A calibration setup for a new type of nano probe


Abstract

A probe has been designed using piezo-resistive strain gauges to measure the bending of three slender rods etched in silicon. This nano-probe is calibrated on a 1D setup using a differential plane mirror interferometer. The calibration setup has less than 5 nm uncertainty, 1 nm resolution and a range of 30 µm. Periodic non-linearities of the laser interferometer are determined and will be compensated by RF-phase-sensitive detection of the interferometer signal. The uncertainty of the probe after calibration is less than 10 nm for vertical probing. For other probing directions, effects due to friction and rolling of the spherical probe tip affect the probe uncertainty.

Keywords: Nano probe, calibration, MST, laser interferometry

1 Introduction

The measurement uncertainty of conventional coordinate measuring machines (CMMs) is limited as a result of its serial mechanisms and violation of the Abbe principle. However, in recent years great improvements have been made in CMM design. Most notable are the CMM designs by Van Seggelen [1], Oiwa [2] and others [3, 4] achieving nanometer uncertainty and enabling tasks like scanning of MST products and measurements on objects for calibration purposes.

The uncertainty in CMM measurements is often limited by the uncertainty of the measuring probe. New probes, using optical sensing, have been developed [5, 6] with an uncertainty of 10 nanometers or better. The laser interferometer used, however, is difficult to implement in a CMM. Other designs, better suited for CMM implementation are often less accurate [7]. A probe with an uncertainty less than 10 nm and compatible with CMM design was developed at the Precision Engineering section by Pril [8, 9]. Its operation and calibration is discussed in this paper.

2 Nano probe

The probe consists of a stylus with a ruby sphere. It is attached to a silicon chip via a three-legged star using epoxy glue (figure 1). The suspended mass is less than 20 mg and the stiffness of the suspension is lower than 200 N/m in order to avoid work piece damage [10].

Further author information:
E.J.C.Bos: E-mail: e.j.c.bos@tue.nl, Phone: +31 (0)40 247 4548
http://pe.wtb.tue.nl/personal/bos
The suspension used in the probe system consists of three slender rods that enable motion of the probe tip in z-direction and pseudo translation in x- and y-direction. The remaining degrees of freedom are fixed. Each rod contains a strain gauge with four piezo resistors in a Wheatstone bridge (figure 2). When the probe tip is moved the strain gauges bend, stretching two resistors and compressing the other two, resulting in a change of voltage $V_m$ across the bridge.

As a result of uncertainty in the production process (in particular etching) of the strain gauges and piezo resistors, the sensitivity of the probe cannot be predicted with sufficient accuracy. In order to achieve nanometer uncertainty each probe therefore needs to be calibrated.

3 Calibration Setup

A 1-dimensional calibration setup can be used for the calibration if the probe system can be positioned on the setup in several different orientations. A flat mirror differential laser interferometer (figure 3a) [11, 12] is used to measure the relative displacement of the moving measurement mirror relative to the reference mirror. The most important features of this setup are:

- The two mirrors can in principle be positioned in the same plane, minimizing the thermal loop and the dead path length in the setup.
- Both interferometer beams reflect two times at the reference or measurement mirror doubling the sensitivity in comparison to a linear interferometer.
- The reference and measurement mirror can be positioned symmetrically around the measurement axis, preserving cylindrical symmetry of the setup.
Figure 3: The calibration setup.

The calibration setup is shown in figure 3. The probe (1) is placed on top of the setup using a bracket (2). Three V-shaped grooves are made on the top and on a side of the bracket. This allows an operator to orient the probe vertically and horizontally on the setup and rotate it under 120 degrees with good reproducibility. The measurement mirror (3) can be displaced relative to a ring shaped reference mirror (4) by a piezo actuator (5).

The calibration setup has a 30 µm range, a 5 nm uncertainty and a resolution better than 1 nm. The accuracy of the calibration setup is limited by non-linearity of the plane mirror interferometer setup. The non-linearity is measured to be 4 nm and will be discussed in the next paragraph.

### 4 Compensation of non-linear errors

To illustrate the operation we assume an idealized signal \((u_1, u_2)\), measured in phase quadrature, in which distortions occur as described by Heydeman [13]:

\[
\begin{align*}
  u_1 &= R \cos(\phi) \\
  u_2 &= R \sin(\phi) \\
  u^*_1 &= u_1 + p \\
  u^*_2 &= \frac{1}{r} (u_2 \cos \alpha - u_1 \sin \alpha) + q
\end{align*}
\]

Here, \(R\) is the signal amplitude, \(\phi\) is its phase and \(p, q, r\) and \(\alpha\) are the elliptic parameters distorting the idealized signal.

The vector \((u_1, u_2)\) of the ideal signal describes a circle with its center in the origin and with radius \(R\). The vector \((u^*_1, u^*_2)\) of the distorted signal describes an ellipse whose center point is no longer in the origin (gray line in figure 4a). This results in non-linear errors when interpolating the measurement signal of the interferometer.

The signals \(u^*_1\) and \(u^*_2\) are measured individually in an initializing measurement and the elliptic parameters are calculated using a least square fit to the ideal signal \((u_1, u_2)\). During the measurement the phase of the signal \((u^*_1, u^*_2)\) is projected on the ideal circle using these parameters, resulting in the black line in figure 4a [14].
Figure 4: a) Measurement of the non-linear error in the calibration setup, b) Non-linear error of the interferometer in the calibration setup.

The elliptical parameters are used to calculate the non-linear error in the calibration setup (gray line in figure 4b). The theoretical non-linear error after applying the compensation is given by the black line in figure 4b. The original non-linear error of 4 nm peak-to-peak can theoretically be reduced to less than 0.1 nm.

From measurements it has been observed that the elliptical parameters (and the non-linear error) vary in time. This is possibly caused by a drift in the optical components of the setup (figure 3). A real-time measurement of the elliptical parameters is needed to adequately compensate for non-linear errors in this setup.

For now, the non-linear error of 4 nm and the total measurement accuracy of 5 nm is sufficient. For the future we plan to implement a compensation for non-linear errors in the interferometer using a real-time measurement of the elliptical parameters.

5 Measurements

Four measurements are performed during the calibration procedure. In each measurement, the probe is placed on the calibration setup in a different orientation (figure 6). For the three horizontal orientations, the probe is rotated over 120°, to ensure that the position of the suspension is equivalent for each orientation.

Figure 6: Orientations of the probe during calibration.
In each orientation, the measurement mirror of the calibrator is used to displace the tip of the probe. For the calibration, a displacement of 4 µm is used. This displacement is measured with the laser interferometer. Simultaneously, the output voltages of the strain gauges are measured.

![Graphs showing measurement signals and residuals](image)

Figure 7: a) Measurement signals for probing in z-direction (orientation r_a) b) Residuals after subtraction of a linear fit (results for strain gauges 2 and 3 shifted).

Figure 7 shows the output voltages of the strain gauges as a result of the displacement of the measurement mirror. The relation between the measurement signal of the strain gauges and the displacement of the probe tip is linear. The sensitivity of the strain gauges is calculated by fitting a line through the measurement signals. This results in three sensitivities (one for each strain gauge) for a displacement in this particular probing direction. The procedure is repeated for the other directions.

### 6 Results

The objective is to find a conversion matrix $A$, which links the output voltages of the strain gauges $V_m$ to the displacements of the probe tip $X_t$:

$$X_t = A \cdot V_m$$

With the sensitivities obtained from the measurements, we get an overdetermined set of equations. Here, $sens_{i,r_a}$ refers to the sensitivity of strain gauge $i$, for orientation $r_a$.

$$\begin{pmatrix} sens_{1,r_a} & sens_{1,r_b} & sens_{1,r_c} & sens_{1,r_d} \\ sens_{2,r_a} & sens_{2,r_b} & sens_{2,r_c} & sens_{2,r_d} \\ sens_{3,r_a} & sens_{3,r_b} & sens_{3,r_c} & sens_{3,r_d} \end{pmatrix} = A \cdot \begin{pmatrix} 0 & 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & 0 & \frac{1}{2} \sqrt{3} & -\frac{1}{2} \sqrt{3} \\ -1 & 0 & 0 & 0 \end{pmatrix}$$

The conversion matrix $A$ is obtained by solving this equation using a least-squares method. The displacements of the probe tip can now be calculated by multiplying $A$ with the measured output voltages of the strain gauges.
The calculated conversion matrix is verified by comparing the calculated displacements with the displacements measured by the laser interferometer. Figure 8 shows the obtained residuals during the measurements for orientations \( r_a \) and \( r_b \). Results for orientations \( r_c \) and \( r_d \) are similar to the results for \( r_b \).

Figure 8: Difference between displacement as measured by interferometer and displacement calculated from strain gauge output (results from x and y are shifted).

As can be seen in figure 8a, the difference between the displacements measured by the laser interferometer and the strain gauges is less than 10 nanometers for probing in the \( z \)-direction. For probing in the \( x-y \)-plane, a linear increasing residual in the \( z \)-direction is found (figure 8 b). This implies a translation of the probe tip in the negative \( z \)-direction (110 nm for a displacement of 4 \( \mu \)m).

The displacement in \( z \)-direction during displacements in the \( x-y \)-plane can be contributed to a rolling effect. When the probe tip is displaced by 4 \( \mu \)m, the stylus of the probe will rotate by about 0.03°. This rotation will cause the sphere, with a radius of approximately 0.2 mm, to roll over a distance of 105 nm (figure 9).

Figure 9: Schematic of the rolling effect during probing in the \( xy \)-plane.

Additional measurements in the three \( xy \)-directions have been performed, in which larger displacements (up to 18 \( \mu \)m) have been investigated. For orientations \( r_c \) and \( r_d \) (as defined in figure 6), the rolling effect remains present: the \( z \)-residual increases linearly to approximately 500 nm for an 18 \( \mu \)m displacement. However, for orientation \( r_b \), the rolling is disturbed after a displacement of about 4 \( \mu \)m and slip seems to occur in the opposite direction. The measurements take on the form of a hysteresis curve. Figure 10b shows the measured displacements in \( x \)- and \( z \)-direction.
Figure 10: A disturbance of the rolling effect in orientation $r_b$ occurs for probing with large displacements. a) residuals b) x-versus-z plot.

The cause for this difference in behaviour for different probing directions may be found in the anisotropic properties of the silicon suspension. Young's modulus, which is dependent on the direction in the wafer, is therefore different for each rod. Studies [15] show, that the rod lying in the crystallographic direction (see figure 1) will have a lower Young's modulus than the other two.

In orientation $r_b$, where the measurements show a hysteresis curve, the probe is oriented so that the rod with lower stiffness is located at the top. Apparently, the balance between the friction force between sphere and surface and the “spring” force generated by the suspension is such that slip may occur. The details regarding the difference in stiffness of the slender rods and its influence on the probe behaviour are currently being investigated.

7 Conclusion

A probe with a suspension consisting of three strain gauges etched in silicon is calibrated on a 1D setup, using differential plane mirror interferometer. The non-linear errors of the interferometer contribute 4 nm to the measurement uncertainty and will be compensated to less than 0.1 nm in the future using real-time RF-phase-sensitive detection of the interferometer signal. The current total measurement uncertainty of the calibration setup is less than 5 nm in its range of 30 $\mu$m.

The uncertainty of the probe is less than 10 nm in its z-direction. For measurements in its x-y-plane a linear increasing z-residual is observed, which can be contributed to a rolling effect of the probe tip on the surface of the calibration setup. Also for measurements in the x-direction of the probe and with displacements larger than 4 $\mu$m the rolling effect is disturbed and slip seems to occur, causing hysteresis in the measurement. This effect is not observed in other measurement directions. As a result of anisotropic material behavior of silicon the Young’s module of the slender rods is dependent on the crystallographic direction and may explain this orientation dependent behavior.
8 Acknowledgement

The authors gratefully acknowledge the IOP Precision Technology for sponsoring this work and Suzanne Cosijns for her work on non-linear errors in the interferometer.

9 References