Dual-CGH Interferometry Test for X-Ray Mirror Mandrels

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ABSTRACT

We describe a glancing-incidence interferometric double-pass test, based on a pair of computer-generated holograms (CGHs), for mandrels used to fabricate x-ray mirrors for space-based x-ray telescopes. The design of the test and its realization are described. The application illustrates the advantage of dual-CGH tests for the complete metrology of precise optical surfaces.

Keywords: Interferometry, optical test, computer-generated hologram, x-ray telescope optics

1. INTRODUCTION

Interferometry is the most widely used form of metrology underpinning the fabrication of precision optics. It is used to measure the form errors of optical surfaces by comparing the surface form with the form of an appropriate reference wavefront. It is instructive to consider the simple case of testing a spherical surface with an interferometer to elucidate the usefulness of optical tests with computer-generated holograms (CGHs). Fig. 1a illustrates the form error measurement of a spherical surface using a spherical reference wavefront which can be generated by a transmission sphere or a zone plate. This setup can be used to measure the deviation of the spherical surface from a best-fit sphere, but it is not possible to completely characterize the surface, because the radius (or radius error) cannot be measured. It is always possible to move the spherical mirror to a position where the fringes disappear and the interferometer is "nulled". For the performance of many refractive imaging systems the accurate measurement of the form error is more important than the radius measurement, because radius errors in lenses can be compensated by adjusting lens spacings.

There are, however, optical surfaces for which the form error *and* the dimensional error must be controlled. Examples are optical systems using segmented mirrors in which all segments must have a common focal plane. Fig. 1b illustrates how the original test in Fig. 1a can be modified with an additional CGH to obtain a test which allows the determination of both form error *and* radius error. The test mirror is tilted and the beam reflected by the test mirror is returned by the second CGH. The mirror under test is now *inside* a cavity formed by the two CGHs and the mirror under test. Unlike in Fig. 1a, there is only *one* position D of the spherical mirror at which the interferometer fringes will disappear and this can happen *only* when the spherical mirror has the correct radius. When the fringes cannot be made to disappear by aligning the test part, they contain information about form error and radius error. The known distance d of the CGHs sets a length scale that can be used, togther with a computer model of the test, to determine the test part radius.

In the following sections we describe how the concept of the dual-CGH cavity test can be applied to test a mandrel for the fabrication of x-ray mirrors.

2. X-RAY TELESCOPE MIRRORS

Modern x-ray telescopes, especially space based ones, have nested mirror systems to achieve high throughput. For the International X-Ray Observatory (IXO) mission, one mirror fabrication technology under consideration is replication via glass slumping of the mirrors over a precisely figured fused silica mandrel.[1-3] The mandrel accuracy needs to be at least a factor of two better than the desired mirror accuracy to allow for errors in the slumping process. The half-power-diameter (HPD), which is the image space angular subtense where the telescope point spread function falls to 50% of its peak value,

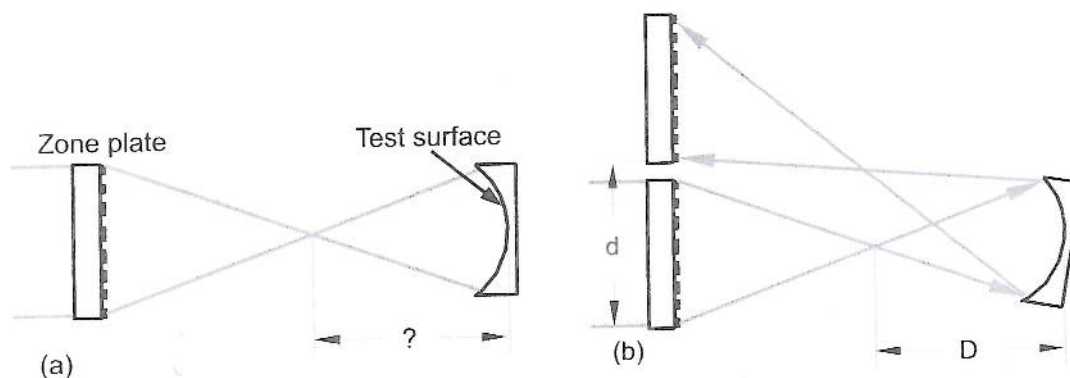Author e-mail information: ulf.griesmann@nist.gov

Figure 1. Schematics of an interferometric test setup for measuring the form error of a spherical surface (a), and a complete test using two computer-generated holograms for measuring both form error and radius error (b).

for the optics of the IXO mission is about 5" which translates into a mirror of about 3" HPD and 1.5" for the replication mandrel.

Although the mandrels have conic surfaces, standard tests for conic surfaces cannot be used to test the mandrels because they are the non-focusing conjugates of the focusing replicated mirrors. It is also important that all mirror segments have a common focal point and thus, both form error and mandrel geometry must be measured with low uncertainty to assure that all the optics are fabricated to the same plate scale demanded by the confocality of the nested systems.

While modern polishing technology can produce such non-focusing optics, the guiding metrology is often inadequate. Probe- and scanning metrology tools have been applied for mandrel characterization. Fawcett[4] used a coordinate-measuriung machine (CMM) with 100 nm resolution and Li et al.[5] a long trace profiler to determine figure and geometry of finished mandrels after polishing. A non-contact CMM with cylindrical geometry was employed by Zhang et al.[6] for the geometric measurement of mandrel surfaces. However, the random and systematic errors of these systems make them inadequate for mandrel characterization, particularly when the polishing step of mandrel fabrication is reached. In addition, all scanning methods result in low spatial resolution and suffer from long acquisition times and concomitant stability issues. The low spatial resolution often requires that a second metrology method must be used to measure the surface form error. Combining the dimensional and surface form measurements into a single test using a CGH cavity in the manner described in Section 1 overcomes these difficulties.

3. MANDREL METROLOGY EXAMPLE AND TEST DESIGN

We demonstrate the advantages of dual-CGH cavity metrology by discussing here the case of the design for a specific mandrel for the IXO mission.[7] The demonstration is a proof-of-concept and of reduced scale relative to the testing of the flight optics. The dual-CGH cavity test we describe in this paper was inspired by the description of a test for cylindrical surfaces first published by Mantel et al.[8] For the mission mandrels, the analog to the test by Mantel et al.[8] would require very large (several hundred mm diameter) CGHs for the outer mirror shells. In the slumping process only a small fraction of the full 360° azimuthal span of the mandrel is used. For IXO's glass mirror development this is 60° for the inner mirror shells and 30° for the outer mirror shells. The slumping area need only extend about 10% beyond these boundaries and the test only needs to cover the slumping area. This results in sector-shaped CGH substrates. The entire mandrel can be tested by rotating it on a spindle and stitching the resulting measurement data. For the demonstration outlined here we employ round CGH substrates because they are more readily available and are less expensive.

The layout of the demonstration test is shown in Fig. 2. The system includes an interferometer (only the reference flat is shown), the CGH pair, and the mandrel under test. A collimated beam from the interferometer impinges on CGH1 resulting in a diffracted wavefront that is incident on the mandrel at angle α. The reflected beam propagates to CGH2, is diffracted and propagates back along its original path. After one measurement the mandrel can be rotated azimuthally and an adjacent strip can be measured. The sequence is repeated until the slumping area or the entire mandrel has been tested. For the demonstration test a CGH diameter of 150 mm was chosen. The mandrel is a paraboloid with a vertex radius of about 0.391 mm, a mid-plane diameter of 250.8 mm, and an axial clear aperture of 275 mm. The CGH1-CGH2
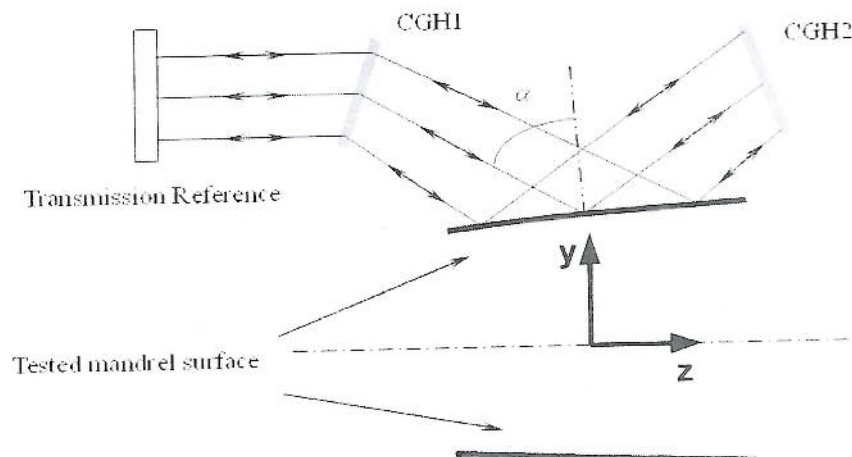
Figure 2. Schematic layout of the CGH cavity test for a x-ray mirror mandrel. Angles and geometry are exaggerated for clarity.

center-to-center distance was set at 400 mm to allow room for the mandrel on a multi-axis mount. As large an angular and axial span of the mandrel as possible must be illuminated to gain sensitivity of the test to mandrel position and the dimensional parameters of the mandrel. This implies a larger glancing angle (measured from the surface normal), which does reduce the height sensitivity of the test. We settled on an angle of 71.6° as a compromise between increased cone angle sensitivity and reduced height sensitivity for the given CGH size. The height sensitivity is reduced to about 2/3 that of a normal incidence test.

An important consideration is the throughput T of the test. It is a combination of CGH diffraction efficiency, $\mathcal{E}$, and mandrel reflectivity R. Assuming identical efficiency for transmission CGH1 and reflection CGH2, the throughput of the test arm is

$$T = \tau^2 R^2 \mathcal{E}^3,$$ (1)

where τ is the transmittance of the uncoated reference flat. When phase CGHs with an efficiency of about 40% are employed and a temporary reflective coating is applied to the mandrel for the test, the throughput, calculated with Eq. 1, is about 3.9% resulting in a good match of the intensity of the test beam to that of the reference beam.

In designing the dual-CGH test for the mandrel a number of constraints had to be considered in addition to the through-put. Since the feature size of the CGHs, especially for the fiducial CGHs (see section 4), is not much larger than the wavelength, 632.8 nm, polarization effects cannot be neglected, especially for CGH2, because polarization effects in reflection CGHs are more significant. The efficiency of CGH2 for transverse electric (TE) and transverse magnetic (TM) polarization directions was modeled as a function of the angle of incidence on the CGH. The angle was then chosen to avoid different efficiencies for the TE and TM polarization components. Another important constraint on the tilt angles of the CGHs is the need to prevent stray beams from undesired diffraction orders from entering the interferometer. A final consideration is the minimal feature size of the CGHs. The diffraction angles must be kept small enough to ensure that the CGHs can be fabricated with the available lithographic tools. The minimum feature sizes on CGH1 and CGH2 are approximately 0.9 μm.

4. PHASE FUNCTIONS AND CGH LAYOUT

The phase functions of CGH1 and CGH2 must be known before they can be fabricated. Generally, polynomials in Cartesian or polar coordinates are used in commercial optical design software. The advantage of polynomials is that the phase functions can be described easily. Polynomials of sufficiently high order ensure that the phase function is computed to the needed overall accuracy. The disadvantage of using polynomials to express the phase function is the presence of high-frequency ripple in the phase function, especially when higher-order polynomials are used. For the two CGHs in the mandrel test demonstration it was possible to derive a semi-analytical expression for the phase functions. They are
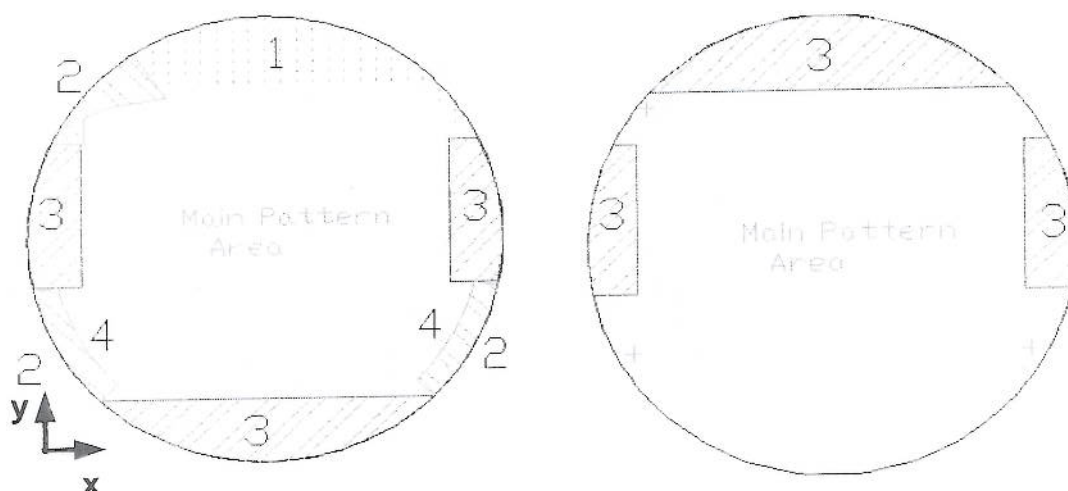
Figure 3. Layout of CGH1 (left) and CGH2 (right). Area 1: tilt alignment fiducial for CGH1 in the interferometer beam; areas 2: coarse alignment fiducials; areas 3: fine alignment fiducials on CGH1 and CGH2; areas 4: fiducials used to align the mandrel in the test cavity.

still polynomials, but only of 3rd order. This greatly reduces the ripple seen in the 10th order generic polynomial functions required for a comparable root-mean-square (rms) phase error. For CGH1 the semi-analytical phase function is

$$\Phi_1(x,y) = -\frac{2\pi}{\lambda}\left[\sum_{k=0}^{3}\sum_{j=0}^{3}C_{kj}\left((y\cos\theta_1+y_C)\tan\theta_1\right)^k\left(\sqrt{x^2+(y\cos\theta_1+y_C)^2}\right)^{j-k}-y\sin\theta_1\right], \quad (2)$$

where (x,y) is the local coordinate of a point on the surface of CGH1 in mm, θ_1 is the tilt angle of CGH1, λ the wavelength of light (632.8×10^{-6} mm), and y_C the y-coordinate of the center of CGH1 in the global coordinate system. The coefficient matrix C is

$$C = \begin{pmatrix} 29.6452 & 0.31265 & 1.1567 & -8.5314\cdot10^{-12} \\ 0.00167 & -0.9499 & 2.093 & -2.3299 \\ 0.276 & -0.0043 & 2.1996\cdot10^{-5} & -3.702\cdot10^{-8} \\ 11.245 & -0.1748 & 0.00089 & -1.5031\cdot10^{-6} \end{pmatrix}\cdot 1\cdot\begin{pmatrix} mm \\ 1 \\ mm^{-1} \\ mm^{-2} \end{pmatrix}, \quad (3)$$

where 1 is the identity matrix of size 4. An expression similar to Eq. 2 can be derived for CGH2. Details of the derivation are given by Gao et al.[9] Fiducials are used to establish the CGH cavity. They serve as guides to eliminate all degrees of freedom of movement between the two CGHs and are an important element of the test method. Four types of fiducials are encoded onto the CGH substrates in addition to the main patterns (see Fig. 3): coarse alignment and fine alignment fiducials for CGH1 to CGH2, a fiducial on CGH1 to align it in the interferometer beam, and fiducials on CGH1 and CGH2 to aid alignment of the mandrel in the test cavity. The coarse alignment fiducials on CGH1 are three zone plates, which focus the collimated beam onto three marks on the surface of CGH2. There are also fine alignment fiducials which focus the collimated beam into line foci in x and y direction between CGH1 and CGH2. These fiducials have a relatively large numerical aperture and are used to set distance and orientation of CGH2 with respect to CGH1 with high sensitivity.

Work to fabricate the CGHs is currently underway in collaboration with the Institute of Technical Optics (ITO) at the University of Stuttgart, Germany.

5. CONCLUDING REMARKS

We have generalized the CGH testing method described by Mantel et al.[8] to the idea of CGH cavity metrology. This idea can be applied to a wide range of metrological problems where it is desirable to test both the geometry and surface figure. This comes at the expense of a reduced throughput for the test, so phase CGHs are normally required. We have derived a semi-analytical phase function for the main CGH pattern that avoids the higher-frequency oscillations ubiquitous to the x-y polynomial phase functions employed by most optical design programs. This reduction of phase ripple is of

great importance for testing of mandrels for X-ray applications and can improve the speed of pattern generation from the phase function. An example fiducial scheme was outlined that constrains the cavity geometry and thus the test and mandrel geometry. Although this fiducial scheme is only one of many that could be devised, the need for this type of fiducial is unique to CGH cavity metrology. The fiducial scheme's sensitivity will ultimately determine the test geometry sensitivity. We are currently working on the fabrication of the CGHs and the implementation of the mandrel test demonstration.

Acknowledgments

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