Development and Results for Stressed-lap Polishing of Large Telescope Mirrors[1]

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Abstract: The University of Arizona Mirror Laboratory polishing program relies on the stressed-lap polishing tool. Its implementation is discussed for recent mirrors including the 8.4m off-axis Giant Magellan Telescope (GMT) and Large Synoptic Survey Telescope (LSST) mirrors. The stressed lap has brought 12 telescope primary mirrors to a successful conclusion. The mirror diameters have spanned 1.8m to 8.4m with aspheric departures ranging from 456 µm (Vatican 1.8m f/1.0) to 14,000 µm (GMT 8.4m off-axis segment). Each has a final surface figure error near 25 nm rms. The strengths of the stressed lap include rapid low order figuring with removal rates near 20 µm/hr / (m/s) / psi over a 1.2m pitch diameter and efficient smoothing of high frequency ripples. The stressed lap is a very stiff large tool with the ability to change its optical shape as it moves over the mirror surface. The lap struggles near the mirror edge and for smoothing at 5-10cm spatial scales. The lap also suffered from erratic drag variations during polishing of the first 8.4m GMT off-axis segment, and required several small rigid conformal non-Newtonian laps for support. The hardware and software implementation of the stressed lap is discussed including the methods used to calibrate its shape and moment control system. Future changes to the stressed lap system for the next GMT off-axis mirrors are summarized.

OCIS codes: (220.4610) Optical fabrication; (220.5450) Polishing; (220.1250) Aspherics

1. Introduction and anatomy of the stressed-lap polishing tool

The stressed-lap polishing tool [1-4] creates a very stiff surface which reproduces the sub-aperture shape of the aspheric mirror corresponding to the tool's position on the mirror surface—thus removing surface errors that protrude from the desired mirror shape and smoothing the surface as it is rotated and translated over the mirror surface.

The 1.2m diameter stressed lap consists of a 7075-T6 aluminum baseplate 1.6m in diameter and 50mm thick. 18 active edge actuators (benders) spaced evenly along the tool periphery create bending and twisting moments capable of producing focus, astigmatism, coma, and trefoil changes to its shape [5]. 100mm square pitch (or other) pads are attached directly to the plate or to an intermediate nylon interface which has an average curvature appropriate for the mirror. The stiffness of the nylon, RTV adhesive, and pitch pad stack-up is approximately 343,000 psi/in.

The lap is attached to the machine spindle with three four-bar linkages that produce a pivot point at the pitch-glass contact, insure that lateral translation forces do not produce unwanted pressure gradients across the lap surface, and provide measurement of the lateral forces and torque being applied to the mirror. Three active axial lifters produce an upward force to adjust the downward polishing pressure, correct for the overturning moment of the tool due to its relatively high center of gravity as it tilts on the mirror surface, and allow the application of pressure gradients helpful to the mirror polishing. The basic elements are shown in Fig 1.

2. Shape and moment calibrations

Lap shape is calibrated by kinematically attaching the lap surface to an array of 32 LVDT displacement sensors that contact the lap baseplate surface through spaces between the pitch pads. The ideal lap shape is a function of the lap's distance from the mirror vertex r and the lap rotation angle θ. The calibration routine optimizes the bender force to minimize the rms shape error at a number of discrete points (r,θ). For each position, the computer calculates the

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desired displacement for each shape sensor relative to the shape of the lap at the mirror vertex. For conic mirror surfaces, analytic equations for the ideal lap shape are used [6]. For mirrors with additional aspheric terms (e.g. LSST M1 and M3 surfaces), an iterative solution is employed. The solution for bender forces is based on the measured influence of the benders on the lap shape. We use a modal solution consisting of force distributions that vary sinusoidally around the perimeter of the lap. The algorithm requires several iterations to find the optimum bender forces at each (r,θ), due to non-linearity in the shape change as a function of bender force, and in order to overcome sensor noise at the level of a few µm. Iteration continues until the shape error is typically below 3 µm rms. After the optimum forces are found for all points (r,θ), Zernike polynomials are fit to each bender's force distribution and sampled into a look-up table used during polishing.

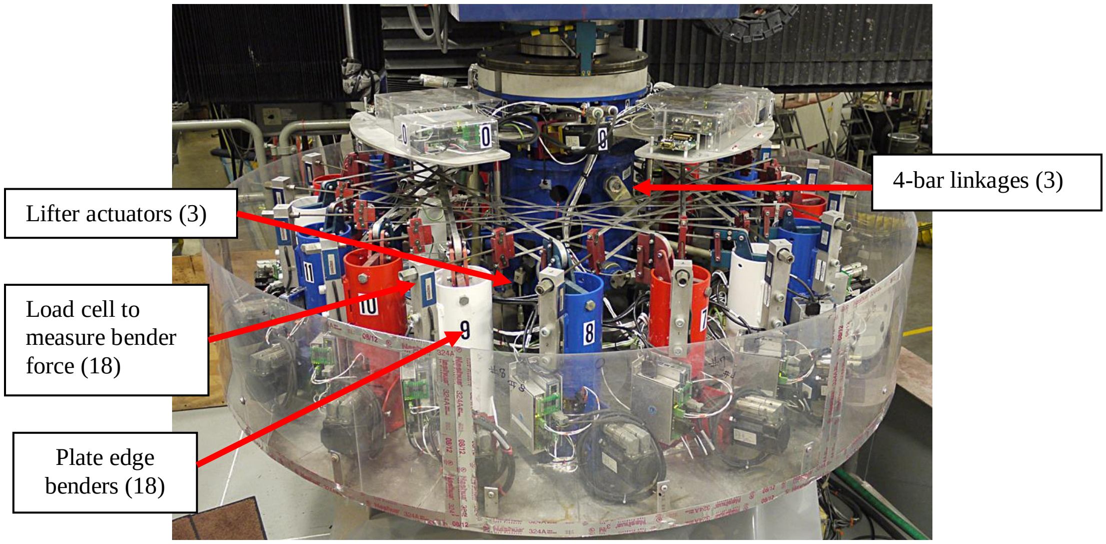

Figure 1: The 1.2m stressed lap with identifying features.

The lap is supported axially by 3 active actuators called lifters. They set the polishing pressure of the lap on the mirror and produce x and y moments on the lap plate. Calibration of the upward force and moments they create is obtained by connecting 3 load cells to the pitch side of the lap plate that in turn contact a hard flat reference surface. The influence of the lifter system on upward force (*i.e.*, polishing pressure) and x and y moments are measured and stored. For a level reference surface, lifter offsets are determined that minimize the moments (*i.e.*, pressure gradients) on the lap plate. By tilting the reference surface, the overturning moment of the lap's high center of gravity and changes in the downward force can be measured and corrected. By rotating the lap on the reference surface, the variation in applied moments can be verified. The proper action of the four-bar linkages can be verified by applying pure lateral forces to the lap in the plane perpendicular to the machine spindle that includes the pivot point and insuring that unwanted pressure gradients are sufficiently small. All the measurement results are contained in a matrix that the computer uses during polishing. The tilt of the lap on the mirror is measured with 3 displacement sensors attached to the machine spindle that contact the lap plate allowing the lifters to compensate for the overturning moment of the lap system.

3. Shape calibration for the 8.4m GMT off-axis segment

The GMT primary mirror is a 25 meter f/0.7 parent surface composed of seven 8.4 meter circular segments, six of which are identical off-axis segments each with 14.2mm of aspheric departure [7]. Changes in the lap shape are calculated relative to the reference shape established at the GMT parent vertex. Lap shape changes over 1.2m diameter are 480 µm p-v and 610 µm p-v for the segment points closest and farthest from the parent vertex respectively. The calibrated force distributions for 3 of the 18 benders are shown in Figure 2.

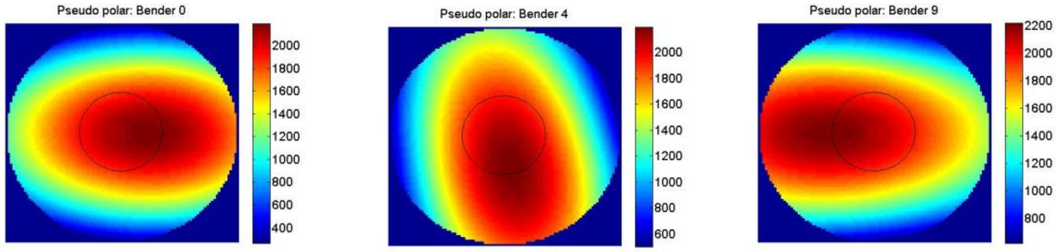

Figure 2: Psuedo-polar force distributions for 3 of the 18 stressed-lap benders over the GMT parent mirror to 12.6m radius. Concentric circles describe the bender force at a given lap position on the parent mirror (*i.e*, rotating the lap at a given point is equivalent to sampling the lap shapes about a circle centered on the parent vertex and containing the lap center). The GMT off-axis segment occupies the area outside of the black circle. Colorbars are bender force (N).

4. Future improvements for GMT stressed-lap polishing.

Rapid fabrication of the remaining GMT segments is paramount. Towards that end, we have identified additional functionality. The principal addition will be the construction of a new low center-of-gravity orbital 60cm stressed lap designed to complement the existing 1.2m unit for mid-scale smoothing and edge work. A rapidly rotating stressed lap places a large burden on the shape change system response for the aggressive off-axis segments. The current lap cannot be rotated faster than 3rpm without introducing unwanted phase errors between the bender commands and their responses. Additionally, high mirror rotation velocities on the first GMT segment caused unwanted drag anomalies and required mirror rotations < 0.5 rpm. Adding orbital motion to the new lap will allow high removal rates without the need to rapidly spin the mirror or lap. Tool paths with slower and gradual shape changes can be chosen without compromising glass removal rate.

When a large tool overhangs the mirror edge, gravity distorts its shape causing systematic up and down high-slope axisymmetric surface features. Using finite element models to predict gravity distortion of the lap plate, we have begun superimposing bender forces to correct this distortion onto the optical shape forces. This correction was started near the end of the 8.4m LSST M1 polishing, and it appeared to provide welcome relief from the high slope edge errors.

5. References

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