10th IMEKO TC14 Symposium on
Laser Metrology for Precision Measurement and Inspection in Industry
Braunschweig, GERMANY, 2011, September 12-14

Interferometric Measuring Systems of Nanopositioning and Nanomeasuring Machines

T. Hausotte, University Erlangen-Nuremberg,
Chair Manufacturing Metrology, Erlangen, Germany;
B. Percle, **N. Vorbringer-Dorozhovets**, **H. Baitinger**,
F. Balzer, **U. Gerhardt**, **E. Manske**, **G. Jäger**,
Ilmenau University of Technology, Institute of Process
Measurement and Sensor Technology, Ilmenau, Germany;
D. Dontsov, SIOS Messtechnik GmbH, Ilmenau, Germany

Abstract:

The Nanopositioning and Nanomeasuring Machine (NMM-1) developed at the Ilmenau University of Technology is equipped with three homodyne plane-mirror miniature interferometers for the measurement of the displacement of a movable corner mirror. The object being measured is placed on the corner mirror, which is positioned by a three-axis drive system. The probing system and the plane-mirror miniature interferometers are fixed on a metrology frame made of Zerodur®. Depending on the selected probing system, the machine is capable of carrying out both 2½D surface scans and 3D coordinate measurements [1, 2, 3]. In this way objects can be measured or scanned in volumes up to 25 mm x 25 mm x 5 mm with nanometre precision using various optical and tactile probe systems.

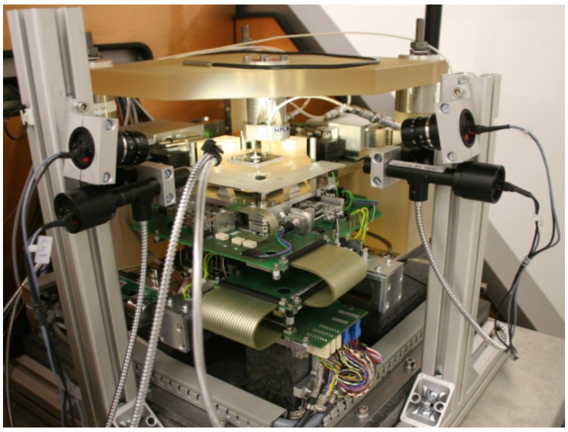

Fig. 1: Nanopositioning and Nanomeasuring Machine (NMM-1) with a measuring range of 25 mm x 25 mm x 5 mm

Because frequency-stabilized He-Ne lasers are used in the interferometers, the measurements are traceable to international standards and ultimately to the definition of the metre.

Positioning uncertainties of less than 10 nm and measurement uncertainties of less than 1 nm are possible within the positioning and measuring volume. The uncertainties of the interferometric length measurements are dependent on several factors. Starting from some aspects of uncertainty analysis, this article describes some practical solutions for further developments of the interferometric measuring systems and their application in both the Nanopositioning and Nanomeasuring Machine (NMM-1) and the newly designed Nanopositioning and Nanomeasuring Machine (NPMM-200), which has a larger measuring range of 200 mm x 200 mm x 25 mm. A description is given for certain influencing factors, such as dead path and the placement of reference point sensors.

The correct dead path length

Interferometric systems are often-used length measuring systems in nanopositioning and nanomeasuring technology because they utilise frequency-stabilized lasers and are highly traceable. In a homodyne interferometer, light from a single light source is split into a reference beam and a measuring beam. After the division the beams are reflected back from the reference and measuring mirrors, respectively. Recombination of the beams at the output of the beam splitter allows the two waves to interfere. The different paths result in two different phases of two waves. Only the phase difference can be determined from the interference signal; it is not possible to specify which mirror has moved. Therefore, one of the mirrors – the reference mirror – is normally fixed. Then the phase changes can definitely be attributed to the movement of the other mirror – the measuring mirror. The wavelength of light in the measuring arm serves as the measurement scale. The actual wavelength depends on the vacuum wavelength and the environment, specifically on the refractive index of air. The unequal paths in the measuring and reference arms along with changes in the wavelength lead to variations of the measurement value, although the mirrors have not actually changed position. The conversion of the fringe counter value $\delta(t)$ into an actual position value $l_m(t)$ must take into account the dead path length l_t, which is the length difference between the measuring and reference paths at the moment the fringe counter was reset [4].

$$l_m(t) = \frac{\lambda_{\mathrm{vac}}(t)}{2n(t)} \cdot \delta(t) + \left(\frac{n(0)\lambda_{vac}(t)}{n(t)\lambda_{vac}(0)} - 1\right) l_t \qquad (1)$$

The equation for a $\lambda/2$- interferometer also includes the refractive index of air $n(0)$ and vacuum wavelength $\lambda_{vac}(0)$ when the counter was set to zero as well as the current refractive index of air $n(t)$ and vacuum wavelength $\lambda_{vac}(t)$. According to the second term in equation (1), a non-zero dead path length leads to an additional uncertainty contribution for the measurement because of the possible change of the refractive index and the vacuum wavelength as well as the determination of the refractive index from the environment sensor values. Sometimes the reference arm is adapted to the length of the measuring arm to keep the dead path length as low as possible. In this case, the influence stemming from the determination of the wavelength for the longer measuring beam is reduced. Simultaneously, however, the influence derived from the thermal expansion of the mounting parts for the reference mirror increases. The longer mechanical connection between the reference mirror and the main beam splitter of the interferometer leads to a larger measurement uncertainty because of the thermal expansion. A decision as to whether to extend and adapt the reference arm to the measuring arm can only be made using an uncertainty analysis [4]. The simplified results of the analysis yield a comparison of the uncertainty contributions from the thermal expansion of the longer mounting parts of reference mirror and uncertainty contributions from the determination of the wavelength for the longer measuring beam. The thermal expansion of the reference mirror mounting components is normally not corrected for interferometer measurements. Therefore the dominant uncertainty contribution $u(\Delta l_{ref}) = l_{ref} \cdot \alpha \cdot u(\Delta\delta)$ comes from the temperature stability $u(\Delta\delta)$ of the reference arm extension l_{ref}. On the other hand the dominant uncertainty contribution from the measuring beam extension l_{mes} results from the uncertainty $u(\Delta\lambda)$ from the determination of the refractive index and the wavelength $u(\Delta l_{mes}) = l_{mes} \cdot u(\Delta\lambda)/\lambda$, respectively. The decision to have a very short reference arm ($l_{ref} < l_{mes}$) or to adapt the reference arm length ($l_{ref}. > l_{mes}$) must be made by comparing the terms $\alpha \cdot u(\Delta\delta)$ and $u(\Delta\lambda)/\lambda$ for the actual measuring set-up and environment conditions. With very high temperature stability, an extension of the reference arm may make sense when the refractive index is not being determined with high accuracy or when using unstabilised lasers. The values $\alpha \cdot u(\Delta\delta) = 1.3 \cdot 10^{-7}$ and $u(\Delta\lambda)/\lambda = 2.1 \cdot 10^{-8}$ for the Nanopositioning and Nanomeasuring Machine (NMM-1) in the Ernst Abbe Centre in Ilmenau leads to favouring the reduction of the reference arm. Because of this, the reference arm length is as short as possible in the newly designed Nanopositioning and Nanomeasuring Machine NPMM-200.

Arrangement of the guide/drive systems and the metrology frame

Additionally a short measuring beam length for the z-interferometer was achieved using a new concept for the arrangement of the guide/drive systems and the metrology frame. Figure 2 a) shows the concept of the NMM-1. The z-interferometer was arranged below the entire positioning system. The measuring beam goes through a hole in the guide/drive system with the size of the lateral measuring range to the corner mirror. The minimum length of the measuring beam is defined by the height of the positioning system as a whole. In the new concept a cantilever beam with the mounted z-interferometer is now above the x-/y-stage and between the elements of the z-stage (see figure 2 b)). This concept leads to a very short measuring beam length for the z-interferometer and a smaller metrology frame .

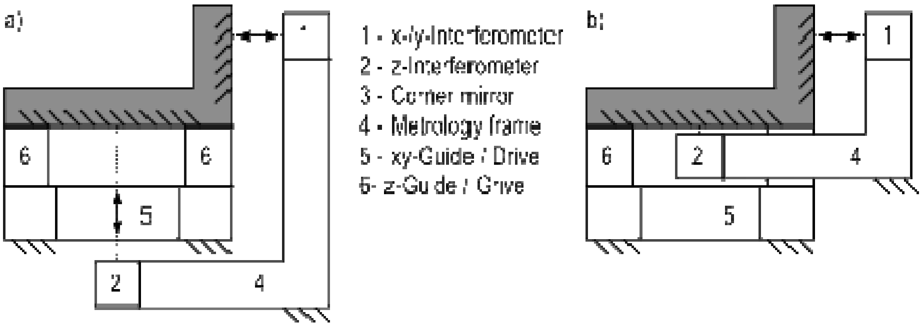

Fig. 2: Concepts for the arrangement of the guide/drive systems and metrology frame: a) z-interferometer below the x-/y-guides and drives (NMM-1), b) z-interferometer above the x-/y-guides and drives (NPMM-200)

Confocal reference point sensor system

The uncertainty analysis also led to the conclusion that the exact dead path determination for an interferometer has a significant influence on the uncertainty. The uncertainty contribution $u(l_d)=\Delta\lambda/\lambda(0)\cdot u(l_t)$ for a simple difference measurement depends on the wavelength change $\Delta\lambda$ during the measurement, wavelength $\lambda(0)$ when the counter was set to zero and the uncertainty for the dead path length determination $u(l_t)$. In turn this uncertainty contribution depends on the fluctuations of the refractive index of $n(t)$ due to changes in environmental conditions. The larger these fluctuations are, the more accurate the dead path length must be determined. An air temperature of 18°C to 24°C, pressure of 70 kPa to 110 kPa, humidity of 30% to 70% and a CO_2 concentration of 300 ppm to 800 ppm leads to a maximum sensitivity coefficient of $\Delta\lambda/\lambda(0)=1.12\cdot10^{-4}$. With a target uncertainty contribution of < 1 nm, the dead path length must be known or adjusted to zero with a maximum uncertainty off $u(l_t)= < 9$ µm. The dead path determination requirements are reduced for more stable environment conditions. As an example environment data for the NMM-1 was measured in the laboratory of Ernst Abbe Centre for a month, which yielded a sensitivity coefficient $\Delta\lambda/\lambda(0)=8\cdot10^{-6}$ and thus produced a required uncertainty for dead path determination of $u(l_t) < 125$ µm. The point where the fringe counter is set to zero and the dead path length is known can be determined by an absolute measuring sensor. For high reproducibility and low drift of the reference position, the sensors must be mounted on the metrology frame and measure directly on the corner mirror with a small Abbe offset with respect to the interferometer axis. These systems should not restrict the motion range of the corner mirror. In the Nanopositioning and Nanomeasuring Machine NPMM-200 a confocal reference point sensors with fibre coupling are used, as shown in figure 3. The fibre end in the sensor head is the pinhole for the illumination and for the detection in accordance with the working principle of confocal microscopes. The intensity curve is recorded during homing and the position at which the counters are then zeroed can be calculated as the centroid of the intensity data above a threshold.

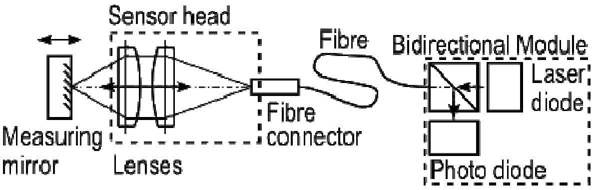

Fig. 3: Confocal reference point sensor system for resetting the interferometer counter at known position

Interferometric measuring systems of the Nanopositioning and Nanomeasuring Machine NPMM-200

The measuring system of NPMM-200 (see figure 4) consists of 7 interferometers for length measurements (2 for the x-axis, 2 for the y-axis and 3 for the z-axis). The measuring beams of the main interferometers intersect in a point (i.e. the probing point or Abbe point), in which the probe system contacts the measuring object. The other 4 interferometers are arranged so that their beams are at a distance of 30 mm from the measuring beams of main interferometers. The length measurement values from the secondary interferometers are used to determine the inclination of the corner mirror about the x- and y-axes (z-interferometers) and the rotation about the z-axis (x- and y-interferometers). The initialisation of the angle measurement and the zero points of the angle values can be realised by two additional autocollimators. The autocollimators are mounted next to the x- and y-interferometer and the measurements are also performed directly on the corner mirror.

Summary

This work gave an overview of the uncertainty aspects with respect to the dead path length, the influence of the thermal expansion of the longer mounting parts for the reference mirror and the determination of the wavelength for longer measuring beams. The contribution also showed a new concept for the metrology frame for nanopositioning and nanomeasuring machines and a confocal reference point sensor. Additionally some information was presented regarding the special interferometer system of Nanopositioning and Nanomeasuring Machine NPMM-200.

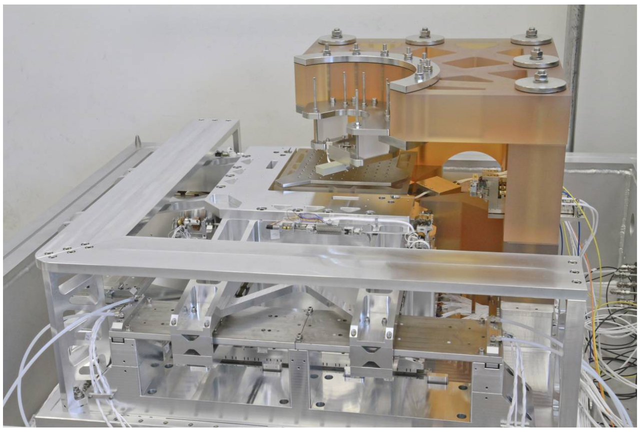

Fig. 4: Nanopositioning and Nanomeasuring Machine NPMM-200 with a larger measuring range of 200 mm x 200 mm x 25 mm

Acknowledgments

The developments presented here are supported by the German Research Foundation and the Thuringian Ministry of Education. Their support is provided within the context of Collaborative Research Centre (SFB) 622 ‘Nanopositioning and Nanomeasuring Machines’. The authors wish to thank all those colleagues at the Ilmenau University of Technology who have contributed to these developments.

[1] T. Hausotte, B. Percle and G. Jäger; Advanced three-dimensional scan methods in the nanopositioning and nanomeasuring machine. *Meas. Sci. Technol.* 20 (2009) 084004 (8pp).

[2] E. Manske, T. Hausotte, R. Mastylo, T. Machleidt T, K.-H . Franke and G. Jäger: New applications of the nanopositioning and nanomeasuring machine by using advanced tactile and non-tactile probes. *Meas. Sci. Technol.* 18 (2007) 520–527.

[3] T. Hausotte, E. Manske, G. Jäger, B. Percle, N. Dorozhovets, T. Machleidt: Combination of high speed surface scanning and tactile 3-D coordinate measurement on the basis of advanced mechatronic and control concepts. *Procs of ASPE 2010 Spring Topical Meeting,* 2010 40–44.

[4] T. Hausotte: *Nanopositionier- und Nanomessmaschinen*, 2010, Habilitation treatise.