XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6−11, 2009, Lisbon, Portugal

IMPROVEMENT OF THE REALIZATION OF FORCES BETWEEN 2 MN AND 5 MN AT PTB – THE NEW 5 MN FORCE STANDARD MACHINE

Falk Tegtmeier [1], *Rolf Kumme*[1], *Mark Seidel* [1]

[1] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, Falk.Tegtmeier@PTB.de
[2] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, Rolf.Kumme@PTB.de
[3] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, Mark.Seidel@PTB.de

Abstract – Since November 2008, PTB's force scale has been complemented in the range from 2 to 5 MN by a further force standard machine. This automatically working 5 MN Force Standard Machine (FSM) utilizes the hydraulic amplification of a 50 kN mass stack and enables low uncertainties of smaller than 0.01% by using innovative methods for the control principle and the link-up of the force standard. In the paper, the constructional design of the machine, the control and the innovative link-up procedure will be published. Supplementary to this, results from comparison measurements of the machine with PTB's 2 and 16.5 MN FSM are presented.

Keywords: Force standard, hydraulic amplification, force transducer

1. INTRODUCTION

In the past, PTB only had the 16.5 MN force standard machine (FSM) at its disposal for the investigation of force transducers with measurement ranges larger than 2 MN. Due to the great demand for calibrations in this upper force range, this caused, time and again, bottlenecks as this machine was not always able to satisfy the great demand for measurements applied for. Among the great number of orders, the share of transducers up to 5 MN amounted to approx. 80%. For this reason, PTB has decided to make use of a hydraulic force standard machine taken over from the former ASMW ("Office for Standardization, Metrology and Commodities Testing" in the former GDR) and to utilize it - after its complete modernization as force standard machine - for forces up to 5 MN. It was aimed at reducing the uncertainty in the force realization of this machine less to 0.01%. At the same time, the updated facility shall allow an efficient, automated operation. Innovative solutions for the control and for the method used to link up the machine with the standards have been investigated and realized.

2. CONSTRUCTION OUTLINE OF THE MACHINE

The renewed measurement device (5 MN force standard machine, Fig.1) works in accordance with the hydraulic amplification principle. This means that - first of all - the weight forces of a 50 kN mass stack (step size 500 N) act on

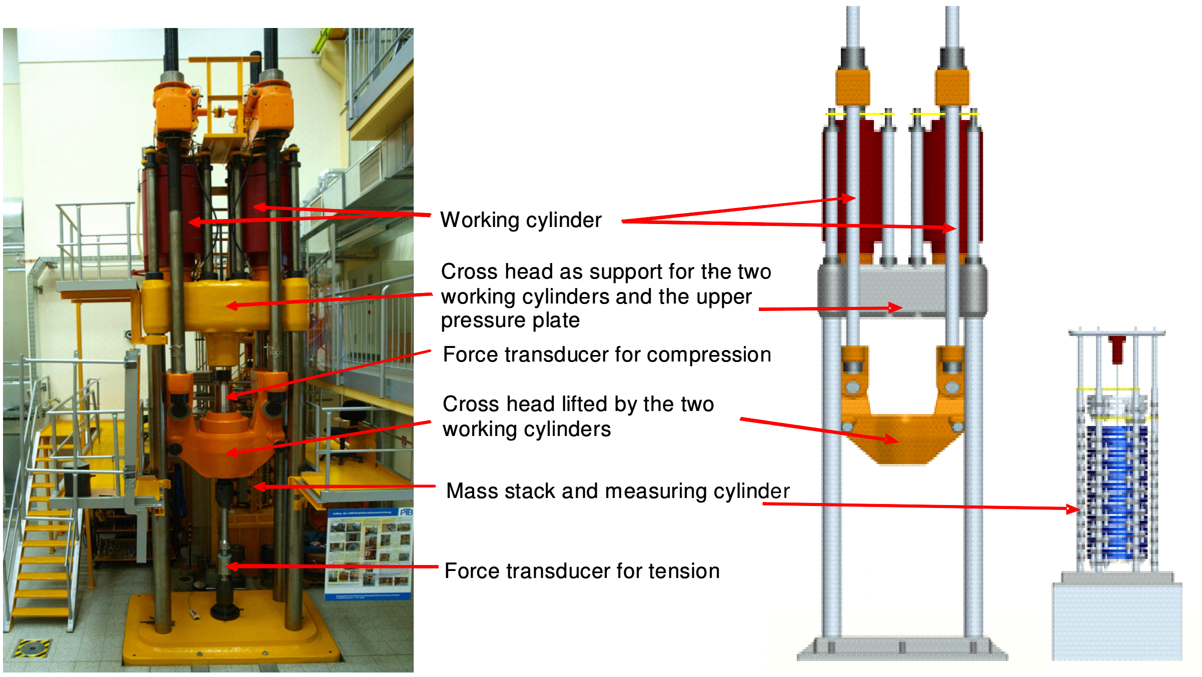

Fig. 1. 5 MN Force Standard Machine.

ISBN 978-963-88410-0-1 © 2009 IMEKO

a piston-cylinder system on the device's measuring side. By a control procedure, which is new for this machine type, force equilibrium is established between the weight force of the weights and the hydraulically generated force. The control procedure comprises the cascade connection of a control unit for hydraulic pressure, residual force and position. Due to the construction, the machine is a highly instable system - in favour of smaller mechanical uncertainties in the force realization. A sophisticated, computer-aided control unit allows the equilibrium of the forces from the oil pressure on the measuring cylinder and the mass stack to be established with uncertainties smaller than $2 \cdot 10^{-5}$. The oil pressure required for this force equilibrium acts simultaneously on two piston-cylinder systems arranged in parallel on the operating side. Due to the relation of the surfaces of the piston-cylinder systems on the operating side and on the measuring side, the forces are hydraulically amplified by a factor of approx. 100 while the pressure remains the same.

Both piston-cylinder systems exhibit a comparably large gap which - even when hydraulic oil of viscosity grade 200 mm^2/s at typical machine temperature is used - causes a considerable loss of leak oil (17 l/min). To rule out that the leak oil flow increases too strongly when the pressure is increasing, a system with a double wall is used to prevent that an elastic enlargement of the cylinder occurs. At the same time, some oil inlets were provided which ensure a stable guiding of the piston thanks to a pressure which is uniform over the entire circumference. In this way - with the larger gap and the oil inlets - it can be avoided that the pistons touch the walls of the cylinder - which would lead to hysteresis-affected friction. Into the two pistons themselves, one hole each has been drilled at two thirds of the height, and the pistons transmit the force from the bottom of the hole towards the upper crosshead via pressure bars which are spherical at the contact surface. This design prevents that torques are applied to the piston which could otherwise press it against the cylinder wall.

3. LINKUP OF THE MASS AND UNCERTAINTY-MODEL

When a force is generated by hydraulic transmission, a force of gravity in the gravitational field of the Earth is - in analogy to direct loading - first acting on the weights. This force is then transmitted by coupled hydraulic piston-cylinder systems. The force generated by the hydraulic transmission principle is described by the following model function:

$$F = m \cdot g_{\mathrm{loc}} \cdot \left(1 - \frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{m}}}\right) \cdot Q \cdot \prod_{i=1}^{3} \left(1 - \Delta_i\right) \qquad (1)$$

The input quantities are:

- m mass of the weights
- g_{loc} local gravitational acceleration at the place place where the weights are installed
- ρ_m density of the weights used
- ρ_L density of the air
- Q transmission ratio
- Δ_1 enlargement of the piston-cylinder systems by oil pressure
- Δ_2 force introduction effects for an ideal test piece
- Δ_3 influences by magnetic properties of the weights

In the past, an uncertainty model for comparable hydraulic standard measuring devices was established in accordance with this model function. It turned out that the uncertainties in the determination of the transmission ratio and the exact weighing of the masses make a considerable contribution to the resulting combined standard uncertainty. This is why the 5 MN force standard machine shall be linked up via a different method. The masses and the transmission ratio are not primarily determined for the uncertainty budget. Due to the place where the 5 MN deadweight force standard machine is installed - i.e. beside the 2 MN deadweight force standard machine - link-up with this device was performed by transfer transducers. The identical environmental conditions without significant transport influences and delays in time worth mentioning allow the device to be linked up with smaller uncertainties than has before been possible by the measurement of the piston-cylinder systems and weighing of the individual masses. In the case of the 5 MN force standard machine, the change of the transmission ratio alone amounts to approx. $1 \cdot 10^{-4}$.

The 5 MN force standard machine was linked up with a build-up system composed of a transducer for forces in tension and forces in compression mounted in parallel as well as of different transfer standards for forces in tension and forces in compression.

Equation 2 describes the uncertainty model for a hydraulic force standard device in accordance with the model function (1).

$$w(F) = \sqrt{w^2(m) + w^2(g_{\mathrm{loc}}) + \left(-\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{m}}}\right)^2 w^2(\rho_{\mathrm{L}}) + \left(\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{m}}}\right)^2 w^2(\rho_{\mathrm{m}}) + w^2(Q) + \sum_{i=1}^{3} w^2(\Delta_i)} \qquad (2)$$

This model shall not, however, be used for link-up of the 5 MN force standard device, as it would not allow the absolute values of the individual uncertainty contributions to be determined with uncertainties as small as they are achieved by direct link-up with the 2 MN force standard device which is explained in the following.

In [1], the best measurement capability is described for the link-up of force measuring devices by means of transfer standards. Chapter 5.2 relates to the link-up of a hydraulic force measuring device. The following uncertainty function is obtained:

$$w(F)=\sqrt{\begin{array}{l} w^2(m)+w^2(g_{\mathrm{loc}})+\left(-\dfrac{\rho_{\mathrm{L}}}{\rho_{\mathrm{m}}}\right)^2 w^2(\rho_{\mathrm{L}}) \quad + \\ \left(\dfrac{\rho_{\mathrm{L}}}{\rho_{\mathrm{m}}}\right)^2 w^2(\rho_{\mathrm{m}})+w^2(Q)+w^2(\Delta_{\mathrm{Traceability}}) \end{array}} \tag{3}$$

Sawla [1] defines the term of the link-up w ($\Delta_{\mathrm{Traceability}}$) uncertainty as follows:

$$w(\Delta_{\mathrm{Traceability}}) = w^2(\overline{F}_{\mathrm{FCM}}) + w^2(\Delta_{\mathrm{HysFCM}}) + w^2(\Delta_{\mathrm{Drift\_TtaStd}}) + w^2(\overline{F}_{\mathrm{FSM}}) + w^2(\Delta_{\mathrm{RelDev}}) + w^2(\Delta_{\mathrm{Realization}}) \tag{4}$$

Where:

$$w^2(\overline{F}_{\mathrm{FCM}}) = \frac{\sum_{i=1}^{n}(x_i-\overline{x}_{\mathrm{FCM}})^2}{n(n-1)\cdot \overline{x}_{\mathrm{FCM}}}$$

$$w^2(\Delta_{\mathrm{HysFCM}}) = \frac{a^2_{\mathrm{HysFCM}}}{3}$$

$$w^2(\Delta_{\mathrm{Drift\_TtaStd}}) = \frac{a^2_{\mathrm{Drift\,TraStd}}}{3}$$

$$w^2(\overline{F}_{\mathrm{FCM}}) = \frac{\sum_{i=1}^{n}(x_i-\overline{x}_{\mathrm{FSM}})^2}{n(n-1)\cdot \overline{x}_{\mathrm{FSM}}^{\,2}}$$

$$w^2(\Delta_{\mathrm{RelDev}}) = \frac{(\overline{x}_{\mathrm{FCM}}-\overline{x}_{\mathrm{FSM}})^2}{24\cdot \overline{x}_{\mathrm{FSM}}^{\,2}} = \frac{a^2_{\mathrm{RelDev}}}{6}$$

$w(\Delta_{\mathrm{realization}}) = 1\cdot 10^{-5}$ (Standard deviation in the realisation of force)

This link-up uncertainty is now used in two ways for the uncertainty model of the 5 MN force standard device.

The uncertainty model on which equation (3) is based contains again - as in equation (2) - the uncertainty contributions of the force component generated on the side of the measuring cylinders as well as the uncertainty contributions of the transmission ratio. In the case of the 5 MN force standard device, the associated quantities were - as described before - not traced back by their explicit determination, but by a comparison between the force obtained as overall result and the reference force of the 2 MN force standard device.

Equation 5 now adds up the machine-relevant components from equation 3. The uncertainty contributions of the single quantities were not determined directly, but the resulting combined uncertainty was quantified with the force comparison. The metrological uncertainty with which the masses were aligned as exactly as possible by comparable measurements and mass corrections, thus corresponds to the uncertainty of the transfer process. The following is thus valid:

$$w^2(m)+w^2(g_{\mathrm{loc}})+\left(-\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{m}}}\right)^2 w^2(\rho_{\mathrm{L}})+\left(\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{m}}}\right)^2 w^2(\rho_{\mathrm{m}})+w^2(Q) = w^2(\Delta_{\mathrm{Tr.without\,Hyst.}}) \tag{5}$$

As the masses were always compared with series at increasing forces, the hysteresis or reversal error is of no significance for the link-up. If equation 3 is complemented with equation 5, the following uncertainty model is obtained for the 5 MN force standard device:

$$w(F)=\sqrt{w^2(\Delta_{\mathrm{Tr.\,without\,Hyst.}})+w^2(\Delta_{\mathrm{Traceability}})} \tag{6}$$

For the mass link-up of the machine, the masses were weighed. Subsequently, comparison measurements were performed with the 2 or 16.5 MN-force standard device. On the basis of the deviations, correction values were calculated and the tare weights were adapted until the deviations became, if possible, smaller than $2\cdot10^{-5}$ in the range from 200 kN to 2 MN and smaller than $4\cdot10^{-5}$ in the range of the measurement with the build-up system composed of the 2 MN transducer for forces in tension and the 5 MN transducer for forces in compression.

Mechanical superstructures for such a "build-up" force transducer arrangement - e.g. a large compression plate under which several transducers are mounted – are, for different reasons which are related with additional mechanical components - not precise enough for the link-up of the machine.

This is why the possibility realized on the 5 MN force standard machine - i.e. direct, simultaneous installation of both a transducer for forces in tension and a transducer for forces in compression - is made use of without causing additional uncertainties by additionally mounted parts. In the different mounting positions and with rotational turning of the transducers, uncertainty components below $3\cdot10^{-5}$ could be detected due to the rotation effect. The transducers had before been calibrated in the 2 MN force standard machine. For this purpose, a force-in-compression transducer up to 3 MN was used, whose interpolation function had been determined in the 2 MN force standard machine and confirmed in the 16.5 MN force standard machine. From the addition of the measurement values of the transducer for forces in compression (3 MN) and the transducer for forces in tension (2 MN), the machine was linked up in the range from 2 to 5 MN to the high-precision 2 MN force standard machine. The photo in Fig. 1 shows both transducers mounted in the 5 MN FSM. Fig. 2 shows the signals of both transducers during a measurement from 2 MN to 4 MN. The smaller transducer for tension with its long bars for mounting is more elastic than the bigger transducer for compression. The exact ratio of force between the two transducers is finally adjusted with the screwed head of the compression transducer.

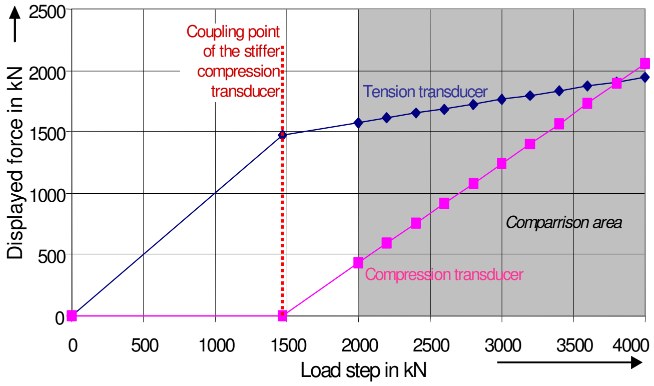

Fig. 2. Caracteristics of the two transducers in the build up system.

The tension-compression tests were performed in two ranges: in load steps from 2000 to 4000 kN and in the range from 4000 to 5000 kN. In the last-mentioned range, the transducer for forces in compression up to 3MN was used. It showed, however, a clearly stronger creep behaviour than in the range up to 5 MN. Accordingly, it was calibrated in the 16.5 MN force standard machine. In the calibrations on the 2 MN force standard machine and on the 16.5 MN force standard machine, the force steps and time dependences were adapted exactly to the force/time curves of the actual tension-compression test. The 2 MN transducer for forces in tension was, for example, calibrated in 10 steps of 1500 to 2000 kN to achieve that the force curve corresponds to the curve shown in the diagram in Fig. 2.

From these calibrations, the inverted 3rd order polynomials to the force-signal curve were calculated and used for evaluation of the individual measuring signals of the two transducers. Table 1 shows a list of the individual results of a measurement, their addition and deviation from the theoretical value.

Table 1. Signals and force value during the calibration as in Fig. 2.

Force	Signal 1	Signal 2	Force Pressure	Force Tension	Addition	rel. Deviation
	mV/V		kN		kN	
2000	1,59712	0,185438	1568,444	431,610	2000,054	0,0027%
2200	1,63858	0,253898	1608,992	591,046	2200,039	0,0018%
2400	1,67878	0,322862	1648,304	751,706	2400,011	0,0004%
2600	1,71805	0,392206	1686,701	913,301	2600,002	0,0001%
2800	1,75661	0,461842	1724,396	1075,626	2800,022	0,0008%
3000	1,79463	0,531684	1761,550	1238,480	3000,030	0,0010%
3200	1,83215	0,601716	1798,222	1401,826	3200,048	0,0015%
3400	1,86928	0,671880	1834,496	1565,527	3400,023	0,0007%
3600	1,90607	0,742132	1870,443	1729,481	3599,924	-0,0021%
3800	1,9425	0,812575	1906,030	1893,927	3799,957	-0,0011%
4000	1,97876	0,883061	1941,445	2058,520	3999,965	-0,0009%

After the measurements had been adjusted as exactly as possible, a concluding series of comparison measurements was performed. The individual parameters for equation (4) were also determined from the concluding comparison measurements. The results are shown in Table 2. The Table also contains the values for the two $\Delta_{Traceability}$ factors and the simple measurement uncertainty of the 5 MN force measuring device calculated in accordance with equation 6.

Table 2. Listing of all uncertainty components and the resulting combined uncertainty.

Force in kN	Reference	x_{FSM}	x_{FCM}	$w^2_{rel\ deviatio}$	w^2_{FSM}	$w^2_{Hys\ FCM}$	w^2_{FCM}	$w^2_{D\ realization}$	$w_{t\ traceability}$	$w_{tr\ without\ Hyst.}$	**$w(F_{FCM})$**
50	2-MN-FSM	0,100015	0,100021	1,50E-10	3,07E-11	7,26E-10	3,46E-10	1,00E-10	3,68E-05	2,50E-05	**4,45E-05**
100	2-MN-FSM	0,199994	0,200001	3,91E-11	5,60E-12	7,26E-10	1,77E-11	1,00E-10	2,98E-05	1,27E-05	**3,24E-05**
150	2-MN-FSM	0,299968	0,299978	4,63E-11	7,12E-12	7,26E-10	8,57E-12	1,00E-10	2,98E-05	1,27E-05	**3,24E-05**
200	2-MN-FSM	0,399962	0,399962	3,66E-14	8,47E-12	7,26E-10	2,77E-11	1,00E-10	2,94E-05	1,17E-05	**3,16E-05**
400	2-MN-FSM	0,799888	0,799898	5,72E-12	5,31E-12	7,26E-10	2,53E-11	1,00E-10	2,94E-05	1,17E-05	**3,16E-05**
600	2-MN-FSM	1,199815	1,199814	1,81E-15	5,34E-12	7,26E-10	1,92E-12	1,00E-10	2,89E-05	1,04E-05	**3,07E-05**
800	2-MN-FSM	1,599720	1,599729	1,25E-12	1,34E-12	7,26E-10	7,36E-12	1,00E-10	2,89E-05	1,05E-05	**3,07E-05**
1000	2-MN-FSM	1,999598	1,999605	6,06E-13	1,99E-12	7,26E-10	9,56E-12	1,00E-10	2,89E-05	1,06E-05	**3,08E-05**
1200	2-MN-FSM	1,202757	1,202764	1,13E-12	1,60E-11	7,26E-10	2,11E-11	1,00E-10	2,94E-05	1,18E-05	**3,17E-05**
1400	2-MN-FSM	1,403161	1,403171	2,01E-12	1,78E-11	7,26E-10	2,76E-12	1,00E-10	2,91E-05	1,11E-05	**3,12E-05**
1600	2-MN-FSM	1,603552	1,603561	1,54E-12	1,32E-11	7,26E-10	1,21E-11	1,00E-10	2,92E-05	1,13E-05	**3,13E-05**
1800	2-MN-FSM	1,803920	1,803914	4,80E-13	1,19E-11	7,26E-10	3,87E-12	1,00E-10	2,90E-05	1,08E-05	**3,10E-05**
2000	2-MN-FSM	2,004293	2,004297	1,76E-13	1,10E-11	7,26E-10	2,82E-11	1,00E-10	2,94E-05	1,18E-05	**3,17E-05**
2200	2-MN-FSM	2200	2200,008	6,17E-13	2,23E-11	4,00E-10	7,56E-11	1,00E-10	2,45E-05	1,41E-05	**2,82E-05**
2400	2-MN-FSM	2400	2400,010	7,87E-13	2,23E-11	4,00E-10	8,89E-11	1,00E-10	2,47E-05	1,46E-05	**2,87E-05**
2600	2-MN-FSM	2600	2600,024	3,46E-12	2,23E-11	4,00E-10	6,40E-11	1,00E-10	2,43E-05	1,38E-05	**2,79E-05**
2800	2-MN-FSM	2800	2800,046	1,13E-11	2,23E-11	4,00E-10	4,41E-11	1,00E-10	2,40E-05	1,33E-05	**2,75E-05**
3000	2-MN-FSM	3000	3000,045	9,25E-12	2,23E-11	4,00E-10	4,46E-11	1,00E-10	2,40E-05	1,33E-05	**2,74E-05**
3200	2-MN-FSM	3200	3200,050	1,02E-11	2,23E-11	4,00E-10	2,27E-11	1,00E-10	2,36E-05	1,25E-05	**2,67E-05**
3400	2-MN-FSM	3400	3400,028	2,81E-12	2,23E-11	4,00E-10	5,07E-11	1,00E-10	2,40E-05	1,33E-05	**2,74E-05**
3600	2-MN-FSM	3600	3600,001	4,53E-15	2,23E-11	4,00E-10	1,59E-10	1,00E-10	2,61E-05	1,68E-05	**3,10E-05**
3800	2-MN-FSM	3800	3800,023	1,58E-12	2,23E-11	4,00E-10	9,47E-11	1,00E-10	2,49E-05	1,48E-05	**2,89E-05**
4000	2-MN-FSM	4000	4000,027	1,92E-12	2,23E-11	4,00E-10	2,53E-10	1,00E-10	2,79E-05	1,94E-05	**3,40E-05**
4200	16,5 MN-FSM	4200	4200,110	2,85E-11	6,00E-10	7,33E-11	3,12E-10	1,00E-10	3,34E-05	3,23E-05	**4,64E-05**
4400	2-MN-FSM, 16,5 MN-	4400	4400,126	3,42E-11	6,00E-10	7,33E-11	2,07E-10	1,00E-10	3,35E-05	3,23E-05	**4,65E-05**
4600	2-MN-FSM, 16,5 MN-	4600	4600,088	1,52E-11	6,00E-10	7,33E-11	1,59E-10	1,00E-10	3,15E-05	3,04E-05	**4,38E-05**
4800	2-MN-FSM, 16,5 MN-	4800	4800,089	1,42E-11	6,00E-10	7,33E-11	2,09E-10	1,00E-10	3,08E-05	2,96E-05	**4,27E-05**
4950	2-MN-FSM, 16,5 MN-	4950	4950,241	9,86E-11	6,00E-10	7,33E-11	2,11E-10	1,00E-10	3,29E-05	3,17E-05	**4,57E-05**
5000	2-MN-FSM, 16,5 MN-	5000	5000,113	2,13E-11	6,00E-10	7,33E-11	2,17E-10	1,00E-10	3,17E-05	3,05E-05	**4,40E-05**

The procedure selected in this model is very safe with respect to the best measurement capability. In the case of many individual uncertainty contributions, the maximum values of an individual result were used for all measurement values of a measurement. When several transducers were used, the worst result was calculated.

The conservative character of the uncertainty model is also shown by the die En values in Table 3. They lie very clearly below 1.

After the completion of last comparisons, the 5 MN force standard machine started calibration service in November 2008 as a national standard up to 5 MN with an uncertainty below $1 \cdot 10^{-4}$. The small uncertainty of the machine's force realization was impressively shown by comparison measurements with the 2 MN and 16,5 MN force standard machine, using high-precision transfer standards. The results are shown in Fig. 3. Last but not least, the revised facility offers, in the range up to 5 MN, twice as many force steps as the 16.5 MN facility.

Long time measurements also approve the stability of the machine. The differences of repeated comparisons to the 2 MN force standard machine are much lower than the typical deviations between these two machines.

The short time stability during a single measurement is assured by a regulated oil-cooling system within the pressure-pipe from the hydraulic aggregate to the machines cylinders, which keeps a stable temperature of 22°C.

Table 3. E_n values for an assumed overall uncertainty of $1 \cdot 10^{-4}$ for a k-factor of 2.

x_{FSM}	x_{FCM}	Deviation	W	E_n
0,399962	0,399962	-0,0001%	0,0102%	-0,01
0,799888	0,799898	0,0012%	0,0102%	0,11
1,199815	1,199814	0,0000%	0,0102%	0,00
1,599720	1,599729	0,0005%	0,0102%	0,05
1,999598	1,999605	0,0004%	0,0102%	0,04
1,202757	1,202764	0,0005%	0,0102%	0,05
1,403161	1,403171	0,0007%	0,0102%	0,07
1,603552	1,603561	0,0006%	0,0102%	0,06
1,803920	1,803914	-0,0003%	0,0102%	-0,03
2000	2000,027	0,0014%	0,0102%	0,13
2200	2200,008	0,0004%	0,0102%	0,04
2400	2400,010	0,0004%	0,0102%	0,04
2600	2600,024	0,0009%	0,0102%	0,09
2800	2800,046	0,0017%	0,0102%	0,16
3000	3000,045	0,0015%	0,0102%	0,15
3200	3200,050	0,0016%	0,0102%	0,15
3400	3400,028	0,0008%	0,0102%	0,08
3600	3600,001	0,0000%	0,0102%	0,00
3800	3800,023	0,0006%	0,0102%	0,06
4000	4000,027	0,0007%	0,0102%	0,07
4200	4200,110	0,0026%	0,0102%	0,26
4400	4400,126	0,0029%	0,0102%	0,28
4600	4600,088	0,0019%	0,0102%	0,19
4800	4800,089	0,0018%	0,0102%	0,18
5000	5000,113	0,0023%	0,0102%	0,22

4. OPERATING PRINCIPLE OF THE AUTOMATIC CONTROL

In the past, the machine was controlled manually, which means that the oil inflow that is required for establishing a equilibrium of the pressure balance between the side of the mass and the side of the force transducer was set by hand. This procedure was extremely difficult due to the fact that the control behaviour of the machine is highly instable. The hydraulic aggregate is located below the machine. Due to the height of the construction, long hydraulic pipes are necessary. At the same time, the two piston/cylinder-systems exhibit a relatively large gap and the machine is very flexible thanks to the fact that is was designed as a long, slim construction (the aim being to achieve only small compulsorily applied transverse forces). Although these factors bear many advantages as regards the achieving of a small total uncertainty of the machine, they have the disadvantage of making a fast and stable automatic control difficult.

For the control principle, different methods were studied but with none of them was it possible to achieve - as a single principle - a stable and sufficiently exact regulation.

A very satisfactory solution was then achieved by a cascade which consisted of (a) an oil pressure control, (b) a residual force regulation on the measurement side and (c) a position control which was designed in a very complex way.

If a load step is to be triggered, first of all the new mass constellation for the force step is composed. If there is already a force on the force transducer, an oil pressure control maintains the force on the working cylinder with an accuracy of 0.02%. With the same oil pressure from the last load step and the new mass stack combination for the next load step, the measuring cylinder decreases or increases towards two limiting bearings between which the measuring cylinder can move by 32 mm. Subsequently, the oil pressure is altered in the direction of the next load step until the difference to the nominal force amounts to only 10 kN. In this state, the selected masses and the measuring cylinder is - via a coupling element - brought into a position centrally between the two limiting bearings. The force which is needed for this is measured by means of a small force transducer. In order to avoid influences from transverse forces which are caused by unavoidable manufacturing and alignment tolerances of the measuring cylinder (which is approximately 2 m long and rotates during the measurement with one revolution every 10 seconds) and from the mass stack applied to it, a transverse-force-compensated force transducer is used, as well as a special flexure pivot which is not able to transmit any relevant torques to the transducer.

After the residual force transducer, located at the measurement side, has been coupled, its signal is used as control quantity in order to reduce same to zero. If this is the case, the oil pressure generates exactly the buoyancy force for the load step selected on the mass stack, i.e., after the hydraulic amplification, the exact calibration force on the force transducer. Originally, this control process was supposed to be sufficient to achieve a small uncertainty of $1 \cdot 10^{-4}$.

Due to various uncertainty influences - mainly in the measurement of the residual force - it was not possible to reduce the reproducibility below a three times larger value. Therefore, a third control step was integrated into the machine. After setting the oil pressure via the residual force compensation as described before, the force transducer used for this is now being decoupled again. The masses and the measuring cylinder, which is now freely pending again, would move - according to the small deviations resulting from the uncertainties of the process described before - against the upper or the lower limiting bearing. Now, a path control is triggered. The position of the measuring cylinder is measured at two points - which, in order to avoid any rotatory effects, lie opposite of each other. A complex control algorithm ensures that after release, the velocity of the measuring cylinder is set to zero.

Thereby, the stable regulation of the machine turned out to be a difficult task. Especially for the deceleration (which should be as fast as possible) of the mass-stack system and the measuring cylinder after its release, fast control parameters of the PID system were necessary - which would normally lead to a resonance. To avoid this, the control parameters change continuously, strongly decreasing in the first seconds. This allows a fast, safe and very precise setting of the required hydraulic pressure. In the range from 100 to 5000 kN, the control variations at the output quantity are smaller than 0.002%.

Attempts to operate the machine without the residual force compensation connected upstream, and only by means of the position control, turned out to be inacceptable. Strong, fast control parameters lead to a resonance and to a behaviour which is, as a matter of principle, unstable. Weak and slow control parameters are - in contrast to this - stable, but they are - by far - too slow.

The cascade composed of oil pressure, residual force and position control is thus the most precise and the absolutely safest method. At the same time, this method is relatively fast: within only 50 seconds, a new load value is being triggered. The time sequence can, however, also be altered in the control program. For example, during the mass link-up, the machine was adapted exactly to the time response (65 seconds during the load step change) of the 2 MN FSM in order to minimize any possible influences of the creep behaviour of the transfer transducers.

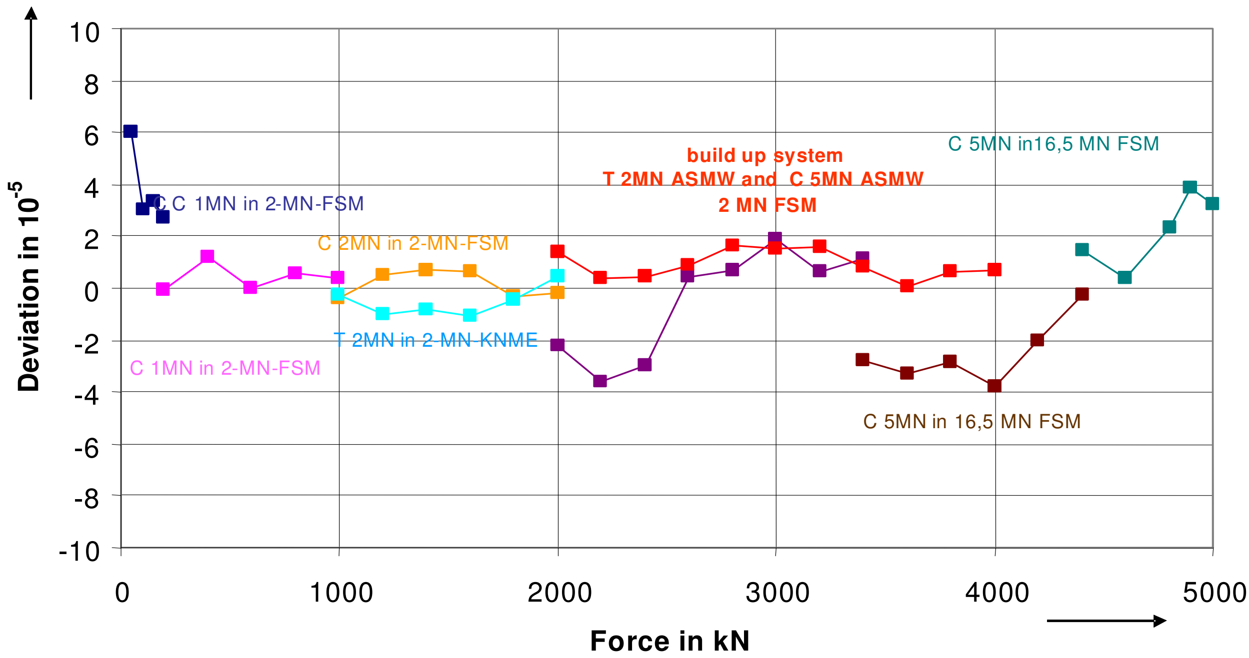

Fig. 3. Results of a comparison between the 5 MN FSM and the 2 MN and 16,5 MN FSM.

4. CONCLUSIONS

PTB's new 5 MN FSM enables low uncertainties in a strongly demanded range of force calibration. The machine works automatically and enables many possibilities for further investigations. It could be possible to reduce the uncertainties to a lower value than the now named $1 \cdot 10^{-4}$. Caused by the flexible outline of the construction, the machine shows extremely low rotational deviations during a calibration. The automatic control still has potential to enable even lower uncertainties. In addition with the linkup of the mass stack system with also lower uncertainties than average for a machine of that type, further investigations with additional build up systems and international comparisons will show the perspective for an even more precise, smaller uncertainty budget of the machine.

ACKNOWLEDGMENTS

The authors acknowledge the companies of WPM in Leipzig and Doli in Munich for their part of the successful modernization of the 5 MN FSM.

REFERENCES

[1] Sawla, A. "Uncertainty scope of the force calibration machines" Proc. of the IMEKO XVI World Congress, Vienna, Austria, 2000, Volume III, TC-3, pp. 253-257.