Design, Realization and Testing of NANOMEFOS

Freeform optics offer many advantages over spherical optics. The applicability of conventional metrology methods is however limited for these surfaces. In the NANOMEFOS project a new non-contact measurement machine has therefore been designed, realized and tested. This PhD project is now nearing completion and the first test results show nanometer level reproducibility and promising measurement uncertainty.

• ***Rens Henselmans*** •

Introduction

High-end optical systems can for instance be found in space, science and lithography applications. Most optical systems employ spherical optics due to their relative ease of high precision manufacturing and measurement. The performance of these optics is however limited by aberrations that are inherent to spherical surfaces. Generally, multiple components are therefore applied in series to optimize the image quality. By applying freeform and aspherical optics (Figure 1) aberrations can be reduced, thereby improving system performance while also decreasing the system mass, size and number of required components.

Local polishing techniques and diamond turning with fast- or slow-tool-servo enable generation of these complex surfaces [1]. The applicability of classical metrology methods is however limited for freeform surfaces, which is currently holding back their widespread application. TNO,

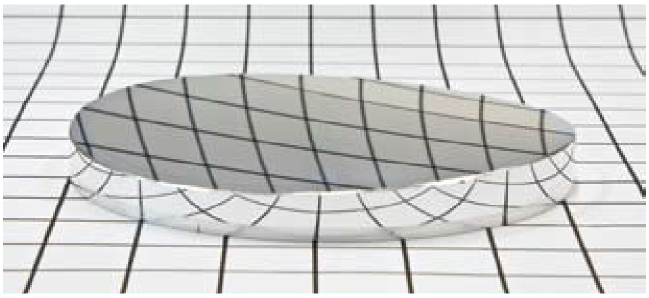

Figure 1. Freeform surface example. (Photo: L. Ploeg)

Eindhoven University of Technology (TU/e) and NMi VSL therefore initiated the NANOMEFOS project in 2004. NANOMEFOS is an acronym for Nanometer Accuracy Non-contact Measurement of Freeform Optical Surfaces. In this SenterNovem IOP Precision Technology project, a universal, non-contact and fast measurement machine with 30 nm uncertainty (2σ) for freeform optics up to ∅500 mm is being designed, realized and tested.

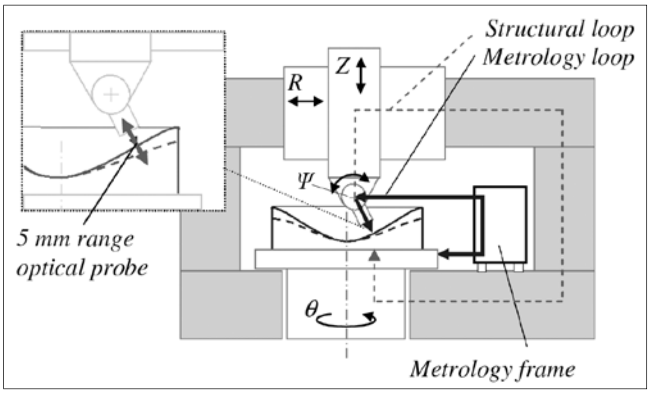

Figure 2. Schematic machine concept.

Concept

Freeform optics usually have up to a few mm departure from rotational symmetry. A cylindrical machine setup is therefore applied (Figure 2). An optical probe is developed to enable contactless measurement at high scanning speeds. While the optic is mounted on a continuously rotating air bearing spindle, the optical probe is positioned over it by a motion system.

The developed optical probe has 5 mm range to capture the departure from rotational symmetry of the surface, allowing the R, Z and Ψ stages to be stationary when measuring a circular track. Mechanical brakes are applied to exclude encoder, amplifier and EMC noise. Such a circular track is measured several times to acquire sufficient data for averaging and drift compensation. This way, a surface can be measured within minutes. The position of probe and product is measured relative to a metrology frame in a separate metrology loop.

Motion system

The realized machine is shown in Figure 3. An air bearing motion system positions the probe in a sub-micrometer uncertainty plane of motion relative to the product. The vertical stage is hereto directly aligned to a vertical base plane of the granite base by three air bearings. Separate preload and position frames are applied throughout to minimize distortion and hysteresis, and the linear motors and brakes are aligned with the centers of gravity of the stages.

Metrology system

The position of the probe relative to the product is measured by a separate metrology system. A short metrology loop for the critical in-plane directions is obtained by directly measuring the Ψ-axis rotor position interferometrically relative to a metrology frame. A vertical and horizontal interferometer beam (Z IF and R IF in Figure 4) measure the displacement of a cylindrical mirror on the face of the Ψ-axis rotor, relative to mirrors on the metrology frame. This frame is covered by an aluminum box that serves as a thermal shield. An angle encoder measures the ψ-rotation of the probe. The product position is determined by capacitive probes that measure the error motion of the spindle.

Mechanical and thermal simulations resulted in silicon carbide as the preferred material for the metrology frame.

Figure 3. The NANOMEFOS prototype at TU/e GTD.
(Photo: L. Ploeg)

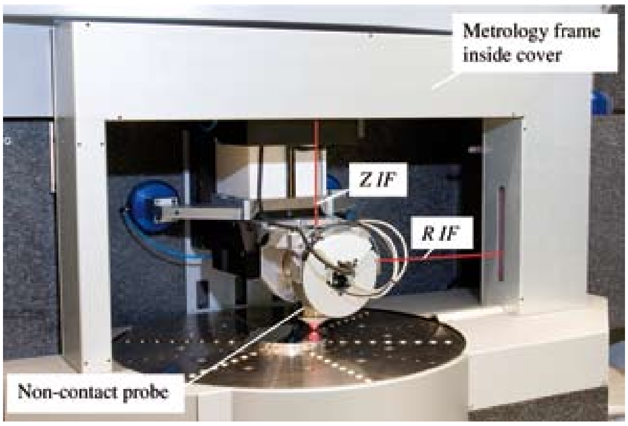

Figure 4. Interferometers of the metrology loop.
(Photo: L. Ploeg)

This material has a high E-modulus and a low density, making it very suitable for light and stiff constructions. The high thermal conductivity in combination with the low expansion coefficient minimizes thermal gradients and the resulting deflection. Furthermore, the material is very hard, allowing it for the reference mirrors to be polished directly onto the sides of the beams. The frame is attached statically determined to the base on SuperInvar struts. The thermal stability is simulated to be about 2 nm, and the first resonance occurs at 620 Hz.

Optical probe

The optical probe has been developed by L.A. Cacace [2]. It is based on the differential confocal method, which measures how well a surface is in focus. When a surface moves through focus, the response is an S-curve with a zero-crossing at best focus and a few µm of near-linear response around it. This method has been optimized by analytical modeling and experiments with a test setup.
A PSD is included to enable calibration and compensation of inclination dependent errors. The range is increased by translating the objective over 5 mm and measuring the displacement with a compactly integrated interferometer. The focusing objective and interferometer mirror are guided by a flexure guidance and actuated by a voice coil. The interferometer measures the displacement of the objective, which results in a short metrology loop. By FEM analysis the guidance was optimized to obtain a first resonance of 1.4 kHz and about 50 g of moving mass. Frequency response measurements indicate an achievable closed loop bandwidth of 500 Hz.

Figure 5. The optical probe. (Photo: L.A. Cacace)

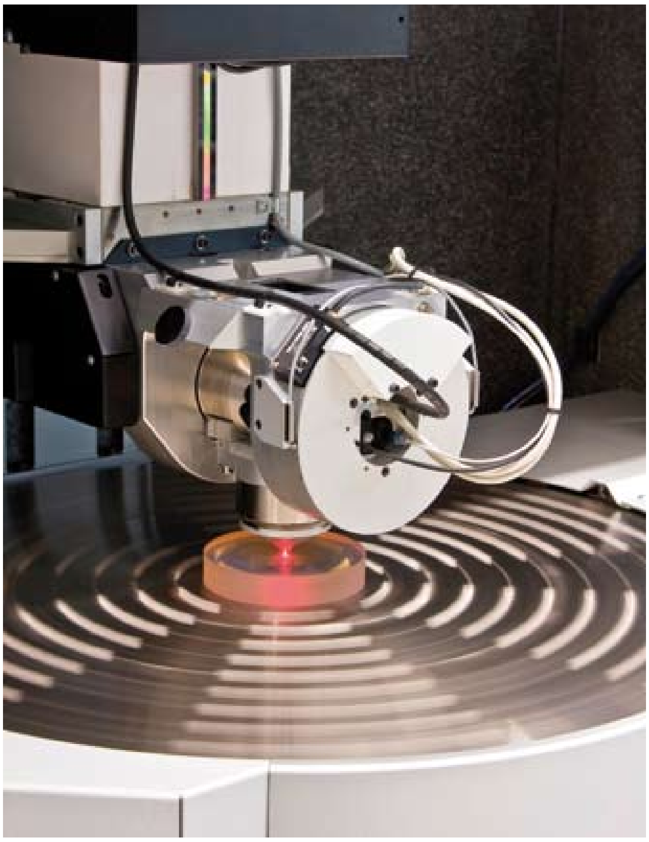

Figure 6. Measurement of an optical flat. (Photo: L. Ploeg)

Figure 5 shows the realized optical probe. The Focus Error Signal (FES) has a sensitivity at the zero-crossing of 5.5 V/µm, and the measurement range is approximately 4 µm. The measured noise level is 0.15 nm rms at the zero crossing and 0.8 nm rms at the ends of the measurement range. Comparing two series of Focus Error Signal measurements taken five days apart show a reproducibility of 4.1 nm rms over the entire range. It should be noted that the temperature was 0.7 °C higher at the second series.

First test results

To test the stability of the machine, a ∅100 mm Zerodur optical flat has been measured. This flat was calibrated by NMi VSL to be flat within 44 nm PV ±20 nm. On the machine, it was first measured with 13 µm tilt (Figure 6). By measuring a radial scan before and after each measurement, the drift that occurs during measurement of the circular tracks is eliminated. The spacing between the circular tracks is 1 mm, and each track was averaged over five revolutions. The rotation speed of the spindle was 1 rev/s, giving a scanning speed of 250 mm/s at the outer edge. The machine operates at 10 kHz, and the tracks are downsampled to 1000 points/rev. The total measurement time for this procedure is about six minutes.

Figure 7 shows the flatness of the surface as measured by the machine. It must be noted that no calibration data has been taken into account yet. The measured flatness is however 8-9 nm rms, which is close to the NMi measured value. This surface was measured three times. The average reproducibility was 2.1 nm rms, calculated relative to the mean of these measurements.

The same measurements were also performed on this surface tilted by almost 2 mm, which serves as a traceable freeform. From ten measurements a reproducibility of 2-4 nm rms was calculated. The measured flatness was 13-15 nm rms, in which some clear calibratable components can be identified, such as the earlier mentioned inclination dependency of the probe. The measurement uncertainty can therefore certainly be further improved by future calibrations and more elaborate data processing.

Conclusion

The design, realization and testing of the prototype, including the custom control software and electronics, has been completed with promising surface measurements. The machine will soon be moved to the TNO facilities in Delft, where it will be further calibrated, optimized and employed in freeform optics fabrication at the optical workshop.

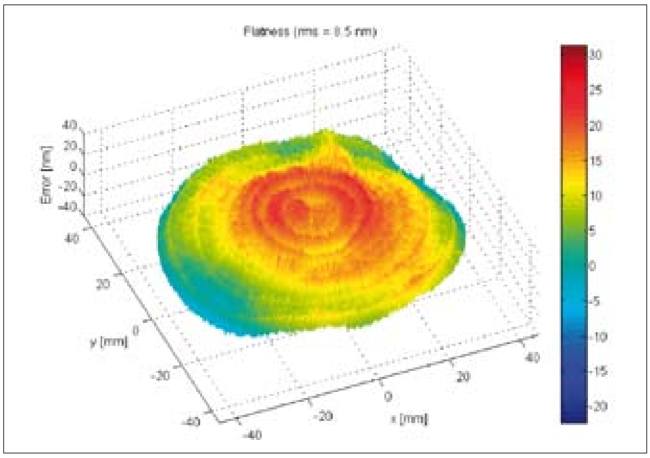

Figure 7. Flatness measurement result of a slightly tilted flat.

Acknowledgement

This project was partially funded by the SenterNovem IOP Precision Technology Program. It would not have been possible without the valuable contributions of many people from TU/e, TNO, NMi VSL, the TU/e GTD and TNO workshops, AC Optomechanix, WimOptik, Eltromat, IME Technologies and many suppliers.

Author's note

Rens Henselmans is a PhD candidate at the Control Systems Technology group of the Mechanical Engineering faculty of Eindhoven University of Technology, where he has been coached by Nick Rosielle and Maarten Steinbuch. He is now working for the Precision Mechanics department of TNO Science & Industry. This article is based on [3], and an extensive description will be published in the author's PhD thesis [4].

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Information

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