.8	0.0049	0.0050	0.0020	0.92
2.0	0.0049	0.0050	0.0020	0.92

Table 24. E_n numbers of the comparison, force range 8 kN … 20 kN, year 2012.

Force kN	Relative deviation MIKES$_{\text{A-B AVE}}$ to PTB %	W_{FSM} ,(k = 2) MIKES %	 PTB %	E_n
8	0.0035	0.0050	0.0020	0.66
10	0.0032	0.0050	0.0020	0.60
12	0.0033	0.0050	0.0020	0.60
14	0.0029	0.0050	0.0020	0.54
16	0.0030	0.0050	0.0020	0.56
18	0.0026	0.0050	0.0020	0.49
20	0.0024	0.0050	0.0020	0.44

Table 25. E_n numbers of the comparison, force range 40 kN … 100 kN, year 2012.

Force kN	Relative deviation MIKES$_{\text{A-B AVE}}$ to PTB %	W_{FSM} ,(k = 2) MIKES %	 PTB %	E_n
40	0.0019	0.0050	0.0020	0.36
50	0.0022	0.0050	0.0020	0.41
60	0.0022	0.0050	0.0020	0.41
70	0.0021	0.0050	0.0020	0.39
80	0.0019	0.0050	0.0020	0.35
90	0.0016	0.0050	0.0020	0.29
100	0.0014	0.0050	0.0020	0.26

Table 26. E_n numbers of the comparison, force range 80 kN … 200 kN, year 2012.

Force kN	Relative deviation MIKES$_{\text{A-B AVE}}$ to PTB %	W_{FSM} ,(k = 2) MIKES %	 PTB %	E_n
80	-0.0223	0.0100	0.0020	-2.19
100	-0.0199	0.0100	0.0020	-1.95
120	-0.0171	0.0100	0.0020	-1.68
140	-0.0155	0.0100	0.0020	-1.52
160	-0.0133	0.0100	0.0020	-1.31
180	-0.0123	0.0100	0.0020	-1.21
200	-0.0104	0.0100	0.0020	-1.02

Table 27. E_n numbers of the comparison, force range 200 kN ... 500 kN, year 2012.

Force	Relative deviation	W_{FSM} ,(k = 2)		E_n
	MIKES$_{A\text{-}B\ AVE}$ to PTB	MIKES	PTB	
kN	%	%	%	
200	-0.0035	0.0100	0.0020	-0.34
250	0.0011	0.0100	0.0020	0.11
300	0.0012	0.0100	0.0020	0.12
350	0.0012	0.0100	0.0020	0.12
400	0.0015	0.0100	0.0020	0.14
450	0.0022	0.0100	0.0020	0.22
500	-0.0007	0.0100	0.0020	-0.07

Table 28. E_n numbers of the comparison, force range 400 kN ... 1000 kN, year 2012.

Force	Relative deviation	W_{FSM} ,(k = 2)		E_n
	MIKES$_{A\text{-}B\ AVE}$ to PTB	MIKES	PTB	
kN	%	%	%	
400	-0.0061	0.0100	0.0020	-0.60
500	0.0042	0.0100	0.0020	0.41
600	0.0038	0.0100	0.0020	0.38
700	0.0037	0.0100	0.0020	0.36
800	0.0053	0.0100	0.0020	0.52
900	0.0056	0.0100	0.0020	0.55
1000	0.0051	0.0100	0.0020	0.50

Table 29. E_n numbers of the comparison, force range 80 kN ... 200 kN, year 2013.

Force	Relative deviation	W_{FSM} ,(k = 2)		E_n
	MIKES$_{A\text{-}B\ AVE}$ to PTB	MIKES	PTB	
kN	%	%	%	
80	0.0051	0.0100	0.0020	0.50
100	0.0037	0.0100	0.0020	0.36
120	0.0028	0.0100	0.0020	0.28
140	0.0012	0.0100	0.0020	0.12
160	0.0006	0.0100	0.0020	0.06
180	0.0010	0.0100	0.0020	0.10
200	0.0008	0.0100	0.0020	0.08

Table 30. E_n numbers of the comparison, force range 200 kN ... 500 kN, year 2013.

Force kN	Relative deviation MIKES$_{A\text{-}B\ AVE}$ to PTB %	W_{FSM}, (k = 2) MIKES %	PTB %	E_n
200	-0.0014	0.0100	0.0020	-0.13
250	-0.0023	0.0100	0.0020	-0.22
300	-0.0025	0.0100	0.0020	-0.25
350	-0.0020	0.0100	0.0020	-0.20
400	-0.0022	0.0100	0.0020	-0.22
450	-0.0020	0.0100	0.0020	-0.20
500	-0.0021	0.0100	0.0020	-0.20

The most of the E_n numbers for these comparison measurements have absolute value lower than 1. The results from 2012 present unsatisfactory results ($|E_n| > 1$) for two force ranges, range from 0.8 kN up to 1.6 kN and range from 80 kN up to 200 kN. However, the results from 2013 present satisfactory results ($|E_n| \leq 1$) for the force range from 80 kN up to 200 kN. Therefor according the E_n numbers for these comparison measurements, given in tables 22 to 27, the overall results of this comparison for the force range from 8 kN up to 1000 kN can be considered as satisfactory due to given rule in “ISO/IEC 17043:2010”.

2.5.3 Measurement results and uncertainties - MIKES internal force comparison

Measurement results and uncertainties of the third set of measurements (MIKES internal force comparison) are shortly presented in the tables 31 and 32. The following designations are used in the tables 31 and 32:

MIKES $_{FSM\ X}$ A = Mean deflection of initial FSM X measurement calculated as $\overline{X}_r$ in table 6.

$W_{FSM\ X\ A}$ = Relative expanded uncertainty (k = 2) of initial FSM X measurement calculated as W in table 6.

MIKES $_{FSM\ X}$ B = Mean deflection of final FSM X measurement calculated as $\overline{X}_r$ in table 6.

$W_{FSM\ X\ B}$ = Relative expanded uncertainty (k = 2) of final FSM X measurement calculated as W in table 6.

MIKES $_{FSM\ X}$ = Mean deflection of reference FSM measurement calculated as $\overline{X}_r$ in table 6.

$W_{FSM\ X}$ = Relative expanded uncertainty (k = 2) of MIKES reference FSM measurement calculated as W in table 6.

The calculation of relative expanded measurement uncertainties W (k = 2) is presented in a table 6.

Table 31. Measurement results and uncertainties, force range 0.2 kN ... 1 kN, year 2015.

Force kN	$MIKES_{FSM\ 20kN}$ A mV/V	$W_{FSM\ 20kN\ A}$ (k = 2) %	$MIKES_{FSM\ 20kN}$ B mV/V	$W_{FSM\ 20kN\ B}$ (k = 2) %	$MIKES_{FSM\ 1kN}$ mV/V	$W_{FSM\ 1kN}$ (k = 2) %
0.2	0.396936	0.0081	0.396931	0.0088	0.396930	0.0051
0.4	0.793895	0.0059	0.793890	0.0063	0.793891	0.0051
0.6	1.190890	0.0055	1.190883	0.0057	1.190882	0.0051
0.8	1.587913	0.0053	1.587909	0.0054	1.587905	0.0051
1.0	1.984974	0.0052	1.984969	0.0052	1.984962	0.0051

Table 32. Measurement results and uncertainties, force range 2 kN ... 4 kN, year 2016.

Force kN	$MIKES_{FSM100kN}$ A mV/V	$W_{FSM\ 100kN\ A}$ (k = 2) %	$MIKES_{FSM100kN}$ B mV/V	$W_{FSM\ 100kN\ B}$ (k = 2) %	$MIKES_{FSM\ 20kN}$ mV/V	$W_{FSM\ 20kN}$ (k = 2) %
2	0.752774	0.0052	0.752789	0.0050	0.752759	0.0050
4	1.505509	0.0051	1.505529	0.0050	1.505499	0.0050

2.5.4 Relative deviations and E_n numbers - MIKES internal force comparison

The relative deviations between MIKES FSMs are presented in the tables 33 and 34. The evaluation of the internal comparison results was the same as the evaluation of the bilateral comparison results. The E_n numbers of MIKES internal force comparison are presented in the tables 35 and 36. The following designations are used in the tables 33 to 36:

$MIKES_{FSM\ X\ AVE}$ = Mean deflection of FSM X measurements calculated according to equation (1).

$MIKES_{FSM\ X}$ = Mean deflection of reference FSM measurement calculated as $\overline{X}_r$ in table 6.

W_{FSM} = Relative expanded uncertainty of applied force (k = 2)

Table 33. Relative deviations between MIKES 20 kN FSM and 1 kN, force range 0.2 kN ... 1 kN, year 2015.

Force kN	$MIKES_{FSM\ 20kN\ AVE}$ mV/V	$MIKES_{FSM\ 1kN}$ mV/V	Relative deviation $MIKES_{FSM\ 20kN}$ to $MIKES_{FSM\ 1kN}$ %
0.2	0.396934	0.396930	0.0010
0.4	0.793892	0.793891	0.0002
0.6	1.190886	1.190882	0.0003
0.8	1.587911	1.587905	0.0004
1.0	1.984971	1.984962	0.0005

Table 34. Relative deviations between MIKES 100 kN FSM and 20 kN, force range 2 kN … 4 kN, year 2016.

Force	$MIKES_{FSM\ 100kN\ AVE}$	$MIKES_{FSM\ 20kN}$	Relative deviation $MIKES_{FSM\ 100kN}$ to $MIKES_{FSM\ 20kN}$
kN	mV/V	mV/V	%
2	0.752782	0.752759	0.0031
4	1.505519	1.505499	0.0013

Table 35. E_n numbers of the internal comparison, force range 0.2 kN … 1 kN, year 2015.

Force	Relative deviation	W_{FSM}, (k = 2)		E_n
	$MIKES_{FSM\ 20kN}$ to $MIKES_{FSM\ 1\ kN}$	$MIKES_{20kN}$	$MIKES_{1\ kN}$	
kN	%	%	%	
0.2	0.0010	0.0050	0.0050	0.14
0.4	0.0002	0.0050	0.0050	0.03
0.6	0.0003	0.0050	0.0050	0.05
0.8	0.0004	0.0050	0.0050	0.06
1.0	0.0005	0.0050	0.0050	0.07

Table 36. E_n numbers of the internal comparison, force range 2 kN … 4 kN, year 2016.

Force	Relative deviation	W_{FSM}, (k = 2)		E_n
	$MIKES_{FSM\ 100kN}$ to $MIKES_{FSM\ 20kN}$	$MIKES_{100kN}$	$MIKES_{20\ kN}$	
kN	%	%	%	
2	0.0031	0.0050	0.0050	0.43
4	0.0013	0.0050	0.0050	0.19

All of the E_n numbers for these comparison measurements have absolute value lower than 1. Therefore, according the E_n numbers for these comparison measurements, given in tables 35 and 36, the results of this comparison for the force range from 0.2 kN up to 4 kN can be considered as satisfactory due to given rule in “ISO/IEC 17043:2010”.

3. Torque comparison

3.1. Laboratory standards and measurement methods of the participants

3.1.1 The Torque Standard Machines of MIKES

A list of MIKES TSMs used to carry out measurements for the torque comparisons is presented in the table 37.

Table 37. MIKES TSMs used in comparisons.

Torque standard machine	Torque standard machine type	Rel. uncertainty W_{TSM}, (k = 2)
20 kN·m	Reference TSM	$5 \cdot 10^{-4}$
2 kN·m	Lever deadweight TSM with mechanical bearings	$4 \cdot 10^{-4}$
50 N·m	Lever deadweight TSM with air bearings	$4 \cdot 10^{-4}$

MIKES 20 kN·m reference TSM

MIKES 20 kN·m reference TSM has three reference torque transducers with nominal capacities of 5 kN·m, 10 kN·m and 20 kN·m. All reference torque transducers of the TSM are Lahti Precision type TT1 shaft type torque transducers. The reference torque transducers are calibrated at PTB on a regular basis. The calibration interval for each reference torque transducer is three years. The reference TSM is controlled by PC and the calibration torque is generated by stepping motor. The PC also records output values of the reference transducer and the calibration object before and after the pre-set target output value of the reference transducer for each calibration point. The calibration torque slightly increases in case of an increasing load series or decreases in case of a decreasing load series during the recording period of the output values. The recording interval of the output values is 5 readings / second and 25 or 50 output values are recorded for each calibration point. Based on the recorded data for each calibration point the results of the calibration are interpolated on an excel-sheet by means of a linear fitting function. The TSM generates clockwise and anti-clockwise calibration torques from 0.3 kN·m up to 20 kN·m. Relative expanded uncertainty of the generated torque is $5 \cdot 10^{-4}$ (k = 2).

MIKES 2 kN·m lever deadweight TSM

MIKES 2 kN·m lever deadweight TSM has a lever length of 1000 mm. The lever is supported by mechanical bearings. The lever is balanced by stepping motor and the balancing is controlled by PC. The TSM has five stacks of deadweights with nominal values of 0.1 kN, 0.2 kN, 0.5 kN, 1 kN and 2 kN. Each stack comprises of 11 pieces of deadweights. Each deadweight has a value of 10% of the stack’s nominal value. Loading of the deadweights is mechanical. The TSM generates clockwise and anti-clockwise calibration torques from 0.01 kN·m up to 2.2 kN·m. Relative expanded uncertainty of the generated torque is $4 \cdot 10^{-4}$ (k = 2).

MIKES 50 N·m lever deadweight TSM

MIKES 50 N·m lever deadweight TSM has a lever length of 250 mm. The lever is supported by air bearing. The lever is balanced by stepping motor and the balancing is controlled by PC. The TSM has seven stacks of deadweights. The deadweight stacks of the TSM are 12 × 0.4 N; 12 × 1 N; 12 × 2 N; 12 × 4 N; 12 × 5 N; 12 × 8 N and 20 × 10 N. Loading of the deadweights is manual. The TSM generates clockwise and anti-clockwise calibration torques from 0.1 N·m up to 50 N·m. Relative expanded uncertainty of the generated torque is $4 \cdot 10^{-4}$ (k = 2).

3.1.2 The Torque Standard Machines of PTB

A list of PTB's TSMs used to carry out measurements for the torque comparisons is presented in table 38.

Table 38. PTB's TSMs used in comparisons.

Torque standard machine	Torque standard machine type	Rel. uncertainty W_{TSM}, (k = 2)
20 kN·m	Lever deadweight TSM with air bearings	$2 \cdot 10^{-5}$
1 kN·m	Lever deadweight TSM with air bearings	$2 \cdot 10^{-5}$
1 N·m	Lever deadweight TSM with air bearings	$2 \cdot 10^{-4}$

PTB's 20 kN·m lever deadweight TSM

PTB's 20 kN·m lever deadweight TSM has a two-armed lever of 1000 mm single-arm length. The lever is supported by an air bearing. The lever is balanced by a motor and the balancing is controlled by PC. The TSM has five stacks of deadweights on the clockwise torque side with nominal values of 10 kN, 5 kN, 2 kN, 2 kN and 1 kN. Each stack comprises of 10 pieces of deadweights. Each deadweight has a value of 10% of the stack's nominal value. Deadweights in different stacks can be selected to be used for the torque generation independently from other stacks but usually increasing or decreasing series are realised. There is a compensation stack of eleven deadweights on the anti-clockwise torque side. The loading of the deadweights is carried out using hydraulic means. The machine generates clockwise and anti-clockwise calibration torques from 0.1 kN·m up to 20 kN·m. The expanded relative uncertainty of the generated torque is $2 \cdot 10^{-5}$ (k = 2).

PTB's 1 kN·m lever deadweight TSM

PTB's 1 kN·m lever deadweight TSM has a two-armed lever of 500 mm single-arm length. The lever is supported by an air bearing. The lever is balanced by a motor and the balancing is controlled by PC. The TSM has seven stacks of deadweights each on the clockwise and the anti-clockwise torque sides with nominal values of 2 kN, 1 kN, 0.4 kN, 0.2 kN, 0.1 kN, 0.04 and 0.02 kN. Each stack comprises of 10 pieces of deadweights. Each deadweight has a value of 10% of the stack's nominal value. Two stacks of deadweights can be selected to be used for the torque generation, one on the clockwise and one on the anti-clockwise torque sides. The loading of the deadweights is carried out using electric means. The machine generates clockwise and anti-clockwise calibration torques from 0.01 kN·m up to 1 kN·m. The expanded relative uncertainty of the generated torque is $2 \cdot 10^{-5}$ (k = 2).

PTB's 1 N·m lever deadweight TSM

PTB's 1 N·m lever deadweight TSM has a two-armed lever of 250 mm single-arm length. The lever is supported by an air bearing. The lever is balanced by a motor and the balancing is controlled by PC. The TSM has five stacks of deadweights each on the clockwise and the anti-clockwise torque sides with nominal values of 4 N, 2 N, 0.8 N, 0.4 N and 0.04 N. Each stack comprises of 10 pieces of deadweights. Each deadweight has a value of 10% of the stack's nominal value. Two stacks of deadweights can be selected to be used for the torque generation, one on the clockwise and one on the anti-clockwise torque sides. The loading of the deadweights is carried out using electric means. The machine generates clockwise and anti-clockwise calibration torques from 0.001 N·m up to 1 N·m. The expanded relative uncertainty of the generated torque is $1 \cdot 10^{-4}$ ($k = 2$) for the range from 0.1 N·m up to 1 N·m.

3.1.3 Measurement amplifiers

Both participating laboratories used their own high-precision frequency-carrier measuring amplifiers with the same amplifier settings. Any comparison of used measuring amplifiers was not included in this comparison. A list of used measurement amplifiers is presented in the table 39.

Table 39. Measurement amplifiers used in comparison.

Measurement amplifier			
Manufacturer	Type	Serial number	Owner
HBM	MGCplus	# 801071127	MIKES
HBM	DMP 40 S2	# 010620004	MIKES
HBM	DMP 41 T6	# 822125801	MIKES
HBM	DMP 40 S2	# 122820045	PTB
HBM	DMP 40	# 010620006	PTB

3.2 Transfer Standards

Several torque transducers with various capacities were used as torque transfer standards for the comparisons. The transducers used for the comparisons are listed in the table 40. All of these transducers have 6-wire connection to measuring amplifier. All used transducers are well known and have suitable characteristics for a use as a transfer standard. Most of them have been used for comparisons over the years. All transducers except one, HBM TB2 200 N·m, belong to MIKES. The HBM TB2 200 N·m transducer belongs to PTB.

Table 40. Torque transfer standards for the comparisons.

Torque transducer			
Manufacturer	Type	Serial number	Capacity
Raute Precision	TT1	# 37233-06	1 N·m
Raute Precision	TT1	# 36733-03	50 N·m
Raute Precision	TT1	# 36751-04	200 N·m
HBM	TB2	# 80830117	200 N·m
Raute Precision	TT1	# 34852-99	1000 N·m
Raute Precision	TT1	# 32058	2000 N·m
Raute Precision	TT1	# 37203-03	20000 N·m

3.3 Organization, chronology and problems during the comparison

The bilateral torque comparison between MIKES and PTB was carried out between 2011 and 2015. All the measurements for the same torque range were carried out according the same measurement procedure.

3.3.1 First set of comparison measurements 2011 and 2012

The first set of comparison measurements were carried out during 2011 and 2012. The initial measurements were carried out at MIKES. After the initial measurements the transfer standards were delivered to PTB and measurements at PTB were carried out. Then the transfer standards were delivered back to MIKES and the final measurements were carried out. The measurements included four different torque ranges. Compared torques were from 1 N·m up to 20000 N·m. Each torque range was measured with different transfer standard.

The results of the first set of comparison measurements indicated some problems related to reported MIKES measurement results on the torque range from 1 N·m up to 50 N·m anti-clockwise torque and the torque range from 10 N·m up to 200 N·m clockwise torque. On the torque range from 1 N·m up to 50 N·m anti-clockwise torque MIKES initially reported incorrect measurement results to PTB. Afterwards it was discovered that these reported incorrect measurement results were caused by an error related to zero reading correction applied to MIKES measurement data. In worst case the error on the zero reading correction of MIKES measurement results resulted a relative deviation higher than 1% compared to PTB’s measurement results on a torque step of 1 N·m anti-clockwise torque. On the torque range from 10 N·m up to 200 N·m clockwise torque the problem related to reported MIKES measurement results was caused by a single measurement reading of a single measurement series from the initial measurements at MIKES on the torque step of 10 N·m. On the torque step of 10 N·m clockwise torque this single incorrect measurement reading resulted a relative deviation higher than 0.15% between MIKES initial measurement result and PTB’s measurement result. The cause of this incorrect single measurement reading and how it was not recognized was not discovered. This incorrect measurement reading may be related to the agreed measurement procedure. The problem related to agreed measurement procedure was that the selected torque steps were not compatible for the deadweight stacks of MIKES 2 kN·m TSM. Therefore, MIKES had to switch between two different deadweight stacks in the middle of measurement series during the measurements on the torque range from 10 N·m up to 200 N·m to apply the selected torque steps to the torque transfer standard. This may have caused interference to the MIKES measurement data.

3.3.2 Second set of comparison measurements 2013

The second set of comparison measurements were carried out during 2013. Because of the problems during 2011 and 2012 measurements related to results of the torque range from 10 N·m up to 200 N·m it was decided that additional measurements were needed. The initial measurements were carried out at MIKES. After the initial measurements the transfer standard was delivered back to PTB and measurements at PTB were carried out. These measurements did not include a second measurement at PTB or MIKES. The measurements included one torque range. Compared torques were from 20 N·m up to 200 N·m. The used torque transfer torque standard was PTB’s HBM TB2 200 N·m.

3.3.3 Third set of comparison measurements 2015

The third set of comparison measurements were carried out during 2015. The measurements were carried out as the first set of measurements. The measurements included two different torque ranges. Compared torques were from 0.4 N·m up to 1000 N·m. Each torque range was measured with different transfer standard.

3.4 Measurement procedures

The comparisons were carried out according to measurement procedures commonly used for comparisons of torque standard machines. For each set of measurements (2011-2012, 2013 and 2015) the measurement procedure was slightly different. All the transfer standards were measured in three (0º, 120º and 240º) or four (0º, 90º, 180º and 270º) rotational positions with one or two series of increasing torque in each position. For some transfer standards measurement procedure also included measurement series of decreasing torque. In order to stabilize the transfer standard before the first measurement series in rotational position 0^0, the torque transducers were loaded with a preload equal to each transducer’s nominal capacity three times. The selected time delay between the start of the torque change (increase or decrease of the torque) and reading of the measurement result varied from 60 seconds up to 180 seconds depending on the used transfer standard and TSMs. However, the same time delay for the same transfer standard was applied in both participating laboratories. The same measurement procedure was applied for clockwise and anti-clockwise torques. Selected torque range and steps for each transfer standards are presented in table 41.

Table 41. Selected torque ranges and steps for the transfer standards.

Torque transducer				Selected torque steps
Manufacturer	Type	Serial number	Capacity	
Raute Precision	TT1	# 37233-06	1 N·m	0.4 N·m … 1 N·m (step 0.2 N·m)
Raute Precision	TT1	# 36733-03	50 N·m	1 N·m, 10 N·m and 500 N·m
Raute Precision	TT1	# 36751-04	200 N·m	10 N·m, 50 N·m and 200 N·m
HBM	TB2	# 80830117	200 N·m	20 N·m … 200 N·m
Raute Precision	TT1	# 34852-99	1000 N·m	500 N·m and 1000 N·m
Raute Precision	TT1	# 32058	2000 N·m	200 N·m and 2000 N·m
Raute Precision	TT1	# 37203-03	20000 N·m	2000 N·m and 20000 N·m

3.4.1 Measurement procedure 2011 and 2012

The transfer standards were measured in four rotational positions with two series of increasing torque in the first rotational position and one series of increasing torque for the following positions. One series with decreasing torque in each rotational position was included in the measurements of the 20000 N·m transducer.

3.4.2 Measurement procedure 2013

The transfer standard was measured in three rotational positions with one series of increasing and decreasing torque in each position. The measurement in first rotational position included one additional series of increasing torque.

3.4.3 Measurement procedure 2015

The transfer standard with nominal capacity of 1 N·m was measured in four rotational positions and the transfer standard with nominal capacity of 1000 N·m was measured with three rotational positions. For both transfer standards each rotational position was measured with two series of increasing torque. These measurements did not include any measurements with decreasing torque.

3.5 Results of the comparison

3.5.1 Measurement results and uncertainties

Measurement results and uncertainties of the first set of measurements are shortly presented in the tables 43 to 46. Measurement results and uncertainties of the second set of measurements are shortly presented in the table 47. Measurement results and uncertainties of the third set of measurements are shortly presented in the tables 48 and 49. The following designations are used in the tables 43 to 49:

$\mathrm{MIKES_A}$ = Mean deflection of initial MIKES measurement calculated as $\overline{X}_r$ in table 42.

$W_{\mathrm{MIKES\ A}}$ = Relative expanded uncertainty (k = 2) of initial MIKES measurement calculated as W in table 42.

$\mathrm{MIKES_B}$ = Mean deflection of final MIKES measurement calculated as $\overline{X}_r$ in table 42.

$W_{\mathrm{MIKES\ B}}$ = Relative expanded uncertainty (k = 2) of final MIKES measurement calculated as W in table 42.

PTB = Mean deflection of PTB measurement calculated as $\overline{X}_r$ in table 42.

W_{PTB} = Relative expanded uncertainty (k = 2) of PTB measurement calculated as W in table 42.

The uncertainties were estimated according to principles laid out in the document "JCGM 100:2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement". The principal components of the uncertainty budget to be evaluated are in accordance with the document "Calibration Guide EURAMET cg-14 version 2.0 (03/2011) - Guidelines on the calibration of static torque measuring devices" [6]. The relative expanded uncertainties of the measurements are mainly calculated to present that the uncertainty contribution of applied torque is the most significant uncertainty contribution. The calculation of relative expanded measurement uncertainties W (k = 2) is presented in a table 42. The uncertainty contribution due to reversibility (w_{h}) has been included to the relative expanded measurement calculations only for the torque range from 2000 N·m up to 20000 N·m.

Table 42. Calculation of relative expanded uncertainties W (k = 2).

Uncertainty arising from	Equation	Statistical distribution	Rel. uncertainty contribution
Reproducibility from rotational (0º … 270º or 0º … 240º) measurement values (*n* = 3 or 4) *b*	$b = \frac{1}{\overline{X}_r} \cdot \sqrt{\frac{\sum_{i=1}^{n}\left(X_i - \overline{X}_r\right)^2}{(n-1)}}$ $\overline{X}_r = \frac{\sum_{i=1}^{n} X_i}{n}$	Normal distribution	$w_b = \frac{b}{\sqrt{n}}$
Repeatability, from first measurement position *b'* (rel. half width value)	$b' = \frac{1}{2} \cdot \frac{\lvert X_1 - X_2 \rvert}{\overline{X}_{wr}}$ $\overline{X}_{wr} = \frac{X_1 + X_2}{2}$	Rectangular distribution	$w_{b'} = \frac{b'}{\sqrt{3}}$
Reversibility (*n* = 4) *h* (rel. half width value)	$h = \frac{1}{2} \cdot \frac{\sum_{i=1}^{n}\lvert X_i - X_i' \rvert}{n}$	Rectangular distribution	$w_h = \frac{h}{\sqrt{3}}$
Resolution of indication *r* (rel. half width value) (*a* = indication step)	$r = \frac{1}{2} \cdot \frac{a}{\overline{X}_r}$	Rectangular distribution	$w_r = \frac{r}{\sqrt{3}}$
Uncertainty of applied torque (*k* = 2)	W_{TSM}	Normal distribution	$w_{TSM} = \frac{W_{FSM}}{k}$
Rel. expanded uncertainty of the measurement (*k* = 2)	$W = k \cdot \sqrt{w_b^2 + w_{b'}^2 + w_h^2 + 2 \cdot w_r^2 + w_{FSM}^2}$		

Table 43. Measurement results and uncertainties, torque range 1 N·m ... 50 N·m, year 2011 - 2012.

Torque N·m	$MIKES_A$ mV/V	$W_{MIKES\ A}$ (k = 2) %	$MIKES_B$ mV/V	$W_{MIKES\ B}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
Clockwise torque						
1	0.026717	0.0631	0.026731	0.0411	0.026733	0.0093
10	0.267322	0.0400	0.267322	0.0401	0.267341	0.0021
50	1.336910	0.0401	1.336846	0.0400	1.336880	0.0020
Anti-clockwise torque						
-1	-0.026735	0.0874	-0.026726	0.0427	-0.026733	0.0105
-10	-0.267359	0.0408	-0.267337	0.0401	-0.267339	0.0022
-50	-1.337066	0.0401	-1.336977	0.0400	-1.336904	0.0020

Table 44. Measurement results and uncertainties, torque range 10 N·m ... 200 N·m, year 2011 - 2012.

Torque N·m	$MIKES_A$ mV/V	$W_{MIKES\ A}$ (k = 2) %	$MIKES_B$ mV/V	$W_{MIKES\ B}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
Clockwise torque						
10	0.066458	0.2748	0.066368	0.0413	0.066357	0.0026
50	0.331954	0.0666	0.331871	0.0401	0.331805	0.0021
200	1.327622	0.0400	1.327639	0.0400	1.327411	0.0020
Anti-clockwise torque						
-10	-0.066371	0.0414	-0.066365	0.0407	-0.066357	0.0046
-50	-0.331852	0.0401	-0.331858	0.0400	-0.331810	0.0021
-200	-1.327569	0.0400	-1.327616	0.0400	-1.327428	0.0020

Table 45. Measurement results and uncertainties, torque range 200 N·m ... 2000 N·m, year 2011 - 2012.

Torque N·m	$MIKES_A$ mV/V	$W_{MIKES\ A}$ (k = 2) %	$MIKES_B$ mV/V	$W_{MIKES\ B}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
Clockwise torque						
200	0.131679	0.0467	0.131690	0.0504	0.131639	0.0025
2000	1.316780	0.0400	1.316891	0.0401	1.316494	0.0020
Anti-clockwise torque						
-200	-0.131678	0.0441	-0.131677	0.0500	-0.131640	0.0028
-2000	-1.316788	0.0400	-1.316919	0.0400	-1.316609	0.0020

Table 46. Measurement results and uncertainties, torque range 2000 N·m ... 20000 N·m, year 2011 - 2012.

Torque N·m	MIKES$_A$ mV/V	$W_{\text{MIKES A}}$ (k = 2) %	MIKES$_B$ mV/V	$W_{\text{MIKES B}}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
Clockwise torque						
2000	0.131451	0.0647	0.131350	0.0547	0.131376	0.0157
20000	1.313808	0.0502	1.313551	0.0501	1.313972	0.0023
Anti-clockwise torque						
-2000	-0.131378	0.0531	-0.131348	0.0503	-0.131379	0.0162
-20000	-1.313991	0.0502	-1.313695	0.0500	-1.314015	0.0021

Table 47. Measurement results and uncertainties, torque range 20 N·m ... 200 N·m, year 2013.

Torque N·m	MIKES$_A$ mV/V	$W_{\text{MIKES A}}$ (k = 2) %	MIKES$_B$ mV/V	$W_{\text{MIKES B}}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
Clockwise torque						
20	0.126918	0.0402	-	-	0.126933	0.0025
40	0.253847	0.0401	-	-	0.253881	0.0022
60	0.380785	0.0400	-	-	0.380842	0.0023
80	0.507735	0.0400	-	-	0.507804	0.0023
100	0.634687	0.0400	-	-	0.634776	0.0021
120	0.761650	0.0400	-	-	0.761757	0.0021
160	1.015580	0.0400	-	-	1.015715	0.0021
200	1.269522	0.0400	-	-	1.269688	0.0020
Anti-clockwise torque						
-20	-0.126912	0.0402	-	-	-0.126937	0.0036
-40	-0.253836	0.0400	-	-	-0.253883	0.0025
-60	-0.380771	0.0400	-	-	-0.380838	0.0021
-80	-0.507715	0.0400	-	-	-0.507801	0.0021
-100	-0.634663	0.0400	-	-	-0.634773	0.0021
-120	-0.761624	0.0400	-	-	-0.761746	0.0021
-160	-1.015530	0.0400	-	-	-1.015698	0.0021
-200	-1.269459	0.0400	-	-	-1.269659	0.0020

Table 48. Measurement results and uncertainties, torque range 0.4 N·m ... 1 N·m, year 2015.

Torque N·m	$MIKES_A$ mV/V	$W_{MIKES\ A}$ (k = 2) %	$MIKES_B$ mV/V	$W_{MIKES\ B}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
Clockwise torque						
0.4	0.542888	0.0403	0.542860	0.0402	0.543049	0.0200
0.6	0.814366	0.0401	0.814317	0.0401	0.814574	0.0200
0.8	1.085784	0.0401	1.085739	0.0401	1.086071	0.0200
1.0	1.357169	0.0402	1.357103	0.0401	1.357502	0.0200
Anti-clockwise torque						
-0.4	-0.543153	0.0404	-0.543085	0.0401	-0.543229	0.0200
-0.6	-0.814896	0.0402	-0.814796	0.0401	-0.814983	0.0200
-0.8	-1.086706	0.0403	-1.086566	0.0400	-1.086805	0.0200
-1.0	-1.358523	0.0401	-1.358370	0.0400	-1.358654	0.0200

Table 49. Measurement results and uncertainties, torque range 500 N·m ... 1000 N·m, year 2015.

Torque N·m	$MIKES_A$ mV/V	$W_{MIKES\ A}$ (k = 2) %	$MIKES_B$ mV/V	$W_{MIKES\ B}$ (k = 2) %	PTB mV/V	W_{PTB} (k = 2) %
Clockwise torque						
500	0.664333	0.0400	0.664313	0.0400	0.664314	0.0025
1000	1.328772	0.0400	1.328739	0.0400	1.328720	0.0026
Anti-clockwise torque						
-500	-0.664313	0.0400	-0.664295	0.0400	-0.664316	0.0024
-1000	-1.328769	0.0400	-1.328723	0.0400	-1.328746	0.0023

3.5.2 Relative deviations and E_n numbers

The results of the comparison measurements are evaluated by using the E_n numbers. The evaluation of the results was uniform to the evaluation of force comparison results. Relative deviations between MIKES and PTB of the first set of measurements are presented in the tables 50 to 53. Relative deviations of the second set of measurements are presented in the table 54. Relative deviations of the third set of measurements are presented in the tables 55 and 56. The E_n numbers of the first set of measurements are presented in the tables 57 to 60. The E_n numbers of the second set of measurements are presented in the table 61. The E_n numbers of the third set of measurements are presented in the tables 62 and 63. The following designations are used in the tables 50 to 63:

$MIKES_{A\text{-}B\ AVE}$ = Mean deflection of MIKES measurements calculated according to equation (1).

PTB = Mean deflection of PTB measurement calculated as $\overline{X}_r$ in table 42.

W_{TSM} = Relative expanded uncertainty of applied torque (k = 2)

Table 50. Relative deviations between MIKES and PTB, torque range 1 N·m ... 50 N·m, year 2011 - 2012.

Torque N·m	$MIKES_{A-B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A-B\ AVE}$ to PTB %
Clockwise torque			
1	0.026724	0.026733	-0.0318
10	0.267322	0.267341	-0.0070
50	1.336878	1.336880	-0.0002
Anti-clockwise torque			
-1	-0.026731	-0.026733	-0.0080
-10	-0.267348	-0.267339	0.0034
-50	-1.337021	-1.336904	0.0088

Table 51. Relative deviations between MIKES and PTB, torque range 10 N·m ... 200 N·m, year 2011 - 2012.

Torque N·m	$MIKES_{A-B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A-B\ AVE}$ to PTB %
Clockwise torque			
10	0.066413	0.066357	0.0845
50	0.331912	0.331805	0.0325
200	1.327631	1.327411	0.0165
Anti-clockwise torque			
-10	-0.066368	-0.066357	0.0176
-50	-0.331855	-0.331810	0.0135
-200	-1.327593	-1.327428	0.0124

Table 52. Relative deviations between MIKES and PTB, torque range 200 N·m ... 2000 N·m, year 2011 - 2012.

Torque N·m	$MIKES_{A-B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A-B\ AVE}$ to PTB %
Clockwise torque			
200	0.131685	0.131639	0.0347
2000	1.316836	1.316494	0.0260
Anti-clockwise torque			
-200	-0.131677	-0.131640	0.0283
-2000	-1.316854	-1.316609	0.0186

Table 53. Relative deviations between MIKES and PTB, torque range 2000 N·m … 20000 N·m, year 2011 - 2012.

Torque N·m	$MIKES_{A\text{-}B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A\text{-}B\ AVE}$ to PTB %
Clockwise torque			
2000	0.131401	0.131376	0.0192
20000	1.313680	1.313972	-0.0223
Anti-clockwise torque			
-2000	-0.131363	-0.131379	-0.0125
-20000	-1.313843	-1.314015	-0.0131

Table 54. Relative deviations between MIKES and PTB, torque range 20 N·m … 200 N·m, year 2013.

Torque N·m	$MIKES_{A\text{-}B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A\text{-}B\ AVE}$ to PTB %
Clockwise torque			
20	0.126918	0.126933	-0.0123
40	0.253847	0.253881	-0.0132
60	0.380785	0.380842	-0.0149
80	0.507735	0.507804	-0.0136
100	0.634687	0.634776	-0.0140
120	0.761650	0.761757	-0.0140
160	1.015580	1.015715	-0.0133
200	1.269522	1.269688	-0.0131
Anti-clockwise torque			
-20	-0.126912	-0.126937	-0.0196
-40	-0.253836	-0.253883	-0.0183
-60	-0.380771	-0.380838	-0.0174
-80	-0.507715	-0.507801	-0.0169
-100	-0.634663	-0.634773	-0.0173
-120	-0.761624	-0.761746	-0.0160
-160	-1.015530	-1.015698	-0.0166
-200	-1.269459	-1.269659	-0.0158

Table 55. Relative deviations between MIKES and PTB, torque range 0.4 N·m ... 1 N·m, year 2015.

Torque N·m	$MIKES_{A\text{-}B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A\text{-}B\ AVE}$ to PTB %
Clockwise torque			
0.4	0.542874	0.543049	-0.0321
0.6	0.814341	0.814574	-0.0285
0.8	1.085761	1.086071	-0.0285
1.0	1.357136	1.357502	-0.0269
Anti-clockwise torque			
-0.4	-0.543119	-0.543229	-0.0202
-0.6	-0.814846	-0.814983	-0.0169
-0.8	-1.086636	-1.086805	-0.0156
-1.0	-1.358446	-1.358654	-0.0153

Table 56. Relative deviations between MIKES and PTB, torque range 500 N·m ... 1000 N·m, year 2015.

Torque N·m	$MIKES_{A\text{-}B\ AVE}$ mV/V	PTB mV/V	Relative deviation $MIKES_{A\text{-}B\ AVE}$ to PTB %
Clockwise torque			
500	0.664323	0.664314	0.0014
1000	1.328756	1.328720	0.0027
Anti-clockwise torque			
-500	-0.664304	-0.664316	-0.0018
-1000	-1.328746	-1.328746	0.0000

Table 57. E_n numbers of the comparison, torque range 1 N·m ... 50 N·m, year 2011 - 2012.

Torque	Relative deviation	W_{TSM} ,(k = 2)		E_n
N·m	$MIKES_{A\text{-}B\ AVE}$ to PTB %	MIKES %	PTB %	
Clockwise torque				
1	-0.0318	0.0400	0.0020	-0.80
10	-0.0070	0.0400	0.0020	-0.17
50	-0.0002	0.0400	0.0020	0.00
Anti-clockwise torque				
-1	-0.008008	0.0400	0.0020	-0.20
-10	0.003351	0.0400	0.0020	0.08
-50	0.008806	0.0400	0.0020	0.22

Table 58. E_n numbers of the comparison, torque range 10 N·m ... 200 N·m, year 2011 - 2012.

Torque N·m	Relative deviation MIKES$_{A\text{-}B\ AVE}$ to PTB %	W_{TSM} ,(k = 2) MIKES %	 PTB %	E_n
Clockwise torque				
10	0.0845	0.0400	0.0020	2.11
50	0.0325	0.0400	0.0020	0.81
200	0.0165	0.0400	0.0020	0.41
Anti-clockwise torque				
-10	0.0176	0.0400	0.0020	0.44
-50	0.0135	0.0400	0.0020	0.34
-200	0.0124	0.0400	0.0020	0.31

Table 59. E_n numbers of the comparison, torque range 200 N·m ... 2000 N·m, year 2011 - 2012.

Torque N·m	Relative deviation MIKES$_{A\text{-}B\ AVE}$ to PTB %	W_{TSM} ,(k = 2) MIKES %	 PTB %	E_n
Clockwise torque				
200	0.0347	0.0400	0.0020	0.87
2000	0.0260	0.0400	0.0020	0.65
Anti-clockwise torque				
-200	0.0283	0.0400	0.0020	0.71
-2000	0.0186	0.0400	0.0020	0.46

Table 60. E_n numbers of the comparison, torque range 2000 N·m ... 20000 N·m, year 2011 - 2012.

Torque N·m	Relative deviation MIKES$_{A\text{-}B\ AVE}$ to PTB %	W_{TSM} ,(k = 2) MIKES %	 PTB %	E_n
Clockwise torque				
2000	0.0192	0.0500	0.0020	0.38
20000	-0.0223	0.0500	0.0020	-0.44
Anti-clockwise torque				
-2000	-0.0125	0.0500	0.0020	-0.25
-20000	-0.0131	0.0500	0.0020	-0.26

Table 61. E_n numbers of the comparison, torque range 20 N·m ... 200 N·m, year 2013.

Torque N·m	Relative deviation MIKES$_{A\text{-}B\ AVE}$ to PTB %	W_{TSM}, (k = 2) MIKES %	 PTB %	E_n
Clockwise torque				
20	-0.0123	0.0400	0.0020	-0.31
40	-0.0132	0.0400	0.0020	-0.33
60	-0.0149	0.0400	0.0020	-0.37
80	-0.0136	0.0400	0.0020	-0.34
100	-0.0140	0.0400	0.0020	-0.35
120	-0.0140	0.0400	0.0020	-0.35
160	-0.0133	0.0400	0.0020	-0.33
200	-0.0131	0.0400	0.0020	-0.33
Anti-clockwise torque				
-20	-0.0196	0.0400	0.0020	-0.49
-40	-0.0183	0.0400	0.0020	-0.46
-60	-0.0174	0.0400	0.0020	-0.44
-80	-0.0169	0.0400	0.0020	-0.42
-100	-0.0173	0.0400	0.0020	-0.43
-120	-0.0160	0.0400	0.0020	-0.40
-160	-0.0166	0.0400	0.0020	-0.41
-200	-0.0158	0.0400	0.0020	-0.39

Table 62. E_n numbers of the comparison, torque range 0.4 N·m ... 1 N·m, year 2015.

Torque N·m	Relative deviation MIKES$_{A\text{-}B\ AVE}$ to PTB %	W_{TSM}, (k = 2) MIKES %	 PTB %	E_n
Clockwise torque				
0.4	-0.0321	0.0400	0.0200	-0.72
0.6	-0.0285	0.0400	0.0200	-0.64
0.8	-0.0285	0.0400	0.0200	-0.64
1.0	-0.0269	0.0400	0.0200	-0.60
Anti-clockwise torque				
-0.4	-0.0202	0.0400	0.0200	-0.45
-0.6	-0.0169	0.0400	0.0200	-0.38
-0.8	-0.0156	0.0400	0.0200	-0.35
-1.0	-0.0153	0.0400	0.0200	-0.34

Table 63. E_n numbers of the comparison, torque range 500 N·m ... 1000 N·m, year 2015.

Torque N·m	Relative deviation MIKES$_{A\text{-}B\ AVE}$ to PTB %	W_{TSM} ,(k = 2) MIKES %	 PTB %	E_n
Clockwise torque				
500	0.0014	0.0400	0.0020	0.03
1000	0.0027	0.0400	0.0020	0.07
Anti-clockwise torque				
-500	-0.0018	0.0400	0.0020	-0.05
-1000	0.0000	0.0400	0.0020	0.00

All, except one, of the E_n numbers for these comparison measurements have absolute value lower than 1. The results from 2011 and 2012 present unsatisfactory result ($|E_n| > 1$) for the torque step of 10 N·m clockwise torque on the range from 10 N·m up to 200 N·m. This unsatisfactory result is caused by a single measurement reading of a single measurement series from initial measurements at MIKES in 2011. Therefor according the E_n numbers for these comparison measurements, given in tables 57 to 63, the overall results of this comparison for the torque range from 0.4 N·m up to 20000 N·m can be considered as satisfactory due to given rule in “ISO/IEC 17043:2010”.

4. Conclusions

The summaries of the bilateral force comparison results and MIKES internal force comparison results are presented in tables 64 and 65. The summary of the bilateral torque comparison results is presented in the table 66.

Table 64. The summary of bilateral force comparison results.

Period	Force	$MIKES_{A\text{-}B\ AVE}$	PTB	Rel. deviation	W_{FSM} ,(k = 2)		E_n
				MIKES-PTB	MIKES	PTB	
	kN	mV/V	mV/V	$\cdot 10^{-5}$	$\cdot 10^{-5}$	$\cdot 10^{-5}$	
16.2.2012 - 28.5.2012	0.8	0.804986	0.804913	9.1	5.0	2.0	1.69
	1.0	1.006256	1.006179	7.6	5.0	2.0	1.41
	1.2	1.207545	1.207468	6.4	5.0	2.0	1.19
	1.4	1.408852	1.408768	5.9	5.0	2.0	1.10
	1.6	1.610172	1.610083	5.5	5.0	2.0	1.02
	1.8	1.811500	1.811411	4.9	5.0	2.0	0.92
	2.0	2.012838	2.012739	4.9	5.0	2.0	0.92
8.2.2012 - 23.5.2012	8	0.800095	0.800067	3.5	5.0	2.0	0.66
	10	1.000175	1.000143	3.2	5.0	2.0	0.60
	12	1.200263	1.200224	3.3	5.0	2.0	0.60
	14	1.400352	1.400311	2.9	5.0	2.0	0.54
	16	1.600442	1.600394	3.0	5.0	2.0	0.56
	18	1.800522	1.800475	2.6	5.0	2.0	0.49
	20	2.000596	2.000548	2.4	5.0	2.0	0.44
7.2.2012 - 23.5.2012	40	0.799841	0.799826	1.9	5.0	2.0	0.36
	50	0.999862	0.999839	2.2	5.0	2.0	0.41
	60	1.199889	1.199863	2.2	5.0	2.0	0.41
	70	1.399934	1.399905	2.1	5.0	2.0	0.39
	80	1.599985	1.599955	1.9	5.0	2.0	0.35
	90	1.800053	1.800025	1.6	5.0	2.0	0.29
	100	2.000128	2.000101	1.4	5.0	2.0	0.26
10.2.2012 - 26.9.2012	80	0.799535	0.799713	-22.3	10.0	2.0	-2.19
	100	0.999552	0.999751	-19.9	10.0	2.0	-1.95
	120	1.199602	1.199808	-17.1	10.0	2.0	-1.68
	140	1.399676	1.399894	-15.5	10.0	2.0	-1.52
	160	1.599771	1.599985	-13.3	10.0	2.0	-1.31
	180	1.799895	1.800117	-12.3	10.0	2.0	-1.21
	200	2.000035	2.000243	-10.4	10.0	2.0	-1.02
15.2.2012 - 27.9.2012	200	0.800165	0.800193	-3.5	10.0	2.0	-0.34
	250	1.000169	1.000159	1.1	10.0	2.0	0.11
	300	1.200178	1.200163	1.2	10.0	2.0	0.12
	350	1.400198	1.400180	1.2	10.0	2.0	0.12
	400	1.600226	1.600203	1.5	10.0	2.0	0.14
	450	1.800267	1.800227	2.2	10.0	2.0	0.22
	500	2.000312	2.000327	-0.7	10.0	2.0	-0.07
14.2.2012 - 23.10.2012	400	0.800265	0.800314	-6.1	10.0	2.0	-0.60
	500	1.000331	1.000289	4.2	10.0	2.0	0.41
	600	1.200411	1.200365	3.8	10.0	2.0	0.38
	700	1.400486	1.400434	3.7	10.0	2.0	0.36
	800	1.600564	1.600479	5.3	10.0	2.0	0.52
	900	1.800639	1.800537	5.6	10.0	2.0	0.55
	1000	2.000682	2.000581	5.1	10.0	2.0	0.50
21.1.2013 - 22.2.2013	80	0.310911	0.310895	5.1	10.0	2.0	0.50
	100	0.388629	0.388614	3.7	10.0	2.0	0.36
	120	0.466351	0.466338	2.8	10.0	2.0	0.28
	140	0.544071	0.544065	1.2	10.0	2.0	0.12
	160	0.621796	0.621792	0.6	10.0	2.0	0.06
	180	0.699524	0.699517	1.0	10.0	2.0	0.10
	200	0.777249	0.777243	0.8	10.0	2.0	0.08
18.1.2013 - 21.2.2013	200	0.777220	0.777230	-1.4	10.0	2.0	-0.13
	250	0.971532	0.971554	-2.3	10.0	2.0	-0.22
	300	1.165860	1.165890	-2.5	10.0	2.0	-0.25
	350	1.360203	1.360230	-2.0	10.0	2.0	-0.20
	400	1.554557	1.554591	-2.2	10.0	2.0	-0.22
	450	1.748921	1.748956	-2.0	10.0	2.0	-0.20
	500	1.943297	1.943337	-2.1	10.0	2.0	-0.20

Table 65. The summary of MIKES internal force comparison results.

Period	Force	MIKES	MIKES	Rel. deviation	W_{FSM} ,(k = 2)		E_n
		FSM_{20kN}	FSM_{1kN}		FSM_{20kN}	FSM_{1kN}	
	kN	mV/V	mV/V	$\cdot 10^{-5}$	$\cdot 10^{-5}$	$\cdot 10^{-5}$	
26.11.2015 - 30.11.2015	0.2	0.396934	0.396930	1.0	5.0	5.0	0.14
	0.4	0.793892	0.793891	0.2	5.0	5.0	0.03
	0.6	1.190886	1.190882	0.3	5.0	5.0	0.05
	0.8	1.587911	1.587905	0.4	5.0	5.0	0.06
	1.0	1.984971	1.984962	0.5	5.0	5.0	0.07
		MIKES	MIKES		W_{FSM} ,(k = 2)		
		FSM_{100kN}	FSM_{20kN}		FSM_{100kN}	FSM_{20kN}	
		mV/V	mV/V		$\cdot 10^{-5}$	$\cdot 10^{-5}$	
25.1.2016 - 27.1.2016	2	0.752782	0.752759	3.1	5.0	5.0	0.43
	4	1.505519	1.505499	1.3	5.0	5.0	0.19

Table 66. The summary of bilateral torque comparison results.

Period	Torque	$MIKES_{A\text{-}B\ AVE}$	PTB	Rel. deviation	W_{TSM}, (k = 2)		E_n
				MIKES-PTB	MIKES	PTB	
	N·m	mV/V	mV/V	$\cdot 10^{-5}$	$\cdot 10^{-4}$	$\cdot 10^{-5}$	
Clockwise torque							
29.11.2011	1	0.026724	0.026733	-31.8	4.0	2.0	-0.80
-	10	0.267322	0.267341	-7.0	4.0	2.0	-0.17
25.1.2012	50	1.336878	1.336880	-0.2	4.0	2.0	0.00
1.12.2011	10	0.066413	0.066357	84.5	4.0	2.0	2.11
-	50	0.331912	0.331805	32.5	4.0	2.0	0.81
27.1.2012	200	1.327631	1.327411	16.5	4.0	2.0	0.41
5.12.2011							
-	200	0.131685	0.131639	34.7	4.0	2.0	0.87
31.1.2012	2000	1.316836	1.316494	26.0	4.0	2.0	0.65
14.11.2011							
-	2000	0.131401	0.131639	19.2	5.0	2.0	0.38
6.2.2012	20000	1.313680	1.316494	-22.3	5.0	2.0	-0.44
	20	0.126918	0.126933	-12.3	4.0	2.0	-0.49
	40	0.253847	0.253881	-13.2	4.0	2.0	-0.46
19.3.2013	60	0.380785	0.380842	-14.9	4.0	2.0	-0.44
-	80	0.507735	0.507804	-13.6	4.0	2.0	-0.42
24.4.2013	100	0.634687	0.634776	-14.0	4.0	2.0	-0.43
	120	0.761650	0.761757	-14.0	4.0	2.0	-0.40
	160	1.015580	1.015715	-13.3	4.0	2.0	-0.41
	200	1.269522	1.269688	-13.1	4.0	2.0	-0.39
	0.4	0.542874	0.543049	-32.1	4.0	20.0	-0.72
8.6.2015	0.6	0.814341	0.814574	-28.5	4.0	20.0	-0.64
-	0.8	1.085761	1.086071	-28.5	4.0	20.0	-0.64
16.7.2015	1.0	1.357136	1.357502	-26.9	4.0	20.0	-0.60
10.6.2015							
-	500	0.664323	0.664314	1.4	4.0	2.0	0.03
16.7.2015	1000	1.328756	1.328720	2.7	4.0	2.0	0.07
Anti-clockwise torque							
29.11.2011	-1	-0.026731	-0.066357	-8.0	4.0	2.0	-0.20
-	-10	-0.267348	-0.331810	3.4	4.0	2.0	0.08
25.1.2012	-50	-1.337021	-1.327428	8.8	4.0	2.0	0.22
2.12.2011	-10	-0.066368	-0.066357	17.6	4.0	2.0	0.44
-	-50	-0.331855	-0.331810	13.5	4.0	2.0	0.34
30.1.2012	-200	-1.327593	-1.327428	12.4	4.0	2.0	0.31
5.12.2011							
-	-200	-0.131677	-0.131640	28.3	4.0	2.0	0.71
1.2.2012	-2000	-1.316854	-1.316609	18.6	4.0	2.0	0.46
11.11.2011							
-	-2000	-0.131363	-0.131379	-12.5	5.0	2.0	-0.25
7.2.2012	-20000	-1.313843	-1.314015	-13.1	5.0	2.0	-0.26
	-20	-0.126912	-0.126937	-19.6	4.0	2.0	-0.31
	-40	-0.253836	-0.253883	-18.3	4.0	2.0	-0.33
19.3.2013	-60	-0.380771	-0.380838	-17.4	4.0	2.0	-0.37
-	-80	-0.507715	-0.507801	-16.9	4.0	2.0	-0.34
24.4.2013	-100	-0.634663	-0.634773	-17.3	4.0	2.0	-0.35
	-120	-0.761624	-0.761746	-16.0	4.0	2.0	-0.35
	-160	-1.015530	-1.015698	-16.6	4.0	2.0	-0.33
	-200	-1.269459	-1.269659	-15.8	4.0	2.0	-0.33
	-0.4	-0.543119	-0.543229	-20.2	4.0	20.0	-0.45
9.6.2015	-0.6	-0.814846	-0.814983	-16.9	4.0	20.0	-0.38
-	-0.8	-1.086636	-1.086805	-15.6	4.0	20.0	-0.35
15.7.2015	-1.0	-1.358446	-1.358654	-15.3	4.0	20.0	-0.34
10.6.2015							
-	-500	-0.664304	-0.664316	-1.8	4.0	2.0	-0.05
17.7.2015	-1000	-1.328746	-1.328746	0.0	4.0	2.0	0.00

According the overall results of the bilateral force comparisons and the MIKES internal force comparisons MIKES CMC can be confirmed as follows:

- Deadweight FSMs, force range from 0.002 kN up to 110 kN, the relative expanded uncertainty ($k = 2$) of the calibration force is $5 \cdot 10^{-5}$.
- Hydraulic amplification FSM, force range from 20 kN up to 1100 kN, the relative expanded uncertainty ($k = 2$) of the calibration force is $1 \cdot 10^{-4}$.

And according the results of the bilateral torque comparisons MIKES CMC can be confirmed as follows:

- Lever deadweight TSMs, torque range from 0.1 N·m up to 2200 N·m, the relative expanded uncertainty ($k = 2$) of the calibration torque is $4 \cdot 10^{-4}$.
- Reference TSM, torque range from 300 N·m up to 20000 N·m, the relative expanded uncertainty ($k = 2$) of the calibration torque is $5 \cdot 10^{-4}$.

5. References

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