Use of Computer Generated Holograms for Testing Aspheric Optics

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It has been more than 36 years since Lohmann and Paris first described computer generated holograms (CGHs) [1] and CGHs have been used to test aspheric optical elements for more than 35 years [2]. Computer generated holograms are now widely used in the testing of aspheric optical elements and it is expected that their use in aspheric testing will greatly increase the next few years as the superb measurement capability of CGHs are better appreciated by more optical manufacturing personnel. While CGHs are most often used to test rotationally symmetric surfaces, a great advantage of CGHs is that they can be made for testing free form optics almost as simply as for testing rotationally symmetric optics. Crosshairs can be put on the CGH to aid in the alignment of the CGH and additional holograms can be placed on the CGH to aid in the alignment of the optics or to aid in calibration of the CGH. CGH interferometers work well with phase-shifting techniques.

BASIC TEST SETUPS

Figure 1 shows one setup for using a CGH to perform an optical test and Figure 2 shows a typical CGH.

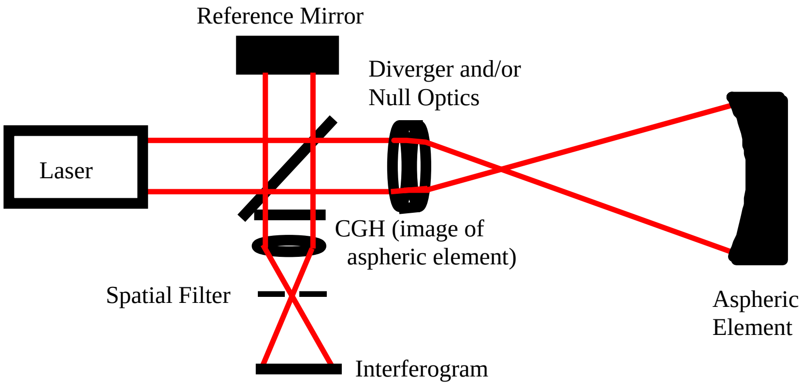

Figure 1. Typical CGH Interferometric Setup.

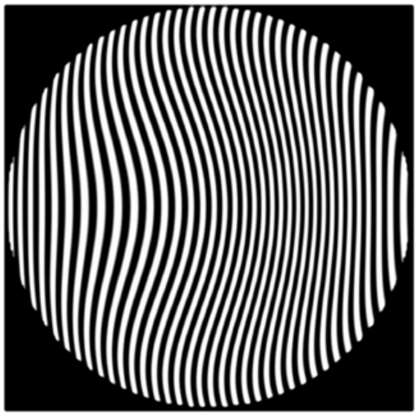

Figure 2. Typical CGH.

The CGH can be thought of as a binary representation of the interferogram, or hologram that would be recorded if we were to interfere the aspheric wavefront coming from a perfect aspheric surface with the reference beam. The procedure for making the CGH is to first raytrace the interferometer to determine the position of the fringes in the theoretical interferogram that would be obtained if the mirror under test were perfect. A plotter, such as a laser beam recorder or an e-beam recorder, is then used to draw lines along the calculated fringe positions.

When the CGH is placed in the interferometer as shown in Fig. 1, the CGH and the interference fringes produced by the interference of the reference wavefront and the wavefront produced by the mirror under test produce a moiré pattern that gives the difference between the CGH and the interference fringes. If sufficient tilt is introduced into the CGH to separate the diffraction orders of interest, spatial filtering can be used to improve the contrast of the moiré pattern. Spatial filtering is accomplished by reimaging the hologram with an appropriately placed small aperture in the focal plane of the reimaging lens. This aperture is placed such that it passes only the wavefront from the mirror under test and the +1 order beam resulting from illuminating the hologram with a plane wavefront, or equivalently passing the reference beam and the -1 order produced by illuminating the hologram with the aspheric wavefront. In the first case we are interfering two aspheric wavefronts, one produced by the aspheric mirror and the second produced by the CGH. In the second case we are interfering two plane waves, one produced by the reference arm and the second produced by the CGH removing the asphericity in the test beam. Figure 3 shows the various diffraction orders produced by a CGH. The requirement for being able to accomplish this spatial filtering is that in the making of the CGH, the slope (tilt) of the plane reference wavefront is at least as large as the maximum slope of the aspheric wavefront along the intersection of the plane of incidence of the plane wave and the aspheric wavefront. Thus, in the interference plane shown, an interferogram is produced that gives the difference between the wavefront produced by the mirror under test and the corresponding wavefront produced by the hologram.

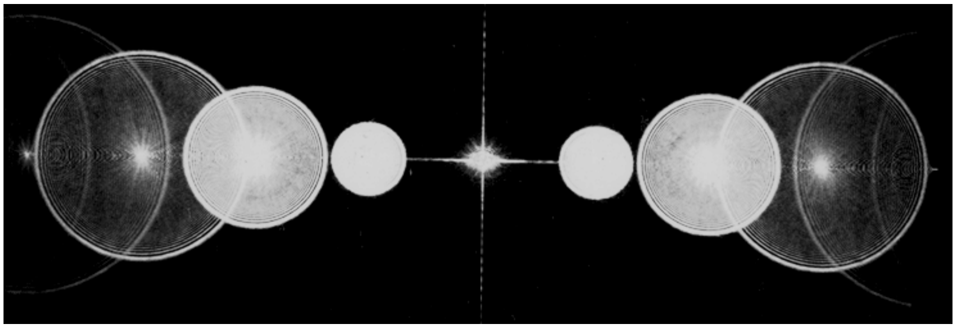

Figure 3. Diffraction orders produced by CGH.

There are many places in the interferometer where a CGH could be placed. One reason it is placed as shown is that thickness variations in the hologram plate have no effect on the results, and thus what could be a very serious source of error is eliminated. A second reason is that the CGH is used in single pass so its diffraction efficiency need not be high. It should be stressed that the above raytracing procedure used to make the holograms can be used for any general optical system. The only requirement is that all the optics in the interferometer be known so the system can be raytraced. An important consequence of raytracing the entire interferometer is that even though the diverger may be corrected only for spherical wavefronts and may introduce additional aberrations in the aspheric wavefront being passed through it, the hologram automatically corrects for these aberrations when a null test (or for all practical purposes, a near null test) is performed.

Figure 4 shows a more common arrangement for placing the CGH in the interferometric setup. An advantage of this setup is that it can be used with commercial interferometers without any need for modifying the interferometer. A second very large advantage is that since the CGH is placed between the asphere and the diverger lens it is not necessary to include the diverger lens in the raytrace and hence it is not necessary to precisely know the design of the specific diverger lens being used. However, in this setup the quality of the CGH substrate must be known so errors introduced by it can be subtracted from the test results.

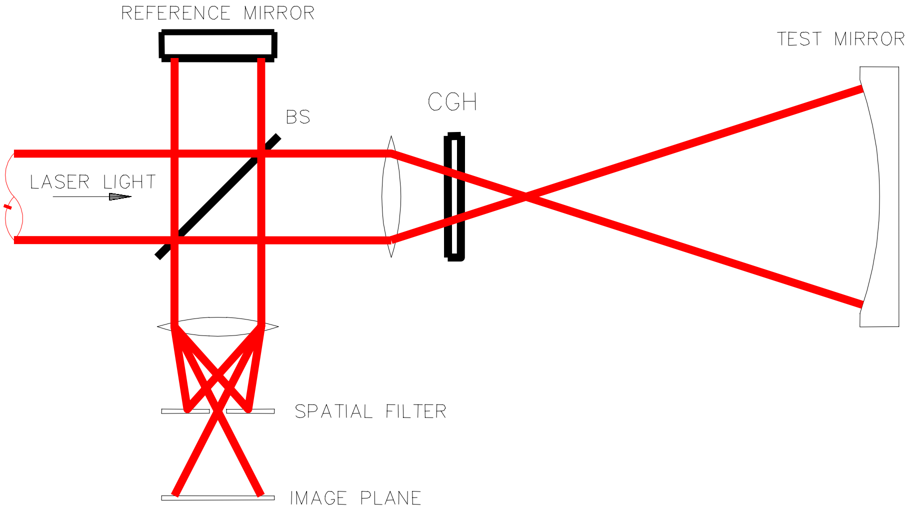

Figure 4. Common setup for using a CGH as a null lens.

ERROR SOURCES

Plotter Errors

The largest source of error is in the drawing of the grating lines [3-4]. To show how the CGH wavefront accuracy depends upon the number of distortion free plotter resolution points and the maximum slope of the aspheric wavefront being tested, let us suppose the plotter has P X P resolution points. Thus, there are $P/2$ resolution points across the radius of the hologram. Since by definition the maximum error in plotting any point is one-half of a resolution unit, any portion of each line making up the hologram could be displaced from where it should be a distance equal to l/P the radius of the hologram. Let the maximum difference between the slope of the aspheric wavefront and the tilted plane wave be S waves per hologram radius. Thus, the phase of the plane wave at the hologram lines can differ from that of the required wavefront at the same lines by as much as

$$2\pi(S/P) \text{ radians or } S/P \text{ waves}$$

Therefore, in the hologram plane the error in the reconstructed wavefront can be as large as S/P waves. In other words, the accuracy is determined by the accuracy with which we draw the grating lines. If we have an error in drawing a grating line of 1/100 the grating spacing, then the resulting error is 1/100 wave.

Figure 5 shows a plot of the OPD and slope of an aspheric wavefront. For this example the maximum OPD is approximately 300 waves (fringes) and the maximum slope is 500 waves/radius. If in the hologram we introduced enough tilt fringes to separate the first and second orders the maximum slope being measured would be 4 times this, or 2000 waves/radius [3]. If we used a plotter having a distortion free resolution cell size of 0.5 microns and a hologram diameter of 50 mm we would have 10^5 resolution points and the maximum error resulting from the hologram plotter would be 1/50 wave.

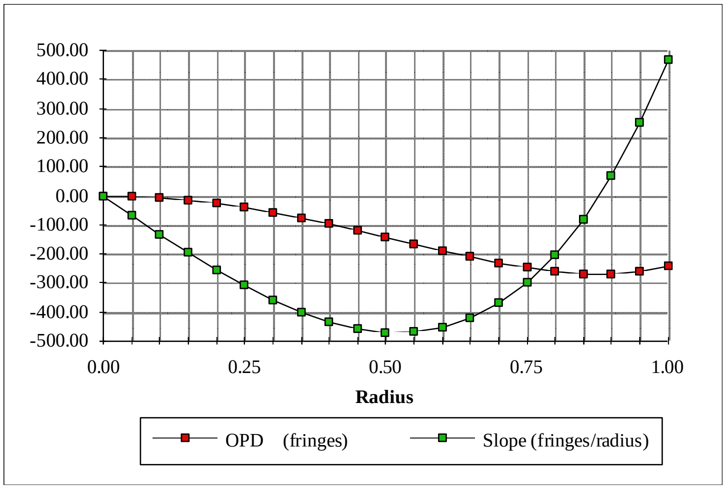

Figure 5. Wavefront departure and slope versus radius

Plotter errors can be measured and removed in the data reduction if either orthogonal straight line gratings or circular zones plates are drawn on the CGH along with the grating used to produce the aspheric wavefront. The straight line gratings will produce plane waves which can be interfered with a reference plane wave to determine plotter errors [5-8]. The circular zone plates will produce a spherical wave which can be interfered with a reference spherical wave to again determine plotter errors.

Alignment Errors

Errors can also result from the hologram being in the wrong location. Errors due to a longitudinal misalignment are less critical in the setup shown in Figure 1 than for Figure 2 because the hologram is placed in nearly collimated light. Lateral displacement errors give errors proportional to the derivative (i.e. slope) of the wavefront [3]. Generally alignment marks, crosshairs, are placed on the CGH to aid in the alignment.

Another good feature of a CGH test is that additional holographic structures can be placed on the CGH to produce alignment spots for the optical setup shown in Figure 2 to aid in the alignment of the optical system under test. Figure 6 shows fiducial marks produced by a CGH. The positions of the crosshairs can be controlled to micron accuracy.

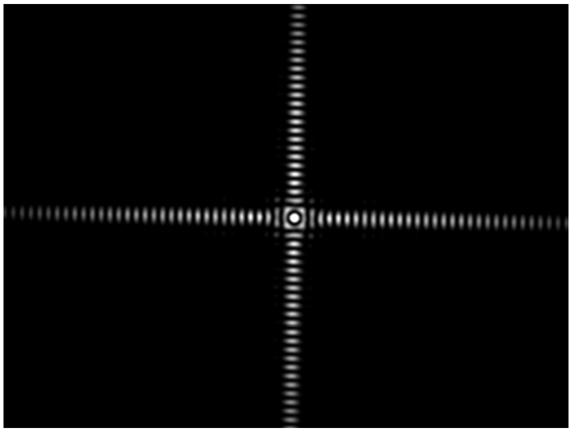

Figure 6. Fiducial marks produced by a CGH 15 meters from the CGH. The central lobe is 100 microns FWHM.

Errors Due to Thickness Variations

When the hologram is placed in only the reference or test beam thickness variations in the CGH substrate will introduce errors. Again, these errors can be calibrated. In some cases the substrate can be interferometrically measured before the CGH is placed on it and this data can be stored and later corrected for in the data reduction. If the CGH is a density hologram the errors introduced by the substrate can be determined by measuring the wavefront quality of the zero order. Determining the errors resulting from the substrate of a binary phase type is more of a challenge because the grating duty cycle can effect the zero order phase distribution but not the first order. Generally in the making of a binary phase grating there is a stage in the fabrication process where the grating has chrome on it and it is best to check the phase distribution of the zero order before the chrome is removed.

PHASE-SHIFTING CGH INTERFEROMETER INSENSITIVE TO VIBRATION

Most optical testing interferometers now use phase-shifting techniques because phase-shifting is a high accuracy rapid way of getting the interferogram information into the computer. CGH interferometers are no exception. Since spurious interference fringes introduce errors in phase-shifting interferometers, it is important that CGHs used in phase-shifting interferometers have sufficient wavefront tilt introduced so spatial filtering can be used to remove the unwanted diffraction orders.

Figure 7 show a phase-shifting CGH interferometer that is very insensitive to vibration because all the phase shifted frames are taken simultaneously [9]. In this arrangement, a Twyman-Green interferometer is used where the reference and test beams have orthogonal polarization. The CGH can be placed either between the diverger lens and the test mirror or it can be placed in the optical transfer assembly. After the two beams are combined they pass through a holographic element that splits the beam into four separate beams resulting in four interferograms. These four beams pass through a birefringent mask that is placed

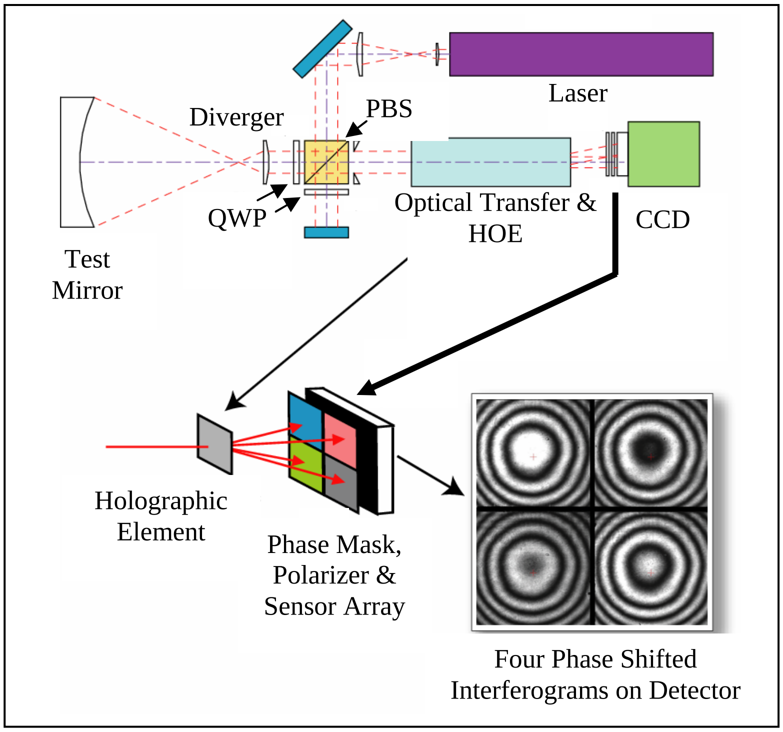

Figure 7. Single shot interferometer (PhaseCam) showing the beam divider and phase shifting mask.

just in front of a CCD camera. The four segments of the birefringent mask introduce phase shifts between the test and reference beams of 0, 90, 180, and 270 degrees. A polarizer with its transmission axis at 45 degrees to the direction of the polarization of the test and reference beams is placed after the phase masks just before the CCD array. Thus, all four phase shifted interferograms are detected in a single shot on a single detector array.

SUMMARY

Using computer generated holograms to test aspheric optics is extremely useful because of the wide variation of aspherics that can be tested. Crosshairs can be put on the CGH to aid in the alignment of the CGH and additional holograms can be placed on the CGH to aid in the alignment of the optics or to aid in calibration of the CGH. Laser recorders and e-beam recorders have the resolution and accuracy required to make high quality CGHs for testing of state-of-the-art aspheric elements. CGH interferometers work well with phase-shifting techniques.

REFERENCES

1. A. W. Lohmann and D. P. Paris, Appl. Opt. 6, 739 (1967).

2. A. J. MacGovern and J. C. Wyant, Appl. Opt. 10, 619, (1971).

3. J. C. Wyant and V. P. Bennett, Appl. Opt. 11, 2833, (1972).

4. Yu-Chun Chang and James H. Burge, SPIE Proc. Vol. 3782, 358, (1999).

5. J. C. Wyant and P. K. O'Neill, Appl. Opt. 13, 2762, (1974).

6. Mathias Beyerlein, Norbert Lindlein, and Johannes Schwider, Appl. Opt. 41, 2440, (2002).

7. Stephan Reichelt, Christof Pruss, and Hans J. Tiziani, Appl. Opt. 42, 4468, (2003).

8. Steven M. Arnold and Robert Kestner, Proc. SPIE 2536, 117, (1995).

9. James C. Wyant, Optics and Photonics News 14, Issue 4, 36, (2003).

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