Integrated On-Machine Metrology Systems

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Abstract – Producing On-Machine Metrology systems can present many benefits for the production of optical components - particularly where complex and delicate parts are concerned. To fulfil the requirements for on-machine metrology a suite of tools would be necessary to characterize manufactured parts at all spatial scales of interest. This extended abstract details a development to address the on-machine metrology problem, particularly in the optics industry, but applicable to other sectors of precision engineering.

Introduction

Great advances have been made in recent years in the state of the art in ultra-precision polishing machines, so that deterministic computer controlled material removal is possible on almost any geometry, provided that adequate metrology exists. Our motivation for this project is to open new ground for the production of ultra-precision surfaces be enabling on-machine metrology. Such metrology is by no means new, but for the traditional optical shop, on-machine metrology is new becoming possible thanks to the application of science and computer control and data acquisition.

Typically optical shops use phase-shifting interferometry for optics form measurement. To this we can add white light interferometry for texture measurement, and perhaps profilometry for lower accuracy form work. These tools normally reside in a metrology room away from the polishing work. However, transferring parts between polishing machine and the metrology instrument can become a risky process where large parts are concerned. We can also add to this the inconvenience of re-aligning the part with the polishing machine's coordinate frame.

We have been working on a series of projects to allow metrology to take place on the part processing machines. The work includes form interferometry, texture measurement and other ancillary measurements to verify, for example, radius of curvature.

Optical Surface Characterization

In this work, we have concentrated on form and texture measurements for optics. Form terms are measured by phase-shifting interferometry at 633 nm, or profiling-type instruments to calculate low-order terms. Scanning white-light interference microscopes provide texture information either directly on the surface under test, or on a replica of a sample area of the surface. For ultra-precision work, for example, X-ray mandrels and mirrors for large segmented telescopes, the specifications are very high. This means that nowadays it is becoming a requirement to provide a complete coverage in frequency for the power spectral density of a surface with no gaps.

ELT Segment Example

We take the example of a typical segment for an Extremely Large Telescope (ELT)[1]. The segments are usually aspheric, entirely off-axis and have a very long base radius of curvature (30 - 90 m). The low order terms (say, 0.5 m^{-1} - 200 m^{-1}) could be measured accurately by interferometry, but this would not give an assessment of the radius of the optic leaving a gap in the PSD description of the surface. Furthermore, there may be a small gap between the form interferometry and white light interferometry at certain spatial frequencies. A sample plot showing approximate coverage in spatial frequency terms is shown in Figure 1.

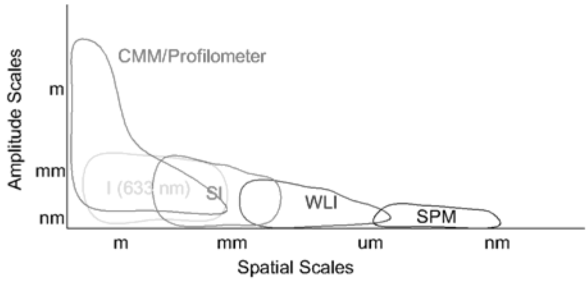

Figure 1. Approximate diagram of instrument coverage for common instruments used in optics characterization. I=interferometry, SI=stitching interferometry, WLI=white light interferometry, SPM=scanning probe microscopy.

For ELT-like segments, the characterization could involve profilometry for form and radius measurement, interferometry as the main form metrology, and then white light interference microscopy to measure the surface finish. Typically, the tests for ELT segments will be very elaborate in order to meet the demanding specifications for form error, aperture coverage and surface finish. Collaborative work at the Optic Technium in N. Wales is using all the tools mentioned in Figure 1 except for SPM for ELT segments, with the advantage that the profiler data can cross-check the form data from the interferometer.

On Machine Measurements

The desire to measure parts on-machine imposes some constraints on the types of equipment that can be used. In general, the polishing machine will be located on a lab or workshop floor with no isolation from vibrations from the underlying buildings. Furthermore, many machines will have some active components generating unwanted vibrations, even when not processing parts. The enabling technology for full-aperture 3D form measurements on-machine has been vibration insensitive phase shifting interferometry, often allowing measurements to be made in quite harsh environments. In recent years it has become possible to buy different types of these interferometers (Twyman-Green and Fizeau for example) from different manufacturers. A similar argument applies to measurement of surface finish. Typically, smaller parts are placed on the microscope table and direct measurements are made. This is not possible with larger optics where surface replication is commonly used. However, even vibration insensitive white light interferometry is becoming available. Fine mechanical adjustment of such instruments is therefore important and will be addressed later.

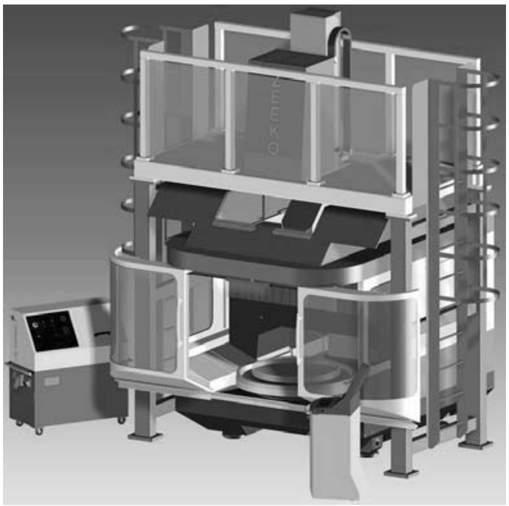

Figure 2. Zeeko IRP 1000 machine, 5-axis motorized stage and 6" Fizeau interferometer.

Other factors are also important like thermal time constants. For easy measurements on-machine, either good thermal control is required, or parts with short thermal time constants, or materials with very low linear expansion coefficients. For the ELT example, the parts are generally low expansion glasses and testing can be carried out at near 20 °C.

An Integrated Development

We have developed an integrated solution for polishing and measuring moderately large concave optics up to 1 m in diameter. The system is based around a Zeeko IRP 1000 polishing machine and a 5-axis motorized stage housing a 6" Fizeau interferometer. A CAD model of the set-up is shown in Figure 2. The work was based around a prototype test tower placed above an IRP 1200 machine at the UCL lab at Optic Technium in N. Wales[2]. A new setup was designed able cope with a wider range of base radii of curvature from approximately 1.1 - 2.4 m, and also to be able to be fitted with different CGH elements for a wide range of optical surface prescriptions

Optical Interferometer and Test Tower

To ensure the maximum flexibility a 6" Fizeau interferometer was chosen such that 4" or 6" transmission elements could be used. The system is a 4D FizCam 3000 unit that provides the vibration insensitivity necessary for the application.

The test tower comprises a stiff steel structure with an upper platform and access ladder enabling the user to adjust the interferometer transmission lens and CGH element together. Computer and alignment displays are located at the upper platform to allow this to be performed by a single person. In previous work we have used an isolated gantry adjacent to the test tower to control the interferometer, but in this work, once the transmission sphere and any CGH are set, all other adjustments are carried out from the ground level.

5-Axis Stage

The accurate positioning of the interferometer is achieved by a motorized 5-axis stage. The optical axis of the interferometer is generally coincident with the rotary axis of the polishing machine, and the stage is able to move in x, y, z, tilt-x and tilt-y. With experience gained in building a manual prototype stage we designed and built a CNC 5-axis stage to position the interferometer accurately with the specifications shown in Table 1.

Table 1. Specifications of the 5-axis CNC stage.

Axis	Range	Resolution
X	± 100 mm	1 um
Y	± 100 mm	1 um
Z	-1440 mm	1 um
A (tilt-y)	± 1 deg	0.135 arc sec
B (tilt-x)	± 1 deg	0.135 arc sec

The z-axis travel allows measurement of surfaces with radii of curvature between 1.1 and 2.4 m. Figure 3 shows a CAD model of the stage and interferometer.

Control of the stage is via a handheld controller, with a digital readout of the axis positions, and the system is designed primarily for testing rotationally symmetric spheres and aspheres, but can be arranged to measure other geometries depending on the exact surface specification.

The stage is also equipped with a CGH holder mounted on a sliding rail system with fine focus to allow different CGH elements to be used with different transmission optics as shown in Figure 4.

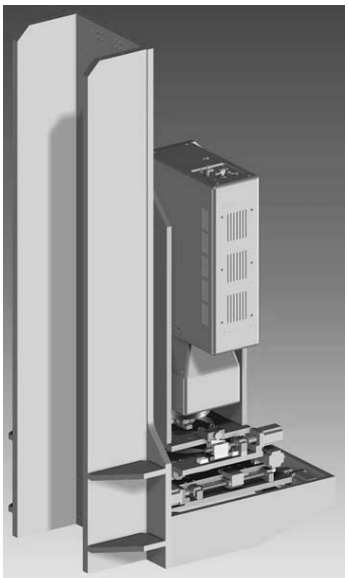

Figure 3. CAD model of the 5-axis stage system with the Fizeau interferometer. The long vertical structure houses the z-axis leadscrew and servomotor.

Figure 4. CGH holder, CGH and interferometer optics.

Complete System

The full system is shown in Figure 5 where the interferometer has been moved down to a testing position inside the enclosure of the IRP 1000 polishing machine.

Initial Work: a half-metre class asphere

Initial work was to polish an f/3.7 convex hyperboloid of 450 mm diameter with just under 30 um of aspheric departure. We took delivery of a Zerodur part polished to best-fit radius.

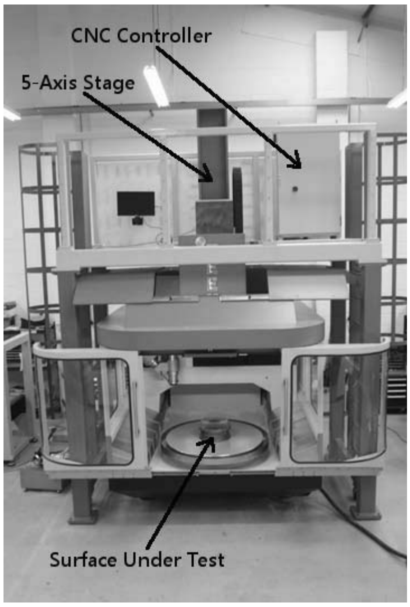

Figure 5. The complete system of polishing machine, test tower and interferometer.

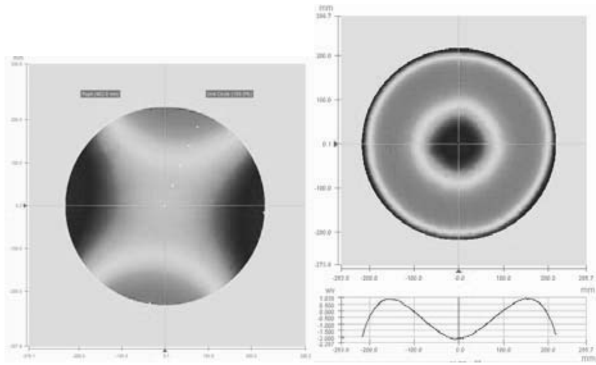

Figure 6. Left: Part received polished spherical to 5λ PV and 1λ RMS. Right, 1st aspherization run showing targeted 3λ departure from best-fit sphere.

Using the on-machine metrology with just an f/3.3 transmission sphere we improved the form to approximately 1 wave spherical before starting to polish in the asphere. After assessing that the removal rates were predictable, we targeted to push the form out to the asphere over several polishing runs in order that it would be imageable using the f/3.3 and CGH. Figure 7 shows phasemaps of the part measured by the system using the CGH until 85% of the surface by clear aperture was in specification (80 nm PV and 16 nm RMS). We will continue processing the part edges until we are out to 100% of the clear aperture at 450 mm dia.

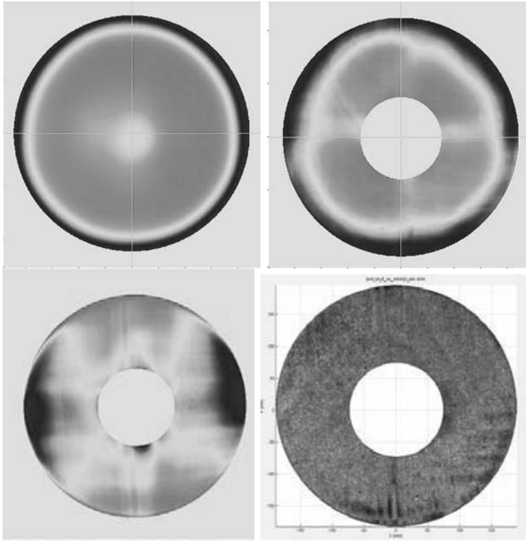

Figure 7. Convergence of the surface. Left-to-right, top-to-bottom. Part after polishing run 23, PV=23λ. After run 25, PV=4.7λ. After run 29, PV = 2.2λ. After run 34. PVq = 79 nm, RMS = 14 nm. Final plot is shaded to highlight slopes.

The polishing and measurement results show that the system can be used to converge aspheric surface forms at the λ/8 level. Previous results on repeatability show that the system should be adequate for at least λ/10[3].

Radius Term

The CGH test of the f/3.7 part can only give the correct radius of curvature if the distance between the asphere and the CGH is well controlled to a few 10s of um. In order to cross check the radius measurement, a laser tracker was used[4] along with a Sphere Mounted Retro-reflector (SMR) that was mounted in custom tooling into the polishing machine's tool chuck, Figure 8.

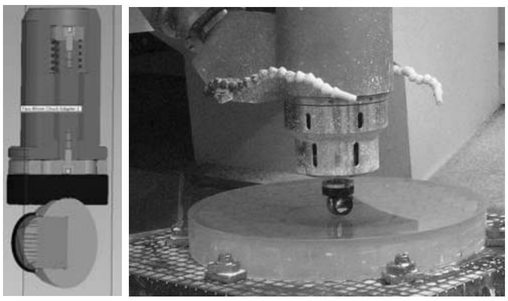

Figure 8. Measuring the base-radius using a laser tracker and SMR. The IRP machine is used to position the SMR on points along a diameter gently, and without applying any force to the surface under test. Only the mass of the SMR and the central shaft is resting on the mirror.

The tool-holder was designed to support the weight of the SMR, but to allow slack when the SMR was placed in contact with the optical surface to avoid damage. The IRP machine was used to position the SMR at several points along a diameter whilst measurements were made with the laser-tracker. After acquisition and SMR ball radius compensation we determined the base radius by asphere fitting.

Completing the measurement

As a final on-machine measurement we measured the surface roughness using an on-machine white light interferometer. The Zeeko STA1 is an instantaneous white light interferometer from 4D technology designed to operate on a machine platform, and especially a Zeeko IRP-type machine. The prototype unit with a x10 objective measured the surface of the asphere on-machine and established a surface roughness of 1 nm RMS, Figure 9.

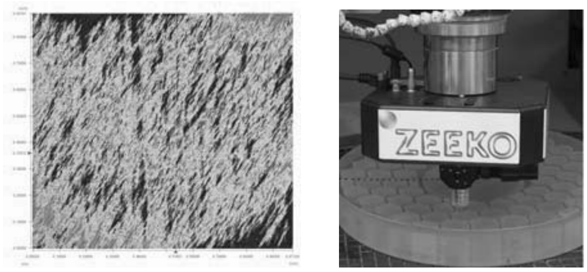

Figure 9. Left, texture measurement, RMS is approx. 1 nm. Right, STA1 and mirror during measurement. Note, some fringe print through is visible in this plot which is an average of 64 measurements.

Currently the instrument is controlled and mounted manually, but we will extend the functionality of the system by including automatic probing and focusing routines such that a grid of sampling points can be chosen on the surface and the points measured automatically.

Conclusion

We have described a new integrated polishing and metrology system designed to process aspheric surfaces up to 1 m in diameter and how we have used this system to determine base-radius of curvature, form error and surface texture for an aspheric part. We will continue develop the technology and to process the mirror to polish out to full clear aperture and will report on the work in greater detail in the future.

References

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[3] King, C., *et al*., “On-Machine Metrology for Aspheric Optics Testing” Proceedings of ASPE Summer Topical Meeting, June, 2010.

[4] Zobrist, T. “Application of Laser Tracker Technology for Measuring Optical Surfaces” PhD Thesis, University of Arizona, 2009.