

NANOPOSITIONING SYSTEM WITH COMBINED FORCE MEASUREMENT BASED ON ELECTROMAGNETIC FORCE COMPENSATED BALANCES

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Abstract: This paper discusses a novel nanopositioning system which is based on an electromagnetic force compensated (EMC) balance. In addition to the positioning the actuating force can also be measured. This enables the measurement of force displacement curves of springs with a wide variety of spring constants. The measurement range of the spring constants is up to 10^{10} N/m with a maximum resolution of about 0.01 N/m. Compared to other principles for measuring the spring constant the introduced method is more sophisticated. Both force as well as the displacement can be measured traceable and simultaneously.

Keywords: nanopositioning system, force displacement measurement, electromagnetic force compensated balances

1. INTRODUCTION

Common nanopositioning systems such as piezo actuators are capable to position samples and work pieces very precise and reproducible. A direct determination of the acting force is possible but with a high uncertainty and low resolution.

To determine force displacement curves of springs for example of atomic force microscope (AFM) cantilevers the cantilever is displaced by a nanopositioning system and the force acting on the cantilever is measured by a high precision balance [1] (see Figure 1 (a)).

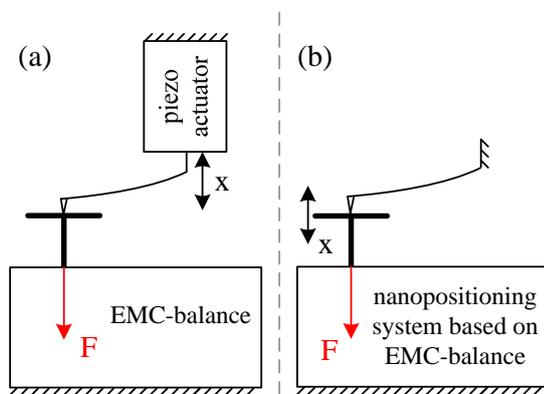


Figure 1: comparison of state of the art (a) and presented (b) nanopositioning system with combined force measurement

A comparable principle can also be used for calibration of force transducers, as described in [2].

Another concept is based on an electrostatic force compensated balance where a piezo sensor cantilever is calibrated and used as a transfer normal [3]. The principle is similar to that one discussed in this paper.

The nanopositioning and nanomeasuring machine which was developed at the Ilmenau University of Technology uses voice coils and an interferometer for the positioning in the z-direction [4]. The acting force is not determined.

The presented nanopositioning system is based on a modified commercial balance system with EMC. The position of the weighing pan can be set to any value in the measurement range with high resolution and reproducibility. In addition to that the acting force on the weighing pan can be determined (see Figure 1 (b)). This enables the possibility to determine both displacement and force simultaneously. The advantage of the system is that also nonlinear spring constants, hysteresis and even strong nonlinear force-displacement relationships (such as stick slip effects of mechanical guiding and adhesive effects [5, 6]) can be determined.

2. NANOPOSITIONING SYSTEM

2.1. Principle

Electromagnetic force compensated balances are state of the art of commercial weighing technology for the determination of forces and masses with high accuracy. The schematic setup of for the nanopositioning system is shown in Figure 2. The schematic includes an interferometer for the displacement measurement of the weighing pan and the EMC balance.

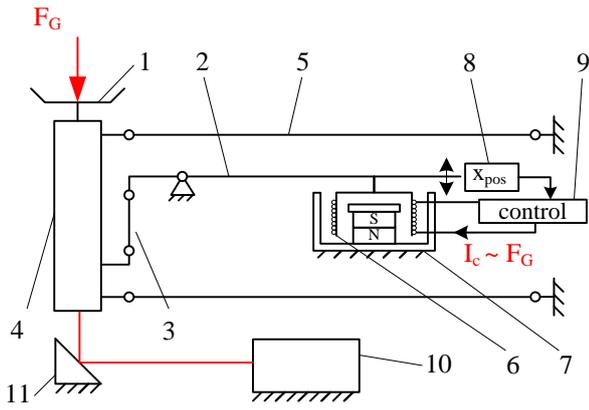


Figure 2: Principle of nanopositioning system; (1) weighing pan, (2) conversion lever, (3) coupling element, (4) pan carrier, (5) parallel guiding system, (6) compensation coil, (7) permanent magnet, (8) position sensor, (9) control loop, (10) interferometer, (11) deflection mirror

If a force is applied on the weighing pan (1), the conversion lever (2) deflects. The conversion lever is coupled by a coupling element (3) to the pan carrier (4). The pan carrier is guided by a parallel guiding system (5). A compensation coil (6) is attached to the conversion lever and immersed in a permanent magnet (7). The position of the conversion lever is measured by an optical position sensor (8). A control loop (9) controls the position of the conversion lever by setting the current of the voice coil, generating a Lorentz force. The current is proportional to the force applied on the weighing pan, if the system is used as a balance and the conversion lever is in equilibrium.

The output signal of the position sensor is proportional to the deflection of the conversion lever [7].

If the system is used as nanopositioning device the position of the weighing pan is measured additionally by an interferometer (10). The laser beam of the interferometer is reflected by a deflection mirror (11).

The conversion lever in commercially available EMC weighing systems is controlled to a fixed zero position. The innovation of the presented system is that the set point (reference position) can be set to any value in the moving range of the balance. Consequently the displacement of the conversion lever can be set to any value in its moving range. The principle of the control loop of the nanopositioning system is shown in Figure 3.

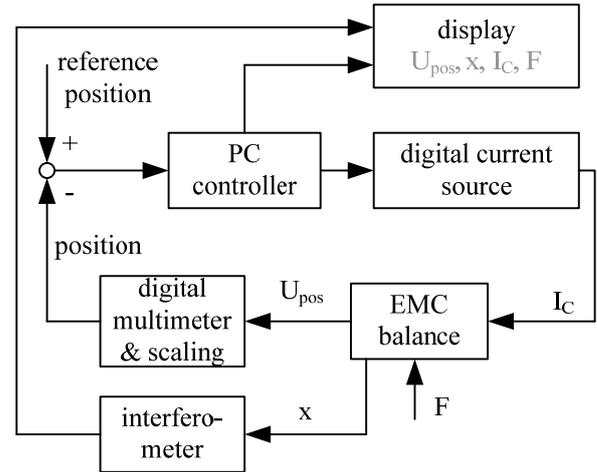


Figure 3: Principle of control loop of nanopositioning system

The output signal of the EMC balance is the differential voltage of the position sensor which is proportional to the position of the conversion lever (U_{pos}). This voltage is measured with a high precision digital multimeter and fed into a PC. The control variable (current of the compensation coil) is computed by a digital controller. The compensation coil is fed with the current I_C by a high precision digital current source.

Since the weighing pan is coupled to the conversion lever and guided parallel it can be set to defined positions. Due to the conversion ratio of the system the setting range of the weighing pan is smaller than the setting range of the conversion lever, subsequently the position resolution is increased by the same factor. The position sensor has a position resolution of approximately 1 nm; hence the balance can be used as a nanopositioning system.

As already mentioned the displacement of the weighing pan is additionally measured with a plane mirror interferometer with a resolution of $\lambda/1000$ [8], thus the displacement measurement is traceable to the SI unit of the length. It is also needed for the calibration of the position sensor.

The system is calibrated to the force by applying standard mass pieces, to get the relation between applied force and the compensation current. Thus the force measurement is traceable to the mass and the gravity. The gravity of the laboratory is taken from PTB [9].

The force measurement range of the EMC weighing system is up to $F_{max}=2$ N with a relative force resolution of $A_{F,rel}=10^{-7}$. The positioning range is $x_{max}=\pm 35$ μ m with a resolution of $A_x=0.2$ nm. With these values a measurement range for the spring constants of up to $F_{max}/A_x=10^{10}$ N/m with a maximum resolution of approximately $A_F/x_{max}=0.01$ N/m can be obtained.

Figure 4 shows the design configuration of the nanopositioning system with combined force measurement.

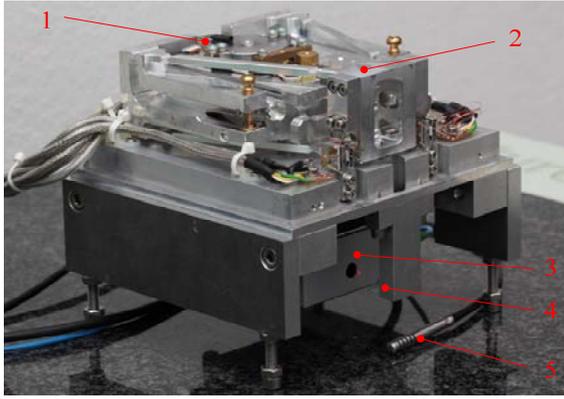


Figure 4: Design configuration nanopositioning system with combined force measurement; (1) position sensor, (2) pan carrier, (3) interferometer, (4) deflecting mirror, (5) temperature sensor

2.2. Determination of spring constant

To measure the spring constant of samples (e.g. AFM-cantilevers), the weighing pan is replaced by a sapphire plate ensuring a sufficient hardness compared to the sample as well as low friction.

The measurement procedure for the determination of the spring constant of samples can be described as follows: The pan carrier is moved to its lower position and the sample is positioned slightly above the weighing pan. The weighing pan is then moved upwards in discrete steps (using the controller). The setting current of the voice coil represents the acting force acting on the sample. Since the displacement is known the resulting force to displacement curve can be determined. Such a measurement is shown in principle in Figure 5.

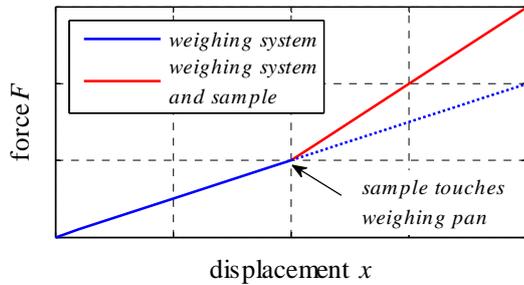


Figure 5: force displacement curve of weighing system and sample; spring constant of system (blue curve) and spring constant of system and sample (red curve)

As long as the sample does not touch the weighing pan, the slope of the force displacement curve equals to the spring constant of the weighing system (blue curve). If the sample touches the weighing pan, the slope of the force to displacement curve changes, representing the sum of the spring constant of the weighing system and the spring constant of the sample (red curve).

The spring constant of the weighing system was determined previously, thus the stiffness of the sample can easily be determined by subtraction of the force displacement curve of the weighing system (see Figure 6).

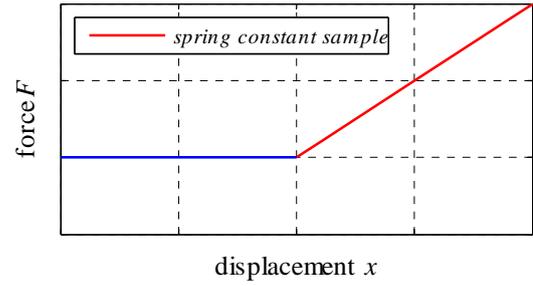


Figure 6: Force displacement curve of sample; spring constant of sample (red curve), sample does not touch weighing pan (blue curve)

3. MEASUREMENTS

3.1. Position measurement

Figure 7 shows the signal of the position sensor (U_{pos}) versus the displacement of the weighing pan (x) measured with the interferometer. The red curve is the standard deviation (reproducibility) of the position sensor's signal ($s(U_{pos})$).

The slope of the curve is the sensitivity of the position sensor referred to the displacement of the weighing pan (linear approximation).

$$E_{pos} = \frac{\partial U_{pos}}{\partial x} \approx 265 \frac{V}{mm} \quad (1)$$

The setting range of the weighing pan is approximately $x = \pm 35 \mu m$. The reproducibility of the position sensor's signal is smaller than $s(U_{pos}) < 60 \mu V$. The reproducibility of the positioning of the weighing pan can be expressed by the reproducibility of the signal of the position sensor and its sensitivity E_{pos} (1). This results a reproducibility of the position of the weighing pan of $s(x) < 0.23 \text{ nm}$.

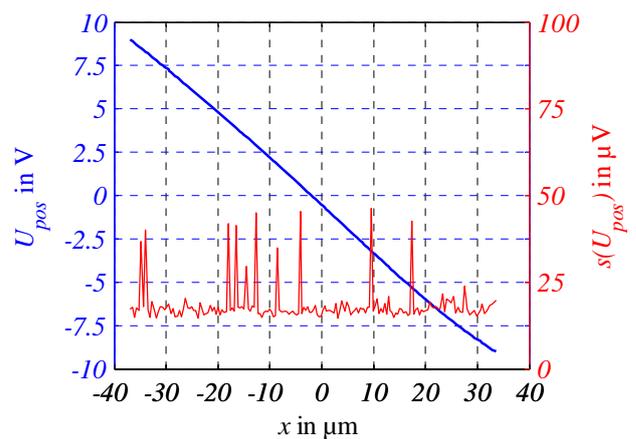


Figure 7: signal of position sensor U_{pos} vs. position weighing pan x (blue curve) and standard deviation of the signal of the position sensor $s(U_{pos})$ (red curve)

3.2. Spring constant of the weighing system

The spring constant of the system was determined by placing standard class F1 mass pieces (according to OIML

R-111 [10]) on the weighing pan and measuring the deflection of the weighing pan using the interferometer. In this case the weight force is not compensated by the compensation coil, leading to a deflection of the weighing pan. The advantage of this approach is that the spring constant is traceable to the SI units of the length and the mass or force respectively.

Figure 8 shows the force displacement measurement of the weighing system. The slope of the curve is the spring constant of the system, which was determined to $c_s = 263.70 \pm 0.2 \text{ N/m}$ ($k=2$) (according to GUM [11]).

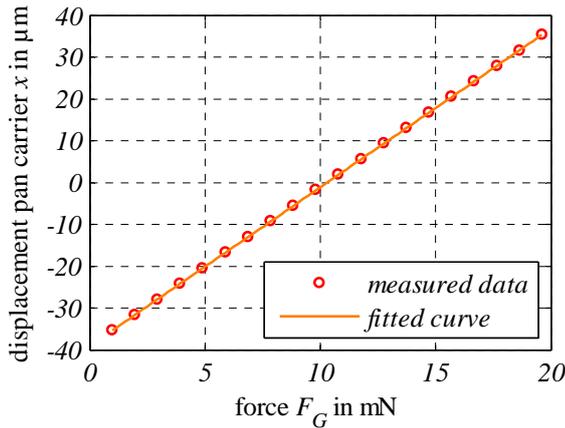


Figure 8: force displacement curve

3.3. Force displacement measurement of AFM-cantilevers

AFM-cantilevers are ideal measurement objects for the presented measurement system as they have a linear spring constant and a lack of hysteresis.

The spring constant of such cantilevers is given by the manufacturer but with a high uncertainty. The presented method enables the possibility to measure the spring constant with a much lower uncertainty.

State of the art of determining the spring constants of AFM-cantilevers is a computation based on their geometrical and physical properties. Due to tolerances mainly in the geometry, the computed spring constants have a high uncertainty.

There are several ways to calibrate cantilevers. Some implicit methods are described and compared in [12]. A more sophisticated method is the determination of the force to displacement curve of such cantilevers as described in [1,2].

Two different AFM cantilever types were measured with the presented setup, a tipless cantilever NSG20 from NT-MDT normally used in the tapping mode with a referred spring constant of 28 .. 91 N/m [13]. The measurement results are shown in Figure 9.

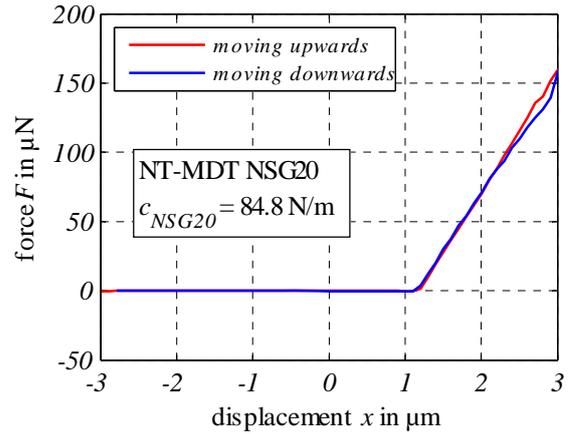


Figure 9: force displacement curve of NT-MDT NSG20

The spring constant for this cantilever was determined to $c_{NSG20} = 84.8 \pm 1.3 \text{ N/m}$ ($k=2$).

The second probed specimen is also a noncontact mode cantilever NSG10 with a lower spring constant which is referred to 3.1 .. 36.7 N/m [14]. Figure 10 shows the force displacement curve of this second cantilever.

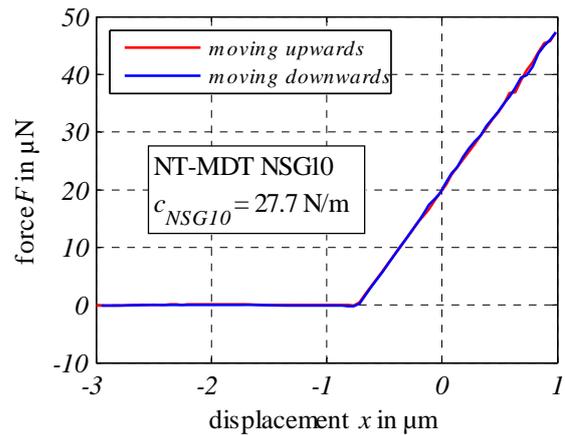


Figure 10: force displacement curve of NT-MDT NSG10

The spring constant of the NSG10 is much lower and was determined to $c_{NSG10} = 27.7 \pm 0.2 \text{ N/m}$ ($k=2$).

The determined spring constants are in the uncertainty range of the manufacturer referred in the datasheets.

4. CONCLUSION

A high precision nanopositioning system with simultaneous force measurement was introduced in this paper.

The position measurement range of the nanopositioning system is $x = \pm 35 \mu\text{m}$ and the reproducibility is better than $s(x) < 0.23 \text{ nm}$. The force measurement range is $F = 2 \text{ N}$ with a resolution of $A_F = 200 \text{ nN}$.

The force which acts on the weighing pan can be measured additionally its displacement. This allows a wide range of applications, e.g. the determination of force displacement curves or spring constants respectively. The

system can also act as an active spring by setting a force and displacement.

The spring constant of the investigated weighing system is $c_s=263.70 \pm 0.2$ N/m ($k=2$). This represents an offset, which is always measured.

The measurements have shown that spring constants of AFM-cantilevers can be determined. The measurements have been performed for relatively stiff cantilevers normally used in noncontact mode. With the presented method a smaller uncertainty for the determined spring constant as referred by the manufacturer is possible.

5. ACKNOWLEDGEMENTS

The Project was sponsored by Bundesministerium für Bildung und Forschung (BMBF): Innoprofile – Unternehmen Region, „Innovative Kraftmess- und Wägetechnik“ in cooperation with Sartorius AG and SIOS Meßtechnik GmbH.

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