Development of a Convex Surface Measurement Using Prescription Retrieval

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Abstract: The test geometry for a subaperture-scanning measurement technique for convex optical surfaces is discussed. Preliminary simulations of a convex spherical measurement using a prescription retrieval algorithm are demonstrated. © 2019 The Author(s)

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1. Introduction

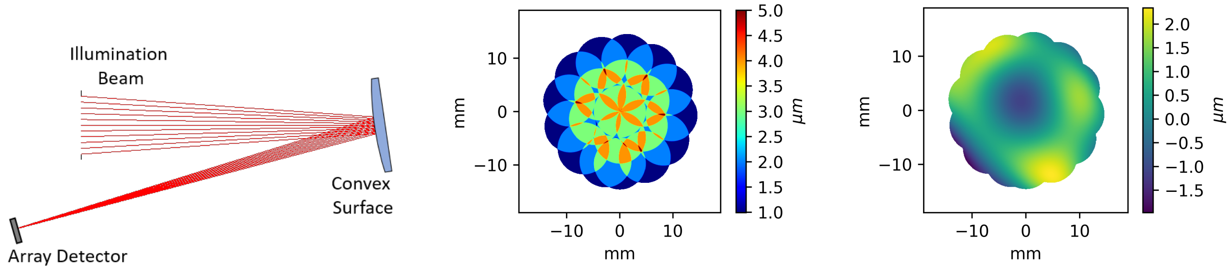
Prescription retrieval is a method of reconstructing optical prescription parameters from measured intensities at the image plane using a combined ray-trace and diffraction model [1–3]. Initially applied to as-built characterization of the Hubble Space Telescope [1], prescription retrieval is attractive for optical surface metrology due to its reduced hardware requirements. Furthermore, prescription retrieval may offer additional flexibility for testing convex optics over a similar approach of wavefront sensing by transverse translation diverse phase retrieval (TTDPR) [4, 5].

In TTDPR for surface testing, a subaperture illumination pattern is scanned over an optical surface and the reflected light from each illumination position is measured on a distant array detector. These intensities are then used to jointly reconstruct the wavefront aberration function near the surface under test, which is used to calculate surface topography error on the optic. TTDPR is well-suited for concave surface measurement because reflected light from either a point source or a collimated beam to be focused on a detector array without requiring additional optics. Furthermore, translating illumination can be easily achieved using a physical translating subaperture upstream of the test surface.

Convex surfaces, however, have negative power in reflection, which can be addressed by introducing a converging illumination beam [6]. To achieve translating illumination across a convex surface, we may take an approach similar to concave-measuring TTDPR, in which a large static beam is clipped by a smaller moving mask. However, this method may require large incoming angles and large-aperture illumination optics, raising practical concerns. An alternative approach is to use smaller illumination optics, so that only a subaperture portion of the surface is illuminated at any given time. This illumination may then be translated by moving the illumination optics, moving the surface under test, or a combination of the two. Moving the surface relative to the illumination beam necessitates a departure from the conventional algorithms used for TTDPR, because each instantaneous wavefront will no longer be part of a single global wavefront. However, the measured intensities can be predicted using prescription retrieval. In the prescription retrieval algorithm, the wavefront aberration function in the exit pupil is calculated directly from optical paths of rays traced through a model of the test system, accurately modeling field-dependent aberrations. From the exit pupil, diffraction propagators are used to simulate the intensity distribution in the image plane. Simulated intensity patterns are compared with laboratory-measured intensities, and gradient-based, non-linear optimization is used to minimize the differences between simulated and measured intensities with respect to prescription parameters such as conic constants and surface sag polynomial coefficients. Additionally, this test approach shares other advantages with TTDPR, specifically the ability to measure aspheric and freeform optical surfaces without requiring null optics.

2. Prescription Retrieval Simulations

Preliminary simulations were performed to demonstrate a convex surface measurement using a moving-part test geometry and a prescription retrieval algorithm, using a prescription retrieval code library developed by Moore and demonstrated in [3]. We simulated a 204.8 mm radius of curvature convex mirror and a converging illumination beam, $\lambda = 632.8$ nm, which illuminated a 9.75 mm circular portion of the mirror. The mirror was simulated with a 8° tilt angle to clear the reflected beam from obscuration. An array detector with 6.0 µm square pixels was simulated a distance ≈228 mm from the simulated mirror, leading to simulated intensities with a sampling ratio [6] $Q \approx 2.5$, higher than Nyquist ($Q = 2$). Figure 1(a) shows a visualization of this geometry. Twenty intensity patterns were simulated, each



(a) (b) (c)

Fig. 1: (a) Subaperture dwell map. Colorbar indicates the number of times a region on the surface is sampled by the illumination. (b) Surface sag departure from base sphere.

corresponding to a different position of the test mirror. Mirror decenter parameters were calculated so that the convex surface moved about its nominal center of curvature to maintain a quasi-constant incident angle on the surface for all positions. Figure 1(b) shows the subaperture dwell pattern for this simulation, which covered an approximately 29 mm diameter circular region on the convex surface. In addition to a base sphere, a 4.2 μm peak-to-valley, 0.83 μm RMS sag departure was added to the convex mirror, modeled using a superposition of 28 Zernike polynomials (through 6^{th} radial order), shown in Fig. 1(c).

The convex surface was reconstructed using gradient-based non-linear optimization. The base convex sphere was used as a starting point, and Zernike polynomial coefficients were varied in optimization. Numerical gradients were calculated using the method of reverse-accumulation automated differentiation, which reduces computation time compared to finite-difference derivatives [2, 7]. First, reconstructions were performed on noise-free simulated intensities. The optimizer converged in 385 iterations, reconstructing the unknown surface with $< 7 \times 10^{-4}$ nm root-mean-squared error (RMSE), essentially demonstrating a machine-limited model match. Next, optimization was performed with simulated detector noise, assuming Poisson noise with 30k peak photoelectrons, and 16 electrons RMS Gaussian read noise. In this case, the optimizer converged in 400 iterations with a final RMSE of 0.14 nm.

3. Summary

We have described a subaperture-scanning measurement geometry for convex surface testing which utilized a prescription retrieval algorithm. Preliminary simulations of a convex surface under test were performed, and successful surface reconstructions were obtained both with and without the presence of simulated detector noise. Prescription retrieval may be a powerful tool for convex surface testing of aspheric and freeform optics.

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