Deflectometry with better Accuracy

Evelyn Olesch, Gerd Häusler

Institute of Optics, Information and Photonics, Friedrich-Alexander-University Erlangen Nuremberg

mailto:Evelyn.Olesch@physik.uni-erlangen.de

Deflectometry is a technique to measure specular surfaces. The principle is simple and the local sensitivity is in the nanometer regime. Difficult, however, is to achieve a good global accuracy which is strongly influenced by the quality of the calibration. To reduce the influence of the calibration errors we combine measurements of several rotation angles.

1 Introduction

Phase-measuring deflectometry (PMD) is a technique to measure specular surfaces [1]. The principle is simple: A remote sinusoidal fringe pattern is reflected at the surface under test. A camera observes the surface and the mirror image of the fringes at the same time. The surface shape can be evaluated from the camera images. PMD has several great features which are summarized in table 1.

technical	• simple, low cost • robust against vibrations
physical	• incoherent, low noise • extremely sensitive against local shape variations (nm)

strategic	• **no retrace error**
	  • no precise object position necessary
	  • wide spectrum of complicated surfaces is measurable

Tab. 1 *Features of PMD*

Of course, nature does never give presents. PMD is extremely locally sensitive but it is very difficult to achieve a good global accuracy. We will demonstrate this by a measurement of a freeform performed with our so called Mini-PMD which has a measurement field of 20x20 mm^2 and an angular dynamical range of ± 10 °. A typical global accuracy is ~ 700 nm peak-to-valley (pv).

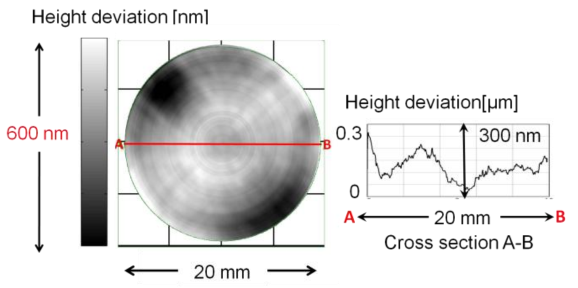

Fig. 1 *Measurement of a freeform: Height deviation. Turning grooves from the manufacturing process can be seen, but as well a low frequency error caused by the sensor.*

After subtracting the design data, local details (turning grooves from the manufacturing process in a turning machine) can be seen but also a global low frequency error mainly caused by the sensor (see Fig. 1). The reason for the global inaccuracy is a systematic calibration error. For a better understanding we will have a closer look at the evaluation and the required calibration.

2 Calibration and evaluation

As explained the camera observes a sinusoidal pattern reflected at the surface under test. The pattern is used to encode the position of the corresponding pixel at the pattern generator (LCD screen). After the measurement every camera pixel “knows” the corresponding point of the screen. The surface itself is still unknown und must be calculated. In principle this is simple. The normal is the bisectrix between the ray of vision of the camera and the reflected ray (reverse light propagation!). But of course the reflection is unknown and must be calculated as well. This is only possible if precise calibration is provided: specifically difficult, but important is the relative position of screen, object and camera. It is difficult, because the camera does not “see” the screen directly. And it is important because a false position or tilt will significantly corrupt the measurement surface slope. We calibrate our sensor by measurements of a sphere in several tilted (unknown) positions. A special optimization algorithm [2] calculates the camera/sphere positions by minimizing the distance d (d ≔ distance between measured points on the monitor and reflected rays of vision of the camera). The object form is known (it is a sphere), the object and camera positions and orientations are optimized.

The evaluation of a measurement works similar [3]. Again the distance d is minimized, but here the camera positions are known, object form and position are optimized. By the use of these calibration and evaluation methods it is possible to reduce the systematic errors significantly. But as Figure 1 demonstrates, systematic errors still remain. How to continue?

3 Improvement of accuray

What are the options to further improve the accuracy?

- Improve calibration of each component:
  → results to be published
- Subtract error image of reference measurement:
  → only valid for one precisely positioned object
- Reduce influence of calibration errors.
  → Solution is given below:

The measurement shown in Figure 1 was performed inside a turning machine (see Fig. 2). By measuring in the machine (without unclamping the workpiece), we can take advantage of its rotation axis. As the calibration errors are rotation independent, the influence of the calibration errors can be reduced by combining measurements at several rotation angles.

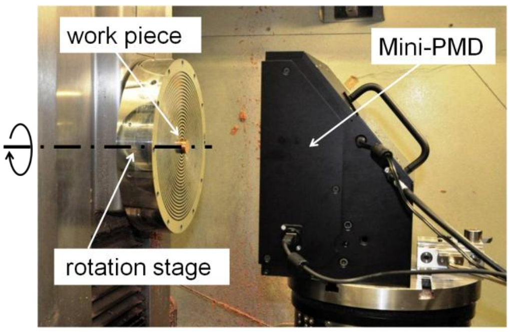

Fig. 2 *Mini-PMD inside of turning machine*

The new measurement procedure is now as follows: We measure the object in one angular position, rotate the object and measure again. We emphasize that the axis of the machine does not have to be the axis of the object, so free forms are still possible. This is possible by calibrating the axis with the sensor.

4 Results

We measured a planar mirror with the Mini-PMD, first by the common method without rotation [4]. The result is shown in Fig. 3 (left). Then we measured the same mirror at 4 rotation angles (90° steps) and combined the four single results by averaging. The height deviation is reduced from ~ 630 nm pv to ~ 110 nm pv (see Fig. 3 (right)). For measurements outside a turning machine we installed an external rotation stage in a PMD-setup with a measurement field of 80x80 mm^2 and a global accuracy of ~ 1 µm pv. We measured a convex sphere with a radius of curvature of 120 mm, first without rotation. The height deviation

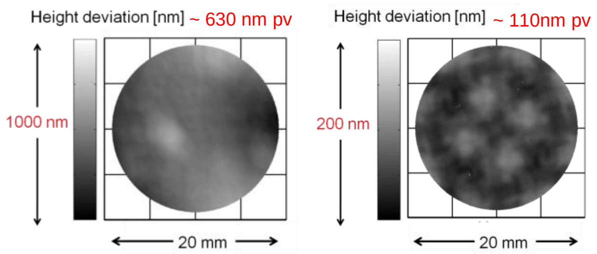

Fig. 3 *Measurement of a planar mirror. Left: Measurement without rotation. The height deviation is ~ 630 nm pv. Right: Measurement at 4 rotation angles. The height deviation is reduced to ~ 110 nm pv.*

after subtracting the design data is ~ 730 nm pv (see Fig. 4 (left)). Then we rotated the object by 180° and measured again. By combining only these two measurements the height deviation could already be reduced to ~ 470 nm pv (see Fig. 4 (right)).

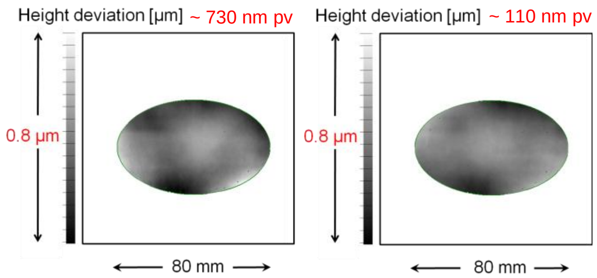

Fig. 4 *Measurement result of a convex sphere (R=120 mm). Left: Measurement without rotation. The height deviation is ~ 730 nm pv. Right: Measurement at 2 rotation angles. The height deviation is reduced to ~ 470 nm pv.*

5 Conclusion

Deflectometry has several great features but one disadvantage: it is very prone to calibration errors. We demonstrated that it is possible to reduce that influence by combining measurements of objects at several rotated orientations.

6 Reference

[1] G. Häusler, “Verfahren und Vorrichtung zur Ermittlung der Form oder der Abbildungseigenschaften von spiegelnden oder transparenten Objekten,” German patent DE 19944354 (1999).

[2] E. Olesch, C. Faber, G. Häusler, “Deflektometrische Selbstkalibrierung für spiegelnde Objekte“, Proc. DGaO 112, A3 (2011)

[3] E. Olesch, C. Faber, G. Häusler, “Object reconstruction by deflectometry“, Proc. DGaO 113, P28 (2012)

[4] Faber, C., Kurz, M., Röttinger, C., Olesch, E., Domingos, D., Löwenstein, A., Häusler, G., Uhlmann, E., “Two Approaches to use Phase Measuring Deflectometry in Ultra Precision Machine Tools,” Proc. Euspen 12 Vol. 2, 84-87 (2012).

submitted: 10.Oct.2014 published: 10.Oct.2014