COMPUTER GENERARED HOLOGRAMS AS 3D CALIBRATION ARTIFACTS

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BACKGROUND

Computer generated holograms[1] (CGH) were developed in the late 1960's as an aid in the interferometric testing of optical surfaces[2]. At the time the devices available for producing the CGHs were fairly low resolution plotting devices akin to the current ink jet printers. Over the years the means for making CGHs improved rapidly and they can now be made by e-beam methods with feature location precision of 10 nm rms or better. This high precision in patterning of the CGHs made it possible to create null optics for quite severe departures from sphericity, and CGHs have become a very practical method of testing aspheres with substantial departures from a sphere and for testing free form optics[3].

In this paper we step back from complex CGH patterns used to test aspheric and freeform optics to ask what can be done with the simplest CGH patterns and the high precision of pattern location on a photomask substrate[4]. We first describe the use of patterns of equally spaced concentric circles to create an axis in space perpendicular to the CGH plane, and the Fresnel zone patterns that produce points in space when illuminated with a point source of light.

We then show how these points and axes are interrogated in a practical manor by means of an autostigmatic microscope (ASM), or for greater precision, with an interferometer. Following this discussion of how points and axes are created and retrieved from simple CGH patterns, we show how these features can be combined to produce artifacts for the calibration of precision instruments and the making of fixtures for the assembly of optical and mechanical components.

SIMPLE CGH PATTERNS AND THEIR PROPERTIES

It is well known that a pattern of equally spaced straight lines, a grating, will diffract light when the spacing of the lines is on the order of the wavelength of light, and the angle of diffraction, α, is given by $\sin \alpha = m\lambda/s$ where m, an integer, is the diffraction order number and λ is the wavelength of the light normally incident on the grating. Now think of a pattern of concentric circles where the spacing of the circles is uniform, and envision a diameter of that pattern. It is a very narrow straight line diffraction grating.

From symmetry, a point source of light above the circular pattern but centered on it will produce cones of diffracted light, one cone converging and one diverging depending on the + or – 1st order as well as other cones of higher orders similar to an axicon[5]. For any practical distance above the pattern a bright spot appears surrounded by dimmer concentric rings when viewed with an ASM centered on the axis as shown in Fig. 1a or with an interferometer in Fig 1b. This pattern is not very efficient light wise so the farther from the CGH the brighter the point source must be. However, a bright spot could still be clearly seen as far away as 10 m.

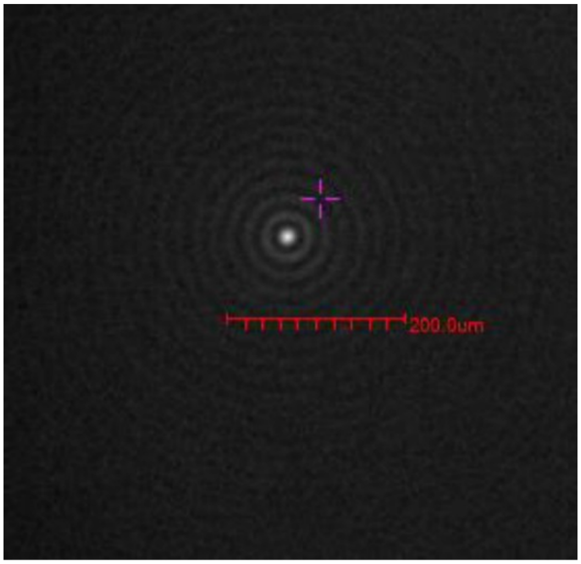

FIGURE 1a. Reflected spot produced by a CGH pattern of equally spaced concentric rings, or a pattern simulating an axicon.

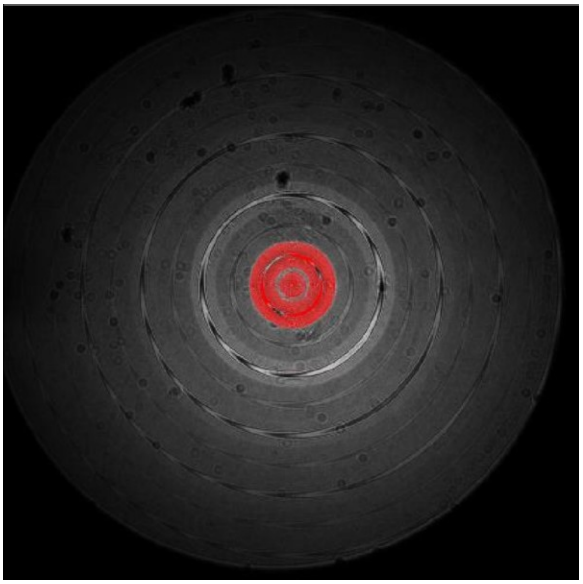

FIGURE 1a. Interferogram of light reflected from a CGH pattern of equally spaced concentric rings, or an axicon pattern. (The red in the center are saturated pixels.)

The Fresnel zones work much the same way as the equally spaced pattern but here the radii of the zones are proportional to the square root of the integer number of the ring in the pattern. If this pattern is illuminated by a quasi-monochromatic point source above and centered on the pattern the diffracted light will come to focus when the ring spacing $s = \mathrm{sqrt}((R+n\lambda/2)^2-R^2)$ where R is the distance above the CGH, n is the integer ring number and λ is the wavelength of the light in the point source. The reason the light comes to focus is that each ring reflects light back that is one wavelength farther away from the focus so all the light is in phase when it reaches the focus.

Since the ring spacing is proportional to R almost any distance above the CGH can be produced within practical limits of the e-beam writing. For example, for $R = 1$ mm a pattern with 100 rings would still have a ring spacing at the edge of the pattern of more than 1 μm, and for $R = 10$ m a pattern with 100 rings would be about 25 mm in diameter although the f/number of the pattern would be very large (f/400) along with a large depth of focus.

The Fresnel zone patterns can be interrogated by either an ASM or interferometer. Typical results at the focus using either instrument are shown in Fig. 2. Using the ASM, in this case a Point Source Microscope (PSM)[6] with a red laser diode point source and a color camera shows the focused image from the Fresnel pattern, Fig. 2a. The image has a 4 point star shape because the CGH pattern was designed with a quarter wave of astigmatism to aid in finding best focus.

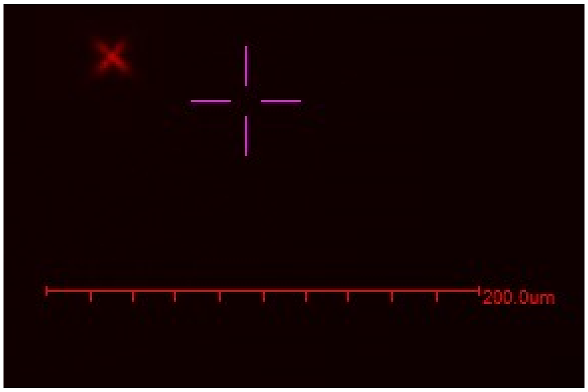

FIGURE 2a. Reflected spot from a Fresnel zone CGH pattern as viewed with a PSM with a 635 nm laser diode source. The cross in the red spot is due to a quarter wave of astigmatism built into the CGH Fresnel zone pattern to aid in focusing.

Best focus was found at 14.944 mm above the CGH and the pattern was designed to focus at 15 mm using light with a wavelength of 632.8 nm where the laser diode was approximately 635 nm, a 0.3% difference in both cases. In fact the color camera was being used to see if the focus changed as expected with a change in source wavelength. At 450 nm there were ball foci for both the + and – 1st orders at 21.09 and 10.67 mm above the CGH, consistent with the change in wavelength of the source.

In the case of Fig. 2b, the reason there is a “hole” in the middle of the interferogram is that there were 3 other Fresnel patterns inside this one that focused 135 mm above the CGH. As the interferometer was brought toward the CGH each pattern focused at its correct location. Since the interferogram can be analyzed with aberration, or Zernike, coefficients it is possible to find focus in 3 degrees of freedom to the nanometer level as opposed to the <1 μm level laterally and 2-3 μm axially for the PSM.

It is this precision in the location of the foci and the intrinsic precision of the photomask pattern to the same level that make the CGHs valuable as calibration artifacts. Further, they are made on fused silica substrates for good thermal stability and the pattern is chrome, a coating that is stable and will take a reasonable amount of abuse without affecting its precision.

FIGURE 2b. Interference fringes from the Fresnel zone CGH pattern at the 135 mm focus. The hole in the fringe pattern is due to out of focus Fresnel patterns inside the hole.

THE AUTOSTIGMATIC MICROSCOPE

Interferometers are well known so it is obvious from the fringe patterns in Figs. 1a and 2b that there is useful and precise data in the fringes. The autostigmatic microscope[7] is less well known so its use in interrogating the CGHs should be understood to appreciate the power of this technique. Fig. 3 shows the ray paths in a contemporary version of an ASM, the Point Source Microscope (PSM).

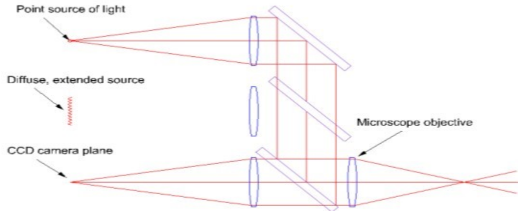

FIGURE 3. Ray path in the Point Source Microscope (PSM) showing how the point source, the focus of the objective and the focus on the camera are all conjugate in three degrees of translational freedom.

The point source is the end of a single mode fiber so the wavefront coming from the fiber is close to "perfect". The wavefront is collimated and sent into a microscope objective via a beamsplitter to form a nominally perfect focused spot that then continues to diverge as a near perfect spherical wavefront. The focus of the objective is conjugate with the point source so that if a point source of light were placed at the objective's focus facing back into the PSM, that light would focus on the camera at a location precisely conjugate to the original point source.

In fact, placing a point source at the objective focus is exactly how the electronic cross hairs (magenta crosses in Figs. 1a and 2a) are centered on the detector. The point source is a specular surface located at the objective's focus so the light from the internal point source is reflected back to the detector using a Cat's eye image. By electronically centroiding on the Cat's eye spot the PSM crosshairs are made conjugate with the point source. (The spots in Figs. 1a and 2a were purposely not centered on the crosshairs so the spot characteristics could be easily seen.)

MAKING THE OPTICAL CGH INTO A PHYSICAL ARTIFACT

Figure 4 shows the rays diverging from the PSM objective to a Fresnel zone CGH pattern where the spacing between the CGH and PSM objective focus is correct for rays to retrace themselves back through focus and on to the camera. Other rays are diffracted to produce a second focus beyond the CGH and the minus 1st order rays diverge back toward the PSM. This is exactly the situation for the spot shown in Fig. 2a with the understanding that only those rays that retrace themselves and go into the objective ever get back into the PSM to be detected.

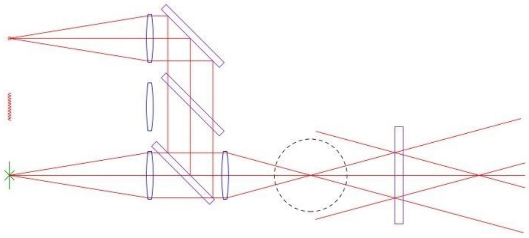

FIGURE 4. PSM ray path with a Fresnel zone CGH and a ball centered on the Fresnel zone focus. The Fresnel zone pattern also produces a conjugate focus on the far side of the CGH.

Now consider the dotted circle surrounding the objective's focus. If this were a steel ball centered on the focus as in Fig. 4, the rays would strike the ball surface at normal incidence and retrace themselves back into the PSM and show up on the detector in exactly the same place as the rays from the Fresnel zone CGH pattern. This is the idea behind making the CGH into a physical artifact, an idea first demonstrated, to the best of our knowledge by Coyle[8]. If the pattern on the CGH produces a spot of exactly the same radius as the ball, once the PSM is aligned to the CGH, the ball may be moved into place on the CGH until the return spot from it is centered on the PSM crosshairs, and the ball cemented to the CGH to sub-µm precision. Now a ball center on the CGH may also be located physically with a tactile probe.

Since Fresnel patterns simulating various radii can be arbitrarily located on the CGH it is possible to make up fixtures for kinematically assembling optical and mechanical parts. In Fig. 5 is an example of a fixture designed for the cementing of doublet lenses without the need for a rotary table. The 3 small balls assure the convex lower half of the lens is centered with its center of curvature on the axis of the Fresnel pattern that is centered with respect to the 3 balls. The PSM picks up the spot from the centered pattern at the center of curvature of the concave half of the lens. Once this half of the lens is centered so its center of curvature reflection is centered in the PSM, the positive half of the lens is added and a concentric Fresnel pattern diffracts the light through the assembly to the same height so the second half of the lens may be centered.

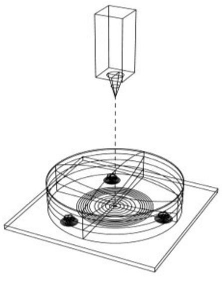

FIGURE 5. CGH fixture for cementing a doublet lens without the need for a rotary table. Lens rests on three balls symmetrically centered about two Fresnel zone patterns with radii matching the concave lower element and the same radius for the assembled doublet.

USING THE CGH FOR CALIBRATION

As a first try at designing a calibration artifact a close packed hexagonal array of 28 mm diameter Fresnel patterns were printed on a photo mask substrate as shown in Fig. 6.

FIGURE 6. A 6" photomask CGH with a close packed hexagonal array of Fresnel zone patterns on 28 mm centers[5]. The interferogram in Fig. 2a is of one of these patterns.

Since the array has an obvious 60° azimuthal period, placing the CGH on a rotary table would allow calibration every 60°. Because the outer patterns are about 100 mm from the center and the foci, or ball centers, can be located to < 1 µm, the calibration can be done to better than 1 arc second when account is taken of the doubling of sensitivity on reflection.

A more interesting use is for 3 dimensional calibrations. There are 4 concentric patterns in each 28 mm diameter patch having ball radii of 5, 15 45 and 135 mm. This CGH was placed on the work table of a CNC machine and the PSM mounted on the spindle. The PSM was centered on the central pattern and then the machine was programmed to move to each ball center at the 45 mm height and at the 135 mm height. Fig. 7 shows the nominal array of 23 ball centers in light grey and the measured offsets from the ball centers at 45 and 135 mm heights in a scale that is expanded by a factor of 2000.

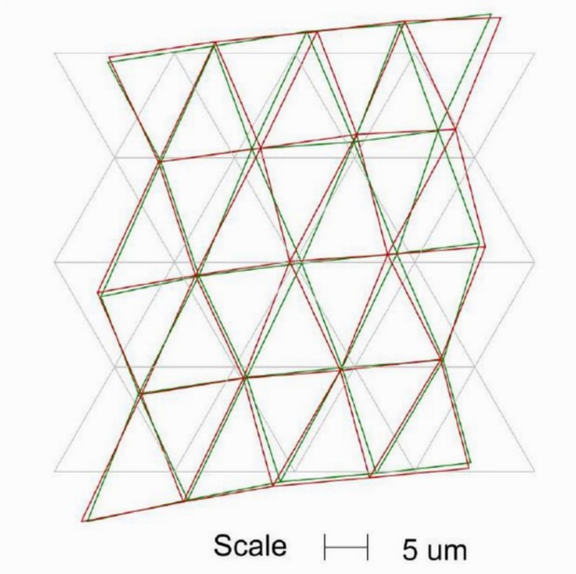

FIGURE 7. 3D calibration of a 3 axis machine tool at heights of 45 and 135 mm above the work table. The grey apexes are the nominal ball centers while the red and green apexes are errors from the nominal centers on a scale expanded 2000x.

It is clear from Fig. 7 that there was a small error in azimuth in setting up the scan, and that it appears the scale is longer in the y direction than x. Both planes look like they match to about 1 µm in most cases. We did not have time to take another set of data with the work table rotated 90° to see if the scale difference was really in the machine as expected or in the CGH.

This is a rather simple example using a prototype CGH design. It is clear now that a better artifact would have evenly spaced planes in z, and longer radii in all cases. Further, the CGHs are not limited to 150 mm square substrates. It is obvious that facilities exist for making photomasks as large as the largest LED TV screens, with less precision than this 150 mm square substrate but probably better precision than for any other kind of calibration artifact.

CONCLUSIONS

We have shown how simple patterns on computer generated holograms can be used as precise calibration artifacts and fixtures when they are interrogated with an autostigmatic microscope or an interferometer. The CGHs provide a flexible, stable, precise and easily reproduced artifact that should find great utility in the field of precision engineering.

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