XVIII IMEKO WORLD CONGRESS
Metrology for a Sustainable Development
September, 17 – 22, 2006, Rio de Janeiro, Brazil

RESEARCH FOR A NATIONAL FORCE STANDARD MACHINE IN THE RANGE FROM MICRO NEWTON TO NEWTON RELYING ON FORCE COMPENSATION

Jens Illemann[1], Rolf Kumme[1]

[1] Physikalisch-Technische Bundesanstalt AG 1.21, D-38116 Braunschweig, Germany, jens.illemann@ptb.de

Abstract: Electromagnetically compensated balances (ECB) are reliable and well-established weighing instruments. As completely electromagnetically compensated types they are commercially available with mass ranges from two grams to several kilograms. They also represent a highly stable and linear scale for force. In this publication it will be shown how ECBs can be used for force standard machines (FSM) having a range of a few Newtons and a feed-back stabilized resolution of single micro Newtons. Moreover, such FSMs conform to the future requirements of continuous calibration.

Keywords: small forces, electromagnetically compensated balance, force standard machine, traceability

1. INTRODUCTION

Worldwide, there is a lack of appropriate facilities for the highly accurate calibration ($<1\cdot10^{-3}$ of value) of force transducers with a full range of less than 5 Newtons. For measurements according DIN EN ISO 376 [1], the force has to be realized in about 10 steps over the full range. For example for transducers with a full range of 1 N, a reference with a resolution and an uncertainty of less than 100 µN is required. Moreover it is intended to introduce continuous calibration for use in the *German Calibration Service (DKD)* [2]. For this, a force standard machine (FSM) with a steplessly adjustable and controlled force is required. An FSM which offers the possibility of an arbitrary continuous run of force allows the assessment of the characteristic line of a complete measuring chain, taking into account higher-periodic artifacts.

The deadweights of a classical FSM comprise three functions simultaneously: the generation of force (mass × local gravity), the calibration and the indication. Every deadweight can only have the indication 1 (loaded) or 0 (not loaded). The main idea is to split these functions into: a sensor as a preferably linear scale, one deadweight for the calibration of the scale factor, and a force generator that has to be fed back to the sensor. In our setup, ECBs are used as sensor. They are commercially available and their technology is well-established after decades of development. They can reach a precision of 6 to 8 digits within an integration time of 1 second. In a previous work [3] it has been shown that an ECB over the full range >10 N features a nonlinearity of less than 10 µN rms. As shown in [4], the indicated value of the transducer depends on its rotational position. Special efforts are necessary to avoid a parasitic shear force or a bending moment onto the transducer. The effect which the thermal expansion of the setup has on the measurement has to be reduced. In the following, experimental results describing the functionality of the new system, and first remarkable measurements will be reported.

2. EXPERIMENTAL

The first measurement approach consists in the direct comparison between the ECB and the force transducer under test (TUT). For this purpose the TUT is mounted into a rack and presses its top surface down on the ECB. In contrast to systems with a load frame, all degrees of freedom are restricted, but can be investigated separately. The influence of shearing, bending and the lateral shift on the TUT has to be taken into consideration.

2.1. Setup

The ECB, the transducer under test, a piezo actuator and a stage are mounted in a vertical arrangement (fig. 1). The setup is thermally decoupled from the laboratory. The

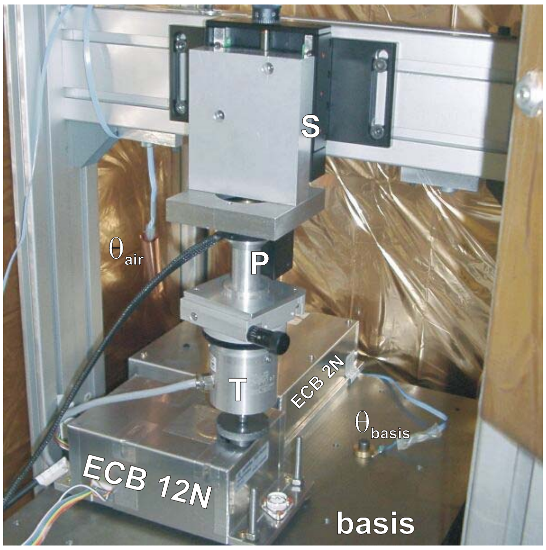

Fig. 1. Experimental setup.
T: force transducer, top-down; P: piezo actuator; S: mechanical stage

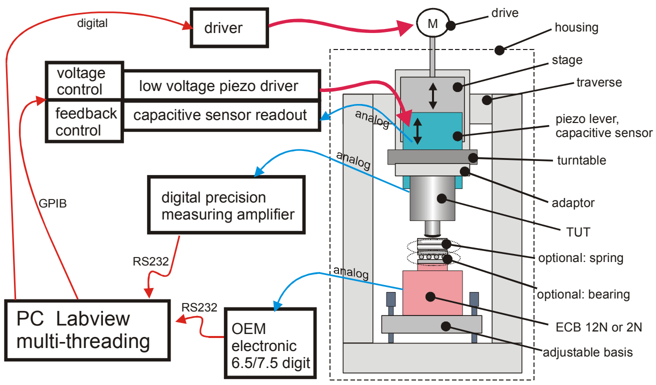

Fig. 2. Diagram of the set-up. Used are ECBs Sartorius make (OEM-version): WZ 215-cw (210g) and WZ 1203 (1200g). The piezo actuator is a 100 µm PIFOC® with a capacitive sensor and a controller by PI. A transducer of type U1A and a precision amplifier of type DMP40 made by HBM serve for testing purposes.

coupling time is about 20 hours. An ECB with a full range of either 1200g (6½ digits) or 210g (7½ digits) can be used. The pressure p, the relative humidity h_r and the temperature θ_{air} are recorded for the correction of the air buoyancy. Additionally, the difference between the temperature of the base plate θ_{base} and θ_{air} is monitored, as the air turbulences and the uniform convection can contribute remarkably to the force.

The mechanical part of the setup (fig. 2) is described by stiffness and function. The rack, including traverse, the stage and the basis, clamps the ECB, the TUT and the force generator together. This rack has a spring constant (SC) of about 1MN/m, i.e. it bends for about 1 micron at a load of 1 Newton. For the WZ215 the SC is higher than 1 MN/m, for the WZ1203 it is about 500 kN/m. The flexure-based leveraged piezo actuator has an SC of 250 kN/m. By this it dominates the entire SC so that the SFM has an SC of around 200 kN/m. This can be reduced by means of an additional elastic element, but not increased. This restricts the piezo-based, frictionlessly adjustable force range depending on the SC of the TUT: for recent experiments, transducers with a full range of 20 N (SC: 70 kN/m) and 10 N (SC: 35 kN/m) have been used. In this way, about 30% of the full range can be adjusted. To extend this to the full range or to allow the additional use of an elastic element, a manual or motorized coarse adjustment via a mechanical stage is possible. A shear force could occur due to a misalignment or run-out of the stage. Thus, a ball bearing is implemented between the ECB and the TUT.

The drive is outside a dust-protecting housing that is lined with heat-reflecting foil. Thus the only thermal sources inside are the ECB and the TUT. Due to the massive basis, thermal drift rates below 1 mK/min are achieved (fig.3). This value leads to a displacement drift of 1 nm/min on a typical length of 10 cm and a thermal expansion coefficient of $10 \cdot 10^{-6}$/°C. This, in turn, corresponds to 70 µN/min (35 µN/min) for the above-mentioned transducers.

To overcome the mechanical limitations, a PC-based acquisition and control system has been established (fig.2). The ECB data can be read with 50 Hz (25 Hz), the TUT data are sampled with about 70 Hz from a carrier frequency precision amplifier (6.5 digits, 2.5mV/V full range). All

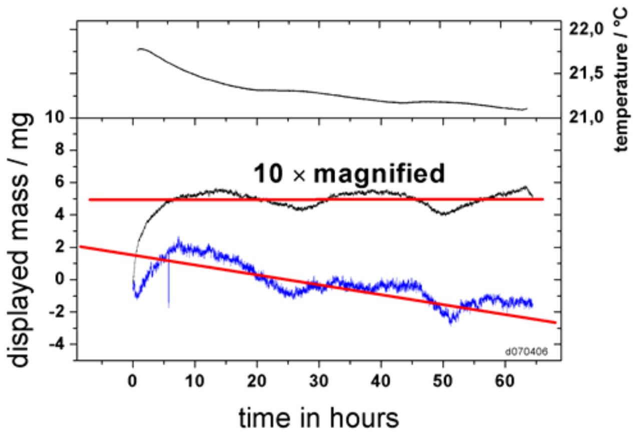

Fig. 3. Zero drift behavior of the ECBs versus the basis temperature. Upper curve: WZ 215, 10 times magnified; lower curve: WZ 1203. No tidal change of *g* with a periodicity of 12 hours and no dependence on the air pressure are observed. The residual run is dependent on the absolute value of the temperature and its second derivative. After a warming-up time of 5 hours, WZ 215 still remains within an interval of ±0.1 mg.

data, including the temperatures, can be stored online on hard disk. Without noteworthy loss of information, 10 to 20 values can be averaged, whereas the resolution slightly increases [5]. As the ECBs do not provide for a hardware trigger, the synchronization is implemented by a software causing a temporal jitter of 20 (40) ms. The quasi real-time capability allows the balance signal to be fed back to the actuator. In this way it is possible to keep the measured value of the ECB stabilized.

2.2. *Tracing back the force*

The scale factor of the ECBs can be traced back to reference weights via a load/unload cycle. Under the measurement condition of manual handling and incomplete thermal equilibrium a precision of at least 1 part in 10^6 can be achieved for the full range of 10 N (fig. 4) and 1 part in 10^7 for the full range of 2N (fig.5). This is no limitation of the targeted goal in force measurement. In force measurement the zero-drift could also limit the precision and the uncertainty because the zero point cannot be

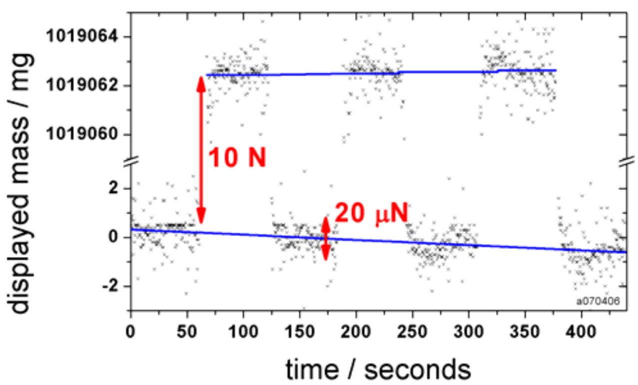

Fig. 4. Tracing back to a 10N-equivalent mass reference. The reference mass is adjusted to local *g* and standard conditions. A weight force of 10 N corresponds to 1019062,2 scale divisions “mg”. The scale unit is meaningless because it is subject to long-term drift. The diagram shows a threefold load cycle with WZ 1203. Any deviations from the standard conditions of the air buoyancy are neglected.

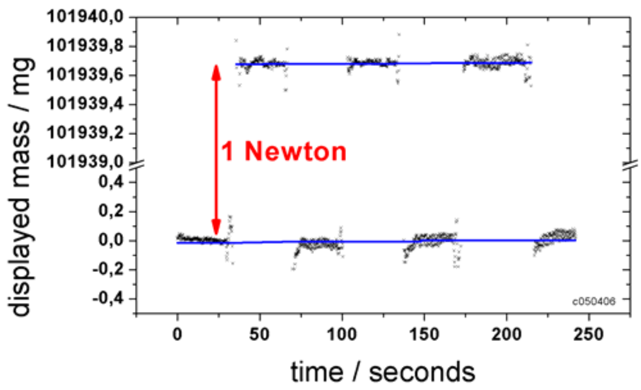

Fig. 5. Tracing back to a 1N-equivalent mass reference. Besides air buoyancy,the mass corresponds to 101939,69 scale divisions "mg" with WZ215. All succeeding measurements are carried out with this ECB.

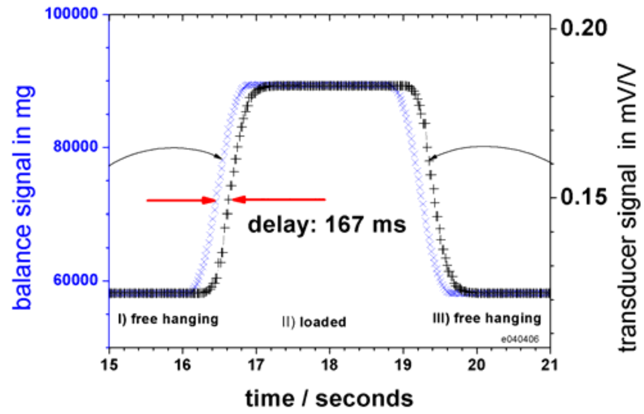

Fig. 6. Relative step answer: ECB versus DMP 40, 0.9 Hz Bessel. The data of ECB are sent with 50 Hz, the data of the amplifier are sent with ~70 Hz. Once a value of the ECB is read, the next value of the transducer sent is assigned to it.

recalibrated during a long-term load cycle. The reactio force is generated by a coil and a permanent magnet and transferred by a flexure-based lever system of the ECB. The magnet is extensively temperature-dependent which is, however, compensated by the OEM electronics. The zero drift of the ECBs used is shown in figure 3 – this is in fact the zero working point of the ECBs and does not necessarily correspond to the vanishing coil current.

To determine the local gravitational acceleration *g*, a network of reference points was measured inside the laboratory building and referenced to an absolute gravimeter [6]. The limitation with regard to the precision is the tidal range. In return for neglecting the tides, $2 \cdot 10^{-7}$ is added to the uncertainty budget. This leads to

$$g = 9.8125161(20) \text{ m s}^{-2}$$

at the position of the facility.

The air buoyancy of the reference mass must be corrected with its known density divided by the density of the air. This can be calculated sufficiently exact with the CIPM formula [7]. For the example shown in figure 5, the conditions were:

$$\theta_{air} = 21.54(5)°\text{C},\ h_r = 39.7(20)\ \%,\ p = 999.9(10) \text{ mbar}.$$

From this, the density of the air results as follows:

$$\rho_a = 1.178(3) \text{ kg m}^{-3}$$

The actual force on the ECB is

$$F = mg\,(1 - \rho_a / \rho).$$

Using the values for the mass m and the density ρ of the "1 N" standard weight (table 1), this force becomes:

$$F = 1.0000029(12) \text{ N}.$$

The resulting deviation of $3 \cdot 10^{-6}$ from the nominal force value can be neglected for common measurements of force transducers.

Table 1. Mass standards used for tracing back the unit Newton

	1 N	2 N	5 N	10 N
mass /mg	101.9261(1)	203.8520(1)	509.6293(5)	1019.2584(10)
ρ / kg·m^{-3}	7927(24)	7927(24)	7927(24)	7927(24)

2.3. *Step answer*

In the continuous intercomparison between a transducer and an ECB, the temporal transfer function plays a crucial role. The (residual) rate of change of the force multiplied by the uncertainty in the sampling time yields the uncertainty in the force. As mentioned above, a minimal jitter of 20 ms will occur in the realized facility. Due to the intrinsic filter algorithm and due to the hardware characteristics, both – the precision bridge amplifier and the ECB – show dead time and filter characteristics. For an easy evaluation it is a robust test to sample the step answer synchronously (fig. 6). The piezo actuator is fed back to the capacitive sensor when the setpoint is changed. Within ~10 ms, the final value of force is set. This relative test between the ECB and the TUT is sufficient as the actual force is not observable. The ECB represents the "true" value. The result shows that the characteristic is in good agreement with the 0.9 Hz Bessel filter characteristic as the precision amplifier is by about 5/3 seconds delayed. Taking these results into consideration will reduce the temporal uncertainty to the above-mentioned estimate.

2.4. *Generating force exactly*

The mechanical force generation is based on the deformation of an elastic element. This element is the TUT

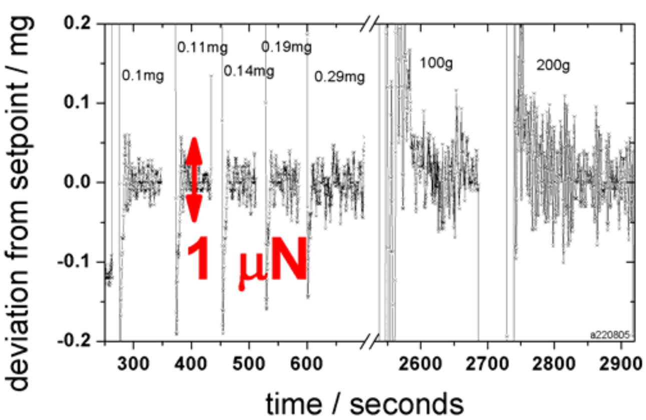

Fig. 7. Stabilization onto a spring (100 N/m). Coarse adjustment was done manually with the stage. Within 30 seconds ready to take value.

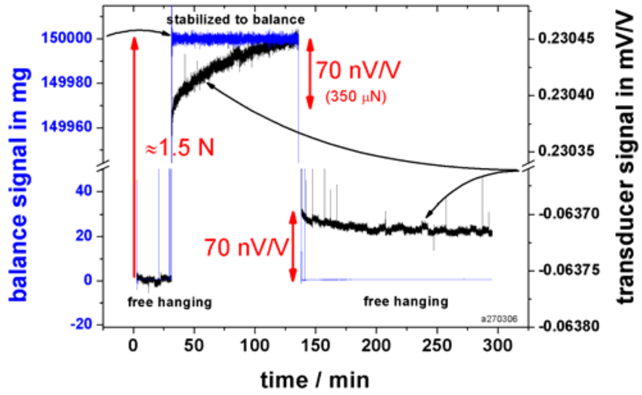

Fig. 8. Creep investigation. Comparison of ECB with transducer under test (Type U1A, HBM). Full range of transducer: 10 N at 2 mV/V signal. The value of about 1.5 N is stabilized to ECB. Spring constant: ~30 kN/m. This transducer is used for all experiments shown.

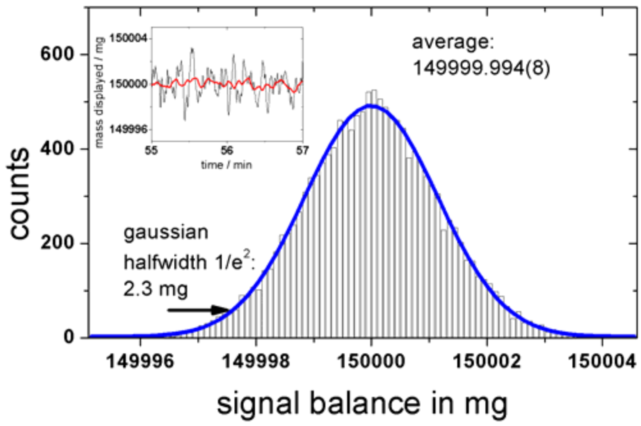

Fig. 9. Distribution of force during 100 minutes of stabilization (fig. 7). The two-stage software feedback loop achieves the 150000 "mg" with a discrepancy of the average of less than 10 µg (0.1 µN).
Inlet: An integration time of 0.4 seconds leads to a statistical deviation of 2.3 mg (23 µN), an adjacent averaging over 10 sec. to 0.6 mg (6 µN).

itself or with an additional element in series. Thermal drifting and creeping leads to a permanent drifting of the force which can be eliminated by a software-implemented two-stage closed loop: the first-stage PI-controller stabilizes the force, but ends with a slowly drifting offset. After an adjustable down-time, the second stage corrects the setpoint of the first stage. The implementation is not easy because of the slow characteristic and dead time of the ECB.

Figure 7 shows the result of an experiment with a spring: the setpoint is set over 7 orders of magnitude on 10 µg, 20 µg, 50 µg, 100 µg, 200 µg, 500 µg, …, 100 g, 200 g. The zero-point of the ECB was -90 µg. The indicated value reaches the setpoint within an interval of ±1 µN within 30 seconds, including the adjustment of the stage. This is in compliance with DIN EN ISO 376. In fact it has to be guaranteed that no shear force, no bending moment and no run-out of contact point between the spring and the TUT occurs. This could produce an apparent run-out of the transducer characteristic line. To achieve this, a spring element is needed which is lightweight – as it is tare mass – and deformable over 1 cm. The spring element must not produce shear forces and the orientation of the contact surface must stay constant for a few arc minutes. For this first experiment a conventional compression coil spring was used.

2.5. Creep measurement

Generation of tension and compression force as well as sensing with strain gages, is limited by solid state mechanics itself. Change of force involves creep. The ECB does not rely on deformation, thus is not limited by creep. Its settling time to better than $2{\cdot}10^{-6}$ is about 1 second after short load (fig. 5). Figure 8 shows a measurement carried out over a period of five hours. Shown are the signals of the transducer and of the ECB over time. In the first and the third phase, ECB and the TUT are decoupled, in the second phase the setpoint is "150000 mg", which corresponds to about 1.5 N. The plotted data points are averaged over 0.4 seconds. The noise then corresponds to 20 µg rms or 1 nV/V rms.

Figure 9 shows the probability distribution during the feed-back phase. Due to feed-back oscillation the distribution has a $1/e^2$ half width of 2.3 mg, i.e. 23 µN. The period of oscillation is about 10 seconds. Adjacent averaging over 10 seconds yields a reduction to about 6 µN. Thanks to the two-stage software feedback loop it is possible to hold the average value constant to better than 10 µg over 100 minutes. With a spring constant of 30 kN/m this corresponds to a displacement of three femtometers.

A more crucial role plays the residual "creep" of the ECB. The load might lead to a creeping of the flexures, but temperature changes in the coil and in the zero-indicating sensor appear more relevant. Figure 10 shows a detailed view of figure 8: after a load of 150 g (~70% of the full range) over a period of 100 minutes the zero value overshoots by about 0.35 mg. This phenomenon appears "viscous" as it completely relaxes with a time constant of about half an hour. During the load phase the actual deviation is not known. The feed-back stabilizes the force to the slightly drifting value of the ECB. This has to be considered in the uncertainty budget for an SFM with $2{\cdot}10^{-6}$ per 100 minutes of load. Further investigations are required to reduce this contribution by use of a model.

In contrast to this, the force transducer in figure 8 has a 100 times bigger creep, i.e. about $230{\cdot}10^{-6}$ in 100 minutes at 15% of the full range. After unloading it does not relax to the original value, at least not on the observed time scale. It

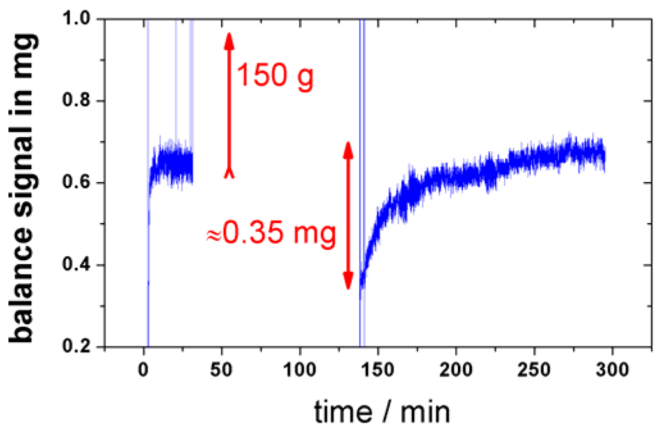

Fig. 10. Detail of figure 8. Creep-back of the ECB after 100 minutes with 150 g load. Data rate is 50 Hz.

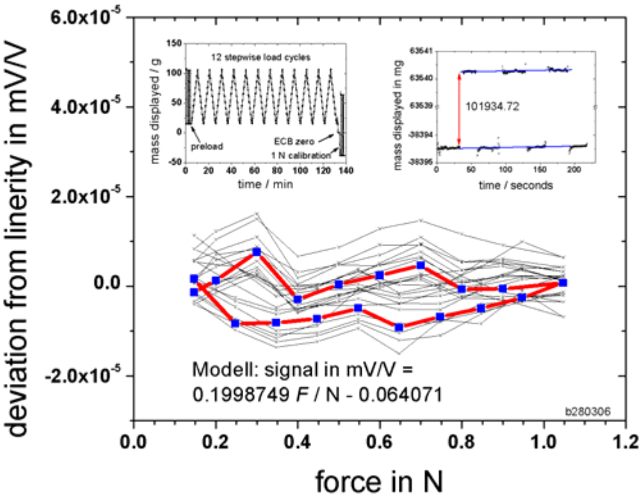

Fig. 11. Stabilized measurement. 3 preload cycles, 12-times-repeated load sequence, sampling of ECB zero, calibration to 1 N without tare (bearing). The highlighted line represents one load sequence.

shows a certain kind of "memory effect" that leads to a drift of zero between subsequent load cycles. The zero drift during a single cycle leads to a contribution to the characteristic line which depends on the cycle time. In particular the hysteresis becomes time-dependent.

This measurement could also be done with a deadweight. But for this range, no SFM exists until now. Additionally, this way allows the characteristic line of transducers to be investigated with an arbitrary and continuous process of force. This corresponds to a more realistic condition of use.

2.6. Stabilized measurement

Figure 11 shows a preliminary experiment. Similar to measurements corresponding to DIN EN ISO 376 prior to the actual experiments, three short load cycles were carried out. This leads to a mechanical settling of the components used and prevents subsequent excessive zero-drift. For the main measurement the software stabilization as described before had been used. A sequence consists of 18 discrete setpoint values and is repeated 12 times. The 19th value of a sequence is the first of the subsequent. Each sequence has a duration of about 11 minutes.

This first value is chosen to be equal to the weight of the exchangeable load button of the TUT. The maximum value is exactly given by adding 0.9 N to the first value. After change of the setpoint, 30 seconds of data had been ignored. The data of the next four seconds are averaged – those of the ECB and of the TUT synchronously. During this period the value of force is stable within an interval of less than 25 µN. At the end of the measurement a calibration to the 1 N artifact standard was performed.

From this, a data set of 12 times 18 values of the transducer signal over the force results. While all values are affected by drift, a priori all values have been assumed to have the same uncertainty. Therefore, the data are least-squares fitted to an affine straight line. The difference to this model is plotted in figure 11. The sensitivity is 0.1998749 mV/V per Newton, the zero-value is meaningless as it is subject to drift. Clearly observable is the hysteresis of the transducer. It corresponds to about $1.5{\cdot}10^{-5}$ mV/V, i.e. $8.3{\cdot}10^{-5}$ of the range used.

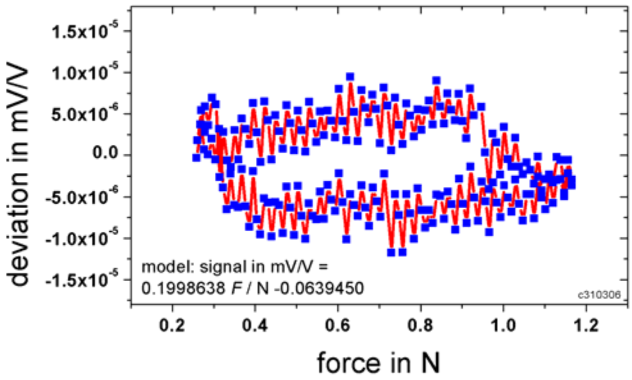

Fig. 12. Quasi-continuous sequence similar to figure 10. Plotted is one sequence of a set. One sequence has a duration of about 14 minutes.

Because no high-stable transducer is available for the range of 1 N, a 10 N type transducer – equivalent to about 2 mV/V – has been used. This limits the measurements due to the available high-precision bridge amplifiers. The residuals from the linear fit shown are in the order of magnitude of the deviations of the amplifier expected. Advanced investigations and error reduction techniques have to be employed.

2.7. Quasi-continuous measurement

After the angular readjustment of the basis, the experiment was repeated three days later, but in quasi-continuous mode: the piezo actuator system is fed back to its capacitive sensor. Thus the displacement of the actuator can be set without the excessive creeping which usually occurs in the case of multilayer-piezo ceramics. Here one sequence contains 100 equidistant steps up and 100 down. The attained force range is about 0.9 N, but the start value is slightly higher than in the case of the previous measurement. After each step two seconds of data are ignored, the next two seconds the data of the ECB and the TUT are sampled synchronously and averaged. During this period the value of force is constant within an interval of less than 50 µN. Figure 12 shows the residual deviation resulting from the procedure described above.

The sensitivity is 0.1998638 mV/V per Newton and differs by less than $6{\cdot}10^{-5}$ relative to the value measured in the previous section. The hysteresis is more clearly observable and agrees satisfactorily with the previously measured $1.5{\cdot}10^{-5}$ mV/V. Remarkable is a sawtooth-shaped artifact with a peak-to-peak amplitude of 5 nV/V and a periodicity corresponding to 27 mN, 5.4 µV/V or 2.8 grams. As a possible cause, an experimental error or a periodic deviation of the ECB electronics or of the precision amplifier have to been taken into account. The latter does not contradict the guaranteed specification. Further investigations are necessary. Therefore, an additional tare could be added to the balance to shift its characteristic line. The use of a transducer with a sensitivity of 2 mV/V at a full range of 20 N would compress the sawtooth feature by a factor of two corresponding to the force. Once the origin of the artifact has been fixed, it should be easy to eliminate this artifact by notching out. This could be done by averaging over a suitable interval.

Periodic artifacts are generated in digitalization processes. In comparison to the stabilized measurement shown in figure 11, it is obvious that these artifacts can be misinterpreted. This effect, which occurs when too few sample points have been taken, is the so-called “aliasing”-effect.

3. CONCLUSION

Due to the growing demand for traceable force transducers in industry, PTB is planning to extend its facilities with force standards down to the range of a few single Newtons and an uncertainty down to micro Newtons. Up to now, no National Metrology Institute has been offering traceable measurements in this range. The new facility at PTB uses the method of direct force compensation with electromagnetically compensated balances.

The investigation here described is based on the use of two different electromagnetically compensated balances with a range of 1200 g as reported before [3,4] and 210 g as a reference for the force. The traceability to the force definition is realized by the subsequent calibration of the balance with a Newton-equivalent deadweight. This – corrected by the air buoyancy – and the local g are traced back to kg, m and s. A first investigation of the ECBs used shows that a precision over a typical measurement time of better than 2 parts in 10^6 has been achieved. This is not a limit to conventional force transducers.

Compared to previous publications the system could be considerably improved with respect to force control and resolution. Now it is possible to feed back the force generation to the ECB, and thus the FSM and the transducer under test are clearly divided systems. Now, in this ECB-stabilized force mode, the force can be stabilized down to 1 µN without offset, depending on the spring constant of the transducer under test. In addition to the stepwise stabilized force calibration it is now also possible to run continuous mode calibrations.

As a matter of principle, the uncertainty budget is limited by the traceability of the force using the ECBs as mentioned before, but moreover different contributions have to be taken into account. The uncertainty is of course limited by the temporal stability of the balance during a measurement. Further influences are the adjustment and creep of the mechanical system, the control system and the force stabilization. A further extensive investigation of the system used will allow in future a proper estimate of the uncertainty. The order of magnitude of $1 \cdot 10^{-5}$ seems plausible for the generation of the reactio force.

As the force is a vectorial quantity, the alignment of the system versus the transducer under test has to be investigated in detail to reduce the influence of parasitic components and cross correlations. To reduce this influence the rack construction, the force introduction parts and the adjustment facilities will be optimized in future. The rotation effect in the small force range has to be investigated in more detail. All this influences have to be taken into account in the uncertainty budget of the calibration of a transducer. This will be the subject of future publications.

ACKNOWLEDGMENTS

This project was initiated and started by Stefan Niehe. He left the working group and is now with the University of Applied Science Hannover. Thanks to Undine Baier-Blott for the thorough linguistic correction of the manuscript.

REFERENCES

[1] DIN EN ISO 376: Metallic materials – Calibration of force-proving instruments used for the verification of uniaxial testing machines, January 2003

[2] “Kontinuierliche Kalibrierung von Kraftaufnehmern nach dem Vergleichsverfahren,” , DKD-R 3-9, 2/2005 *German Calibration Service*

[3] S. Niehe, “A New Force Measuring Facility from the Range of 10 mN to 10 N”, Proc. of the XVII IMEKO World Congress, Dubrovnik, 2003, pp. 335-340

[4] S. Niehe, “New Experiences with a Force Measuring Facility from the Range from 1mN to 5N”, Proc. of the 19th Int. Conf. on Force, Mass & Torque IMEKO TC3, Cairo, 2005

[5] R.B. Frenkel, L. Kirkup, "Monte Carlo-based estimation of uncertainty owing to limited resolution of digital instruments", Metrologia **42** (2005) L27-L30

[6] A. Lindau, R. Kumme, A. Heiker, “Investigation in the local gravity field of a force laboratory of PTB”, Proc. of the Joint Int. Conf. IMEKO TC3/TC5/TC20, Celle 2002, pp. 589-598

[7] M. Kochsiek, M. Gläser, "Comprehensive mass metrology", Wiley VCH, Berlin, 2000