Deflectometry for Ultra-Precision Machining - Measuring without Rechucking

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By ultra-precision turning it is possible to manufacture specular freeform surfaces with very high accuracy. In order to obtain the best possible contour accuracy, machine integrated quality control is required. We present a novel method to use Phase Measuring Deflectometry (PMD) within an ultra precison lathe, making use of the machine's axes to increase the angular dynamic of the sensor.

1 Application and approach

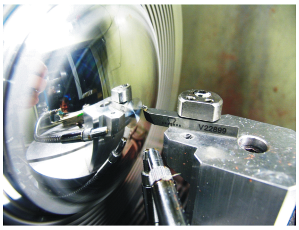

Fig. 1 *Ultra-precision turning of a specular surface*

Ultra-Precision Machining (UPM) allows the manufacturing of aspheric optical surfaces with a roughness of less than 10 nm P-V and a shape accuracy better than P-V = 0.5 µm (see Fig. 1). To optimize the product's shape, it is essential to determine the quality with high accuracy. Therefore it is necessary to measure the global form of the workpiece and use this data to carry out correction cycles. This however is only possible *without rechucking* the object, as mounting always results in positioning errors. Therefore *machine integrated quality control* is desired.
The combination of the specific requirements, like *high z-accuracy*, *high angular dynamic*, *small installation space*, accumulates to a considerable challenge, severely limiting the possible measurement techniques, that may be considered: Stylus based probes are able to measure a surface with very high accuracy and within a limited operating space (e.g. inside a UPM, see Fig. 2).

Fig. 2 *Ultra-precision lathe*

However, this is not the system of choice as it is not only slowly (pointwise), but also leaves scratches on the surface under test. Therefore an optical approach is necessary. For common optical systems (e.g. interferometers, confocal sensors) it is usually problematic to measure freeform surfaces within a high angular dynamic range of $\pm 30°$ on a measurment field of $120\,$mm, within a machine and requires high technical effort (e.g. stitching or making use of CGHs). Moreover, most systems (especially interferometers) are very susceptible to vibrations, which makes machine integration almost impossible.
One measurement technique capable of meeting all the above requirements is *Phase Measuring Deflectometry* (PMD) [1].

2 The principle of PMD

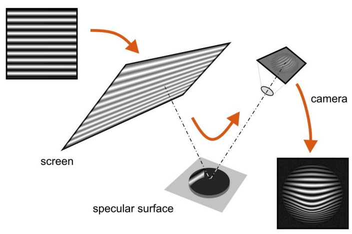

Fig. 3 *The principle of PMD*

Figure 3 shows the basic principle of PMD. The sensor is based on the observation of *sinusodial fringe patterns* on a large screen using the object under test as a mirror. Due to local slope variations of the surface, the mirrored fringe pattern is distorted.
The distortion and thus the *local slope* of the object can be found using standard phase-shifting techniques. The advantage of measuring slope data is a very high sensitivity for local details and defects (down to 20 nm in height). The object's shape can be calculated by numerical integration.

3 Machine integration of PMD

Though this system already provides a very high accuracy and the possibility of fullfield measurement of freeform surfaces, the angular dynamic range for machine integrated measurement still is a big problem. In PMD the angular dynamic of the sensor is directly related to the spatial size of the lightsource (usually a TFT, see section 2). Although it can be arranged that each camera sees the whole object, for a limited screen size only a part of the surface is reflecting the fringe pattern (see Fig. 4) and therefore can be measured.

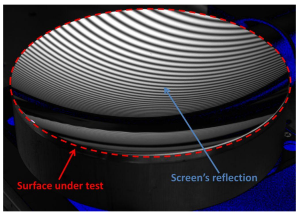

Fig. 4 *The screen reflects only in a part of the surface*

To overcome this difficulty one could use a bigger illumination pattern. This however is problematic within the limited working space inside the machine. To solve this issue a new approach is desired.
Instead of using a large illumination pattern one could observe the object from different directions, using several cameras and hence increase the field of measurement [2]. This solution however makes handling inside the lathe difficult and makes a good calibration almost impossible.
Therefore we use a different aproach by making use of the inherent accuracy of the machine's axes, to produce *virtual camera positions*. These are created by simply rotating the object around a certain angle, using the machine's C-axis, which is the same as positioning *virtual cameras* around the surface under test. As a result the field of measurement can be increased easily.

4 Experimental setup

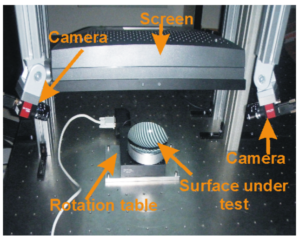

Fig. 5 *Laboratory setup*

To carry out first measurements demonstrating the required angular dynamic range a laboratory setup outside the machine was realized (see Fig. 5). The object is positioned onto a rotation stage, to simulate the C-axis of the UPM. Thereby it is possible to create *virtual camera positions* by simply rotating the surface under test. Putting the measurement results together gives us the whole surface.
In future this *offline setup* will be integrated into the UPM as a permanent solution (see Fig. 6).

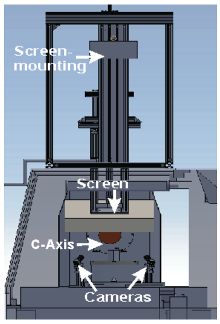

Fig. 6 *CAD simulation of a machine integrated setup*

To prevent damage, the screen will be mounted onto a linear stage, as it has to be moved out of the machine's interior during the turning process. This however requires the sensor to be recalibrated after each machining process. By making use of a new concept of *self calibration*, recalibration of the system is easy feasable [3].

5 Results

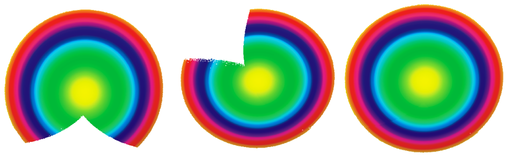

Fig. 7 *Measurement field without rotation of the object (left);*
Measurement field after rotating the object by $90°$ *(center);*
Fullfield measurement after combining the measurements (right)

Figure 7 shows the measurement of a concave sphere with a radius of curvature 120 mm and a diameter of 120 mm. The maximum object slope is $\pm 30°$. The two cameras measure only a part of the workpiece (see Fig. 7, left and Fig. 7, center). By introducing a rotation of $90°$, realized by the rotation stage, it is possible to cover the whole surface of the object (see Fig. 7, right).

6 Acknowledgement

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References

[1] M. Knauer, "Phase Measuring Deflectometry - A new approach to measure specular free-form surfaces," Optical Metrology in Production Engineering; Proc. SPIE, pp. 366–376 (2004).

[2] C. Richter, "Machine-Integrated Measurement of Specular Free-Formed Surfaces Using Phase-Measuring Deflectometry," Proc. EUSPEN 2009, pp. 90–93 (2009).

[3] E. Olesch, "New Holistic Self-Calibration Method for Deflectometric Sensors," Proc. DGaO 2010 (2010).