Fabrication and Dynamic Deflectometry Testing Methods for Freeform and Deformable Optics

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Abstract: The diverse design space of freeform and deformable optics allows the design of innovative optical system concepts. A manufacturing technology is the remaining piece that prevents full realization of a freeform and adaptable optics age.

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1. Introduction

The Optical Engineering and Fabrication Facility (OEFF) at the College of Optical Sciences, University of Arizona (Fig. 1 left) is capable of manufacturing 6.5 m diameter optics. Resources include state-of-the-art computer controlled grinding and polishing machines along with a 40 m vertical optical test tower in a temperature stabilized environment. Successfully completed projects include a 4.2 m diameter Daniel K. Inouye Solar Telescope [1,2], a technology demonstrator for the James Webb Space Telescope (JWST) and a convex mold to be used for the technology demonstrator in the Far Infrared Space Telescope (FIRST) program.

The Richard F. Caris Mirror Lab (RFCML), a part of the Astronomy Department at the University of Arizona (Fig. 1 right), is a unique facility that creates custom, extremely large, 8.4 m diameter telescope mirrors with superior performance and quality, starting from glass chunks. The critical advantage of RFCML's large and fast (i.e. small f-number) mirrors is their lightweight honeycomb structure with excellent structural rigidity and thermal control capability. RFCML's honeycomb manufacturing creates some of the world's most powerful telescopes such as the 2 × 8.4 m Large Binocular Telescope (LBT) and the 25 m Giant Magellan Telescope (GMT). The first 8.4 m off-axis GMT segment was successfully completed to an accuracy of 19 nm root mean square (RMS) error in 2012 [3-5].

Fig. 1. (left) 6.5 m primary mirror lowering down to the Optical Engineering and Fabrication Facility at the College of Optical Sciences, University of Arizona with specialized facilities and integrated testing tower for large optics fabrication, engineering and testing. (right) Dual-head 8.4 m class Large Polishing Machine with a 1.2 m stressed lap (blue arrow) on the tertiary optical surface and a Rigid Conformal lap (red arrow) on the primary optical surface of the Large Synoptic Survey Telescope primary-tertiary mirror at the Richard F. Caris Mirror Lab, University of Arizona [5].

2. Conformal Fabrication Technology for Freeform Optics

Active shape-changing tools, such as the 1.2 m diameter stressed lap (blue arrow in Fig. 1 right), adjusts 18 benders in real-time to match local freeform surface shapes. Recently this system has been upgraded with orbital tool stroke motion and edge shape compensation. One of the most significant advantages of orbital motion is the required shape change magnitude within a tool stroke motion. For instance, if a 1.2 m stressed lap on the 8.4 m GMT off-axis segment is located near the right-side edge (i.e. the center of the tool stroke motion: 12.61 m away from the parent vertex), the required shape change magnitude is only 33 μm peak-to-valley for the orbital stroke mode compared to the 1042 μm for the spin stroke case [5]. This greatly improves the active bending control accuracy as the target lap shape variation is very small within a local tool stroking motion.

The Rigid Conformal (RC) lap (red arrow in Fig. 1 right) [6] uses a non-Newtonian fluid that flows much more quickly than pitch to conform to local freeform shapes. This maintains the tool's rigid behavior to preserve the smoothing efficiency within a local tool stroke timescale. The RC lap's as-built performance was successfully demonstrated by completing the 8.4 m GMT off-axis primary mirror with 13 mm of freeform departure at the RFCML [3].

3. Dynamic Metrology for Freeform and Deformable Optics

A newly developed adaptive metrology uses a deformable mirror (DM) as an adaptable null component for interferometric tests [7]. To determine the optimal null shape for the DM, we use a stochastic parallel gradient descent (SPGD) algorithm. The final changes to the shape of the DM can be precisely measured by a deflectometry system, which has sufficient dynamic range to measure the DM. The on-demand null condition enables swift measurement of unknown freeform surfaces while keeping the entire system stationary. When incorporated into an interferometric null test, the adaptive system showed outstanding results for the measurement of an unknown freeform/aspheric surface. Fig. 2 shows a sample SPGD search case, showing the actual fringe restoration over time and a graphical representation. In this demonstration, the number of NaN (Not-a-Number) pixels in the measured fringe intensity map is chosen as the merit function [8].

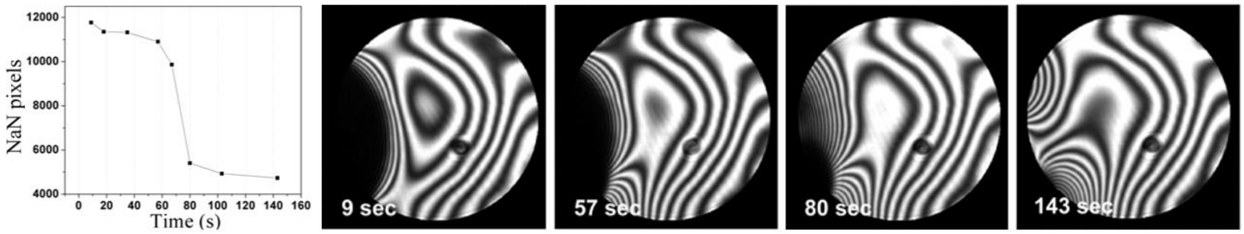

Fig. 2. Time evolution of a SPGD-guided fringe restoration process along with evaluation criteria change that guides the process [8].

An instantaneous phase shifting deflectometry measurement was developed and tested against a time varying deformable mirror using an iPhone 6 for measurements as shown in Fig. 3 [9,10]. The instantaneous method is based on multiplexing phase shifted fringe patterns with color, and decomposing them in x and y using Fourier techniques. We have made several measurements and verified the new method by cross-checking with conventional three phase shifting deflectometry and a commercial interferometer as shown in Fig. 3 (a). The error between all three methods is of the order of 30 nm RMS, when measuring surface features with about 2 µm PV, Fig. 3 (b). This level of agreement demonstrates that the instantaneous phase shifting deflectometry method is an accurate tool to measure deformable mirror or freeform optics. The current iPhone system has a temporal bandwidth of the order of 10 Hz.

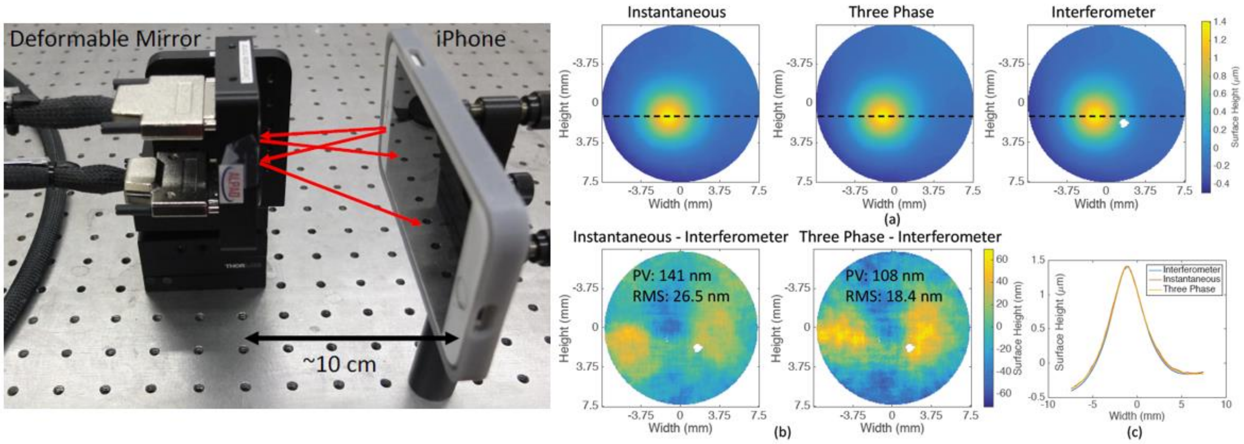

Fig. 3. (left) The experimental setup demonstrating the instantaneous phase shifting deflectometry measurement using a deformable mirror and the iPhone 6. (right) Comparison between instantaneous and conventional three phase shifting deflectometry methods and an interferometric method. We see about 30 nm RMS difference between the instantaneous, three phase, and interferometric results, showing that the instantaneous method is an accurate tool. The surfaces in (a) are the measured surface maps for all three methods, shown in (b) are the difference maps between the labeled methods, and (c) is the line profile data for all three methods corresponding to the black dashed line in (a). (Note that PV is the peak-to-valley of the map.) [9]

4. Concluding Remarks

Freeform optics receives great interest for various future optical system applications such as head mounted displays, highly compact camera systems, asymmetric solar energy concentrators and segmented extremely large telescopes. While it opens up a fascinating optical design and performance optimization space, the manufacturing of freeform optics has been a critical and practical limitation preventing its wide and general application. A rapid and efficient freeform optics manufacturing process has been investigated and developed through two innovations: fabrication and metrology technology. The freeform surface fabrication process has been developed using highly stable conformal tools, such as the stressed lap and RC lap. Adaptable nulling changes the spatial properties of a customized null component by introducing a deformable mirror controlled by the output from an SPGD search algorithm. Multiplexed deflectometry changes the temporal aspect of a conventional metrology by making an instantaneous phase shifting measurement demonstrated on a deformable mirror that varies with time. This deterministic fabrication process based on dynamic metrology will increase the overall manufacturing efficiency, saving significant amount of manufacturing related resources including machine run time, optics shop maintenance, human resources, mechanical/chemical polishing materials, and overall cost.

5. References

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Note: This conference paper mostly summarizes the original research works that have been separately reported and published [2, 5-7, 9]. Please, refer to the original publications for details.

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