

## **Investigation of the Measurement Uncertainty of the Force Standard Machines of IPQ by Intercomparison Measurements with PTB**

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### **Abstract**

Two new deadweight force standard machines with capacities of 5 kN and 100 kN have been installed at IPQ. This paper describes the results of an intercomparison between the force standard machines of the National Metrology Institutes of Portugal (IPQ) and Germany (PTB). For the intercomparison, PTB used a set of force transfer standards which covered the whole force range from 50 N to 100 kN. The measurements were performed following the procedure used by PTB in intercomparison measurements. The influence of temperature differences in the various measurements was reduced by taking the temperature dependence of the force transducer sensitivity into account. This way of proceeding, considerably improved the results of the intercomparison and allowed relative deviations to be achieved which are smaller than the relative measurement uncertainty of the force standard machines.

### **1. Introduction**

In 1999, two new deadweight force standard machines with capacities of 5 kN and 100 kN were installed in the National Metrology Institute of Portugal, the IPQ. The machines have been designed and constructed by Gassmann Theiss Messtechnik GmbH, Germany, according to the requirements of IPQ. After installation, the machines were investigated by intercomparison measurements carried out by PTB in October 1999.

### **2. Force Standard Machines of IPQ**

Two new deadweight force standard machines with capacities of 5 kN and 100 kN have been installed at IPQ. The basic construction principle is similar to that of the 20 kN and 100 kN deadweight force standard machines of PTB [1]. However, some modifications were made by the manufacturing firm, Gassmann Theiss Messtechnik GmbH, to meet the requirements of IPQ. The loading frame was modified to place temperature

chambers in the machine for load cell tests according to OIML requirements. A four-column load frame is, therefore, used in the 100 kN machine and a two-column load frame in the 5 kN machine.

The 100 kN force standard machine of IPQ generates forces in compression and tension from 1 kN to 100 kN. To carry out calibrations of 10 kN, 20 kN, 50 kN and 100 kN in steps of 10%, the following force steps can be generated: 1 kN, 2 kN, ..., 10kN, 12 kN, 14 kN, 15 kN, 16 kN, 18 kN, 20 kN, 25 kN, ...50 kN, 60 kN, ... 100 kN.

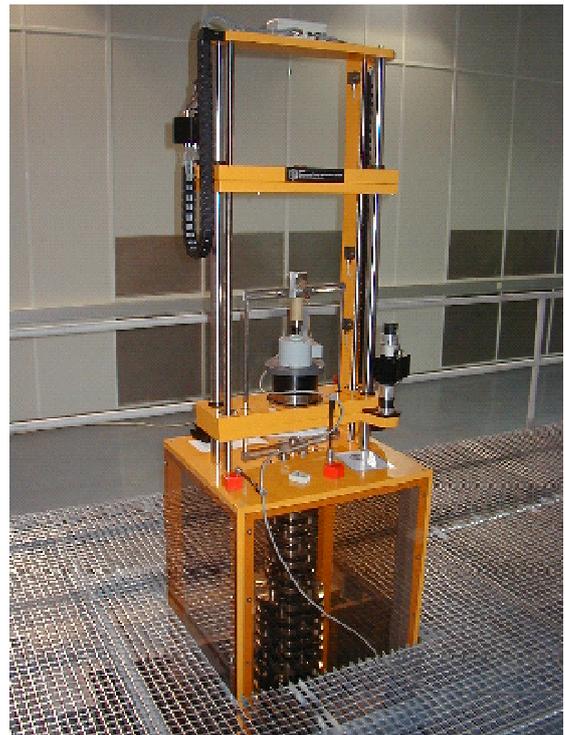


**Figure 1:** Photograph of IPQ's 100 kN deadweight force standard machine.

The 5 kN force standard machine of IPQ generates forces in compression and tension from 50 N to 5 kN. To carry out calibrations of 500 N, 1000 N, 2000 N and 5000 N in steps of

10%, the following force steps can be generated: 50 N, 100 N, ..., 500N, 600N, ..., 1000N, 1200N, 1400N, 1500N, 1600N, 1800N, 2000N, 2500 N, ..., 5000N.

In both machines the first force step is generated by the loading frame. The other steps are realised by a stack of deadweights which are coupled by special coupling elements patented by the manufacturer. The stack of deadweights is placed on a lift table which can be moved down or up to increase or decrease the force. Both machines are operated by a PC programmable logic control and can work in an automatic mode.



**Figure 2:** Photograph of IPQ's 5 kN deadweight force standard machine.

The force is generated according to the well-known equation:

$$F = m \cdot g_{loc} \cdot \left(1 - \frac{\rho_a}{\rho_m}\right).$$

For both machines the masses of the deadweights are adjusted to values in Newton according the following laboratory conditions at IPQ:

local value of gravity:  $g_{loc}=9,8006759 \text{ m/s}^2$

mean density of air:  $\rho_a=1,2015 \text{ kg/m}^3$ .

The deadweights of the 5 kN machine are made of stainless steel of densities between  $\rho_m=7910$  and  $7914 \text{ kg/m}^3$ , and the deadweights of the 100 kN machine are made of chemically nickelized ST52-3 steel with a density of  $\rho_m=7850 \text{ kg/m}^3$ . The adjustment and determination of the deadweight masses was carried out by the PTB's Mass Section with a relative uncertainty of less than  $5 \cdot 10^{-6}$ . To investigate the measurement uncertainty of the new force standard machines, which is specified to be smaller than  $2 \cdot 10^{-5}$ , intercomparison measurements were carried out by the Force Section of PTB.

### 3. Principle of Intercomparison

For the intercomparison, PTB used a set of force transfer standards which covered the whole force range from 50 N to 100 kN. The force transfer standards had been calibrated against the 100 kN, 20 kN, 2 kN and 200 N deadweight force standard machines of PTB. The measurements were performed following the procedure used by PTB in intercomparison measurements [2,3,4]. The whole force range

was covered by a number of force transducers which were measured in the range from 40% or 50% to 100% of the nominal load and which overlapped in the force range to investigate the interactions of the transducers with the machine (overlapping effect) [2,3].

The interaction between the force transducer and the force standard machine can significantly influence the measurement results. To take this influence into account the response of each force transducer was measured at five positions relative to the axis of the machine ( $0^\circ$ ,  $90^\circ$ ,  $180^\circ$ ,  $270^\circ$ ,  $360^\circ$ ). In the  $0^\circ$  position the transducer is loaded three times with a preload of 100% returning to zero after each maximum load application. The force steps are applied in the  $0^\circ$ ,  $90^\circ$ ,  $120^\circ$  and  $270^\circ$  position in two measurement cycles in force steps from 40% or 50% to 100%. In the  $360^\circ$  position one measurement cycle with increasing and decreasing force is carried out to determine the relative deviation to the  $0^\circ$  position and to determine the hysteresis of the transducer.

All measurements were carried out at time intervals of 120 seconds, because the transducers showed a small creep influence in this time interval which is also related to the relative fast loading and unloading times of the machines in the range up to 100 kN.

The 100 kN force standard machine of IPQ was compared with that of PTB in the range from 5 kN to 100 kN. To cover this range, the following set of compression force transducers was used:

100 kN (steps: 50 kN, 60 kN, 80 kN, 100 kN),  
 50 kN (steps: 20 kN, 30 kN, 40 kN, 50 kN),  
 20 kN (steps: 10 kN, 14 kN, 18 kN, 20 kN),  
 10 kN (steps: 5 kN, 6 kN, 8 kN, 10 kN).

The intercomparison was carried out in the compression range. The results of a tension calibration were, however, compared in the tension range. A tension force transducer of 100 kN capacity was, therefore, calibrated at IPQ and at PTB in 10 % steps according to DIN EN 10002-3. The measurement values were taken 30 s after load application.

The 5 kN force standard machine of IPQ was compared with that of PTB in the range from 50 N to 5 kN. To cover the whole range, the following set of compression force transducers was used:

- 5 kN (steps: 2 kN, 4 kN, 5 kN),
- 2 kN (steps: 1 kN, 2 kN)
- 500 N (steps: 250 N, 500 N),
- 100 N (steps: 50 N, 100 N).

The time interval for the measurements again was 120 sec.

Operation in the tension range was investigated using a 5 kN tension transducer which was calibrated at IPQ and PTB in 10 % steps according DIN EN 10002-3. The measurement values were taken 30 sec. after load application.

#### 4. Results of the Comparison of the 100 kN Machine

The mean values of the measurements carried out first at PTB, then at IPQ and,

finally, again at PTB are summarized in Table 1. The measurement signal is the difference between the readings of the force measuring device in the loaded and unloaded state (zero signal before loading) respectively. And the mean values are calculated from the measurements in the 0°, 90°, 120° and 270° positions.

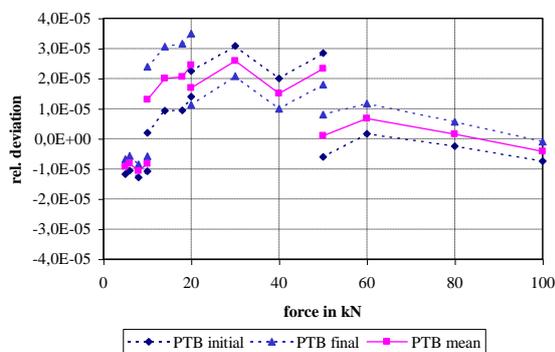
**Table 1.** Measurement results of the comparison in the range 5 kN to 100 kN.

Force kN	PTB initial	IPQ	PTB final	Rel dev. IPQ-PTB
Force transducer 10 kN				
	19,1°C	19,3°C	20,2°C	
5	1,019922	1,019910	1,019917	-9,3E-06
6	1,223981	1,223968	1,223975	-8,2E-06
8	1,632176	1,632155	1,632169	-1,1E-05
10	2,040469	2,040447	2,040459	-8,3E-06
Force transducer 20 kN				
	19,1°C	19,5°C	19,9°C	
10	1,002354	1,002356	1,002332	1,3E-05
14	1,403417	1,403430	1,403387	2,0E-05
18	1,804530	1,804547	1,804490	2,1E-05
20	2,005093	2,005121	2,005051	2,4E-05
Force transducer 50 kN				
	21,8°C	19,5°C	20,1°C	
20	0,800924	0,800942	0,800933	1,7E-05
30	1,201496	1,201533	1,201508	2,6E-05
40	1,602146	1,602178	1,602162	1,5E-05
50	2,002836	2,002893	2,002857	2,3E-05
Force transducer 100 kN				
	21,7°C	20,0°C	19,9°C	
50	0,999485	0,999479	0,999471	1,0E-06
60	1,199441	1,199443	1,199429	6,7E-06
80	1,599424	1,599420	1,599411	1,6E-06
100	1,999458	1,999443	1,999445	-4,3E-06

As the temperatures at IPQ and PTB differed, it was very important to take the temperature differences into account. During the start of the initial measurements at PTB, the temperature at IPQ was not exactly known because of temperature variations. The initial measurements with the 100 kN and 50 kN transducers had already been finished at a higher temperature when the temperature at IPQ had stabilized at about 19 °C. For the

other measurements the temperature at PTB was therefore reduced to about 19 °C. To take the temperature differences into account, additional measurements carried out at PTB at different temperatures were used to determine the temperature sensitivity of the force transducers. For the final measurements at PTB the temperature was increased to about 20 °C because the temperature at IPQ was between 19 °C and 20 °C. To take the temperature differences into account all temperature values are listed in the table.

The relative deviations of the measurements at IPQ from the initial and final measurements at PTB and the mean deviation are plotted in Fig. 3 for the range investigated (5 kN to 100 kN). The relative deviations between IPQ and the mean values of PTB are already less  $3 \cdot 10^{-5}$ .



**Figure 3:** Relative deviation between IPQ and PTB

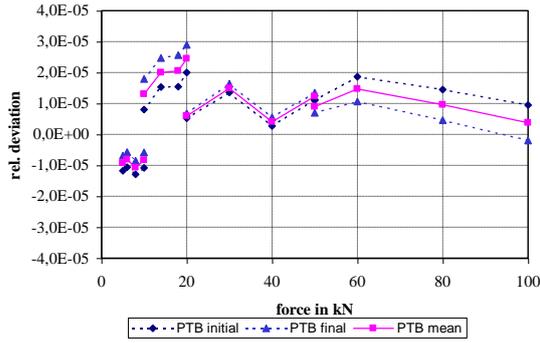
To reduce the influence of temperature differences in the various measurements, the temperature dependence of the force transducer sensitivity must be taken into account. The measurements were therefore carried out at PTB at different temperatures. The results obtained with the 100 kN, 50 kN

and 20 kN transducers are summarized in Table 2. The last two columns show the relative deviation per degree Kelvin compared with to the lowest temperature. It can be seen that the relative change of the output signal of the 20 kN transducer is about  $-1,5 \cdot 10^{-5}/K$ , that of the 50 kN transducer about  $-7,5 \cdot 10^{-6}/K$  and that of the 100 kN transducer about  $+1 \cdot 10^{-5}/K$ .

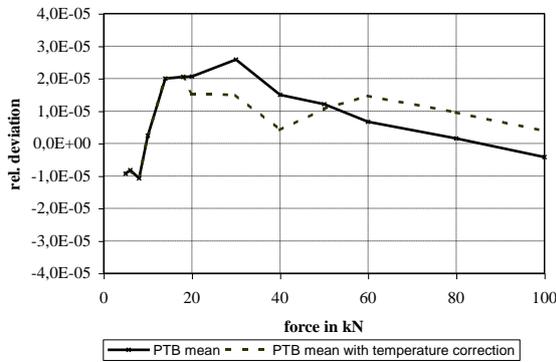
**Table 2.** Measurement results at PTB at different temperatures.

Force transducer 20 kN			Rel. deviation/K		
kN	17,3 °C	21,6 °C	24,9 °C	21,6 °C	24,9 °C
10	1,002372	1,002307	1,002262	-1,5E-05	-1,4E-05
20	2,005133	2,005003	2,004909	-1,5E-05	-1,5E-05
Force transducer 50 kN			Rel. deviation/K		
kN	17,6 °C	21,6 °C	28,8 °C	21,6 °C	28,8 °C
25	1,001230	1,001200	1,001158	-7,5E-06	-6,4E-06
50	2,002916	2,002852	2,002752	-8,0E-06	-7,3E-06
Force transducer 100 kN			Rel. deviation/K		
	18,1 °C	21,8 °C	29,0 °C	21,8 °C	29,0 °C
50	0,999423	0,999463	0,999525	1,1E-05	9,4E-06
100	1,999370	1,999439	1,999553	9,3E-06	8,4E-06

These temperature sensitivities have been taken into account in the results plotted in Figure 4. For the PTB measurements with the 20 kN, 50 kN and 100 kN transducers, the temperature dependency has been taken into account according to the temperature difference to the measurements at IPQ. This way of proceeding considerably improved the results of the intercomparison and allowed relative deviations to be achieved which were smaller than the relative measurement uncertainty of the force standard machines. Furthermore the differences between the initial and final measurements at PTB could be reduced because all measurements are related to the same temperature. The mean value of the relative deviation between PTB and IPQ is plotted in Figure 5.



**Figure 4:** Relative deviation between IPQ and PTB with temperature correction for the 20 kN, 50 kN and 100 kN transducers.



**Figure 5:** Final results for the relative deviation between IPQ and PTB in the range from 5 kN to 100 kN.

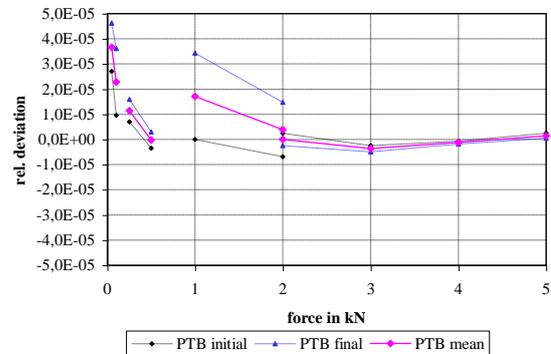
## 5. Results of the Comparison of the 5 kN Machine

The mean values of the measurements at PTB and in the 5 kN deadweight machine of IPQ are summarized in Table 3. The temperature difference between the measurements at IPQ and the measurements at PTB is less 1 Kelvin. Therefore it was not necessary to take the temperature influence into account for the comparison of the 5 kN machine of IPQ.

**Table 3:** Measurement results of the comparison in the 50 N to 5 kN range

Force kN	PTB initial	IPQ	PTB final	Rel dev. IPQ-PTB
Force transducer 100 N				
	19,1°C	19,9°C	20,0°C	
0,05	0,995616	0,995643	0,995597	3,7E-05
0,10	1,991045	1,991064	1,990992	2,3E-05
Force transducer 500 N				
	19,1°C	19,6°C	20,2°C	
0,25	1,004873	1,004880	1,004864	1,1E-05
0,50	2,009911	2,009904	2,009898	-2,5E-07
Force transducer 2 kN				
	19,0°C	19,4°C	20,0°C	
1	1,019965	1,019965	1,019930	1,7E-05
2	2,040387	2,040373	2,040343	3,9E-06
Force transducer 5 kN				
	19,5°C	19,5°C	20,0°C	
2	0,816444	0,816446	0,816448	0,0E+00
3	1,224768	1,224765	1,224771	-3,7E-06
4	1,633174	1,633173	1,633176	-1,2E-06
5	2,041695	2,041700	2,041699	1,5E-06

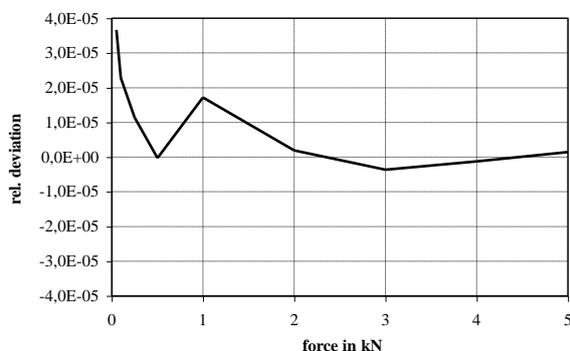
The relative deviation between the measurements at IPQ and the initial and final measurements at PTB are plotted in Figure 6.



**Figure 6:** Relative deviation between IPQ and PTB in the range from 50 N to 5 kN.

The mean value of the relative deviation is plotted in Figure 7. The relative deviation of the mean values of PTB from those of IPQ is smaller than  $2 \cdot 10^{-5}$  in the range from 0,25 kN to 5 kN. Only for the lowest force steps of 50 N and 100 N do the relative deviations increase by  $3,7 \cdot 10^{-5}$  because of the stronger

interaction between force transducer and force standard machine.



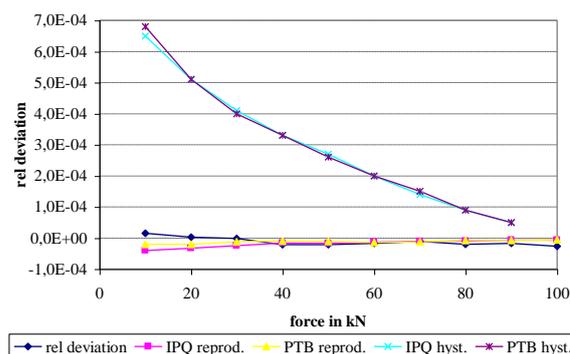
**Figure 7.** Final results for the relative deviation between IPQ and PTB in the range from 50 N to 5 kN.

## 6. Comparison of Calibration Results in the Tension Range

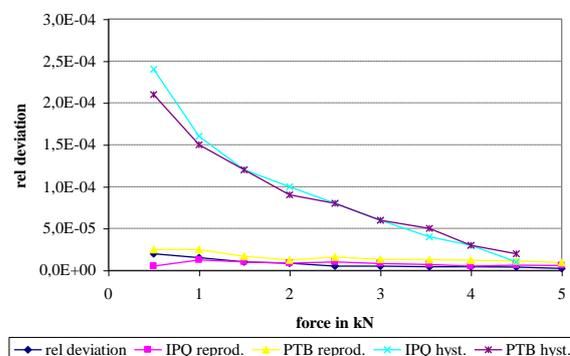
The intercomparison was carried out in the compression range. However, to test the operation of the IPQ machines in the tension range, one tension transducer of 5 kN capacity and one of 100 kN capacity were calibrated at IPQ according to EN 10002-3. The results were compared with the results of a calibration carried out at PTB during the final measurements. The results obtained with a 100 kN and a 5 kN compression transducer are shown in Figures 8 and 9.

The relative deviations between the mean values measured at IPQ and PTB are smaller than  $2 \cdot 10^{-5}$  for both transducers, which is in the order of the relative measurement uncertainty of high-precision intercomparison measurements.

The rotation and hysteresis influences are compared for the measurements at IPQ and PTB. As shown in Figures 8 and 9, similar results are obtained in both machines for rotation and hysteresis. The results therefore demonstrate that good agreement between PTB and IPQ was achieved in the tension range as well.



**Figure 8.** Results obtained with the 100 kN tension transducer.



**Figure 9.** Results obtained with the 5 kN tension transducer.

## 7. Conclusions

The relative deviations of the force intercomparison measurements carried out at IPQ and PTB are smaller than the relative measurement uncertainty of the force standard machines. To reduce the influence of

temperature differences during the various measurements, the temperature dependence of the force transducer sensitivity was taken into account. This procedure allowed the results of the intercomparison to be considerably improved and therefore confirmed the uncertainty of the new force standard machines of IPQ.

### **Acknowledgement**

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