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Advances in small-tool polishing for free-form surfaces

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Abstract: Free-form surfaces look set to revolutionise optical design. We report on recent development of the *Precessions* process for polishing free-form surfaces from the precision-ground state, and correcting form-errors. On-going experimental results are presented.

OCIS codes 220.1250; 220.5450; 220.3630

1. Introduction

Free-form surfaces introduce additional mathematical degrees-of-freedom into an optical design, compared with axially-symmetric or simple off-axis aspheric designs. In general, this implies that a given level of "performance" (however that may be defined) can be achieved with some or all of the following: fewer surfaces, lower mass, smaller package-size, and reduced stray-light and infrared emissivity. Alternatively, free-form surfaces can enable imaging performance otherwise impossible. With space-born imaging systems in particular, complex reflecting surfaces can permit optical systems to be folded into compact instruments, which would be impossible with simple (e.g. axially-symmetric lens) solutions. Free-form optics also allow novel solutions, advanced illumination systems being a case in point.

Moreover, complex systems are usually subject to an error-budget analysis during their design. It may prove possible in axially-symmetric designs to relax the error budget (reducing risk and cost), then assemble the system, measure the residual wave-front aberrations through the system, and polish a corrective form on a single optical surface. In the general case, wave-front errors may originate in surface form-errors, thickness and wedge errors, component-spacing and de-centration errors, glass-inhomogeneities etc. The general nature of the corrective profile will then be a freeform surface. Clearly, there is a strong case for a versatile free-form polishing process, that handles both polishing from the ground state, and correction of form-errors.

The work presented here is based on Zeeko's *Precessions* axially-symmetric polishing process and machines, which have been described extensively in the literature, e.g. [1] and the references quoted therein. The first step in demonstrating a free-form version of the process was reported earlier this year [2]. This showed deterministic polishing of a depression representing the Zeeko logo (a Z and a spot) into both flat and curved surfaces, by rastering and dwell-time control.

In this paper, we present the next step that has been taken in the process development, comprising the first attempts to control a real measured form-error. We conclude with some comments on metrology.

2. Recent examples from the free-form process-development

In the example shown in Figure 1, a freeform lens surface had been measured using a Form Talysurf profilometer to establish its form-error (4 microns peak-to-valley) over a 100mm diameter region. The error was mathematically inverted to produce a desired removal-profile, with the objective of polishing this into the surface of a flat glass sample. According to standard practice, the Gaussian influence-function of the tool was experimentally determined by polishing a depression in a witness sample. The 3D numerical optimisation code then computed the dwell-time map, which was then converted into a traverse-speed map for raster-polishing. The part was rastered, and the kinematics of the 7-axis CNC machine correctly maintained the same tool-geometry with respect to the local surface-normal at all points over the surface.

Figure 1 shows one of the screens from the 3D optimiser. Within this figure, the top-left picture shows the removal profile as predicted by the optimiser, and the top right the actual removal achieved as measured with a Zygo interferometer. Note that the measurement has been scaled by a factor 0.91, as the part had been slightly over-polished by some 10% in absolute depth. The lower picture shows the resulting residuals, which are 0.4 microns peak-to-valley. This required a single 72 minutes polishing run.

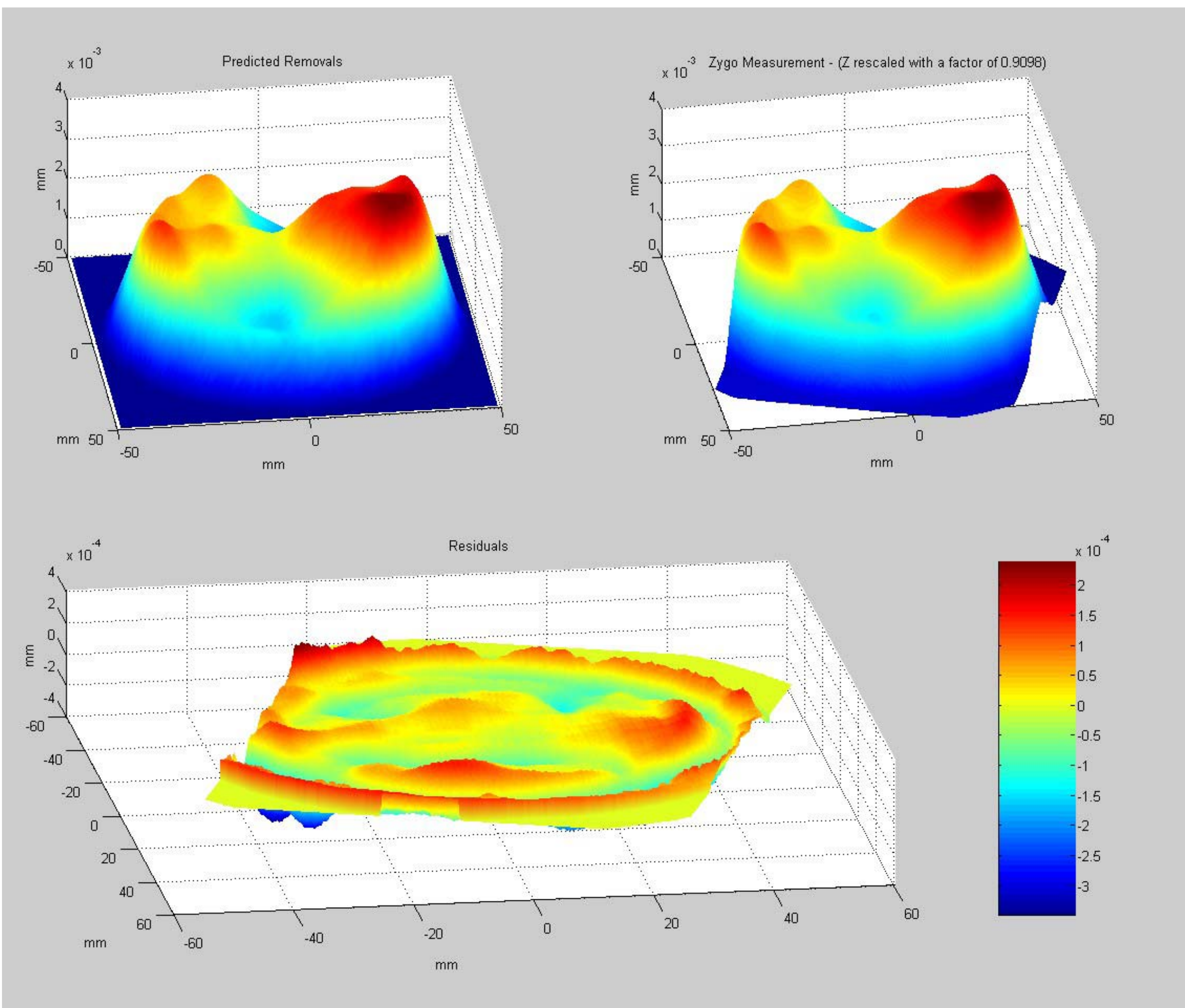

Fig. 1 Predicted and measured free-form removal on flat part, and residuals

The second example is a very preliminary experiment polishing a true free-form lens. This lens was measured using a Form Talysurf with a motorised Y-stage, providing capability to raster-measure a 3D form.

The central region of the part (approximately 50 by 100 mm) was raster-polished, after a 3D optimisation of dwell-times. This region was similar to a toroid in form, with radii of curvatures approximately 4000mm in the long direction and 450mm in the short. The form-error was reduced from 7 to 4.5 microns peak-to-valley in the first run of 130 minutes, and from 4.5 to 3 microns in the second run of 85 minutes.

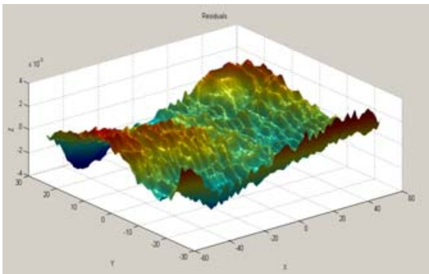

Fig. 2 Measured initial error on free-form lens

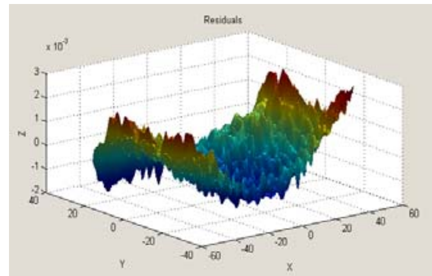

Fig. 3 Measured error after first polishing run

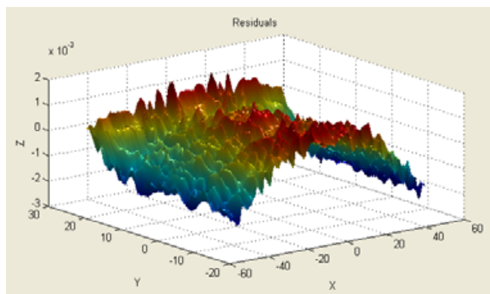

Fig. 4 Measured error after second polishing run

3. Conclusion

The experiment removing a pre-determined amount of material from a flat according to a free-form prescription was extremely successful, demonstrating a convergence rate similar to that achieved in the regular axially-symmetric process. This validates the operation of the free-form optimiser. The experiment on the true free-form curved surface reduced form error from 7 to 3 microns peak-to-valley in two runs. We are currently investigating the source of the residuals, and suspect a combination of two effects. One is uncertainty in the metrology of the surface (we had been using an outdated version of the software driving the Form Talysurf), and the other is a discrepancy in the volumetric removal rate between acquiring the influence function data and polishing the surface. Future work will focus on improving the convergence of true free-form surfaces.

It is worth noting that the largest challenge in free-form form-correction is likely to be acquiring metrology of adequate quality, and relating the metrology coordinate frame to that of the polishing machine. Interferometry with holographic null lenses is possible, but inconvenient and costly. Interferometry also poses problems defining the lateral scale and the base-radius. Profilometeric techniques such as the Form Talysurf are attractive, not least because they can in principle provide absolute vertical and horizontal measurements, and can directly probe fiducials on the surface.

4. References

[1] David Walker, David Brooks, Andrew King, Richard Freeman, Roger Morton, Gerry McCavana, Sug-Whan Kim, "The '*Precessions*' tooling for polishing and figuring flat, spherical and aspheric surfaces", Optics Express, Published by Optical Society of America on http://www.opticsexpress.org/, Vol. 11, issue 8, April 21st, pp958-964

[2] David Walker, Anthony Beaucamp, Christina Dunn, Richard Freeman, Andreas Marek, Gerry McCavana, Roger Morton, David Riley, "First results on free-form polishing using the *Precessions* process", Proc. ASPE Winter Conference 'Freeform Optics, Design, Fabrication, Metrology, Assembly', Vol. 31, Chapel Hill, N. Carolina, pp29-34