ACCURACY OF MEASUREMENT IN NANOMETROLOGY

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DOI : 10.17973/MMSJ.2016_12_2016203

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The presented article focuses on measurements of extremely small dimensions in nanometrology using tactile probes. It addresses a newly developed method of precise measurements in nanometrology by touch probes, where the measurements are carried out on the machine SIOS NMM-1. The aim of this work is to determine accuracy of measurements on this machine.

The main contribution of this work is a creation of a methodology for the measurement of precision parts and determination of accuracy of measurement when using this device in nanometrology. The work also includes methodology for the calculation of measurement uncertainty, a keystone in determining the accuracy of measurement in nanometrology.

The article provides results of representative sets of measurements of ruby ball diameters, including the evaluation of statistical parameters and determination of the combined measurement uncertainty.

KEYWORDS

accuracy of measurement, length measurement, measurement repeatability, measurement reproducibility, measurement uncertainty, measuring device, nanometrology, ruby ball

1 INTRODUCTION

The issue of very precise measurements of small and precisely machined objects (tools, gauges, standards) has been topical for a relatively long time. Demands for very precisely machined components of various devices can be tracked down to the 1950s, and these demands have been continuously increasing with the progress of miniaturization and growing emphasis on quality, reliability and safety.

Modern precision engineering is characterized by the demand for uncertainties on the order of a few nanometers for the manufacturing of special mechanical, optical and semiconductor components [Jaeger 2012].

Today, great advancements in nanotechnologies allow us to achieve a much higher resolution when examining measured parameters. Furthermore, we can obtain greater quality and quantity of measured data than in the past. Present-day technologies facilitate examination of small measurands that we commonly encounter in metrological practice by tools used in nanometrology, both within the system of calibration laboratory measurement standards and in the industry during production of precision parts and devices.

1.1 CMM SIOS NMM-1 Characteristics

NMM-1, Nanopositioning and Nanomeasuring Machine(Fig.1 and 2), is designed for three-dimensional coordinate-measurement and exhibits 0.1nm resolution in a range of 25x25x5 mm. Its unique customized probe system enables Abbe error-free measurements in all three measurement axes. The high measurement accuracy is possible thanks to a unique arrangement of three laser interferometers, whose measurement axes cross in the contact point of the scanning system and the measured object. The measured object is situated on a positioning table fitted with a corner reflector, and its position is monitored by three fixed laser interferometers. The positioning table allows movement in three directions.

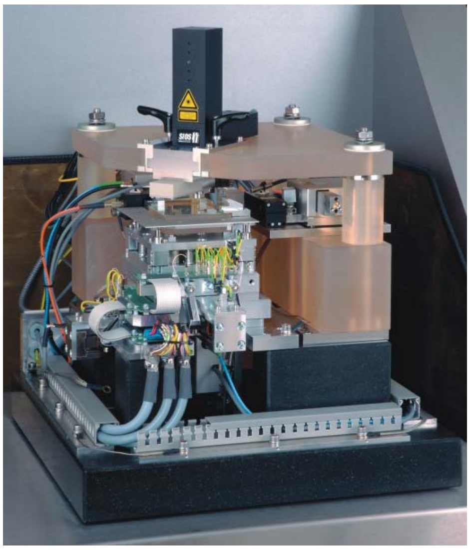

Figure 1. Nanopositioning and nanomeasuring machine NMM-1 SIOS [SIOS 2012]

Any angular deviations that can arise during movements of the positioning table are monitored by two angle sensors and adjusted for. The light of stabilized lasers is guided along optical fibers directly from its electronic source unit. This solution provides compact and thermally stable solution. The electronic heart of NMM-1 is the DSP (digital signal processor), which processes all incoming signals, operates drives and controls the measurements.

Interferometric measuring system of NMM-1 provided by the SIOS Company employs a laser interferometer with a wavelength of 633 nm with highly stable frequency and fully automated movement in all axes. The interferometer set up is based on Michelson's principle.

It is possible to apply different appropriate tactile probes and tools. The resolution of the device is less than 0.1 nm. Traceability to international standards and the definition of the meter is ensured. Highest accuracy can be achieved, with uncertainty of less than 10 nm.

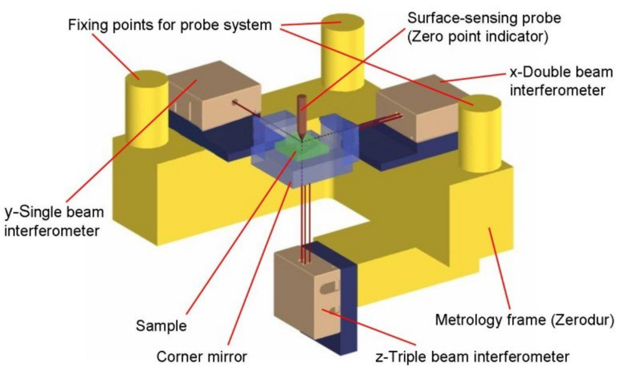

Figure 2. Operating principle of NMM-1 [SIOS 2012]

1.1.1 Technical parameters of the NMM-1*:*

- Three-dimensional Abbe offset-free design (Abbe offsets of less than 0.1 mm);
- Accurate reference coordinate system defined by the corner mirror;
- Straightness errors of the linear guide elements have no effect on measurement results because the interferometers measure the position of the corner mirror and, thus, the sample directly;
- Guide path error compensation of the linear stages is achieved by a closed-loop control system;
- Touch probe system equipped with a sapphire ball diameter of 0.3 mm, see Figure 3.

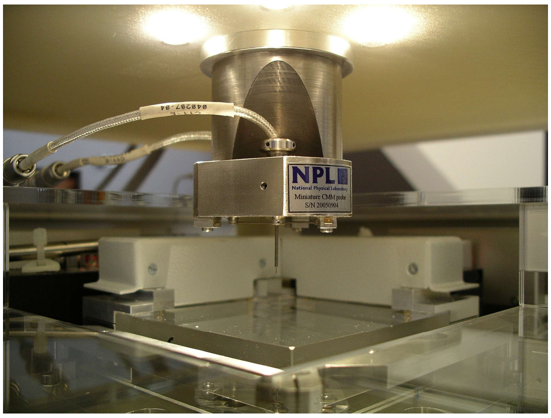

Figure 3. Using a touch probe in detail [SIOS 2012]

Angular control systems compensate the two angular errors φ_x and φ_y with four drives of the *z*-axis.

1.2 Measurement Accuracy and its Quantification

It is important to introduce basic terminology and definitions to provide a comprehensive overview of methods employed to determine accuracy of measurement when measuring instruments used in nanometrology, including the uncertainty in very precise measurements.

Measurement accuracy is, according to VIM [TNI 01 0115:2009], a closeness of agreement between a measured quantity value and the true quantity value.

Measurement accuracy is a qualitative term that cannot be given a numerical quantity value. The numerical quantity value that expresses the accuracy of a result is known as measurement uncertainty. When evaluating the measurement results, two basic characteristics are quantified [Sramek 2015]:

- Mean estimate (mean value, position), as a correctness (trueness) characteristic;
- Variability estimate (variance) as a precision characteristic.

It can be divided according to specified conditions [Sramek 2015]:

- Precision under repeatability conditions;
- Precision under reproducibility conditions.

This value is most often expressed numerically, for example by standard deviation. In practice, there is no measurement method or instrument that is perfectly precise. It means that the measured and true value of a monitored parameter are always different. The difference between true and measured value is caused by various factors or their combinations. When determining the measured parameter, various errors can occur and influence the final result.

The measurement result is always within a certain range from the true value, which we never know exactly. Therefore, measurement uncertainty is determined for the resulting measurement. Measurement uncertainty constitutes an inseparable part of determining the measurement accuracy of an instrument because it enables its quantification.

1.3 Repeatability and Reproducibility of a Measurement Method

Repeatability and reproducibility are terms that express the measurement accuracy under exactly specified conditions.

Measurement repeatability is defined as precision of measurement under a set of repeatability conditions of measurement [TNI 01 0115:2009], i.e. the same machine, operator, ambient conditions, measurement method and the measured object with measurements carried out within a short time interval.

Measurement reproducibility is defined as precision of measurement under a set of reproducibility conditions of measurement [TNI 01 0115:2009], i.e. measurement conditions out of a set of conditions that includes different measurement procedures and different conditions during replicate measurements on the same object.

1.4 Statement of a Measurement Uncertainty

Methods used in determining combined and expanded measurement uncertainty differ in cases of direct and indirect measurements. Measurements conducted by touch probes of the machine NMM-1 are direct.

1.4.1 Statement of a standard measurement uncertainty by a Type A evaluation during a direct measurement

Type A evaluation of standard uncertainty is applied in compliance with the document EA 4/02 [EA 4/02 M:2013].

1.4.2 Statement of a standard measurement uncertainty by a Type B evaluation during a direct measurement.

The Type B evaluation of a standard measurement uncertainty is a method of evaluating the uncertainty by means other than the statistical analysis of a series of observations. In this case the evaluation of the standard uncertainty is based on scientific knowledge and judgment of the operator who makes the measurements and consequently evaluates the uncertainty. The uncertainty can be deduced based on:

- Data and experience from previous measurements;
- Experience with behavior measuring equipment or his general knowledge;
- Manufacturer's specifications;
- Data provided in calibration protocols;
- Applied measurement methods;
- Uncertainties of reference data in handbooks and other documents.

1.4.3 Combined and Expanded Measurement Uncertainty

In most cases, a combined measurement uncertainty is defined. It is a result of combination of both, standard evaluation types A and B or a sum of a set of readings of the measurement uncertainty that follow a Gaussian distribution.

This combined standard uncertainty $u_C(x)$ is applied in compliance with the document EA 4/02.

The term "standard" expresses that the uncertainty is expressed as standard deviation. In some cases, the distribution of uncertainty defined this way can be considered approximately normal.

Expanded measurement uncertainty U is applied in compliance with the document EA 4/02.

Assuming normal distribution, we can apply coverage factor k = 2 for coverage probability of approximately 95%.

2 PROPOSED SOLUTION

Implementation of all suggested experiments is time consuming for both the operators and the machines that are normally uses for experimental, educational or business activities of their owners. The following is the procedure of our proposed solution:

- Proposal of an experimental measurement model for ruby balls;
- Proposal of methodology for individual measurements;
- Measurements on the machine NMM-1 observing repeatability conditions;
- Measurements on other instruments observing reproducibility and repeatability conditions;
- Implementation of the measurement under reproducibility and repeatability conditions;
- Comparison and evaluation of obtained deviations in selected ball parameters;
- Description of main factors influencing the accuracy;
- Quantification of the measurement uncertainty of a given device.

3 EVALUATION AND COMPARSION OF INDIVIDUAL MEASUREMENT METHOD

Evaluation from the perspective of adherence to reproducibility and repeatability conditions is a prerequisite for a successful evaluation of the measurement accuracy, and there are several measurement methods and procedures to achieve this goal. The result should serve as a manual for users of various gauges and instruments used for accurate length measurements in nanometrology, both in the CEITEC Research Institute and the Department of Nanometrology of the Czech Metrology Institute, Regional Inspectorate Brno.

To date, results imply that the most accurate measurements of ball diameters is provided by a single-axis length measuring instrument SIP, upgraded with a high performance length measuring system, the Renishaw XL-80 laser interferometer. Obviously, this precise length measuring instrument, specialized single-purposed measuring instrument, serves as a suitable hardware base for repeated measurements. The laser interferometer XL-80 upgrades the device to an outstanding platform for measuring of simple dimensions and traceability to standards in nanometrology.

It can be assumed, that highly accurate machine SIOS NMM-1 is suitable for probe measurements in nanometrology. Furthermore, it supports measurements and evaluation of more dimensions and more complicated measuring tasks, when compared to the SIP length measuring instrument.

Repeated measurements of ruby balls with a diameter of 0.5; 1; 2 and 3 mm were made using two measuring instruments. This ensured the conditions of measurement reproducibility and repeatability.

3.1 Probe Measurements of Size by SIOS NMM-1

The measurements were carried out in an underground laboratory of the Czech Metrology Institute in Brno where the SIOS NMM-1 machine is located. A special fixture that would allow firm gripping and positioning of the ball attached to a carbon stylus whose size and weight does not exceed limits of the NMM-1 machine had to be made, see Figure 4.

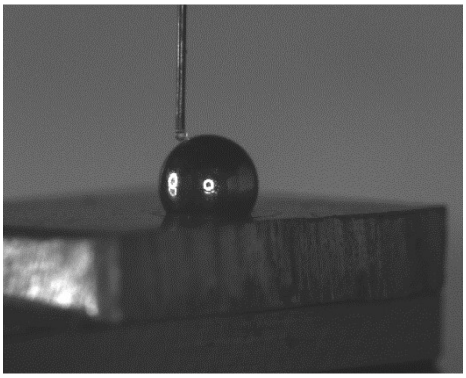

Figure 4. Example of measurement a ruby ball using a touch probe – detail [Sramek 2015]

The number of scanned points and their position on the ball was chosen in compliance with ISO 10 360 standard. All the available balls were measured. The measurements were replicated to obtain a sufficient set of data to evaluate the reproducibility of this measuring method. The measurement was repeated 10x for every defined position of the ball.

For fixed and defined attaching a specially designed holder was used, which enabled measurement for compliance repeatability.

3.2 Probe Measurements on the SIP Length Measuring Instrument with Interferometer XL-80

To ensure the reproducibility of ruby ball measurands, there is another method that allows measurement of ruby balls on the very precise length measuring machine SIP 1002M, that can be connected to an industrial laser interferometer Renishaw LX-80, see Figure 5. Both of these devices are owned by the Czech Metrology Institute in Brno. The digital length measuring machine is a single-axis device with tactile probes facilitating measurements of sizes up to 1 m and resolution of 0.0001 mm. This measuring method is used for calibration of measuring standards and has been accredited by Czech Accreditation Institute.

Laser interferometer Renishaw LX-80 is used to enhance the accuracy of measurements. It is situated directly in the axis of the measurement conducted by the length measuring instrument SIP, therefore it adheres to Abbe principle. This measuring method for calibrations by laser interferometer was also accredited by Czech Accreditation Institute.

Figure 5. Measuring at the length measuring machine SIP combined with laser interferometer Renishaw XL80 [Sramek 2015]

During the measurement, a special device was used that provides fixation of the ruby balls and adjustment of their position towards the measuring plane. These measuring planes were chosen to obtain results comparable with the nanoCMM measurement method.
For the measurements of 0.5 and 1 mm balls, flat cylindrical reductions for touch probes were used. For other diameters, reductions with ball probes were used. The measuring force was set for 0.25N. Ambient temperature and temperature of the measuring instruments was monitored and ranges 20°C ± 0,3°C.

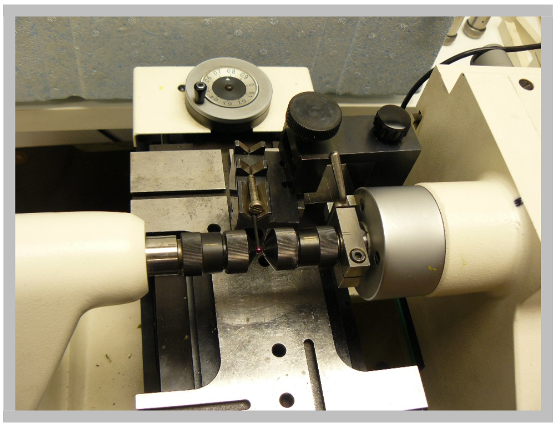

Figure 6. Measuring of ruby ball diameters [Sramek 2015]

All available balls were measured. The measurements were replicated to obtain a sufficient amount of data to evaluate repeatability of this measuring method. The measurement is replicated 10x for every defined position of the ball. For fixed and defined attaching a specially designed holder was used, which enabled measurement in compliance with repeatability.

4 EVALUATION OF RESULTS AND STATEMENT OF MEASUREMNT ACCURACY

Based on results obtained from the measured and statistically evaluated data (Type A evaluation), repeatability and reproducibility of conditions were assessed, as were the selected methods of measurements and exact specifications of individual factors of the Type B evaluation of uncertainty that influence the obtainable accuracy of SIOS NMM-1 measurements [4]. All nomenclature was specified in compliance with the international dictionary of metrology VIM [TNI 01 0115:2009].
The result is the determination of the combined standard uncertainty and expanded uncertainty of measurement on the machine SIOS NMM-1.
For the determination of the combined standard uncertainty in accordance with document EA 4/02 [EA 4/02 M:2013] the following equation was used:

$$u_C(x) = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)} \quad , \qquad (1)$$

which was adjusted in accordance with the document EA 4/02:

$$u_C(x) = \sqrt{u_A^2 + u_{CMM}^2 + u_{Abbe}^2 + u_H^2 + u_L^2 + u_{\Delta t}^2 + u_{\Delta\alpha}^2} \qquad (2)$$

where:
u_A – Type A evaluation of standard uncertainty;
u_B – standard uncertainty contributed by the probe systems CMM;
u_{Abbe} – standard uncertainty contributed by the Abbe principle of measurement;
u_H – standard uncertainty contributed by the fixing ruby balls;
u_L – uncertainty contributed by the laser interferometer;
$u_{\Delta t}$ – standard uncertainty contributed by the temperature difference in the measurement of specified temperature 20° C;
$u_{\Delta\alpha}$ – standard uncertainty contributed by the difference in thermal expansion coefficients of the ruby ball and the construction CMM.

Expanded measurement uncertainty U was applied in compliance with the document EA 4/02 [EA 4/02 M:2013]. Expanded measurement uncertainty is calculated as:

$$U = k \times u_C(x) \qquad (3)$$

Assuming normal distribution, coverage factor *k* = 2 was applied for coverage probability of approximately 95%.

5 EXAMPLE

Two representative sets of measured values were chosen as an example. The Set A includes the values measured by the length measuring instrument SIP 1002M and laser interferometer Renishaw XL80 (further only SIP/XL80), see Table 1.

balls [mm]	standard dev. [mm]	u_A [nm]	u_B [nm]	u_c [nm]
0,5	0,00012	3,79	2,48	4,55
1	0,00013	4,27	2,84	5,13
2	0,00015	4,67	3,11	5,61
3	0,00019	5,93	3,95	7,12

Table 1. Data measured by SIP/XL80 (set A)

The Set B provides the values obtained by SIOS NMM-1, see Table 2.

balls [mm]	standard dev. [mm]	u_A [nm]	u_B [nm]	u_c [nm]
0,5	0,00020	6,33	4,22	7,61
1	0,00021	6,53	4,35	7,85
2	0,00042	13,42	8,94	16,12
3	0,00041	13,04	8,68	15,66

Table 2. Data measured by NMM-1 (set B)

In both cases, extremely accurate length measurements were achieved, see Figure 7.

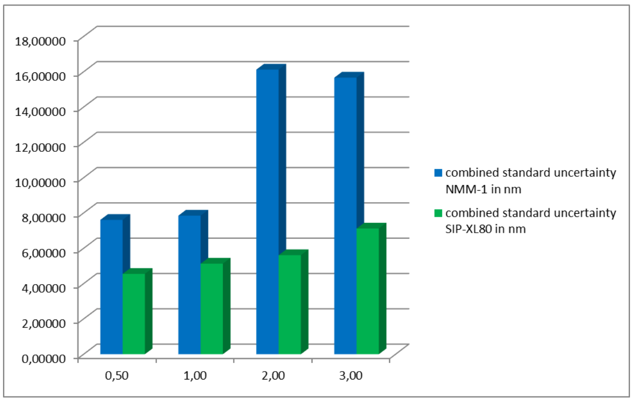

Figure 7. Graphical comparison of statistical data. On the axis *x* – value of ruby balls diameters in mm. On the axis *y* – value of combined standard uncertainty in nm.

All measurements were conducted under the conditions of repeatability and reproducibility.

6 CONCLUSIONS

This article has briefly addressed the current situation in the area of defining the measurement accuracy in nanometrology using the machine SIOS NMM-1. This precise coordinate measuring machine constitutes an upgrade to measuring instruments standardly used in metrology, especially multi-axial and multi-purpose measuring instruments that, due to their functional principle and construction, cannot yield measurements as precise as provided by nanotechnologies.

The evaluation of representative sets of the measured data shows that both measuring methods facilitate very accurate length measurements in nanometrology. As expected, the combined measurement uncertainty of the machine SIOS NMM-1 was found to be 1.5 – 2.6 times higher than the combined measurement uncertainty of the SIP/XL 80.

The machine SIOS NMM-1 could play a key role in the area of primary standardization of piston gauges within the system of metrological traceability, especially in the calibration laboratory at the Czech Metrology Institute in Brno. However, due to the range and characteristics of individual factors influencing the measurement uncertainty, this field is so complex that this overview article cannot describe all aspect of NMM-1 used as an accurate measurement standard in detail. The machine NMM-1 is owned by the CEITEC Research Institute.

ACKNOWLEDGEMENTS

This work has been supported by Brno University of Technology, Faculty of Mechanical Engineering, Czech Republic (Grant No. FSI-S-14-2401, FV 16-37).

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