Microforce measurements – a new instrument at METAS

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Abstract. METAS designed and developed a new instrument for calibrating microforce sensors in the range of 1 nN to 60 mN. The calibration is realised by means of electromagnetic force compensation of a balance and traceable to the SI unit of mass. The expanded measurement uncertainty (type B) of our measuring apparatus is 0.125 µN (absolute) and 2400 ppm (relative). Our measuring apparatus was verified in a bilateral comparison between METAS and PTB. The degrees of equivalence are in excellent agreement between the two institutes.

1. Introduction
Force measurements play an important role in our day-to-day life. They cover a large variety of industrial, environmental and scientific applications and range from mega Newton down to micro Newton. Especially the domain of micro Newton has come into focus in recent years for developing new generation sensors capable of measuring e.g. the mechanical stiffness of MEMS structures, the deformation of piezoresistive cantilevers or even the mechanical properties of biological materials such as cell membranes. We present our newly developed instrument capable of calibrating such sensors based on a load cell while providing traceability to the SI unit of mass.

2. Measurement system
Our new instrument was designed and developed at METAS to calibrate microforce sensors (Figure 1). The instrument allows for the calibration of single-axis force sensors between 1 nN and 60 mN. The key element of our system is a high precision balance (*XP6U Micro Comparator, Mettler-Toledo*) with a range of 6 g and a resolution of 0.1 µg. The load cell of the balance was modified by shortening the force introduction. This modification increased the rigidity, but as a consequence, the overload protection had to be removed. The force introduction is done directly on the load cell by a sapphire sphere with a diameter of 1 mm. The load cell has an internal calibration system to adjust the sensitivity. The quality of the adjustment is verified by using external reference masses that are traceable to the national prototype of the kilogram. A 3-axis micro-stage with a range of 25 mm and a minimum step size of 95.25 nm is used for fixing the sensor and aligning the sensor tip above the balance. An additional translation stage, based on piezoelectric ceramic, with a maximum vertical displacement of 30 µm and a resolution of 0.06 nm is used in order to produce a precise and continuous vertical movement of the sensor for the force generation. A tilt stage is used to align the

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sensor’s vertical axis in the direction of the force generated and the gravitational field. Two CMOS cameras are used to monitor the angles of the sensor axes and the approaching process of the sensor tip and the sapphire sphere. The system and the measurements are fully controlled by an in-house developed LabView programme capable of regulating the mechanical movements, setting the system parameters and recording the output signals of the sensor and the balance.

![Figure 1: New instrument at METAS for calibrating microforce sensors. (a) Overview, (b) sensor aligned above force transmission point of modified balance, (c) technical drawing.](image)

2.1. Influence factors
The load cell shows a zero point stability of 0.0026 μN, a linearity of 0.06 μN and a reproducibility of 14 ppm. The influence of the direction of the force applied on the load cell was investigated for both angles X and Y. An angle deviation of 0.3° between the sensor’s axis and the force introduction on the load cell produces an error of 38 ppm.

The influence of temperature on the load cell is, according to the manufacturer, 1 ppm/°C. The air pressure affects the buoyancy of the balance’s internal calibration weights. A change of 50 hPa, which corresponds to a relative change of 5% in air density, results in a relative change of the measured force by 8 ppm. The gravitational constant was determined with an uncertainty of 0.5 ppm. As the uncertainty contributions of the temperature, pressure and gravitational constant are very small and the environmental conditions in our laboratory are very stable, they become negligible.

The readout delay of the balance with respect to the sensor is less than 0.14 s and the position stability of the translation stage is better than 0.2 nm. All these factors add up to a relative uncertainty of 2400 ppm and an absolute uncertainty of 0.125 μN (k=2).

3. Sensor calibration
We primarily designed our system to calibrate microforce sensors from FemtoTools AG, a Swiss high-tech company offering ultra-high precision instruments for mechanical testing and robotic handling in micro and nano regions. We measured sensor types of three different ranges: 200, 2000 and 20 000 μN. We used silicon sensors with a tip size of 50 μm × 50 μm capable of measuring compression and tension forces. The sensors were manufactured in an etching process. They have two interlocking combs causing a change in capacitance when moved (Figure 2). A change in the sensor’s capacitance results in a change of the electrical output voltage. The measured force is then calculated by the output voltage and the sensor gain. For all sensor types tested the uncertainty contribution for the hysteresis and repeatability was found to be less than 0.1%, and less than 1% for the reproducibility (Figure 3).
4. Validation of our instrument

To evaluate the measurement capabilities of the measuring apparatus at METAS and PTB we made a bilateral comparison using multiple sensors of three different ranges: FT-S200 (0–200 µN), FT-S2000 (0–2’000 µN) and FT-S20000 (0–20’000 µN). The selected sensors were measured first at METAS, then at PTB and finally at METAS again. Both institutes followed the same measurement procedure.

To compare the measurement data from METAS and PTB we first calculate the comparison reference value (CRV) and its associated uncertainty according to Cox [1].

\[
F_{CRV} = \left( \frac{F_{allSens,METAS}}{U^2_{METAS}} + \frac{F_{allSens,PTB}}{U^2_{PTB}} \right)^{-1} \left( \frac{1}{U^2_{METAS}} + \frac{1}{U^2_{PTB}} \right) \quad (1)
\]

\[
\frac{1}{U^2_{CRV}} = \frac{1}{U^2_{METAS}} + \frac{1}{U^2_{PTB}} \quad (2)
\]

where \(F_{allSens,i}\) is the weighted mean of all the sensors used within the same measurement range and \(U_i\) is the combined measurement uncertainty of institute \(i\). Then, we calculate the degree of equivalence, \(d_i\), for both institutes.

\[
d_i := F_{allSens,i} - F_{CRV} \quad (3)
\]

\[
U(d_i) := \sqrt{U^2_i - U^2_{CRV}} \quad (4)
\]

The results show an excellent agreement between the METAS and PTB measurements, especially in the lower force range of the individual sensors. The degrees of equivalence of the two institutes are always smaller than their respective measurement uncertainties (Figure 4).
5. Discussion

METAS has successfully developed a new instrument for the calibration of microforce sensors traceable to the SI unit of mass and laid the foundation to enter a new field of activity. The results of the bilateral comparison show that the degrees of equivalence of both METAS and PTB with respect to the comparison reference value are in good agreement. However, the degree of equivalence is getting larger as the target force is increased. We attribute this increase to the sensor’s non-linearity in the higher range of its tolerable force. The non-linearity is a direct result of the inherent construction of the sensor and its functional principle on capacitive measurement. A small change in the elastic properties yields a disproportionately high signal, relative to the expected signal, when operated near the maximum range.

METAS will go on to improve the measurement capabilities of the instrument by further reducing the uncertainty contributions of the most dominant factors.

Acknowledgments

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References

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