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A NEW FORCE MEASURING FACILITY FOR THE RANGE OF 10 mN TO 10 N

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Abstract – In this contribution a new force measuring facility for the range from 10 mN to 10 N consisting of a piezoelectric adjustment unit and a precision compensation balance is presented. A metrological characterization of the individual components of the device and first results of an examination of a force transducer using the new force measuring facility are given.

Keywords: small forces, force measuring facility

1. INTRODUCTION

In the era of microsystem and nanotechnology, the traceability of smallest forces has also become a demand of industry. Typical applications are atomic force microscopy, coordinate measuring machines, stylus systems and hardness measuring devices as are used to determine the mechanical properties and dimensional measurands of a test object by tactile tracing methods. With increasing miniaturization of the sample structures, the tracing or penetration forces must be reduced to the mN and µN range so as to obtain small probing uncertainties and not to destroy the surface of the test object [1].

At the Force Section of the PTB, forces in the range from 0,5 N to 2 MN are generated in deadweight force standard machines by the weight force of mass stacks in the gravitational field of the Earth. The smallest force which can be generated in these force measuring machines is defined by the weight force of a load frame designed to accommodate the mass stacks responsible for force application to the force transducer. As regards smaller forces, due to the mechanical stability of the load frame and the problems due to applying the force, this procedure is limited, so new methods must be investigated as regards their suitability for the realization of the force scale.

Within this setting, a new force measuring facility has been set up, which in a first step covers the range from 10 mN to 10 N which is of interest, for example, to microhardness testing [2] and in the upper range allows comparison with existing deadweight force standard machines.

2. SET-UP OF THE MEASURING FACILITY

The measuring facility is represented in Fig. 1. It essentially consists of a piezoelectric 1D fine adjustment unit with an integrated capacitive feedback sensor and a precise electrodynamic compensation balance with lever mechanism. The force transducer to be investigated is screwed overhead, together with the fine adjustment device, and traced by the coarse adjustment unit to contact the balance. When the fine adjustment device travels downwards, the force transducer presses the load receptor of the balance downwards. A position sensor records the movement of the lever arm, and the balance automatically changes the current through a coil rigidly connected to the lever arm. The action of force on this current-carrying coil in a magnetic field produces a counterforce and thus ensures resetting to the initial position by the position sensor. The force-proportional coil current is a measurand of the balance. By variation of the piezoelectrically produced translation, the force transducer can be loaded in compression with different forces which are recorded by the balance.

For damping, the whole arrangement is screwed via a metal frame to a massive granite plate, and a plexiglass housing reduces thermal influences and especially air circulation which might disturb the indication of the balance.

The balance is calibrated at regular intervals against a weight force of 10 N and thus ensures traceability of the measuring facility to the mass scale.

3. COMPONENTS

The individual components of the force measuring facility must be examined for their suitability for the application outlined.

3.1. Compensation balance

In the new testing device the electrodynamic force compensation balance is used as the force measuring system. Calibration is carried out at regular intervals against the weight force of a calibrated weight which - for the particular place of use and the climatic conditions prevailing at the laboratory – was adjusted to the nominal value of 10 N with a relative standard uncertainty of $u = 3{,}6 \cdot 10^{-6}$. In the measurement mode, the indication of the balance is then used to calculate the associated force value in the computer. According to the measurement range of the balance of 1,2 kg at a resolution of 1 mg, a force measurement range of approx. 12 N at a resolution of $1 \cdot 10^{-5}$ N is obtained.

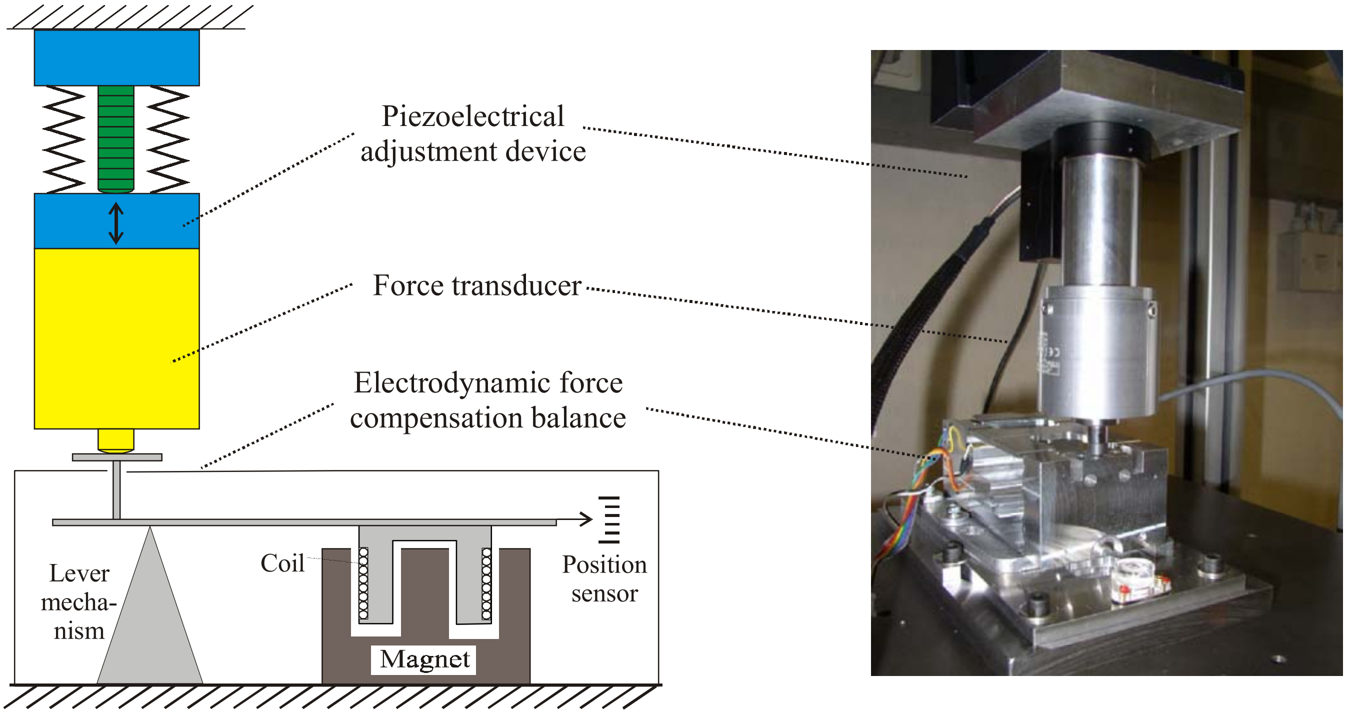

Fig.1. Measuring facility

The force compensation balance was separately checked against weight forces of calibrated weights with a relative standard uncertainty of $u = 3{,}6 \cdot 10^{-6}$ in three measurement ranges, viz. 10 mN to 100 mN, 100 mN to 1 N, and 1N to 10 N. In accordance with DIN EN ISO 376 [3] relating to the calibration of force-proving instruments, the loading process in each of these measurement ranges first consists of two measurement series with increasing force only and then of another two measurement series with increasing and decreasing force. Prior to each of the measurement series – which in the following are consecutively numbered from (1) to (4) – the preloadings stated in [3] were realized. The value indicated by the balance was recorded at an interval of 30 s after application of the next weight, and at the beginning of each measurement series, the indication of the unloaded balance was reset to zero.

The absolute measurement deviations of the balance shown in Fig. 2 from the weight force applied are less than $\pm 3 \cdot 10^{-5}$ N, and the maximum spread within one force step is $4 \cdot 10^{-5}$ N. A systematic dependence cannot be seen.

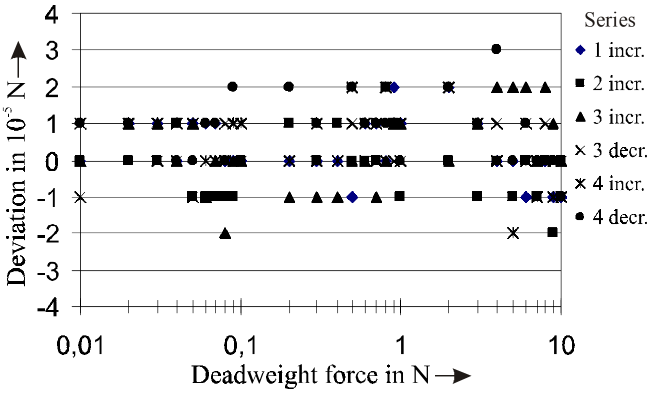

Fig.2. Measurement deviation of compensation balance

The hysteresis, i.e. the difference between the balance indications at increasing and decreasing force in the third and fourth measurement series lies within $4 \cdot 10^{-5}$ N, and a marked variation of the hysteresis cannot be recognized.

Within a period of some days, without recalibration of the balance, significant changes in the measurement processes were not observed even though the measurement interval was altered, neither did repeated measurement series within three months with recalibration of the balance reveal changes of the measurement data.

Altogether, irrespective of the loading process, the measurement deviations of the balance for the determination of weight forces from 10 mN to 10 N lay always within $\pm 5 \cdot 10^{-5}$ N for the whole data material.

For the envisaged application, not only the metrological characterization of the balance but also the mechanical characteristics are of importance. The load-dependent lowering of the load receptor position in particular must be minimized so that, if possible, the total displacement of the piezoelectric fine adjustment device can be used for force generation. The modifications and the ensuing reduction of the lowering at a weight force of 10 N, which was measured by interferometry, are shown in table I.

For reinforcement of the base plate and for direct tracing of the point of force application, the casing of the balance had to be removed. Disturbing effects of the resulting reduction of the electrical and thermal shielding of the balance could not be identified.

After the structural alterations in table I were made, there still is a slight linear dependence of the tracing position on the force introduced, which was interferometrically determined to be 9 µm at 10 N. This is essentially due to the resilience of the lever mechanism. According to the compensation principle of the balance – see also left half of

Fig. 1 –, the position sensor keeps the position of the coil end of the lever constant but due to the finite stiffness of the overall lever mechanism the tracing end is lowered with the force introduced.

The residual slight lowering is of no importance for conventional force transducer testing as the traceability will be realized independently of the tracing position via the balance signal to the mass scale. But microsystem technique also uses purely passive sensors, e.g. silicon bending beams which serve to determine forces via the stiffness only. The traceability of such sensors requires that force deflection characteristics be determined and then also that the lowering of the tracing point be taken into account [1].

TABLE I. Modifications of the balance

Modification	Reduction of lowering at 10 N
Removal of spring overload protection	≈ 150 µm
Reinforcement of base plate	≈ 20 µm
Removal of three-point support	≈ 10 µm
Direct tracing of force application	< 1 µm

3.2. Piezoelectric fine adjustment

In the novel testing machine the piezoelectric fine adjustment is responsible for force generation. With increasing deflection in force traction, the value of the force also increases according to the stiffnesses of the components involved, and we have to do with a displacement/force conversion.

The piezoelectric adjustment allows a displacement up to 100 µm. According to the manufacturer's specifications, a high-resolution capacitive sensor measures the displacement with a resolution of 1 nm and a repeatability of the position of ± 5 nm. The linearity deviation is smaller than ± 20 nm.

For the testing of force transducers, the high stability of the measurement values and the associated high stability of the effective force are of advantage; for the characterization of purely passive sensors, the small measurement deviations of the fine adjustment system are also important.

Owing to the design, undesirable misalignment in the displacement is minimized by a sophisticated flexure guiding system of the fine adjustment device.

3.3. Coarse adjustment device

The manual coarse adjustment of 25 mm serves to mount and remove different force transducers of different height. Due to the design of the present arrangement (see photo at top of Fig. 3), the displacement axis of the manual coarse adjustment is not in alignment with the displacement axis of the piezoelectric fine adjustment but is parallel at a distance of about 50 mm. The two displacement devices are joined via an angle. In the measurement mode with force traction, the arrangement is lifted due to the backlash of the coarse adjustment unit, which is always present, and in addition, the junction element is tilted as the axes are not in alignment. In different positions of the junction element, the total displacement Δl resulting from lifting and tilting was interferometrically measured at a force of 10 N. From the curve at the bottom of Fig. 3 the lifting can be roughly estimated < 1 µm and the angle of tilt at about $\alpha = \arctan(0{,}00015) \approx 0{,}01°$.

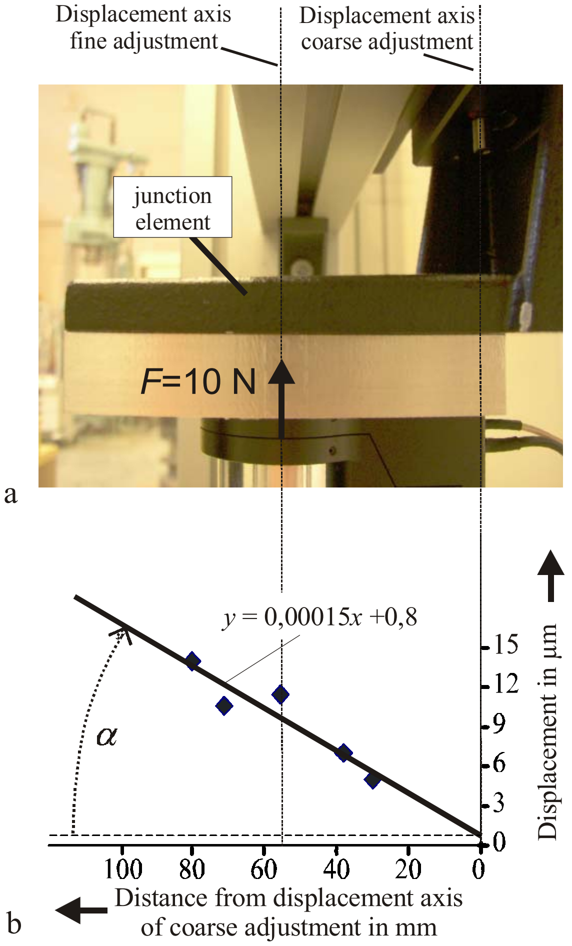

Fig.3. a) Connection of fine and coarse adjustment
b) Displacement and tilt angle of the junction element at a force of 10 N

At a force of 10 N, the total displacement of the angle in the axis of force application, i.e. the axis of the fine adjustment, is about 10 µm and – similar to the lowering of the tracing position of the balance – also reduces the displacement path available to the fine adjustment for force generation.

According to the angle of tilt α, the force transducer no longer traces the balance vertically. The relative measurement deviation due to the cosine error is $(1-\cos(\alpha)) \approx 1{,}5 \cdot 10^{-8}$ and can be neglected. For cross-sensitive force transducers, however, the increase in tilting, proportional to the load, and thus in the tilting of the force vector in the point of force introduction can lead to falsifications of the measurement.

4. FIRST RESULTS

To obtain first fundamental knowledge of the metrological properties of the new testing machine, a strain gauge force transducer of accuracy class 0,1 with a nominal force of 20 N was investigated in the new testing facility over a nominal measurement path of 210 µm and the results were evaluated via a measuring amplifier using carrier frequency methods. The alignment of the individual components was carried out by optical means.

4.1 Mechanical set-up

In the new testing machine, this transducer can be compressed by the piezoelectric fine adjustment device by about 85 µm, corresponding to a load of about 8 N. The lowering of the balance tracing position and the raising of the junction element between coarse and fine adjustment together are about 15 µm in this case.

If the force transducer is placed directly on the balance, the latter is loaded not only by the weight force of the transducer but in part also by the weight force of the measurement cable to the amplifier. Even if the cable is carefully fastened to the frame of the measuring facility, there will be non-reproducible force shunts whose values depend strongly on the state of the cable and thus strongly influence the balance signal. A waiting time of at least one day must be complied with until the indication of the balance still shows only slight creepage. During the measurement series, even smallest vibrations propagating through the measurement cable produce non-reproducible balance indications.

These serious shortcomings were overcome by screwing the force transducer with its bearing surface to the fine adjustment device overhead (see also Fig. 1). In this way the weight forces of cable and of transducer are completely diverted via the frame, and the balance is now loaded only with the force to be measured. This ensures rapid measurement less susceptible to failure.

4.2 Closed-loop operation modes

Fig. 4 shows the possibilities of controlling the new testing machine. At present, the open-loop control as well as the closed-loop control with displacement feedback A and with a feedback B from the force transducer have been realized with time constants in the millisecond range and investigated by measurements.

In open-loop operation, the piezo driver applies only a stable voltage value irrespective of the ensuing displacement. Due to creepage and thermal expansion effects from all components involved in the force traction, and in dependence on the loading process, the force value changes by up to 80 mN in 60 s, and the indications of balance and force transducer drift accordingly.

The piezo actuator is usually operated by closed-loop control A based on an integrated position feedback sensor. The deflection is determined with the aid of the capacitive sensor and compared with the specified reference voltage. In the case of deviations, the controller alters the voltage applied to the piezo actuator via the piezo driver and thus corrects the deflection. According to the reference voltage value selected, different deflections can thus be adjusted. In this closed-loop control A, the change of the force value due to the disturbing effects described above is recorded with the balance and the force transducer and is still only 8 mN at most in 60 s.

A closed-loop control with a force feedback B is realized by the analog force-proportional output signal from the measuring amplifier of the force transducer to be investigated. By variation of the reference voltage, it is possible to apply the desired force controlled by the force transducer to the system. This should ideally eliminate all disturbing influences on force generation but possible creepage effects of the force transducer then are no longer reflected in the indication of the transducer itself – which due to the closed-loop control is stable – but in the variation of the balance indication. Changes of the force value recorded with the balance are still 0,4 mN at most in 60 s. This value cannot be explained solely by the creepage of the force transducer, which was checked with deadweights. To study the remaining disturbing influences, further investigations, also with different force transducers, will be necessary.

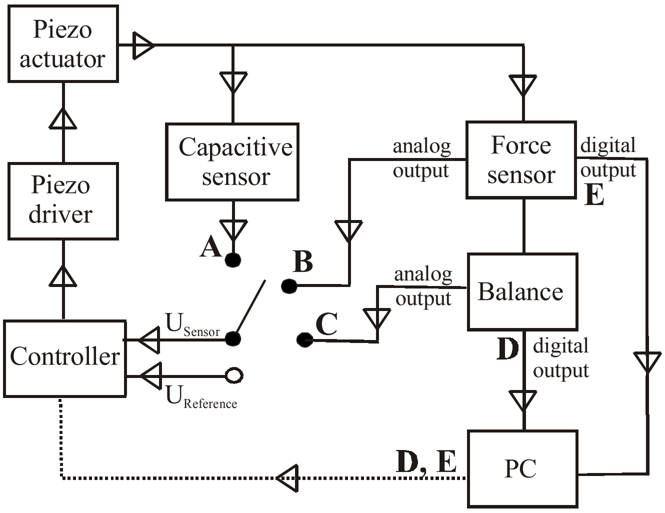

Fig.4. Closed-loop operation modes

Further closed-loop controls which have not yet been realized will now be briefly presented. The system can be controlled by the analog coil current signal C of the balance but the dependence of the coil current on the temperature determined inside the balance by sensors and corrected in the indication must then be additionally recorded and taken into account.

These problems can be circumvented by a closed-loop control D with a feedback from the digital balance indication. In the PC the adjusted reference value and the actual value are compared, and via an interface module the piezo controller can be directly triggered; here the time behaviour is to be critically investigated. This closed loop D with a feedback of the indicated value of the balance, which is traceable to the mass scale, should be aimed at in the long term as the desired force values can be generated in a simple and reproducible way and independently of the transducer.

A similar closed-loop control E can naturally also be based on the digital indicated value of a force transducer but then has the same disadvantages as control B realized with a feedback of the analog force transducer signal.

4.3. Investigation of a force transducer

Due to the results of the analysis of different control versions, several measurement series were carried out in the closed loop control B with a feedback of the measuring

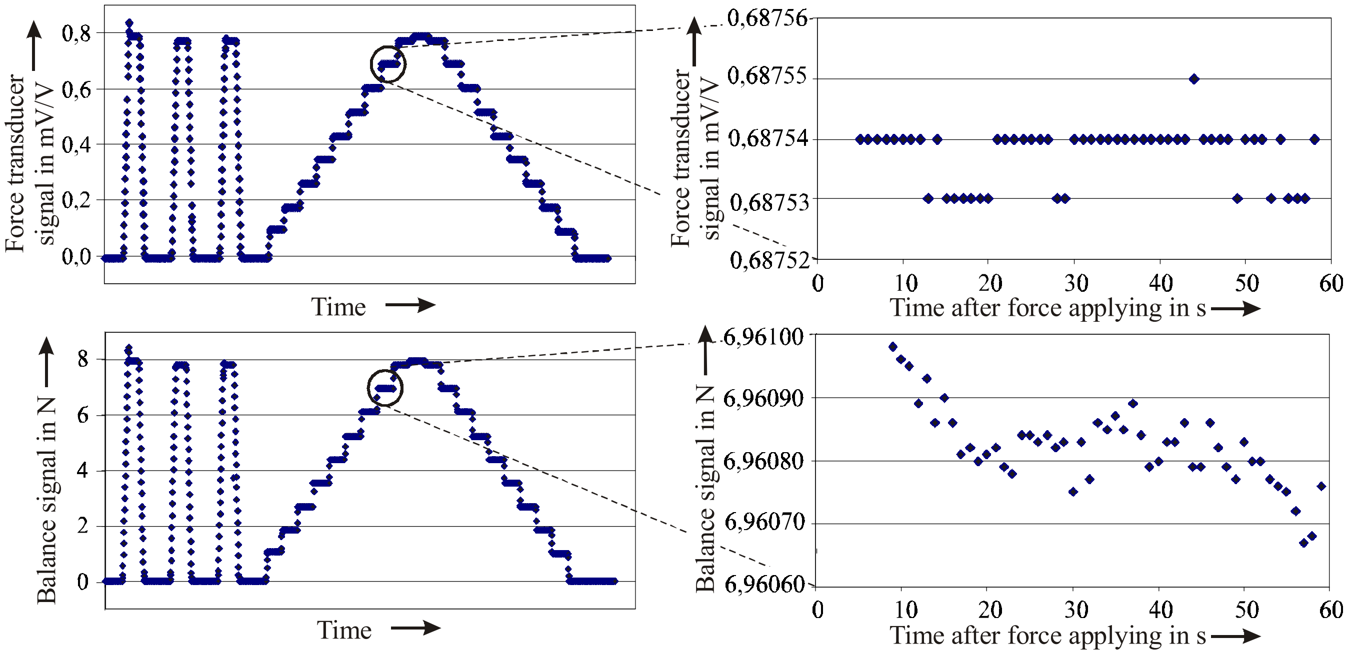

Fig.5. Pattern of force transducer and balance signal during a loading series

amplifier of the force transducer to be investigated itself. Fig. 5 shows a typical measurement series.

The two upper curves show the signal patterns of the force transducer over time and the two lower curves those of the balance. In the left half the signal during the whole loading process can be seen which after three preloadings increases and then decreases again in 10 steps from 0 to 8 N. The left half shows a typical detail, here of the force value of 7,2 N. The stability of the controlled force transducer signal of ± $1 \cdot 10^{-5}$ mV/V – corresponding to one digitizing step of the measuring amplifier – shows the quality of the control loop. The time dependence of the balance shows the drift already mentioned in the description of the control modes above, here of about 0,3 mN in 60 s.

For the force transducer check, the zero-corrected indicated values of the transducer are plotted against the calibrated balance indication - converted into force values - for all load steps with increasing force. In accordance with [3], after applying a force no reading is to be taken before 30 s have elapsed. Fig. 6 shows the measurement values determined with a specified waiting time of 30 s from the curves in Fig. 5 and the linearity deviations from the regression line forced through the origin. The high linearity with a correlation coefficient of r^2 = 0,99999999 shows linearity deviations of ± $3 \cdot 10^{-5}$ mV/V at most. The slope *m* of the regression line provides the relation between the indication of the force transducer to be tested and the force produced and measured with the new measuring facility and hus corresponds to the sensitivity of the transducer determined with the measuring facility. With decreasing forces, the measurement deviations from the regression line lie within ± $5 \cdot 10^{-5}$ mV/V. Here the deviation increases with the force value but this still needs to be investigated in more detail.

From the curves in Fig. 5 the regression line can also be determined for other waiting times $t > 30$ s; the variation of the linearity deviations change only slightly, and the maximum linearity deviations are always smaller than ± $5 \cdot 10^{-5}$ mV/V. The slope *m* shows a slight relative range of dispersion of ± $2 \cdot 10^{-5}$ depending on the waiting time.

The high linearity within a measurement series was confirmed by a great number of measurements but within a period of two weeks, the value *m* and thereby the calculated sensitivity of the force transducer to be investigated varies by ± $1 \cdot 10^{-4}$ in relative terms. Over a prolonged period of two

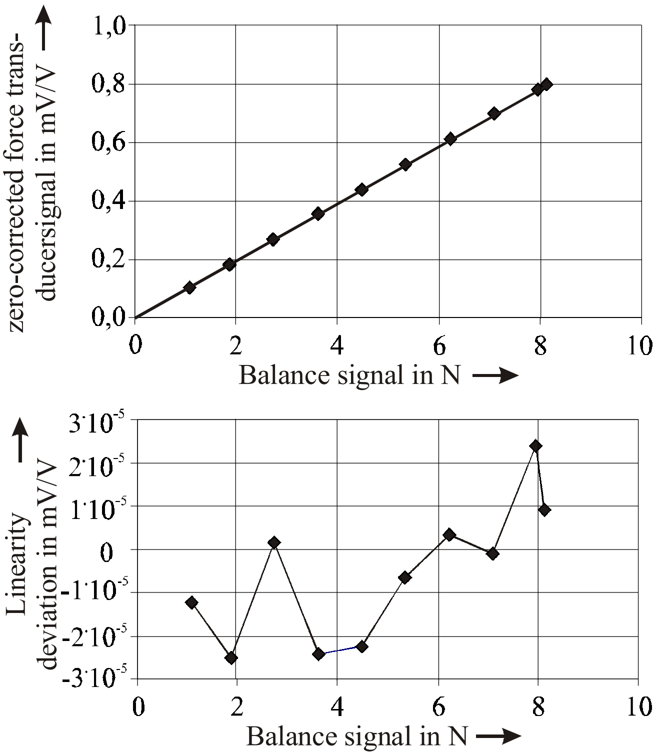

Fig.6. a) Force transducer against balance with regression line
b) Linearity deviations

months during which the transducer is repeatedly mounted and dismounted, a mean slope $m = 0{,}100266 \frac{(\mathrm{mV/V})}{\mathrm{N}}$ with a relative spread of $\pm 3 \cdot 10^{-4}$ is obtained.

4.4 Comparison with the 200 N deadweight force standard machine (FSM) of the PTB

The force transducer with measuring amplifier investigated in 4.3 was calibrated in the 200 N FSM of the PTB with eight force steps up to 8 N in accordance with DIN EN ISO 376 [3]. As in 4.3, the relation between force transducer signal and relevant force step is described by a first-order polynomial passing through the origin. With increasing and decreasing forces, the deviations of the measurement values from this polynomial lie within $\pm 5 \cdot 10^{-5}$ mV/V and correspond to the values of the linearity deviations in 4.3. The polynomial coefficient is $0{,}099895 \frac{(\mathrm{mV/V})}{\mathrm{N}}$, and the transducer sensitivity determined with the new testing machine, the slope *m* in 4.3, deviates from this value by $4 \cdot 10^{-3}$ relative.

This deviation can be due to different causes. In the new testing facility as described in 4.1, the force transducer is firmly screwed with its area of support to the fine adjustment unit. The mounting position thus is fixed and the transducer cannot be rotated. Potential interactions between force transducer and testing machine thus cannot be averaged as prescribed in [3] by rotation of the transducer about its own axis. In the case of purely optical alignment of the testing machine components, due to false adjustments or to the angular tilt described in 3.3, these influences can lead to great measurement deviations. Another cause may be the fitting position with the support surface pointing upwards, and hence is rotated by 180° compared to the normally and also in the 200 N FSM used fitting, thereby influencing the indication of the force transducer.

5. CONCLUSIONS

The realization of a new force measuring facility for the range of measurement from 10 mN to 10 N and the results obtained on the individual components are presented.

For the force measurement a electrodynamic force compensation balance with a resolution of $1 \cdot 10^{-5}$ N and maximum measurement deviations of $\pm 5 \cdot 10^{-5}$ N is used. The force is generated via a piezoelectric fine adjustment unit with a maximum displacement of 100 µm, a resolution of 1 nm and linearity deviations below 20 nm. The results obtained by a closed loop control with a feedback of the measuring amplifier of the force transducer to be investigated itself provides very high linearity with relative linearity deviations of $\pm 3 \cdot 10^{-5}$ between the force transducer and the force generated and measured with the new measuring facility. The long-term stability of the slope value of the regression line and thus also the sensitivity determination for the transducer over three months with repeated mounting and dismounting of the transducer shows a relative spread of $\pm 3 \cdot 10^{-4}$, and the absolute value deviates by $4 \cdot 10^{-3}$ from the transducer calibration in the 200 N FSM of the PTB.

New findings for the improvement of the measuring facility are expected from the integration of a rotary table for the measurement of rotation effects, from improvements of the mechanical set-up with aligned axes of the individual components and from investigations on further force transducers. Owing to the modular measuring device, the exchange of the balance as the force measuring system makes it easy for the force range to be extended into the µN region.

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