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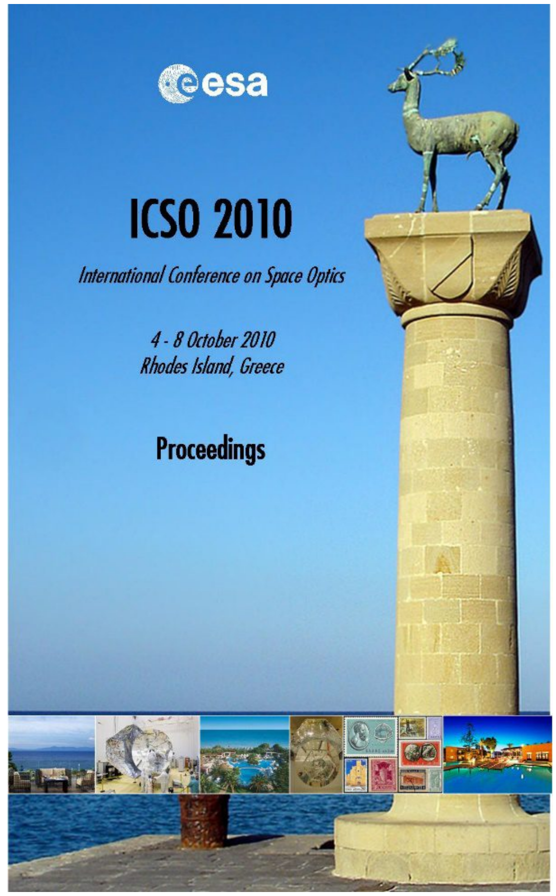

NANOMEFOS non-contact measurement machine for aspheric and freeform optics

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NANOMEFOS NON-CONTACT MEASUREMENT MACHINE FOR ASPHERIC AND FREEFORM OPTICS

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I. INTRODUCTION

Applying freeform optics in high-end optical systems can improve system performance while decreasing the system mass, size and number of required components. Their widespread application is however held back by the lack of a suitable metrology method. TNO, TU/e and NMi VSL have therefore developed the NANOMEFOS measurement machine [1], capable of universal non-contact and fast measurement of aspherical and freeform optics ranging from convex to concave and from flat to freeform, up to ∅500 mm, with an uncertainty below 30 nm (2σ).

II. ASPHERE AND FREEFORM PRODUCTION

The application of freeforms requires new techniques for optical design, manufacture and measurement. Fig. 1 shows the production scheme as it is applied at TNO. This process generally starts with conventional pre-machining, such as milling or grinding. This step is followed by a conventional measurement step, such as a spherometer or a CMM. Next, the surface is machined for optical quality, by diamond turning or computer controlled polishing. An iterative loop is then performed between precision measurement with the NANOMEFOS machine and machining, to give the surface its required form. After an acceptance measurement, a coating might be applied.

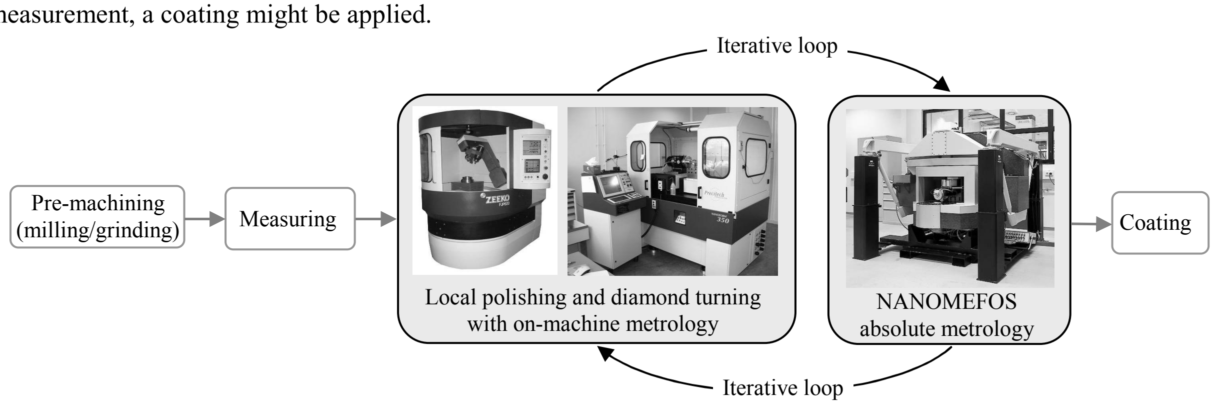

Fig. 1. Asphere and freeform production at TNO

III. THE NANOMEFOS MACHINE

Suitable absolute metrology is the key step in the value chain, for which the machine was specifically developed. This machine incorporates five characteristics that are important in single-piece high-precision optics production:

- Universal (from flat to aspherical and freeform, from convex to concave)
- Large measurement volume (∅500x100 mm)
- High accuracy (30 nm, 2σ)
- Non-contact
- Fast (minutes)

Since fabricating aspheres and freeforms often involves local machining techniques, mid-spatials are of large concern. The NANOMEFOS machine scans the surface with an optical probe, and therefore has variable point spacing. For measuring form, ~1 mm is usually applied, but examples will also be shown where line scans with μm point spacing was applied.

IV. MACHINE DESIGN

The chosen cylindrical concept resembles a giant cd-player (Fig. 2). The product is mounted on an air-bearing spindle, which is rotating continuously at for instance 1 rev/s. A non-contact optical distance probe is mounted on a rotation axis (Ψ-axis) which positions it perpendicular to the rotationally symmetric best-fit of the product. The probe can be moved in radial and vertical direction by the R and Z-stage, respectively.

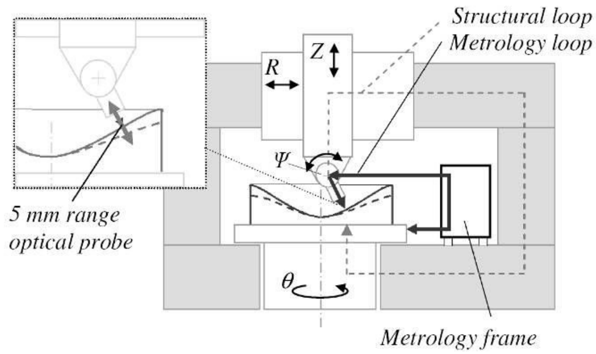

Fig. 2. Machine concept

The probe positioned on a circular track on the product after which the stages will be blocked. This improves the positioning stability of the stages since the electronic noise of the motors and encoders is cancelled. The track can be measured multiple times with little extra effort, to obtain redundant data, for instance for averaging. After this, the stages are moved about 1 mm further to the next track and the process is repeated. This allows for measurement times in the order of 15 minutes for large surfaces. When a freeform surface is rotating on the spindle, the surface may for instance vary between the continuous and dotted line in Fig. 2 by 5 mm PV. Optical probes generally only have a focal depth of a few micrometers when nanometer resolution is required. Keeping the probe in focus by actuating the R and Z-stage requires large accelerations of these heavy stages, resulting in undesirable dynamics. To avoid this, a probe with 5 mm range is required. This way the stages can be kept stationary, even when measuring a freeform track. This reduces the dynamically moving mass from a few hundred kg for the stages to only about 50 g of the probe objective lens. This improves system dynamics and allows for maintained high scanning speed for freeforms surfaces.

The measurement uncertainty is mainly determined by the metrology loop between the probe and the product. By applying a separate metrology system relative to which the probe and product position are measured, the metrology loop becomes much shorter than the structural loop. Hereby most of the stage errors are eliminated from the metrology loop.

The completed machine is shown in Fig. 3. The machine design can be split into three main parts: the motion system, the metrology system and the non-contact probe.

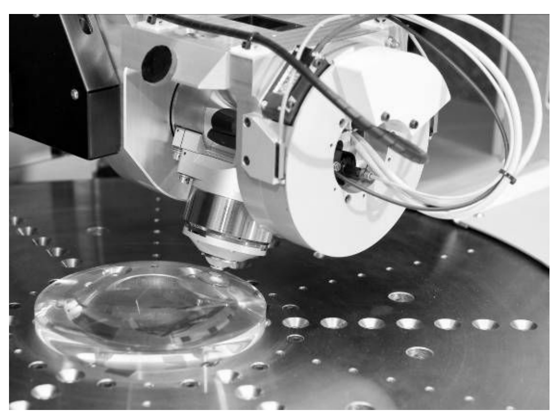

Fig. 3. The completed machine prototype and the inclined optical probe during measurement of a convex lens

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 with 3 air bearings. Further, 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.

A short metrology loop in the plane of motion of the probe is obtained by directly measuring the probe position interferometrically relative to a metrology frame. Mechanical and thermal simulations resulted in Silicon Carbide as the preferred material for this metrology frame. The error motion of the spindle is measured relative to this frame with capacitive probes.

Fig. 3 shows an example of the measurement of a convex lens, where the optical probe can also be seen. This probe is a compact integration of a differential confocal system and an interferometer [2]. The focusing objective and interferometer mirror are guided by a flexure guidance and actuated by a voice coil, with a closed loop bandwidth of 500 Hz and nanometer order servo errors.

V. MACHINE VALIDATION

Various tests have been done to validate the machine performance. First, the noise and repeatability were tested. Next, each individual error source was calibrated, to convert repeatability into measurement uncertainty.

A Noise and repeatability

The noise level when measuring to a stationary surface is about 0.9 nm rms (Fig. 4, left). When measuring a ∅100 mm flat tilted by 1.6 mm (i.e. a 'freeform' with 1.6 mm departure from rotational symmetry), the average repeatability over 10 measurements during a day is 3.4 nm rms. A typical difference between two measurements is shown in Fig. 4 (right), showing that the error is mainly noise, with very little form. Filtering may thus further improve this. The repeatability of single nanometers rms is typical, and also shows for concave and convex measurements.

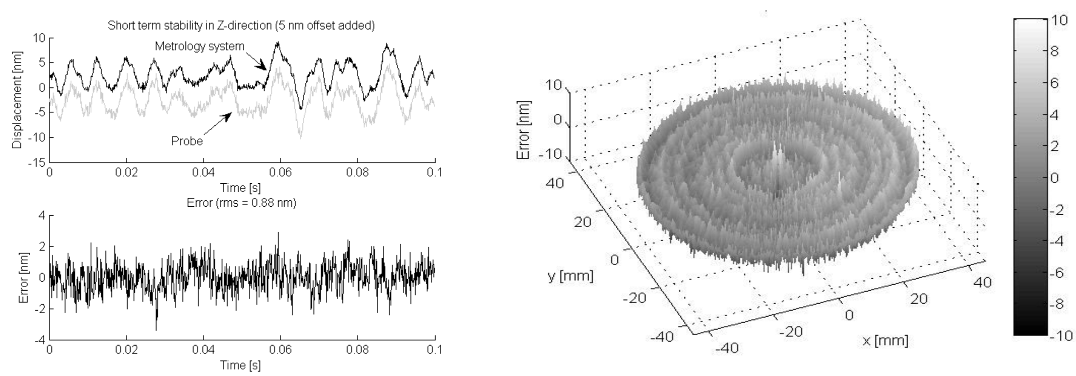

Fig. 4. Noise level at standstill, and typical repeatability for ∅100 mm tilted flat

B Calibration

With the repeatability demonstrated, all individual error sources have been calibrated next. Since this machine is universal, various well-known artifacts that are calibrated using other means (i.e. interferometers, spherometer etc.), can be measured to provide traceability. This allows for cross-checking the results in multiple ways, to minimize the risk of systematic errors. Fig. 5 for instance shows the measurement of a precision Al_2O_3 sphere with a diameter known to ±0.1 µm, which was used to calibrate the probe length and to double-check the reference mirrors that had previously been calibrated. As can be seen, the roundness error of the sphere is determined to be 18.7 nm rms over a 60° angle, which corresponds to the tolerance of the artifact.

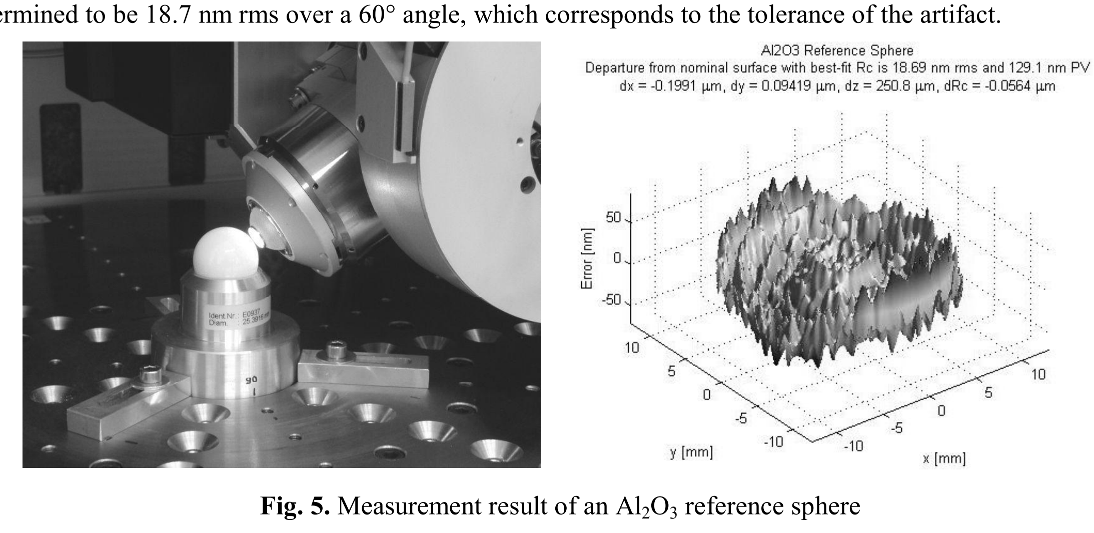

Fig. 5. Measurement result of an Al_2O_3 reference sphere

To verify performance on a freeform surface, a tilted flat was used again. One of the main error sources in this measurement is the surface not being perpendicular to the optical probe, which causes the reflected light to travel back differently into the probe. A PSD is present to monitor this, after which corrections are made using a calibration table [3].

The result before correction is shown in Fig. 6 (left). At the centre, there is no vertical displacement, only tilt. The probe however does indicate vertical displacement, which causes the discontinuity at the centre. The result after application of the calibration table is shown in Fig. 6 (right). The actual flatness of the surface (as measured with an interferometer) is 7.1 nm rms, so this result matches the actual flatness well.

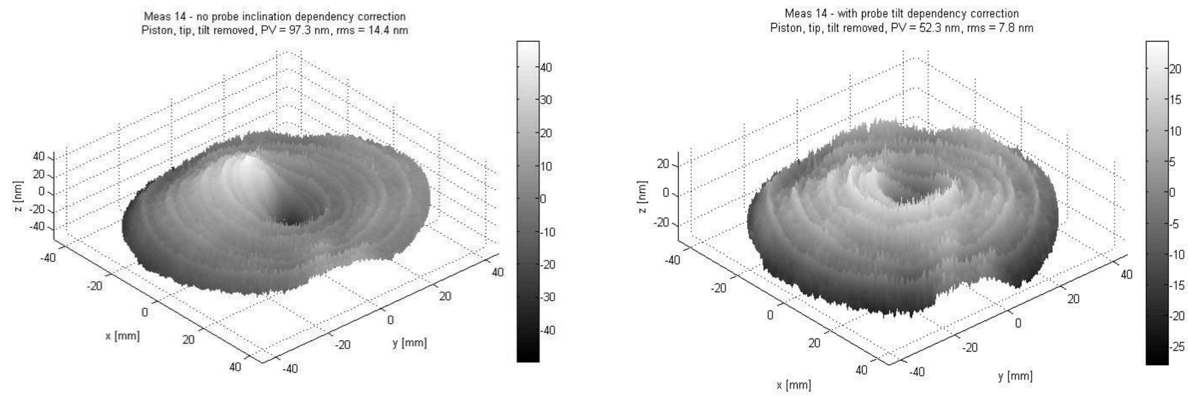

Fig. 6. Tilted flat measurement without (left) and with (right) the probe inclination dependency calibration

VI. APPLICATION IN OPTICS PRODUCTION

With the machine calibrated, it is now being applied in aspherical and freeform optics production and fabrication process research at TNO. A few examples are given here to illustrate the machine's versatility.

A Measuring form

For a project of TNO, four ∅380 mm convex aspherical lenses are being made (Fig. 7, left). The base radius is 637.8 mm, the departure from the base radius is 320 µm, and the departure from the best-fit-radius is 78 µm. Fig. 7 shows a measurement of this surface after pre-polishing. The measurement point spacing is 1 mm, and the measurement time is approximately 10 minutes. A measurement also includes some radial line scans that reveal high-density data that also includes mid-spatial information (see next section).

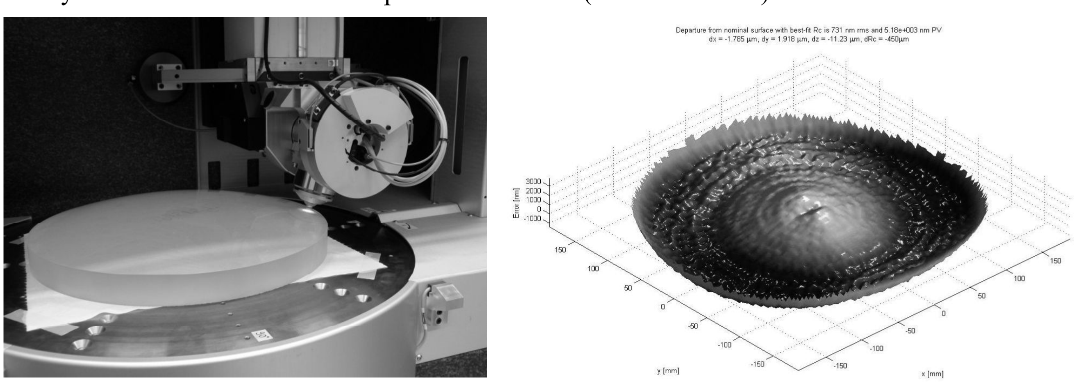

Fig. 7. ∅380 mm convex aspherical lens measurement (320 µm departure from base radius)

Fig. 8 shows a concave mirror strip of 130 x 20 mm, with a radius of 108 mm. This mirror was machined and measured 1 mm off-axis, to simulate a true freeform which could still be measured using a conventional phase-shifting interferometer. As can be seen, the NANOMEFOS and Zygo result correspond well.

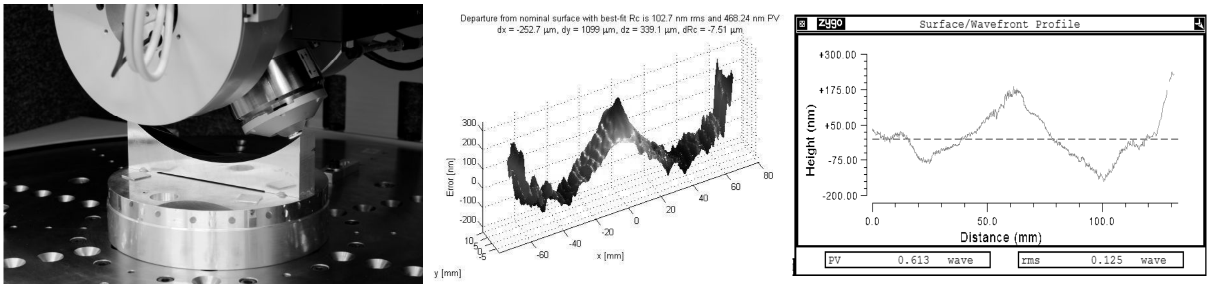

Fig. 8. Diamond turned freeform strip mirror (1 mm off-axis sphere), and NANOMEFOS and Zygo result

B Measuring mid-spatials

Since the machine is fully running on air-bearings and is equipped with nm-resolution linear scales, high-spatial resolution measurements on small areas are also possible, to show mid-spatials (sub-mm spatial frequency range). Fig. 9 (left) shows an example of a spiral groove and centre defect after an (unsuccessful) spiral polishing test. The track-spacing is 1 mm, and the PV value is about 40 nm. Fig. 9 (centre) shows a radial line scan on the same surface, again showing the spiral grooves and the centre defect. This scan has a lateral point spacing of about 2 μm. Similarly, Fig. 9 (right) shows a raster pattern on a convex aspherical surface that was raster pre-polished. The spatial frequency is 0.5 mm, and the PV value of the raster pattern is about 50 nm. The area shown is ∅30 mm.

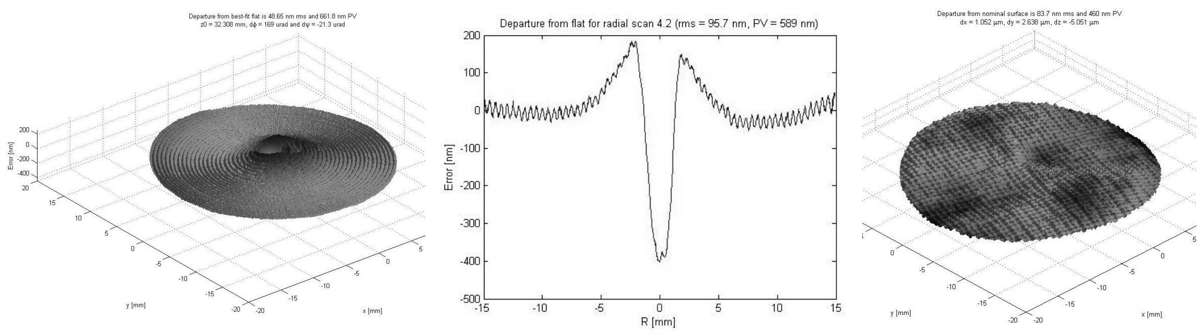

Fig. 9. Measurement of mid-spatials (spiral, centre defect and raster pattern from deterministic polishing)

VII. CONCLUSION AND OUTLOOK

The NANOMEFOS machine has been completed and calibrated. It is capable of fast, universal and non-contact measurement of aspherical and freeform surfaces up to ∅500 mm with an uncertainty below 30 nm (2σ). It is now being applied in the aspherical and freeform optics production at TNO, of which polishing and diamond turning examples have been shown. It is proving to be a very powerful tool that creates more design freedom for optical designers, and gives fabricators insight in the surface quality over a very large spatial frequency range.

VIII. REFERENCES

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