Extrait de

APPLICATIONS DE L'HOLOGRAPHIE

Comptes rendus du Symposium International

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BESANÇON - Juillet 1970

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Edité par J.-Ch. Viénot, J. Bulabois, J. Pasteur

COMPUTER GENERATED HOLOGRAMS FOR TESTING ASPHERIC OPTICAL ELEMENTS

James C. Wyant and Alan J. MacGovern

Itek Corporation, 10 Maguire Road, Lexington, Massachusetts 02173

The high performance requirements of modern optical systems has made the inclusion of aspheric surfaces in the design increasingly advantageous. A major obstacle in using aspheric surfaces has been the difficulty involved in accurately testing them. To interferometrically test an optical element which gives an aspheric wavefront, an accurately known aspheric reference wavefront must be produced. This paper shows that computer generated holograms can produce moderately severe aspheric wavefronts with a root mean square error of less than 1/15th wave.

In 1967, Lohmann and Paris[1] showed that wavefronts could be produced with a binary hologram divided into equispaced resolution cells. The number of resolution cells needed depends on the complexity of the wavefront that is to be produced. A rectangular aperture is placed in each cell. The area of this aperture is made proportional to the amplitude of the wavefront at the hologram plane. The apertures are positioned so that at each aperture the phase of the illuminating wavefront is equal to the required phase of the reconstructed wavefront. That is, the apertures of a Lohmann and Paris type hologram simply lie along the maximas of the interference fringes of a conventional hologram.

For all the holograms we have been concerned with, the amplitude of the desired reconstructed wavefront is constant across the hologram plane. Thus, the apertures making up the hologram can be connected to form lines. A line hologram of this type can be thought of as an off axis zone plate.

Figure 1 shows one method of using a computer generated hologram with a Twyman-Green interferometer. The hologram is placed in the image plane of the piece under test. Thus, the wavefront the hologram is required to produce is simply the departure of the desired wavefront from a best fitting spherical wave.

In general, several wavefronts (different diffraction orders) emerge from the hologram. The order of particular interest is selected by spatial filtering, as shown in the figure.

Since the small apertures making up the Lohmann and Paris type hologram are positioned so the phase of the illuminating wavefront at these apertures is precisely that of the required wavefront at the same points, a sampled version of the required wavefront exits from the hologram. If the filtering aperture in the focal plane of the imaging lens is removed, an image of this sampled wavefront is obtained at a set of discrete points, but not between the points. This is true no matter where or how many sampling points are taken. The fringe pattern obtained with the filter removed is simply the moiré between the hologram and the interference of the plane wave and the wavefront from the aspheric element. The spatial filter introduced into the focal plane of the imaging lens has the effect of distributing the light from each sampling point to the area between the corresponding points in the image plane. If the hologram is divided into sufficient equispaced resolution cells and one sample is taken per cell, then this distribution of light results in a reasonable approximation to the required wavefront at all points in the image plane.

The two largest sources of error in the computer generated holograms made for testing optical elements are:

1) Quantization error
2) Graphic recorder nonlinearity and photographic distortion.

A simple argument gives an estimate of the quantization errors. Suppose the graphic device has PxP resolution points. Let N be the chosen number of resolution cells across the hologram. Thus, there are P/N aperture positions per cell. The maximum error due to quantization of position of an aperture is N/2P of a wave. The rms error will be approximately half this or N/4P of a wave. The plotter we are using has 6000 x 6000 resolution points. Thus, if we want to keep the r.m.s. error due to quantization less than 1/20 wave, we can use a maximum of 1200 resolution cells across the hologram.

The non linearity and distortion errors can be found empirically by analyzing the reconstruction of plane waves from holograms. Experiments showed that for the holograms included in this paper the nonlinearity and distortion error was less than 1/15 wave peak to peak.

The general procedure for generating the synthetic holograms is as follows: The mathematical expression describing the wavefront to be reconstructed is fed into a CDC-3300 computer, and the output data is delivered to a CalComp plotter. The output plot is photographically reduced to give the required hologram.

Fig. 2 shows half of a hologram made, using the Lohmann and Paris technique, for reconstructing a defocused parabolic wavefront suitable for testing an f/5, 45 cm diameter parabolic mirror. The other half of the hologram is identical to that shown in the figure. The function was sampled at 256 by 256 points with phase quantization of about 15.5 degrees, i.e. a peak to peak error of approximately 1/20th wave. The output plot was photographically reduced from 75 cm in diameter to about 1 cm in diameter to give the required hologram.

It should be mentioned that the apparent discontinuity in the positioning of the apertures in the hologram is a result of an approximation made in calculating the aperture positions. This approximation resulted in a theoretical maximum peak wavefront error of 1/20th wave. The approximation was not used in making the other holograms shown in this paper.

To test the fidelity of the wavefront produced by this hologram, its reconstruction was interfered with a plane wave. Fig. 3 shows the resulting interferogram. Analysis of the fringe positions shows that the hologram produced the required wavefront to an rms accuracy of about 1/15 wave.

The Lohmann and Paris type hologram of Fig. 2 was used to test an f/5 parabolic mirror using the modified Twyman-Green interferometer shown in Fig. 1. Fig. 4 shows the fringes resulting from this test with some tilt introduced. Since the hologram was already tested to 1/15 wave, most of the departure from straightness of these fringes may be directly attributed to errors in the parabola. An optician looking at the fringe pattern could tell what work must be done to correct the mirror surface.

Fig. 5 shows a line hologram made to test an f/3, 40 cm diameter parabolic mirror. Figure 6a shows the figures obtained using the hologram with the modified Twyman-Green interferometer shown in Fig. 1. Figure 6b shows the fringes obtained by testing this mirror in auto-collimation using a 61 cm diameter flat mirror. Allowing for the fact that when the mirror was tested in auto-collimation it was tested in double pass, it is seen that the two resulting fringe patterns closely agree.

Another line hologram was made to test a refractive element having 50 waves of third and fifth order spherical aberration. Fig. 7 shows the experimental setup used for the test. Fig. 8 shows the interference fringes which resulted from the test. An analysis of this fringe pattern shows that the wavefront produced by the refractive element and the wavefront produced by the hologram differed by less than 1/15 wave r.m.s.

The above results show, at least for simple aspherics, that computer generated holograms provide a convenient and practical means of producing an aspheric reference wavefront. Results have been shown only for the testing of rotationally symmetric elements, but there is no reason why the same technique cannot be applied to the testing of nonrotationally symmetric elements. With more sophisticated graphic devices, aspheric wavefronts several times more extreme than have been considered up to now may be generated.

The authors wish to acknowledge the support and technical assistance of W.P. Barnes, Dr. I.P. Adachi, and J.C. Chastang and the invaluable contribution of M.G. Hurwitz in the development of the computer programs.

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1. Lohmann, A.W. and Paris, D.P., Appl. Opt., 6.1, 739 (1967).

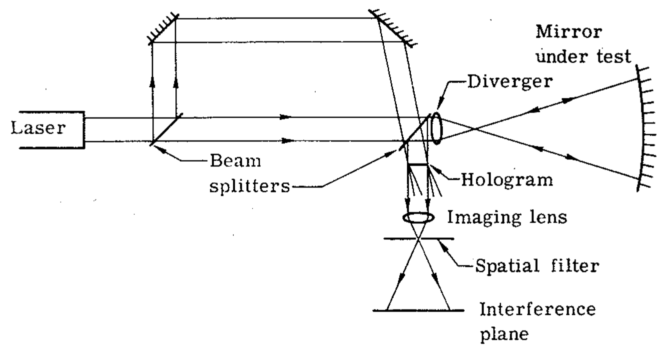

Fig. 1 — Modified Twyman-green interferometer

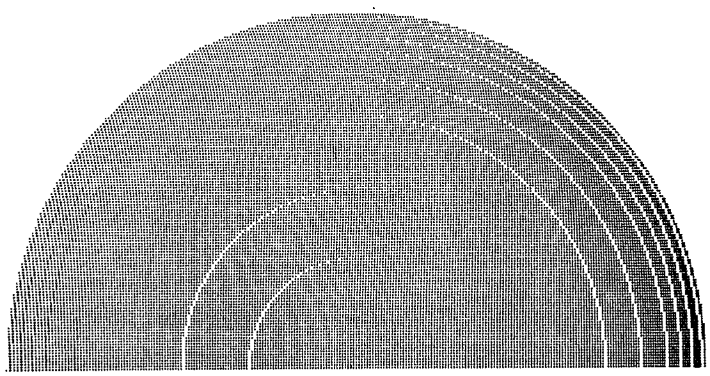

Fig. 2 — Hologram for testing f/5 parabolic mirror

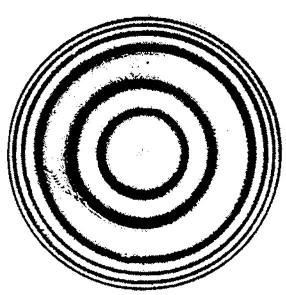

Fig. 3 — Interferogram resulting from interfering plane wave with parabolic wavefront produced by hologram

Fig. 4 — Result of holographic test of f/5 parabolic mirror

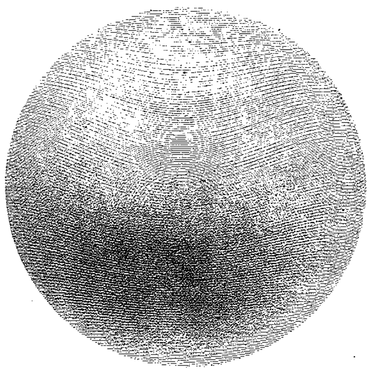

Fig. 5 — Line hologram for testing f/3 parabolic mirror

a. Holographic test (single pass)

b. Test in autocollimation (double pass)

Fig. 6 — Result of test of f/3 parabolic mirror

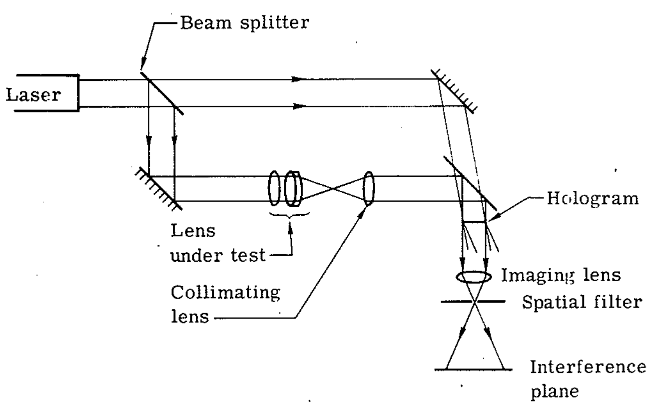

Fig. 7 — Setup for holographic testing of lens

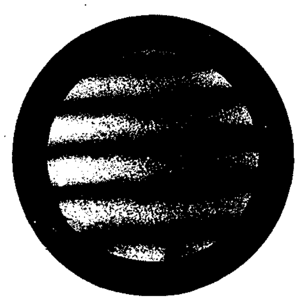

Fig. 8 — Result of holographic test of lens having 50 waves of third- and fifth-order spherical aberration