NEW EXPERIENCES WITH A FORCE MEASURING FACILITY FROM THE RANGE FROM 1 mN TO 5 N

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ABSTRACT

In this contribution new experiences with a force measuring facility [1] for the range from 1 mN to 5 N consisting of a piezoelectric positioning unit for force generation and a precision compensation balance for force measuring are presented. The enhancement of the facility by means of a rotational table allows to rotate the force transducer under test around its axis and to measure the sensitivity of the transducer at different positions. By averaging the measured sensitivities of a complete rotation cycle the rotation effect can be taken into account and the deviation from the calibration of the investigated force transducer in a deadweight force standard machine is then of the order of 10^{-4} in relative terms. This improves the deviation of earlier results [1] without consideration of rotation effects about a factor of 8.

1. INTRODUCTION

In the era of microsystem and nanotechnology, the traceability of smallest forces has 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.

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 force measuring facility has been set up, which in a first step covers the range from 1 mN to 5 N which is of interest, for example, to microhardness testing 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 a rotary table which is connected with the fine adjustment device, and traced by the coarse adjustment unit to contact the balance. When the fine adjustment device

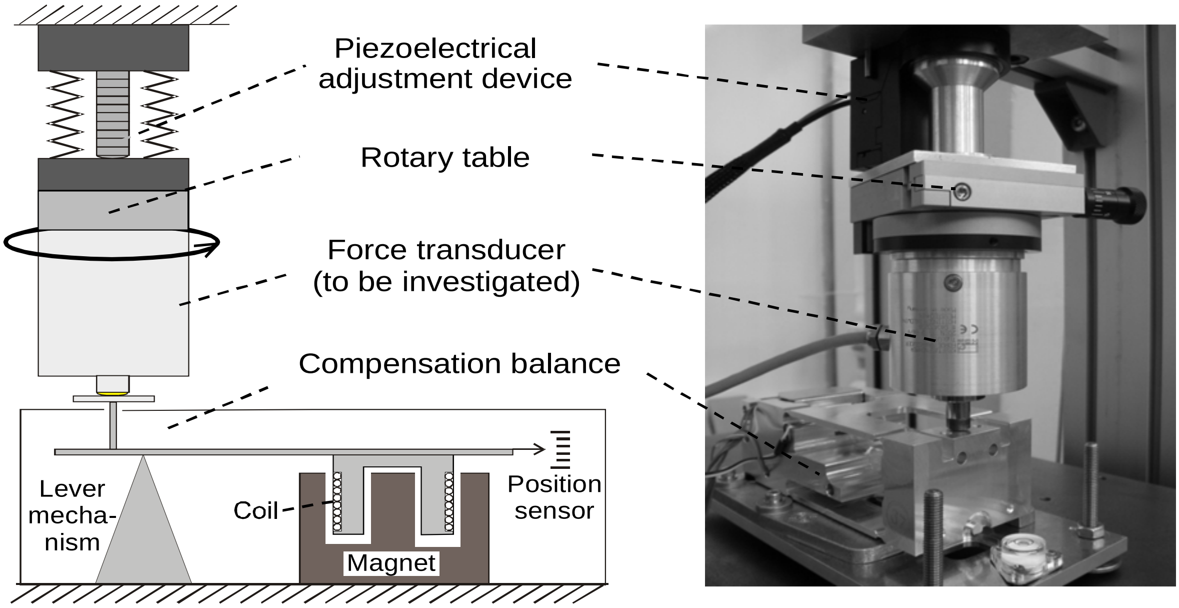


Figure 1: Measuring Facility with rotary table

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. The piezoelectric fine adjustment unit allows a maximum displacement of 100 µm with a resolution of 1 nm and linearity deviations below 20 nm.

By integration of a rotary table into the force measuring device, the transducers to be investigated can be rotated about their longitudinal axis. This allows different positions of the transducers to the measuring device to be realized and rotational effects, i.e. possible interactions between transducer and measuring device to be investigated.

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. The resolution of the balance is $1 \cdot 10^{-5}$ N and maximum measurement deviations are within ± $5 \cdot 10^{-5}$ N. All presented results obtained by a closed loop control with a feedback of the measuring amplifier of the force transducer to be investigated itself , for details see [1].

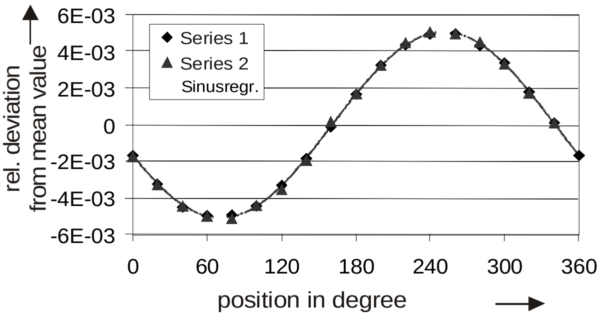
3. ROTATIONAL EFFECTS

Calibration of force transducers according to DIN EN ISO 376 [2] requires rotation of the transducer around its force axis and averaging over three positions each rotated through 120° relative to the testing machine. This allows interactions between testing machine and force transducer – which are referred to as rotational effects – to be taken into account. The cause of these rotational effects are deviations from the ideal rotational symmetry in the case of real testing machines and force transducers [3]. Together with mechanically and electrically asymmetric properties of the force transducer, asymmetric compliances of the testing machine lead to indicated values of the transducer which depend on the position of the force transducer vis-à-vis the testing machine.

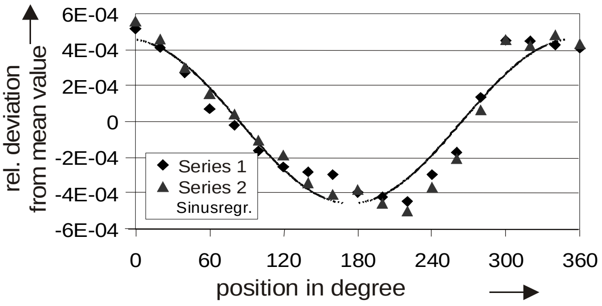
Figure 2 shows the rotational effects of 3 different force transducers during testing in the force measuring device presented. With the aid of the rotary table, the position of the force transducer was rotated anticlockwise, in 20° steps, relative to the initial position. After each rotation, the respective force value was adjusted with a closed loop control to the force transducer signal, and after 30 seconds the measurement value was recorded. The diagrams show the relative deviation from the mean value above the position.

The shape of curve 2a shows a pronounced rotational effect for a 20 N strain gauge precision transducer at 7 N load with the typical sinusoidal curve with an amplitude of $\pm 5 \cdot 10^{-3}$. The amplitude is larger by the factor 100 than the amplitude of the rotational effect when the

a) 20 N strain gauge transducer, load 7 N



b) 10 N strain gauge transducer, load 3 N



c) 50 mN inductive transducer, load 20 mN

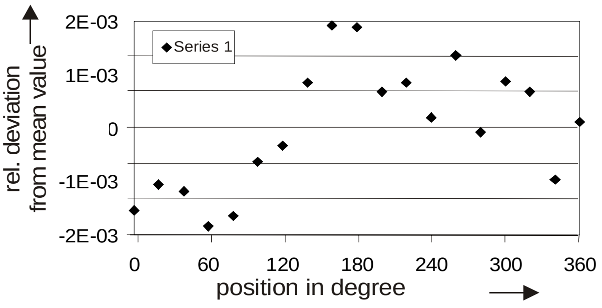


Figure 2: Rotational effects of three different force transducers at different loads

transducer is calibrated in the 20 N deadweight force standard machine (FSM) of the PTB. The mean value shows a relative deviation of $-5\cdot10^{-4}$ compared with the calibration in the FSM. This is an improvement by the factor 8 compared with earlier results [1] obtained without taking the rotational effect on the same transducer into account. After demounting and re-installation of the transducer, the shape of the curve does not show any significant changes.

The shape of curve 2b also shows a pronounced rotational effect for a 10 N strain gauge precision transducer at 3 N load, with an amplitude of the sinusoidal curve of $5\cdot10^{-4}$. The value of the amplitude is, however, larger only by the factor 10 than the amplitude of the rotational effect when the transducer is calibrated in the FSM. The mean value shows a relative deviation of only $-3\cdot10^{-5}$ with respect to the calibration in the FSM and lies in the order of magnitude of the expanded measurement uncertainty U=$2\cdot10^{-5}$ (coverage factor k=2) of the FSM. The shape of the curve is reproducible after the transducer has been dismounted and re-installed.

The shape of curve 2c shows the same investigations on an inductive 50 mN transducer at 20 mN load. No rotational effect can be recognised, the values scatter rather randomly with a relative spread of ± $2\cdot10^{-3}$. The relative deviation of the mean value of the transducer check with calibrated weights amounts to $3\cdot10^{-3}$ and is in the order or magnitude of the transducer accuracy.

Summed up, the measurement series show that the rotational effect decreases with decreasing load and that the deviation of the mean value of the calibration of the transducer in the FSM also decreases with decreasing rotational effect.

A more exact analysis of the cause of the extremely high magnitude of the rotational effect according to Figure 2a is therefore necessary especially for the higher load range. At first, only the force-measuring balance in Figure 1 was rotated anticlockwise about approx. 60°, whereas all other components of the measuring device and the transducer itself maintained their alignment. Measurement series 2a with the same transducer was repeated in steps of 60°, the result is shown in Figure 3. The shape of the curve does not show any change compared with the diagram in 2a, the same positions of the transducer continue to show approximately identical deviations from the mean value. However, as balance and transducer have been rotated against each other by approximately 60°, the high rotational effect cannot be attributed to an interaction between these devices. This indirectly confirms the high mechanical stability of the balance's axis of force application and thus of the parallel rod system of the balance.

In another measurement series, only the force-generating, piezoelectric fine adjustment unit with the coupling elements for the transducer shown in Figure 1 was rotated clockwise around approx. 60°, whereas all other components of the measuring device and the transducer itself maintained their alignment. The associated measurement series shown in Figure 4 has been phase-shifted with respect to the original shape in Figure 2a by exactly these 60°, with

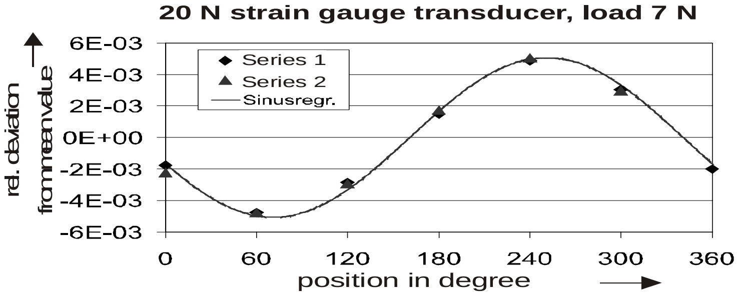


Figure 3: Rotational effects after a 60°-rotation of the balance

otherwise identical curve shape.
The high magnitude of the rotational effect can thus mainly be attributed to an interaction between piezoelectric fine adjustment unit and force transducer. As the rotational effect of the same transducer is approximately 100 times smaller in the FSM, the extreme magnitude of the rotational effect in 2a seems to indicate a lower mechanical stability of the piezoelectric fine adjustment unit. This unit consists of a solid-state joint translation stage with integrated piezoactor, whose maximum displacement must be lever-transmitted by the factor 4 to generate the displacement required of approx. 100 µm. This involves, however, a lateral displacement due to the system and possibly, in the case of load, also tilting of the direction of the applied force which depends on the amount of the effective force. Together with the interfering effects of the force transducer investigated, for example the cross senstivity, this may be the cause of the high magnitude of the rotional effect in the case of force values of a few Newton.

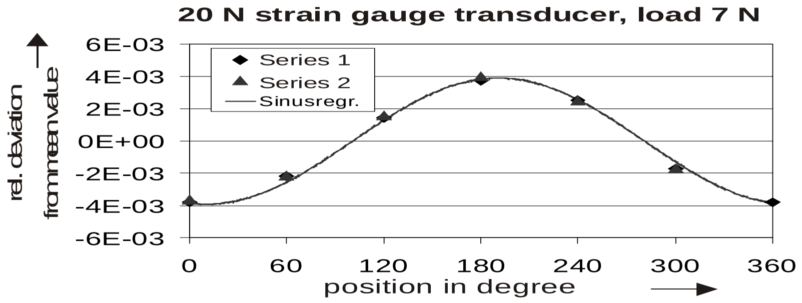


Figure 4: Rotational effects after a 60°-rotation of the piezoelectrical fine adjustment

4. CONCLUSIONS

The enhancement of an existing force measuring facility [1] by means of a rotational table allows to rotate the force transducer under test around its axis and to measure the sensitivity of the transducer at different positions. Thereby a rotation effect, that means an interaction between the force transducer and the facility becomes obvious. The magnitude of the rotation effect is dependent on the investigated force transducer and 10 up to 100 times higher then the rotation effect of the same force transducer calibrated in a deadweight force standard machine of the PTB. Further investigations confirm the assumption that the asymmetrical stiffness of the force generation system, i.e. the flexure guiding system with an integrated motion amplifier of the piezoelectric positioning unit, inclines the alignment of the applied force at higher forces. This misalignment of the force generation system is probably responsible for the high amount of the rotation effect, which is of course dependent on the cross sensitivity of the force transducer under test.

By averaging the measured sensitivities of a complete rotation cycle the rotation effect can be taken into account and the deviation from the calibration of the force transducer investigated in a deadweight force standard machine is then of the order of 10^{-4} in relative terms. This improves the deviation of earlier results [1] without consideration of rotation effects about a factor of 8.
New findings for the improvement of the measuring facility are expected from enhancements of the mechanical set-up with aligned axes of the individual components and from a closed loop control with a feedback of the indicated value of the balance, which is traceable to the mass scale. 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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