euspen's 15th International Conference & Exhibition, Leuven, Belgium, June 2015
www.euspen.eu

Development of a virtual instrument to improve the estimation of measurement uncertainty of a metrological atomic force microscope using Monte Carlo method

P. Ceria[1], S. Ducourtieux[1] and Y. Boukellal[1]

[1]*LNE – Laboratoire National de Métrologie et d'Essais – 29 avenue Roger Hennequin, 78197 Trappes - France*

E-mail: paul.ceria@lne.fr

Abstract
A short range metrological Atomic Force Microscopy (mAFM) is developed by LNE (Laboratoire National de métrologie et d'Essais), the French metrology institute. It is devoted to the traceable measurement of structures at the nanometre scale and the calibration of transfer standards dedicated to SPM and SEM. The relative displacement of the sample with regard to the tip is 60 µm in the X, Y plane and 15 µm along Z axis. The traceability to the meter as defined by the International System of Units (SI) is ensured thanks to four differential interferometers used in an original configuration [1]. The design of the instrument is optimized to minimize the main components into the uncertainty budget (thermal dilatation, Abbe error, geometrical error...) [1]. The measurement uncertainty expected for the position measurement of the tip relative to the sample is about 1 nm for the full range of displacement, without taking into account the contribution of the tip/sample interaction. A first uncertainty budget has been completed thanks to experimental evaluations of the main error sources that perturb the measurement process [1-2]. For others components, the evaluation is complex or experimentally impossible. To refine the uncertainty budget, a numerical model of the instrument (a Virtual AFM) has been developed to evaluate all the components (mechanical and optical) linked to the geometry of the position measurement system. The model also allows us to take into account components experimentally evaluated and finally to determine the measurement uncertainty using Monte Carlo methods [3-4].

Keyword: metrological atomic force microscopy, virtual instrument, modelling, Monte Carlo method, measurement uncertainty.

1. Measurement system

To measure the position of the sample relative to the tip and to obtain a measurement directly traceable to the SI, the mAFM uses interferometers whose He-Ne laser sources are frequency-calibrated. The mAFM interferometric position measurement system is composed of four interferometers whose measurement axes have been tilted with respect to x, y and z axis in order to place all the interferometers in a more favourable symmetric configuration, below the sample and the scanning stage. Each interferometer is located on one corner of a square pyramid (figure 1). All the interferometers are placed in a horizontal plane below the sample, symmetrically distributed around the tip which is centred at the origin of XYZ coordinate system. The beams are tilted of 35° from the XY plane and rotated around z direction of 45°.

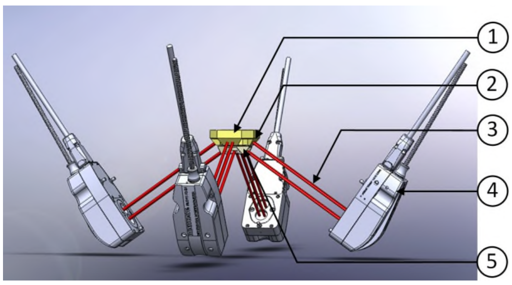

Figure 1. The interferometric position measurement system with (1) the reference prism, (2) a mirror face, (3) the interferometer beams, (4) a differential double path interferometer, (5) the measurement prism.

To measure the displacement, the interferometers point at mirrors directly polished on two prisms made of Zerodur (low thermal expansion ceramic). Due to the geometry of the system, the two prims have the shape of a truncated inverted four-face pyramid with a half top angle of 55° (figure 1)

The first prism is linked to the AFM head and supports the reference mirrors for the interferometers. It is associated with the tip position. The second one, the measurement prism, supports the mirrors associated with the sample displacement. To reduce dead path errors, the two prisms are positioned and sized to make the mirror faces coplanar.

2. The modelling process

The LNE's mAFM uses an original interferometer configuration in which measurements coming from each interferometer (I_1, I_2 I_3 and I_4) are linearly combined to calculate the relative displacement of the sample with regard to the tip along X, Y and Z directions.

With such a configuration, the evaluation of certain contributions in the uncertainty budget is experimentally difficult if not impossible. To precisely determine their impact on the mAFM, a numerical model of the mAFM has been developed. It represents a faithful modelling of the metrological chain. It has been developed under Matlab using object oriented programming. This model takes into account the laser beams, the AFM's tip position, the measurement and reference prisms and their mirrors as shown on figure 2.
Six DoF displacements can be generated on the mobile prism to evaluate measurement errors.

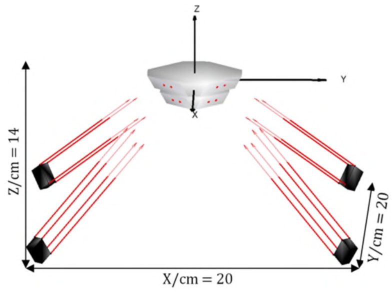

Figure 2. Matlab view of the interferometer position measurement system model taking into account the four interferometers and their sixteen Gaussian beams, also the two prisms with the eight mirrors.

2.1. The prisms modelling

The mirrors are modelled by using a 3D cloud of points which will allow the easy transfer of experimental data to the model in order to take into account the real shape of the mirrors (shape, roughness for instance). The model can control the length and height of the mirror, and also the number of the points inside the cloud. The mirror positions are saved in a matrix containing three vectors (XYZ) and a fourth to facilitate the calculations using a dedicated formalism [5]. This formalism is used to rotate and translate the mirror in space. The number of points in the cloud can be adapted to fit the measured data for shape and roughness. The mirror shapes can also be controlled using analytic functions. The mirror configuration respects the one of the real mAFM's prisms.

2.2. The interferometer beam modelling

The interferometers are not modelled in our first approach. Only the four beams emerging from the differential double pass interferometer are taken into account. These beams are modelled with a source point, a direction defined with a vector targeting the mirror and a Gaussian profile. In this way, the four beams act as four mechanical probes that only measure the distance from the source to the corresponding mirror taking into account the Gaussian profile and the impacted surface of the mirror as shown in the figure 3. To feed the model with experimental data, the real interferometer beams have been analysed to get their shapes and dimensions. The data are computed with Matlab to found the best coefficients that define the modelled Gaussian profile (standard deviation, mean and amplitude). For each beam, the distances are calculated and then processed to evaluate the differential displacement between the reference mirror and the mobile mirror as measured by one interferometer (I_1, I_2 I_3 or I_4).

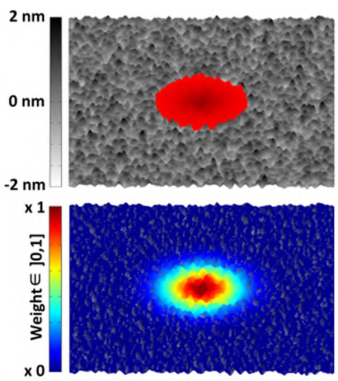

Figure 3. Representation of the impact of the Gaussian beam on a rough mirror as modelled under Matlab.

3. Measurement uncertainty

With this model, it is possible to simulate complex displacements of the prisms taking into account rotation errors. Therefore, different sources of uncertainty can be identified, such as: misalignments of the interferometer beams, parasitic rotations of the scanning stage, Abbe errors, roughnesses, shapes and orthogonality errors of the mirrors and basic linear dilatation of the system.

This model allows an estimation of several components that perturb the measurement process by using Monte-Carlo method. It shows that in our setup and with the used experimental data, the roughness and the shape have a very low impact (4.10^{-4} nm which are negligible) on the interferometric measurement if the beam radius is higher than 0.1 mm. In the same way, thermal dilatation contribution has been estimated to 1 nm for a temperature variation of ±0.3°C. In our instrument, the temperature is stabilised to better than 0.1 °C making the dilatation contribution of the metrology loop negligible. Nevertheless the model shows a high sensitivity to the orthogonality error of the mirrors. A deviation of 42 µrad from the orthogonality is sufficient to create an error of 1 nm in the uncertainty budget. The angular relations between the mirror of the prisms have to be measured experimentally to determine whether this contribution is negligible or not. The model shows also the influence of parasitic rotations with 1 mm Abbe offset. The calculation is performed on displacements range of 60 µm x 60 µm x 20 µm. The results show that Abbe errors have a linear trend with the parasitic rotations and do not exceed 12 nm of uncertainty for the whole range.

The final work will allow evaluating the contribution of a much more components that could perturb the measurement process, to determine the covariance between them and their sensitivities to finally establish an uncertainty budget for the mAFM. Thanks to the object oriented programming, the model is easily reconfigurable to other instrument geometry to evaluate the measurement uncertainties. It could be applied on other measurement machines.

Acknowledgments

The research was supported by EURAMET joint research project "Six degrees of freedom" receiving funding from the European Community's Seventh Framework Programme, ERA-NET Plus, under Grant Agreement No. 217257.

References

[1] S. Ducourtieux, B. Poyet 2011 *Development of a metrological atomic force microscope with minimized Abbe error and differential interferometer-based real-time position control* Measurement Science and Technology 22(9):094010

[2] Y. Boukelal, S. Ducourtieux, B. Poyet 2013 *Improvement of the LNE's metrological Atomic Force Microscope (mAFM) performace: Design of new mAFM head dedicated for nanometrology applications* 16th International Congress of Metrology 06008 (Paris)

[3] JCGM-WG1 101 2008 *Evaluation of measurement data – Supplement 1 to the "Guide to the expression of uncertainty in measurement" - Propagation of distributions using a Monte Carlo method* ISO/IEC Guide 98-3-1

[4] JCGM 100 2008 *Evaluation of measurement data - Guide to the expression of uncertainty in measurement* ISO/IEC Guide 98-3

[5] Paul, Richard P. 1981 *Robot manipulators: mathematics, programming, and control* The MIT Press (Cambridge, MA) pp 9-40