PTB's "new" 2 MN Deadweight Force Standard Machine

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ABSTRACT

In this contribution, the new 2 MN deadweight force standard machine of PTB, which was moved from Berlin to Braunschweig and has been completely modernised, is presented. The determination of the mass of the deadweights with a special mass comparator is described. The uncertainty of the machine is theoretically analysed and experimentally verified by force measurement procedures.

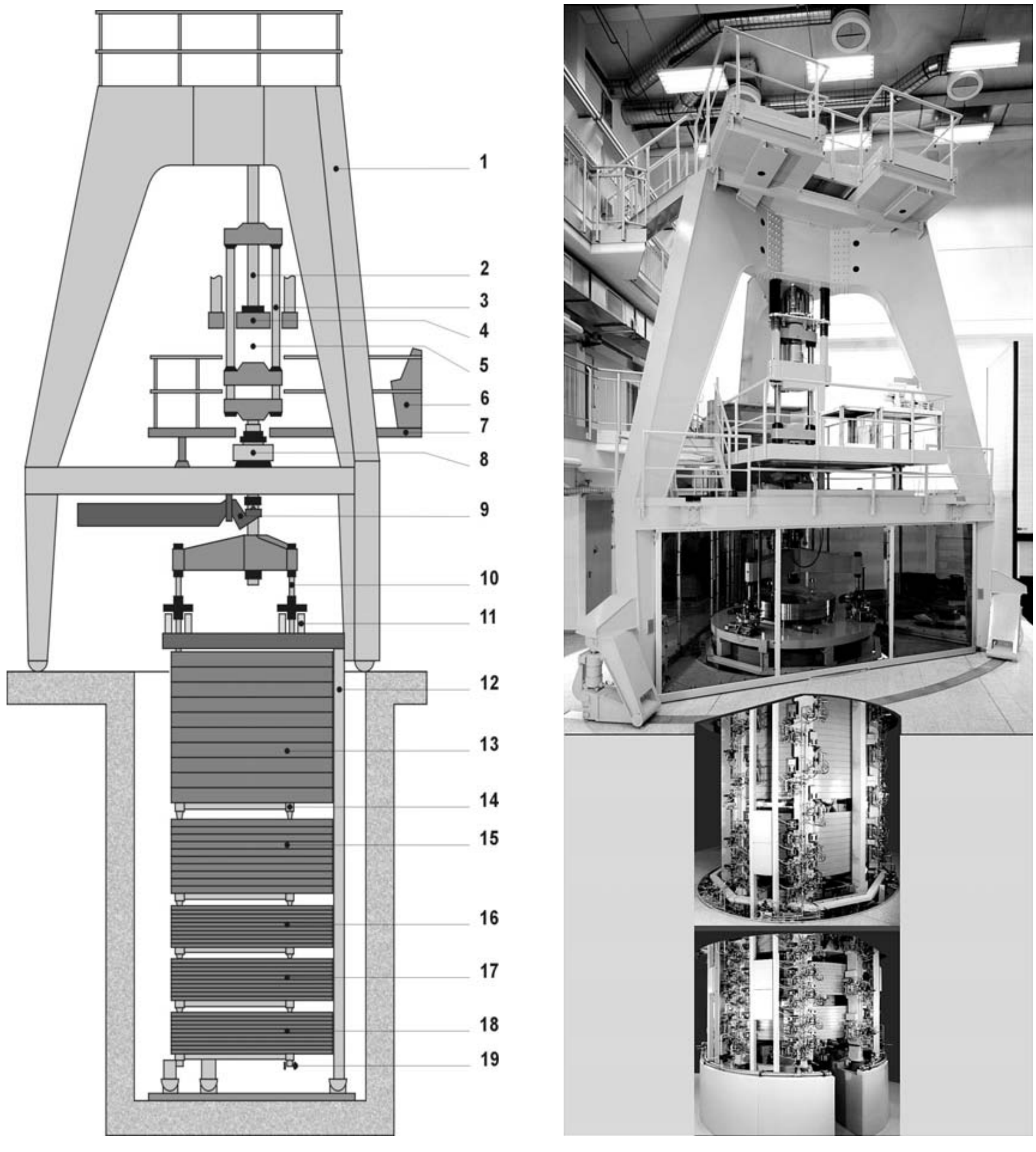

Fig. 1: 2 MN deadweight force standard machine
1 tripod platform, 2 fitting room for compression devices, 3 frame 50 kN, 4 crosshead (adjustable), 5 fitting room for tension devices, 6 control console, 7 working platform, 8 frame support (old), 9 compensating lever, 10 three columns of the scale pan, 11 scale pan support / centering, 12 support rack for the deadweights (9 columns), 13 stack 5: 10 x 100 kN, 14 frame, 15 stack 4: 10 x 50 kN, 16 stack 3: 10 x 20 kN, 17 stack 2: 10 x 20 kN, 18 stack 1: 10 x 10 kN, 19 air bearing

1. INTRODUCTION

The 2 MN deadweight force standard machine (2-MN-FSM) was installed in 1979 in the National Metrology Institute of the former GDR in the east part of Berlin [1]. After more than 20 years of intensive operation, the machine was moved from Berlin to the Force Department of the PTB in Braunschweig, where it has been completely modernised.
With the erection of a new building for a second hall for force standard machines, the PTB has created the special conditions for the installation of the 2 MN force standard machine (17 m over three floors), including climatisation of the underground floors (fig. 1). The operation principle of the 2-MN-FSM is based on the single-mass control of the 50 load masses to realize a load change without intermediate unloading. This principle differs from other FSMs which are designed with chain frames or geometrically graduated load masses with additional force stabilizers to control the force during load change.
Thanks to the possibility of combining up to 10 deadweights for 10 kN, 20 kN, 50 kN und 100 kN, all force steps can be realised in multiples of 10 kN. It is thus possible to realise 200 different force steps. The separate operation of every mass disc is the basis for realising an equal period of time for each force step - be it for 10 kN or 2000 kN (start of the operation up to the stable force value, which will be reached after approx. 50 s). For special creep tests it is possible to realise an operation time of< 20 s.
The offset generated by the frame with 50 kN can be compensated by means of a tare balance. In that case, the deformation of the equipment under load is regulated automatically at the main knife position of the tare balance without additional influence of the uncertainty budget in 10^{-5}. But if the machine is used as a national standard the frame is the first load step of 50 kN and no tare balance is used.
Substantial improvements of the operability were reached by a modernisation of the hydraulic system. Each load mass is moved by 3 cylinders. The wear of the load masses' centering bodies was reduced substantially by an improved synchronisation, and the entire vibration response was optimized.
At two of the three vertical rods, vertically arranged cylindrical air bearings prevent a support of the load frame to hunting oscillations during load change. In comparison with other direct loading machines it was possible to reduce the variable disturbing quantities (bending and torsion) by one to two orders of magnitude.
The design was altered in such a way that the moving cross head was converted from a two-column design into a more stable three-column cross head symmetrically to the machine rack. At the same time it is now possible to accurately adjust the force application elements horizontally and vertically to the machine axis and - thus - to the load masses.
Maximum hunting oscillations of < 0.5 mm in horizontal direction were measured at a distance of 8 m from the point of force application. Already at the time of commissioning in 1978 all load masses had been balanced in such a way that the position of the center of gravity was adjusted with maximum deviations < 0.3 mm to the centering bodies of the load masses.
The machine has been automated according to standard loading procedures (e.g. ISO 376) and meets the requirements for future automations according to other loading procedures.

2. DETERMINATION OF DEADWEIGHTS

Due to the change in gravity and to changes in the centering parts of the deadweights, a completely new adjustment and determination of the mass of the deadweights became necessary. To determine the deadweights of the 2-MN-FSM with a mass of about 1 t, 2 t and 5 t, a balance had to be developped and manufactured which is able to carry out this work effectively and parallel to the mounting of the 2-MN-FSM. The PTB’s 5-t-balance was not suited for taking up any masses with an outside diameter of 2800 mm.
A 2-t-weighing-platform (made by Schenck) already existed and was altered into a mass comparator. The operating principle of this mass comparator is shown in Fig. 2. Below the balance bridge, the stack of special 5 x 1 t reference masses (built-in weights) was arranged, and

above the platform the test mass could be located. Force transmission into the balance bridge was effected in both cases by the same points and with a deviation from the centre of gravity of less than 0.5 mm. For data acquisition a force transducer, coupled at the main lever, was used in connection with a precision measuring instrument DMP 40. A new feature of this mass comparator was the application of a counter mass suspended by a cylindrical air bearing in order to compensate about 90 % of the force at the main lever of the balance bridge as well as the test mass and/or the built-in weights. Earlier investigations [2] showed that for the air bearing used we can expect errors due to friction of less than $1{\cdot}10^{-7}$.

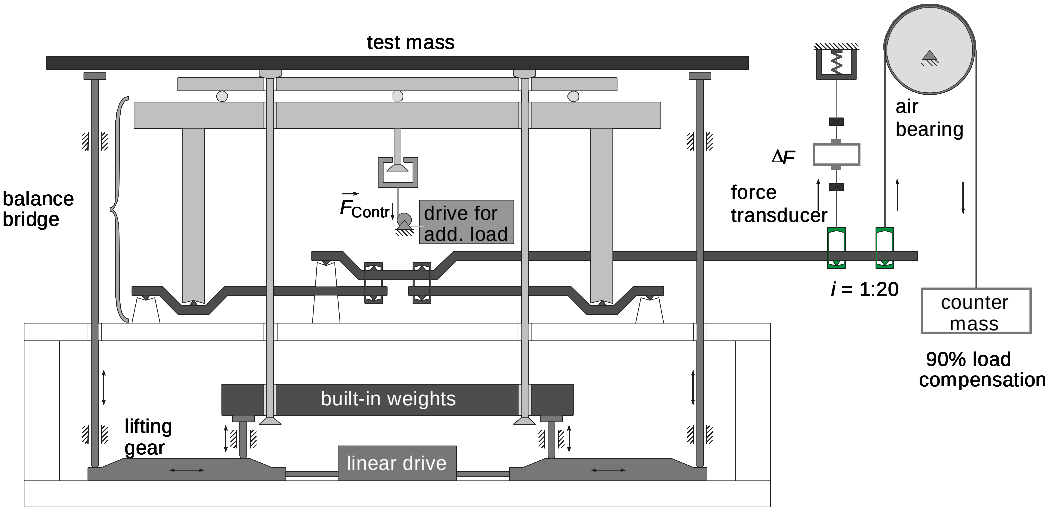

Figure 2 Schematic diagram of the mass comparator

That force transducer was selected in such a way that it could be operated up to nominal load of the force transducer, which is 10% of the maximum force at the main lever of the mass comparator. With this arrangement a resolution of the measured values of 0.1 g (measuring range 1 t, 2 t) and 0.3 g (measuring range 5 t) was reached.
The mass comparator was provided with a housing in order to keep away disturbing airflows.
A special automated control was developed for the weight exchange process between test mass and built-in weight under constant load at the balance bridge. Figure 3 shows the time flow of the weight exchange process which is measured with the force transducer. The experience gathered a few years ago in optimal organization of the weight exchange process with the manufacture of a 1-t-mass comparator [3] has helped to reduce the influence of coincidental errors due to micro hysteresis and variable disturbance at the force transducer. With both, a 1 t mass and a 5 t mass, a relative standard deviation of the balance of less than $3{\cdot}10^{-7}$ was reached (fig. 4). It didn’t make any substantial difference whether the measurements took place in the daytime, while assembly in the hall was going on, or at night after 11 o’clock p.m. with 20 to 50 exchange cycles.

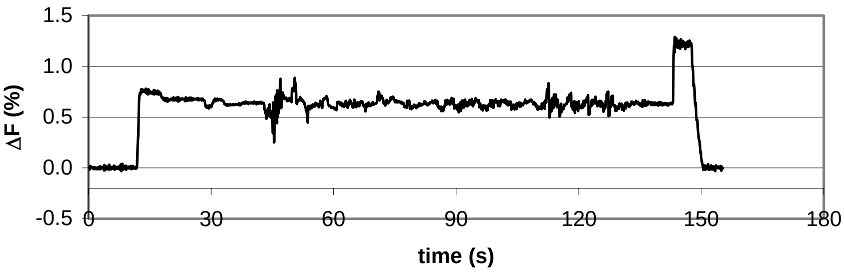

Figure 3: Time flow of the whole weight exchange process (about 140 s)

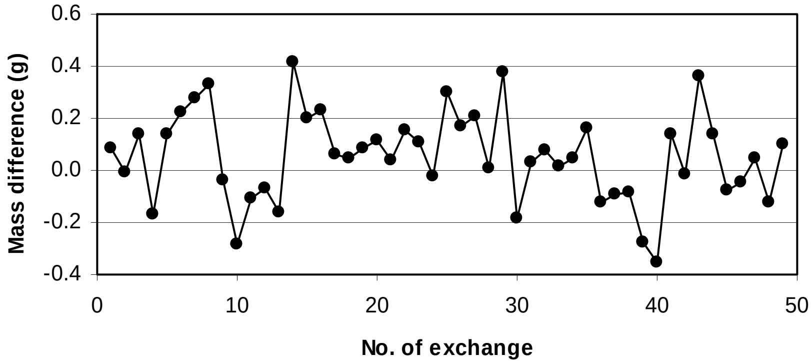

Figure 4: Result of the determination of the 1 t mass

Figure 5: 20 pieces of 50 kg mass standards on the mass comparator

All deadweights of the 2-MN-FSM were determined with a relative uncertainty of $3{\cdot}10^{-6}$ (k = 2). To achieve this, intensive investigations were necessary to eliminate systematic errors of magnetic interaction between test masses and balance as well as the influences of the stiffness of the base frame of the balance.
For the determination of the 1-t-deadweights, first a direct comparison was executed between 20 pieces of 50 kg mass standards and the internal 1-t-reference-masses, comparable to the determination on the PTB's 5-t-balance (equal-arm balance). These 20 pieces of 50 kg, together with a 1-t-deadweight (No. 10), were placed on the mass comparator as test mass (fig. 5). In a second step, the 20 mass standards were exchanged for the 1-t-deadweights which had to be determined.
Besides that smaller uncertainty of the determination of the 1-t-deadweights through this procedure the operability of the mass comparator could be proven. Thereby the determination of the 1-t-deadweight No. 10 was carried out once with the help of the 20 pieces of 50 kg mass standards which have a relative uncertainty of $3{\cdot}10^{-7}$ (k = 2) and once with the built-in-weights. The difference between these two measurements lies with $<8{\cdot}10^{-7}$ within the uncertainty of PTB's-5-t-balance.
However, the problem of the determination of the deadweights was not yet completely solved in this way. The mass of the loading frame of the 2-MN-FSM, which consists of approx. 60 individual parts, could finally be determined after installation and complete assembly by an

integrated 5-t-mass comparator. For this purpose, substantial components of the balance which before had been used for the determination of the deadweights, were implemented into the force standard machine.
Besides the extensive work of determination, also the transport, storage and cleaning of the 60 deadweights with altogether 200 t of mass requires a great logistic effort.
Possibly, magnetic interactions between the deadweights have already been investigated in former publications [4]. But thanks to the selection of suitable mass combinations, the influences of magnetic forces are negligible and do not contribute significantly to the uncertainty. The deadweight combinations with magnetic influences are already known from the investigations carried out between 1980 and 1983 and will be further investigated in future.
It was also for the first time that during the installation process of a large deadweight machine the change in the gravitational acceleration by the deadweights of 200 t was investigated [5], and it was shown that there are no significant influences.

3. MEASUREMENT UNCERTAINTY

The force generated in the 2 MN deadweight force standard machine can be described in a simplified way by the following model:

$$F = m \cdot g_{loc} \cdot (1 - \frac{\rho_L}{\rho_m}) \cdot \prod_{i=1}^{3} (1 - \Delta_i)$$

with the following quantities:

m	mass of deadweights
g_{loc}	local gravity at the position of deadweight
ρ_{m}	density of the deadweights
ρ_{L}	density of air
Δ_1	relative deviation due to magnetic forces
Δ_2	relative deviation due to influences of the compensation lever
Δ_3	relative deviation due to other effects like force introduction (verified by ideal force transducers)

This model takes not only the gravitational force into account. There are also other effects - e.g. magnetic influences, effects of the compensation lever and effects of the interaction of the transducer with the force standard machine and others - which are verified by PTB in internal comparisons with high-quality force transducers.
For uncorrelated input quantities the standard measurement uncertainty $u(F)$ of the force F is given by the law of error propagation. According to the model, the relative standard uncertainty $w(F)=u(F)/F$ of the force generated by deadweights can be calculated as follows:

$$w(F) = \sqrt{w^2(m) + w^2(g_{loc}) + \left(-\frac{\rho_L}{\rho_m}\right)^2 w^2(\rho_L) + \left(\frac{\rho_L}{\rho_m}\right)^2 w^2(\rho_m) + \sum_{i=1}^{3} w^2(\Delta_i)}$$

For the realization of the force in Newton the mass m of all deadweights of the 2-MN-FSM was adjusted and determined taking into account the local gravity g_{loc} depending on the position of the deadweight and the density ρ_{m} = 7830 kg/m^3 ±30 kg/m^3 of the deadweights and the mean density of the air ρ_{L} = 1.19 kg/m^3 ±0.02 kg/m^3. The relative uncertainty of the local gravity which was determined at different points in the building of the 2-MN-FSM is estimated at $1 \cdot 10^{-7}$ (k = 2) as the time dependence of the gravity measurements is not taken into account [5]. The uncertainty contribution to the force is estimated at $3 \cdot 10^{-7}$ (k = 2) because only one gravity value is used for each stack. Table 1 shows the considered height related to the floor, the corresponding local gravity and the mass of the corresponding deadweights for the different stacks of the 2-MN-FSM. The mass is determined with a relative uncertainty of $3{\cdot}10^{-6}$ (k = 2).

Stack No.	Deadweight No.	Height in m	g_{loc} in m/s^2	m in kg	F in N
Scale pan	m_0	0.82	9.8125166	5096.3072	50000
Stack 5	m_5	-1.50	9.8125221	10192.6087	100000
Stack 4	m_4	-3.30	9.8125263	5096.3021	50000
Stack 3	m_3	-4.00	9.8125279	2038.5205	20000
Stack 2	m_2	-4.85	9.8125298	2038.5201	20000
Stack 1	m_1	-5.65	9.8125315	1019.2599	10000

Table 1: Mass of the deadweights used in the different stacks

If only the gravitational force is taken into account, relative uncertainties of $5{\cdot}10^{-6}$ (k = 2) are theoretically possible. The mass of the deadweights with density ρ_m = 7830 kg/m^3 are adjusted according the mean air density ρ_L = 1.19 kg/m^3. To take the effect of changes of the air density into account the acting force F_a can be calculated for each force step F under consideration of the actual air density ρ_a during each measurement.

$$F_a = F \cdot \frac{(1-\frac{\rho_a}{\rho_m})}{(1-\frac{\rho_L}{\rho_m})} \quad \text{with} \quad \rho_a = \frac{0.34848 \cdot p - 0.009024 \cdot h_r \cdot \exp(0.0612 \cdot t)}{273.15 + t}$$

The air density ρ_a can be calculated by this approximation formular which follows from the BIPM formular [6]. In this equation the pressure p has to be used in mbar, the relative humidity h_r in % and the temperature t in °C to calculate the air density ρ_a in kg/m^3. In this way systematic influences due to the air density in the order of $3{\cdot}10^{-6}$ can be taken into account for high precision measurements.

But it is well known that other effects can significantly influence the uncertainty of force measurement. The main problem is the determination of the other influences. PTB uses the procedures of force measurement to determine the influences of the other effects, because low uncertainties can only be given if the values can be verified by force measurement techniques. The internal comparison measurements have shown that the 2 MN deadweight force standard machine has a relative uncertainty of $\leq 2{\cdot}10^{-5}$ for k=2 in the whole measurement range but that for selected force steps, lower uncertainties can be obtained. This was verified for the 500 kN, 1 MN and 2 MN force step with high-quality force transducers. For selected force steps the magnetic effects are less than $1{\cdot}10^{-6}$. The compensation lever is not used and has, in the range from 50 kN up to 2 MN, no connection with the deadweights. Therefore, this uncertainty contribution is 0 for this range. But the alignment of the transducer in the machine and effects of force introduction can also significantly influence the force measurement. With excellent transducers the relative deviations between the measurements in the 2-MN-FSM for the 500 kN and 1 MN force step are in the order of $5{\cdot}10^{-6}$. This effect depends on the alignment of the transducer in the machine and on the short time drift of the transducer. If this effect is taken into account the uncertainty for the measurement of the applied force increases up to $\leq 1{\cdot}10^{-5}$ (k=2), depending on the force transducer. This relative uncertainty is also in agreement with the relative deviations obtained between the 2-MN-FSM and the 1-MN-FSM.

4. INTERNAL COMPARISON MEAUREMENTS

In the 2-MN-deadweight machine the forces can be generated by different combinations of dead weights. Therefore it was possible to carry out force comparisons between the different stacks of deadweights in the machine. The force step of 1050 kN can be generated by the scale pan and stack 5 (10 x 100 kN) or by the scale pan and the combination of stack 4, 3, 2 and 1. A high-precision 2 MN force transducer and a DMP 40 were used for this comparison in the 2 MN machine. The loading procedure was 0 kN, 1050 kN, 0 kN, 1050 kN, ... and the time interval was 6 minutes. With this procedure, 3 preloads are carried out first and then 3 measurements (No. 1,2,3) with the combination stack 4,3,2,1; then 3 measurements (No. 4,5,6) with stack 5 and, for repeatability, 3 measurements with combination stack 4,3,2,1 (No. 7,8,9) and 3 measurements with stack 5 (No. 10,11,12). Figure 6 shows the relative deviation of these measurements from the mean value, which amounts to less than $2{\cdot}10^{-6}$ and is thus an excellent result compared to the resolution of the DMP 40, which is already $1{\cdot}10^{-6}$ for a deflection of 1 mV/V. As only full stacks are used, there are no magnetic effects.

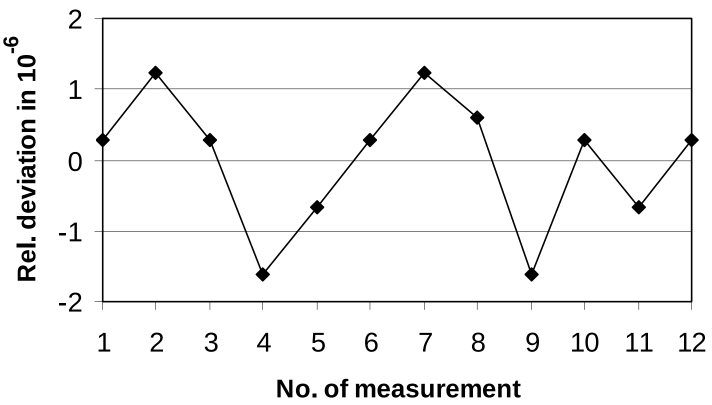

Figure 6: Relative deviation of the measured force of the single measurements from the measured mean force. Measurement no. 1, 2, 3, 7, 8, 9 with stack 4,3, 2, 1 and measurement no. 4, 5, 6, 10, 11, 12 with stack 5.

Similar measurements are carried out with a 1 MN force transducer and a time interval of 6 minutes. The different combinations are shown in table 2. The number in brackets shows the combination for the 1 MN step, the number without brackets the combination for the 500 kN step. The measurement results are shown in figure 7. These results show no significant magnetic effects. Therefore it can be estimated that the influences of the magnetic forces for the 500 kN, 1 MN and 2 MN force step are less than $1{\cdot}10^{-6}$.

	steps in comparisons			No. of measurement				
load	2 MN	1 MN	500 kN	1-3	4-6	7-9	10-12	13-15
scale pan	1	1	1	1	1	1	1	1
stack 5	10	-	-	-	4(9)	4(9)	-	4(9)
stack 4	10	10	-	(10)	-	-	(10)	-
stack 3	10	10	10	10	-	-	10	-
stack 2	10	10	10	10	-	-	10	-
stack 1	5	5	5	5	5	5	5	5

Table 2: The table shows the deadweight combinations used in international comparison measurements for the force steps 2 MN, 1 MN and 500 kN and the combinations used in 15 different measurements for internal comparison. The number in brackets is related to the 1 MN step.

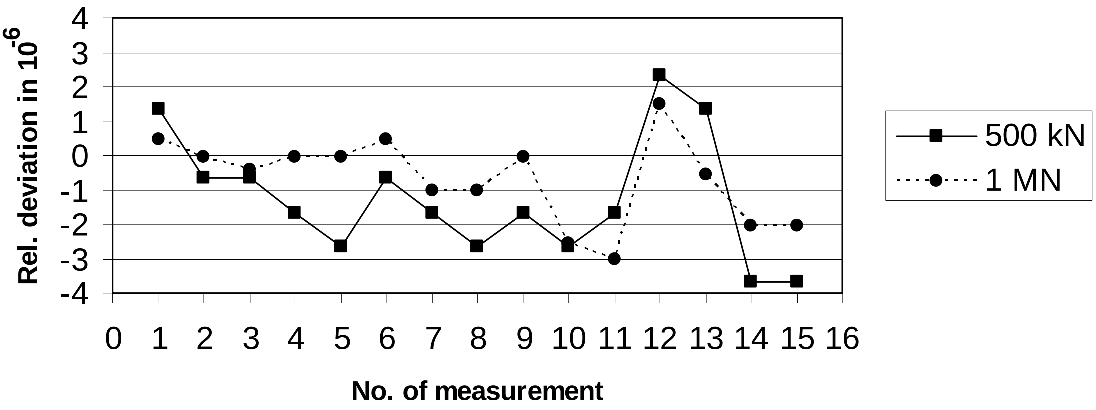

Figure 7: Relative deviation of the measured force of the single measurements from the measured mean value for 500 kN and 1 MN force step of the first 3 measurements with the standard mass combination for 500 kN and 1 MN.

But the magnetic influences can increase up to $1 \cdot 10^{-5}$ if different stacks are combined with only small numbers of deadweights. As an example measurements are carried out with the different mass combinations shown in table 3. The results of the single measurements are plotted in Figure 8. Shown is the relative deviation from the measured mean force value which is calculated from the first 3 measurements. The results demonstrate the deviations due to magnetic foces which have to be taken into account. To reduce these effects in the automatic control, mass combinations are used in such a way that mainly full stacks are used to reduce the magnetic effects to a minimum. This will be further investigated in future.

	steps in comparisons			No. of measurement														
load	2 MN	1 MN	500 kN	1-3	4-6	7-9	10-12	13-15	16-18	19-21	22,23	24	25,26	27	28,29	30	31,32	33
scale pan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
stack 5	10	-	-	-	-	4	2	2	-	2	3	3	2	2	3	-	1	-
stack 4	10	10	-	-	9	-	1	2	-	1	1	1	2	2	1	9	2	-
stack 3	10	10	10	10	-	-	-	-	10	-	-	-	-	-	-	-	-	10
stack 2	10	10	10	10	-	-	5	5	10	5	2	3	4	5	1	-	8	10
stack 1	5	5	5	5	-	5	10	5	5	10	6	4	7	5	8	-	9	5

Table 3: The table shows the deadweight combination used in international comparison measurements for the force steps 2 MN, 1 MN and 500 kN and the combinations used in 33 different measurements for internal comparisons for the 500 kN force step.

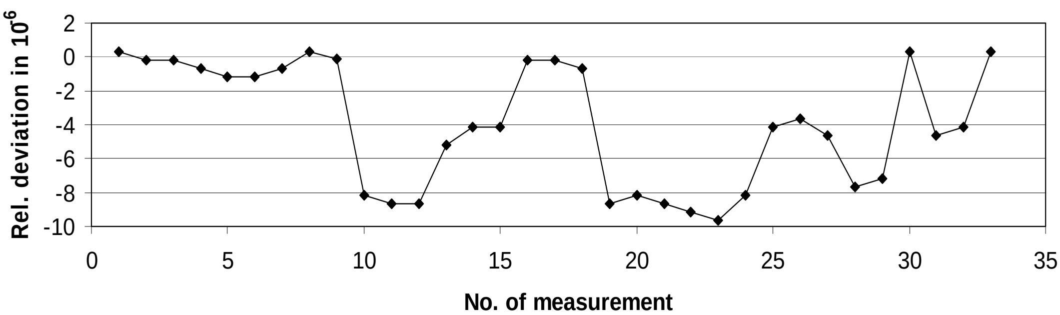

Figure 8: Relative deviation of the measured force of the single measurements from the measured mean force of the first 3 measurements, which is the standard combination for 500 kN.

Figure 9 shows a measurement result obtained in the 2-MN-FSM according to the key comparison procedure for the 500 kN and 1 MN step. The measurements are taken in time intervals of 6 minutes and the transducer is rotated twice. The rotation effect is less than $1 \cdot 10^{-5}$ and highly reproducible. If the measurement is repeated within a few days it is possible to reproduce the mean value with $5 \cdot 10^{-6}$.

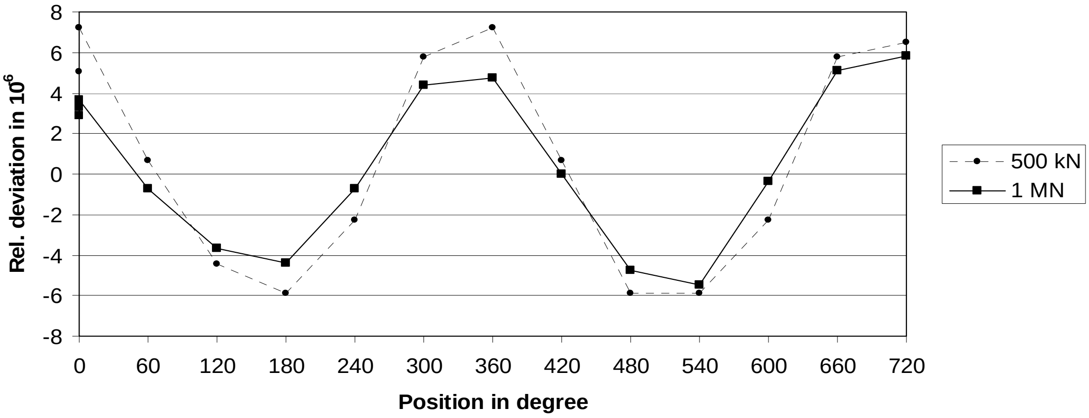

Figure 9: Relative deviation of the measured force in different positions from the mean force obtained from two rotations (60 to 720 degrees).

Finally the measurements are also compared with the 1-MN-FSM. Internal comparison measurements between PTB´s deadweight machines were carried out to verify the measurement uncertainty which is less than $2 \cdot 10^{-5}$ (k = 2) over the whole range from 50 kN to 2 MN. Internal comparisons with selected transducers have shown that the relative deviations of less than $1 \cdot 10^{-5}$ can be obtained by using special measurement procedures as those used in international comparison measurements. In order to reduce the measurement time, the first intercomparisons are carried out with a time interval of 3 minutes. Two 1-MN force transducers and two 500-kN-transducers of different types and makes (HBM and GTM) were used for this comparison. The first results obtained in PTB's 2-MN-FSM and 1-MN-FSM are summarized in table 4.

	Rel. deviation between measurements in 1-MN-FSM and 2-MN-FSM			
Force step	Transducer A 1 MN capacity	Transducer B 1 MN capacity	Transducer C 500 kN capacity	Transducer D 500 kN capacity
500 kN	7.0 E-6	12.4E-6	3.5E-6	13.9E-6
1000 kN	4.5 E-6	10.9E-6		

Table 4: Relative deviation of the measurements in PTB's deadweight machines.

The relative deviation between the 1-MN- and the 2-MN-FSM is for all 4 transducers $< 1.4 \cdot 10^{-5}$ and therefore the En number is also < 1 for relative measurement uncertainties of $1 \cdot 10^{-5}$ (k = 2). In the final phase of the preparation of the force key comparisons for 1 MN, further comparisons are carried out with the time interval of 6 minutes in order to reduce the effect of the different loading times of the deadweight machines.

5 CONCLUSION AND OUTLOOK

The investigations demonstrate that for selected force steps and for special measurement procedures a reduction in the measurement uncertainty should be possible. The uncertainty budget and the internal comparisons have shown that for selected force steps lowest uncertainties of about $1 \cdot 10^{-5}$ (k = 2) can be obtained for the measurement of the applied force. For the case that the machine is used over the whole range, as e.g. for ISO 376 calibrations, the uncertainty for the measurement of the applied force is $\leq 2 \cdot 10^{-5}$ (k = 2).
These measurements are also very important for the 500 kN and 1 MN CIPM force key comparisons, which will be carried out by PTB as a pilot laboratory. In EUROMET also the 2

MN and 4 MN comparisons will be carried out by PTB. For the 500 kN, 1 MN and 2 MN the 2 MN force standard machine will be used.

A further advantage of the 2 MN deadweight force standard machine is that the machine can be used for compression and tension [4], so that machines with higher capacities up to 4 MN and with one crosshead for compression and tension can be calibrated by using a compression and tension transducer in parallel. This procedure will be used for the calibration of PTB's 5 MN hydraulic amplification machine which was also transferred from Berlin to Braunschweig.

ACKNOWLEDGEMENTS

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