DESIGN, REALIZATION AND TESTING OF THE NANOMEFOS NON-CONTACT MEASUREMENT MACHINE FOR FREEFORM OPTICS

Rens Henselmans[1,2], Lennino Cacace[3], Nick Rosielle[1] and Maarten Steinbuch[1]
[1]Control Systems Technology, Mechanical Engineering faculty, Technische Universiteit Eindhoven, the Netherlands
[2]Precision Mechanics department, Advanced Precision and Production Equipment, TNO Science & Industry, Delft, the Netherlands
[3]AC Optomechanix, Eindhoven, the Netherlands

INTRODUCTION

By applying freeform optics (figure 1) in high-end optical systems such as used in space, science and lithography applications, system performance can be improved while decreasing the system mass, size and number of required components (for instance [1]). The applicability of classical metrology methods is limited for freeform surfaces, which is currently holding back their widespread application. TNO, TU/e and NMi VSL therefore initiated the NANOMEFOS project in 2004 [2]. The development of this universal non-contact and fast measurement machine with 30 nm uncertainty (2σ) for freeform optics up to ∅500 mm is now nearing completion.

FIGURE 1: Freeform surface example

CONCEPT

Freeform optics usually have up to a few mm departure from rotational symmetry. An optical probe is developed to enable 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 (figure 2).

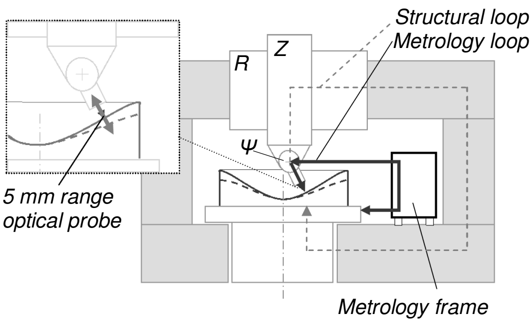

FIGURE 2: Schematic machine concept

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 track. Such a circular track is measured several times to acquire sufficient data for averaging and drift compensation. This way, a surface can be measured in minutes. The position of probe and product is measured relative to a metrology frame in a separate metrology loop.

MOTION SYSTEM

The machine is shown in figure 3. An air bearing motion system positions the probe relative to the product, with sub-micron uncertainty in the out-of-plane directions. Here, an accurate plane of motion is provided by directly aligning the vertical stage to a vertical base plane on the granite base. Separate preload and position frames are applied throughout to minimize distortion and hysteresis, and the motors and brakes are aligned with the centers of gravity of the stages.

FIGURE 3: NANOMEFOS machine

For optimal positioning stability when measuring a track, the stages are braked by mechanical clamps, to exclude encoder, amplifier and EMC noise. To test this stability, 3 orthogonal reference capacitive probes are mounted on the (stationary) spindle and measure to a target that is mounted to the ψ-axis, such that the measurement point coincides with the focal point of the later to be mounted optical probe. Figure 4 shows the measured relative displacement between spindle and probe tip in radial (R), out-of-plane (Y) and vertical (Z) direction. This is an indication of the stability of the structural loop.

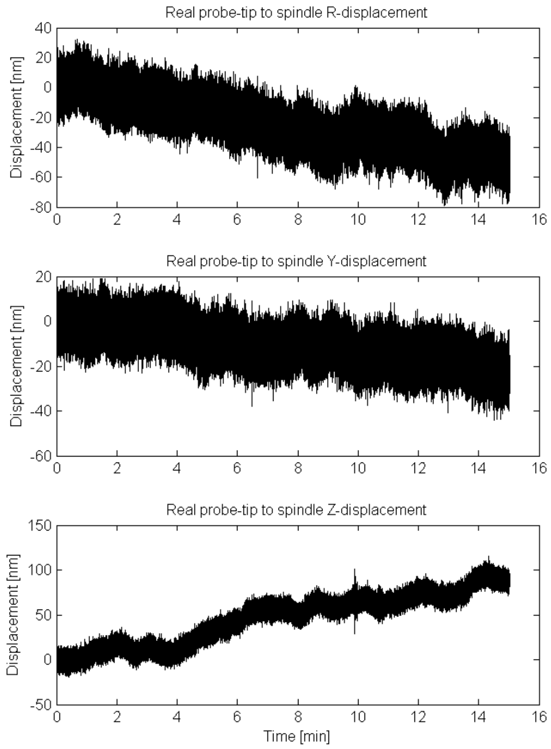

FIGURE 4: Displacement at the probe tip relative to the spindle, measured by reference capacitive probes

As can be seen, the position of the probe tip relative to the product has a noise level of 45 nm, 35 nm and 25 nm PV in R,Y,Z respectively. It is suspected that this is mainly caused by acoustic disturbances due to turbulent flow in the air-supply system. The drift over 15 minutes is typically 50 nm, 20 nm and 85 nm. A shock in the nearby workshop can further be seen at t = 10 minutes.

METROLOGY SYSTEM

As explained, the position of the probe is measured by a separate metrology system. A short metrology loop for the critical in-plane directions is obtained by directly measuring the probe rotation axis position interferometrically, relative to a metrology frame. A vertical and horizontal interferometer beam (Z IF and R IF in figure 5) measure the displacement of a cylindrical mirror on the face of the Ψ-axis, relative to mirrors on the metrology frame. This frame is mounted inside an Aluminum box that serves as a thermal shield. An angle encoder measures the ψ rotation of the probe.

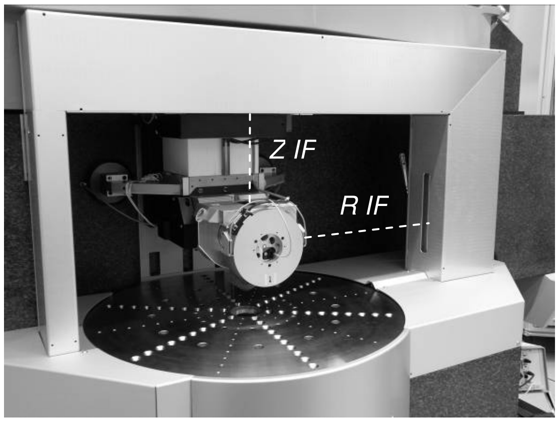

FIGURE 5: Interferometers of the metrology loop

Mechanical and thermal simulations resulted in Silicon Carbide as the preferred material for the metrology frame. The reference mirrors are polished directly onto the beams of this frame (figure 6), and it is mounted statically determined on SuperInvar struts. The thermal stability is simulated to be about 2 nm, and the first resonance occurs at 620 Hz.

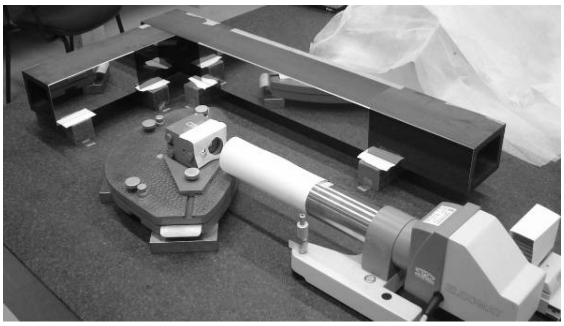

FIGURE 6: Silicon Carbide metrology frame during alignment

The product position is measured relative to this same frame with capacitive probes which measure the spindle error motion. The multi-probe method [3] is applied to separate roundness error of the reference edge and the spindle error motion in five degrees of freedom by Fourier decomposition. Simulations show nanometer level uncertainties. The method is currently being tested.

Figure 7 shows the real displacement in Z-direction during 0.1 s, as measured by the three reference capacitive probes as explained in the previous section (*Real*), and the displacement as calculated by combined results of the capacitive probes around the spindle and the interferometers in the metrology system (*Measured*).

As can be seen, most of the mechanical vibrations as shown in figure 4, are also measured by the metrology loop and thus cancel out. The 17 nm PV displacement is herewith reduced to 4 nm PV or 0.6 nm rms over 0.1 s.

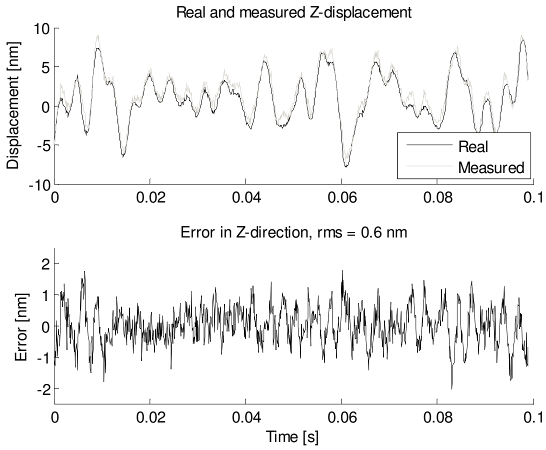

FIGURE 7: Short term measurement error in Z-direction

Similarly, the error in R,Y and Z-direction over the 15 minute measurement of figure 4 is shown in figure 8. Including the remaining drift, the error is 8.2 nm rms in R, 8.2 nm rms in Y and 2.3 nm rms in the (most critical) Z-direction. Five consecutive measurements show consistent results of 2.0 – 3.2 nm rms error in Z.

Almost all drift in the in-plane directions (R and Z) that was present in figure 4, has been eliminated by the metrology system. This also holds for the shock at 10 minutes. Refractive index changes of air are compensated with a pressure, temperature and humidity sensor. What remains is mainly air turbulence in the interferometer beams, since they operate in open air. The vibration levels in the R-directions are higher compared to the Z-direction due to the Abbe offset in this direction. Since the Z-direction would be normal to the surface to be measured in this case, this has most influence on the final shape measurement uncertainty that can be achieved.

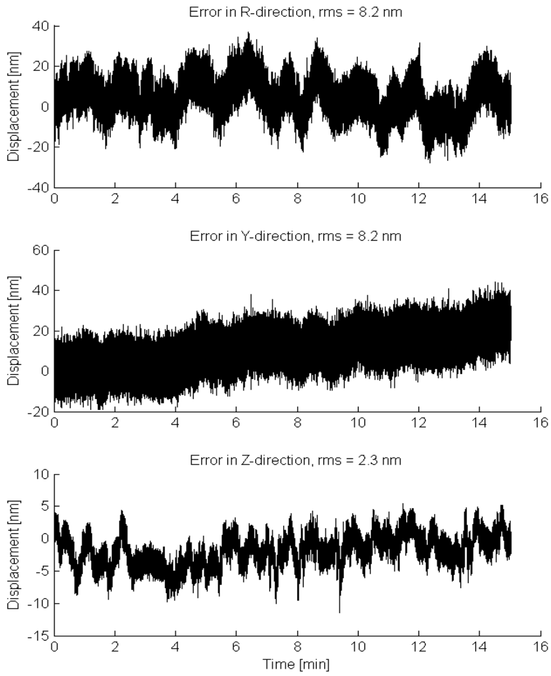

FIGURE 8: Resulting measurement error

OPTICAL PROBE

The optical probe concept is based on the differential confocal method, which has been optimized by analytical modeling and experiments with a test setup. The range is increased with an interferometer compactly integrated in series [4]. 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 with minimal sensitivity to thermomechanic effects in the actuator. By FEM analysis the guidance was optimized to obtain a first resonance of 2 kHz and about 50 g of moving mass, resulting in an expected closed loop bandwidth of 700 Hz.

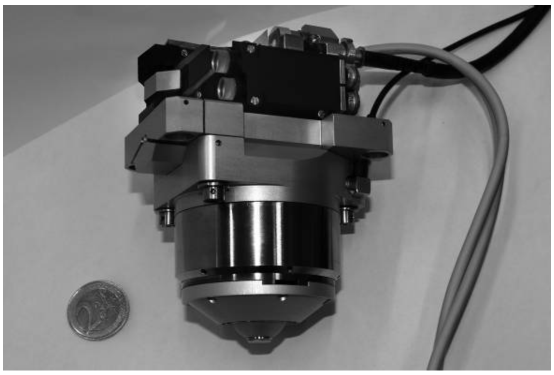

FIGURE 9: Optical probe

Figure 9 shows the developed optical probe. The differential confocal system was tested by scanning a mirror mounted on a piezo through the focus of the probe. The Focus Error Signal (FES) is shown in figure 10, which shows 55 consecutive measurements. The sensitivity at the zero-crossing is 5.5 V/µm. The measurement range is approximately 4 µm.

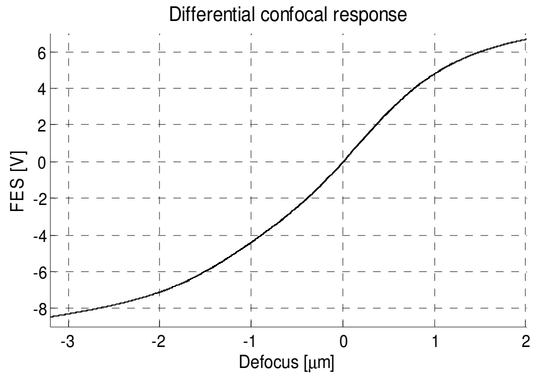

FIGURE 10: Focus error signal (FES)

The noise level is 0.15 nm rms at the zero crossing and 0.8 nm rms at the ends of the measurement range. The achievable measurement uncertainty was estimated by fitting a curve to the average of similar FES measurements 5 days earlier, as if it were a calibration result. Figure 11 shows the variation of the above 55 curves to this fit. It should be noted that the temperature was 0.7℃ warmer at that time. A ghost interference determines most of the deviation, giving an rms error of 4.1 nm.

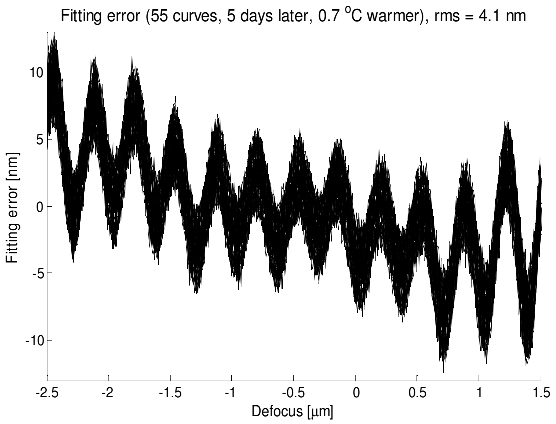

FIGURE 11: FES error relative to measurement of 5 days earlier

The extension of the range to 5 mm by scanning the objective and measuring its displacement with the interferometer has been tested separately, and full functionality of the probe will be tested when mounted onto the machine.

CONCLUSION

The realization and testing of the prototype, including the custom control software and electronics is now almost complete. After the optical probe is mounted, the stability and repeatability of the instrument will be further tested and traceable calibrations are performed by NMi VSL. Full surface measurements will follow to demonstrate the suitability of the new instrument for measuring freeform optics.

FIGURE 12: Current realization status

ACKNOWLEDGEMENT

This research is partially funded by the SenterNovem IOP Precision Technology program of the Dutch Ministry of Economic Affairs. It would not have been possible without the valuable contribution of many people from TU/e, TU/e GTD workshop, TNO and NMi VSL.

REFERENCES

[1] Winsor, R., et.al., *Optical design of an Infrared Multi-object spectrometer utilizing freeform optical surface, ASPE winter topical meeting, 2004*

[2] Henselmans, R., et.al., *NANOMEFOS – Nanometer Accuracy Non-contact Measurement of freeform optical surfaces,* ASPE winter topical meeting, 2004

[3] Whitehouse, D.J., *Some theoretical aspects of error separation techniques in surface metrology*, J. of Physics E, Vol. 9, 1976

[4] Cacace, L.A., et.al., Development of a new differential confocal probe with nanometer accuracy at large acceptance angles for measurement of freeform surfaces, Proc. of Euspen Annual meeting, 2007