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Subject: Optical Testing by Holographic Interferometry

References:
(1) F-013747-KU, Applications of Holography to Interferometric Testing, 14 March 1967

(2) F-013819-KU, 17 March 1967

(3) F-016546-KU, 25 April 1967

(4) A-002003-KU, Coherence Versus Fringe Visibility In Laser Interferometers, 19 April 1967

Summary

A new interferometric optical testing technique has been found which shows promise in performing tests heretofore not possible with conventional interferometry. Some preliminary results are presented of an attempt to establish the fundamental feasibility of the new technique. With the new approach, a hologram is substituted for both the beam splitter and the reference mirror of a conventional interferometer (Williams, Twyman-Green, Mach-Zehnder, etc.)

The interferograms which result are indistinguishable in quality from those obtained by more conventional techniques.

Introduction

There exist a number of optical tests which are either very difficult and time consuming or are quite impossible to perform using conventional interferometric techniques.

One of these is the real-time, direct comparison of a deformed optical surface with its undeformed self. Using conventional interferometry, two interferograms must be made of the test surface, one for each of its two states of deformation. Differences must then be computed from the two interferograms in order to determine the actual deformation of the optical surface.

Using holographic interferometry, a single interferogram can be made which will give the surface deformation directly, and without need for a high quality reference surface. The technique is applicable to both diffuse and specularly reflecting surfaces, and can even be used for vibration analysis.

The purpose of this memo is to give a preliminary indication of the technical feasibility of the new technique, as well as to indicate some of the problems which will be encountered in its application.

The results discussed were obtained during weeks 19 and 20 with a model 123 HeNe gas laser borrowed from Spectra-Physics.

For a general review of the holographic principles involved see reference (1). For an indication of specific tests envisioned for the new technique see references (2) and (3).

Holographic Interferometry

Discussion

The configuration selected for preliminary tests (and necessitated by available equipment) is shown schematically in figure 1. This is a hybrid arrangement in the sense that spherical wavefronts were used to test plano mirrors and division of wavefront rather than division of amplitude was used in order to obtain the test and reference beams. Actually the designation of test and reference beams is quite arbitrary, as will be shown later.

For the purposes of this discussion, however, let us designate mirror M_1 in figure 1 the reference mirror and mirror M_2 the test mirror. During hologram readin, the interference between the beams coming from M_1 and M_2 is recorded in the hologram. After processing, the hologram is replaced in its holder.

The passage of beam 1A from M_1 through the hologram plate causes the creation within the hologram of a new beam 2B traveling along the direction of beam 2A coming from M_2. If M_2 has not been removed from the apparatus, then the waves reflected by it will interfere with those created within the hologram to produce interference fringes in the region traversed by the beam from M_2. These fringes can be re-

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Sheet 3a

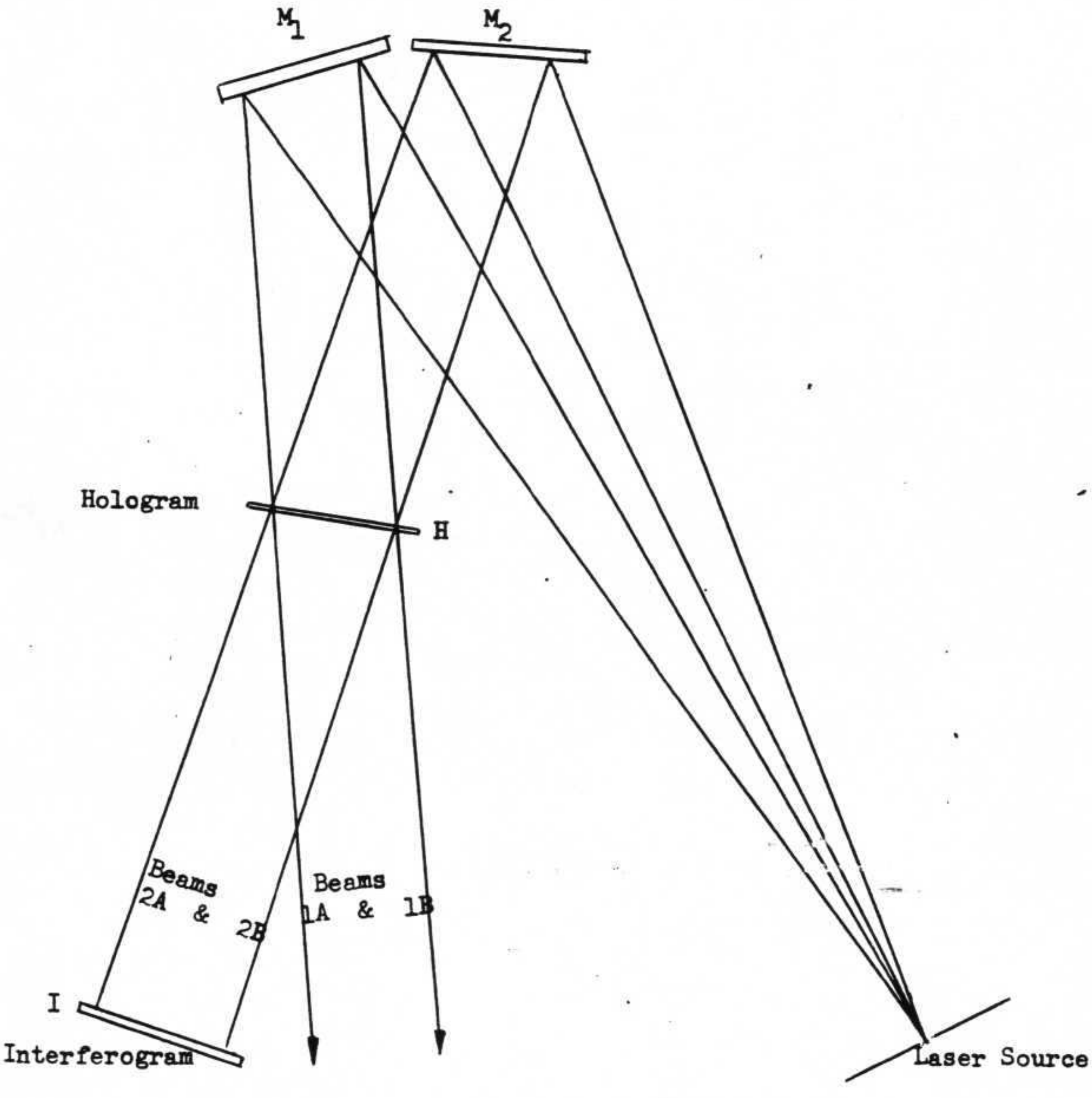
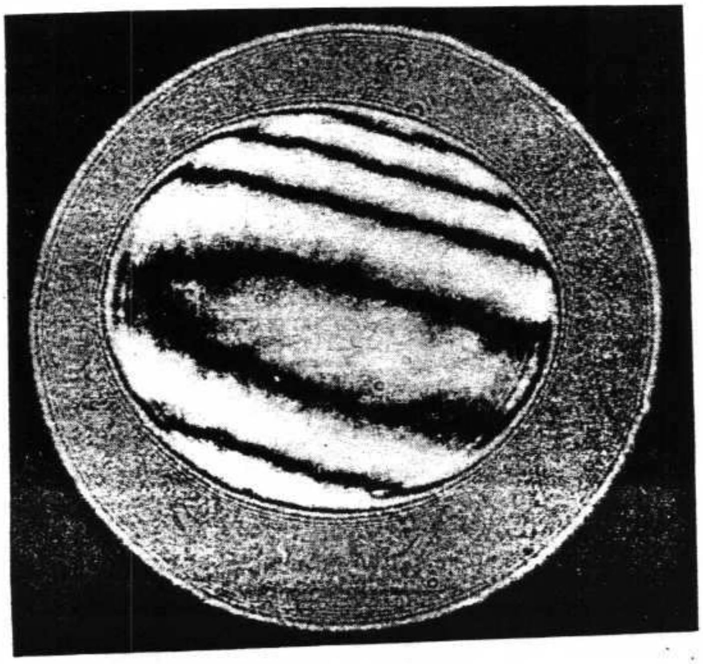


Figure 1. Configuration for preliminary evaluation of fringe quality in holographic interferometry.



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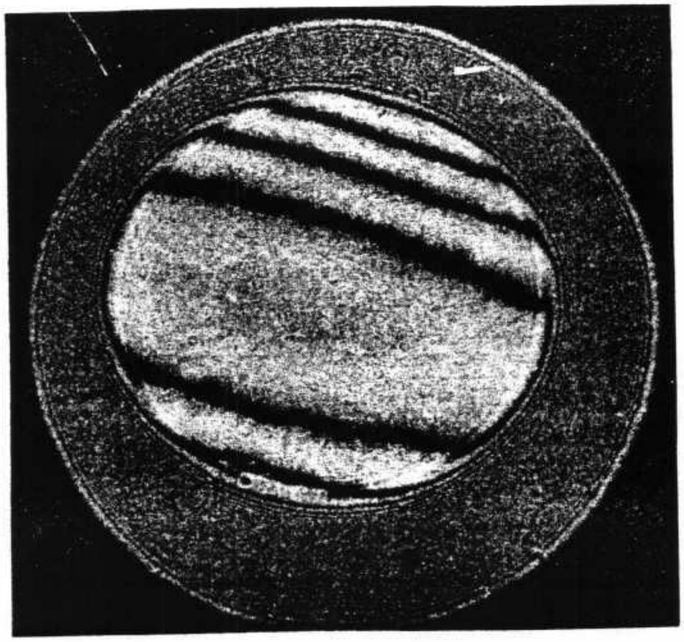

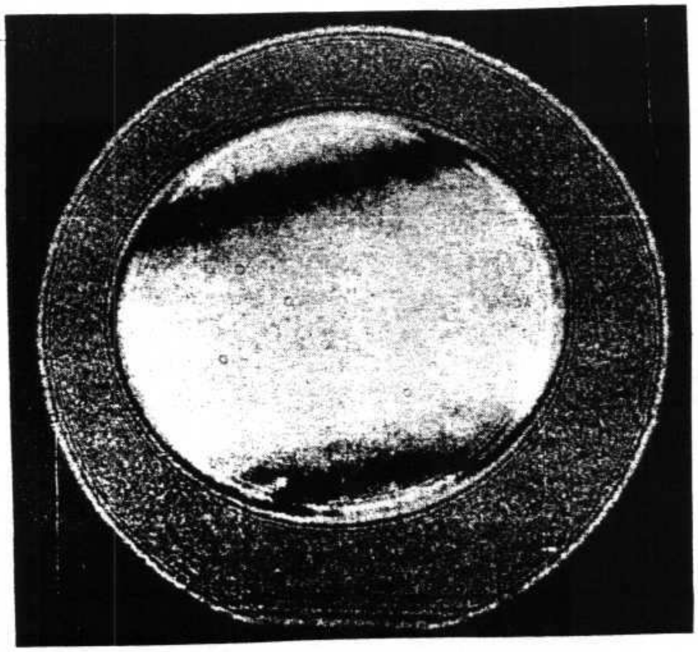

c

Figure 2. Interferograms obtained from a hologram of a plane mirror at successive stages of hologram drying.

corded at I as an interferogram.

The beam from mirror M_1 simply provides carrier or reference waves for recording and reconstructing light waves holographically. The fringes recorded at I result from the interference between light from M_2 and light from the <u>image</u> of M_2 recorded in the hologram (beams 2A and 2B).

Since there are only three optical elements along the optical path from the laser source to the interferogram, the nature of the fringes recorded will depend strictly upon these three elements. They are mirrors M_1, M_2, and hologram H. If each of these three elements has identically the same position, shape, and orientation during readout that it had during readin, then the waves from M_2 and the image of M_2 will interfere constructively and the interferogram will be uniformly bright. Displacement or distortion of any one of the three elements between readin and readout will be evident as interference fringes at I. These fringes will be a direct measure of the distortion and/or displacement of the element under consideration.

Results

Figure 2 shows three interferograms made with the hologram as the variable element. The hologram from which these were made was exposed in an ordinary 4" x 5" plate holder. For readout it was placed in another such holder with the center cut out to allow for transmission. Two masks with different sized circular holes in

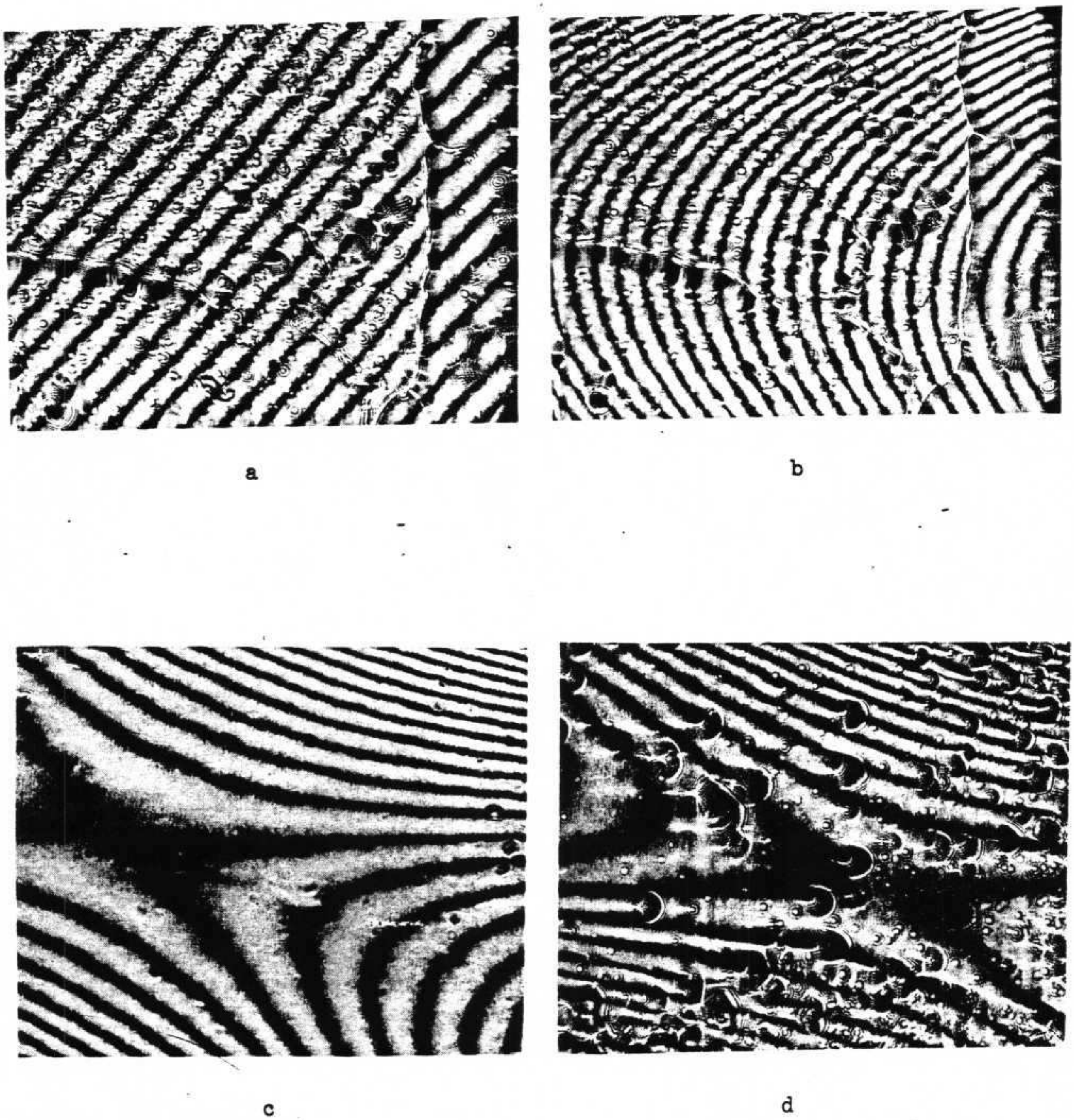

Figure 3. Interferograms obtained from a hologram of a plane mirror at successive stages of emulsion shrinkage.

them were placed over the mirrors to simulate the appearance of interferograms produced by circular plano mirrors of different diameters. The similarity between the resulting interferograms and those produced by a Williams interferometer is quite striking. The use of a different holder for readout caused a change in the surface of the hologram which introduced the interference fringes shown in figure 2a. This interferogram was made with the emulsion still wet from the processing. As the emulsion proceeded to dry, the ring radii increased as shown in figures 2b and 2c, indicating a decrease in the distortion of the hologram, or a return toward its original shape. A discussion of this distortion problem will be presented later.

The low noise which is evident in the interferograms of figure 2 is the result of several "beam cleaning" techniques:

(1) Use of a pinhole spatial filter in the light coming from the laser source.

(2) Use of mirrors which were relatively free of dirt, dust, and scratches.

(3) Moderate care to keep the photographic plate as clean as possible at all times.

Quality of Fringes

Since the interferograms in figures 2 and 3 could easily represent the distortion of mirror M_2, rather than that of the hologram, we can use them to evaluate the attainable quality of such interferograms. Though it may not be evident from the reproduction, the original interferograms have high contrast and very little noise.

The high contrast was obtained by slightly over exposing the hologram. In the particular configuration used, 6.5 seconds was found to be about nominal for maximum contrast. Small changes from this value, while not noticeably affecting the reconstruction, have a marked affect on fringe contrast.

When the exposure was as little as 5 seconds or as great as 8 seconds fringe contrast became very poor. There is evidently a narrow exposure region over which a high ratio of diffracted to direct beam intensity can be obtained. High fringe contrast indicates approximately the same intensity in the two beams that produce the fringes. In order to get a quantitative confirmation of this conclusion the intensities in the four beams* coming from the hologram were measured with a precision photometer. The results of this measurement are shown below.

Beams*	1A	1B	2A	2B
Relative Intensity	36%	21%	25%	18%

* Beams 1A and 2A are the direct beams of light coming through the hologram from mirrors 1 and 2, respectively. Beams 1B and 2B are the diffracted beams of light created by beams 2 and 1 upon passage through the hologram respectively. Beams 1A and 1B follow the same path, as do beams 2A and 2B. It is the interference between beams 2A and 2B that is shown in figures 2 and 3.

This explains the high contrast obtained in beam 2. Numerically, the fringe visibility obtained was 0.76, according to the above results. The attainment of this contrast was not done without sacrifice, however, since only 2% of the light incident on the hologram goes into beams 2A and 2B which form the interferogram.

The distinction between reference and test beams is quite arbitrary in this configuration, as mentioned earlier. This fact is illustrated quite graphically by the appearance of an apparently identical set of fringes in the beam from mirror M_1 previously designated the reference beam. This results from the fact that beam 2A is now acting as the reference beam for mirror M_1. It produces a diffracted image of M_1 (designated beam 1B) traveling along with beam 1A. The distortion from the hologram is introduced into beam 1B in exactly the same way it was introduced into 2B. Hence the fringes in both beams have the same appearance.

One is tempted to suggest that this phenomenon can be used to extract the effect of a distorted hologram. One could simply take the differences between the two interference patterns formed by the two beams and the wavefront error produced by the hologram would then cancel out. There are two objections to this approach. First, having to take differences between two interferograms eliminates some of the directness and simplicity that were unique features of the technique as originally proposed. Secondly, from the standpoint of information transfer, any deformation introduced into one of the mirrors will produce wavefront error in both beams. If M_1 is deformed between readin and readout, this deformation will be carried along both beams 1A and 2B. Since the light in beam 2B has been diffracted by some small angle θ, the information content in this beam will have been altered slightly. Taking differences between the interference patterns produced by the two beams will not only cancel the wavefront error introduced by the hologram, but it will also cancel a major portion of that introduced by the test mirror itself. This difference technique is then undesirable.

Surface Quality of the Mirrors

As long as the mirrors remain accurately positioned between readin and readout, there will be no stringent requirement on their surface quality. For example, an independent measurement of the flatness of the test mirror M_2 has shown it to have saddle distortion of approximately ten fringes in one direction and five in the other. If figure 2c were a conventional interferogram this distortion would be quite evident in the set of fringes produced. Mirrors with surface errors in excess of 50λ could have been used, and, if there were no distortion of the hologram, would have produced fringes which in conventional interferometry would have indicated mirror surface errors less than $\lambda/20$. The fundamental reason for this startling fact is that with holographic interferometry you are comparing a surface of arbitrary shape with itself, rather than with some other "reference" surface. Of course, by changing mirror M_2 for another between readin and readout, you could very easily perform a more conventional interferometric test. But your interferometer now has one less arm and it has no beam splitter. The hologram takes the place of the beam splitter.

Hologram Repositioning Tolerance

It can here be noted that the hologram translational and angular repositioning tolerances (0.5 cm, 0.4°) predicted analytically have been confirmed experimentally.

Problem Areas

The only major problem encountered was that of the distortion of the hologram between readin and readout. As mentioned before, figures 2a, b, and c show fringes at successive stages of hologram drying. The nature of the changes indicates a decrease in the distortion of the hologram as the hologram dried.

We conclude that this was caused by emulsion shrinkage as the hologram dried, which compensated to some extent the distortion introduced by changing plate holders. Of course the cause could have been purely thermal in origin, but this is doubtful. In Figure 3 is shown another sequence of interferograms, with the mirror masks removed. The hologram plate was clamped in a specially designed rigid stainless steel holder before exposure and remained there throughout processing and readout.

In this sequence of interferograms, the hologram at first had relatively little distortion. As the emulsion dried, the distortion became significantly worse. In an attempt to make the hologram return to its original shape, it was placed back in the wash bath for fifteen minutes. Figure 3d is the interferogram made at the end of this soaking. The distortion is still present. Perhaps the strong clamping of the plate holder served to retain the distortion in spite of any emulsion expansion which may have occurred.

For the testing of mirror M_1 the only element free to change (either by replacement or deformation) between readin and readout should be the test mirror M_1. Hence the hologram deformation must be eliminated. Several possibilities can be suggested in order to eliminate wavefront errors produced by the hologram itself. These are:

(i) Use of a liquid gate to prevent the emulsion from drying.

(ii) Coat the emulsion with some kind of non-volatile substance of uniform thickness which either seals the water into the emulsion or replaces the water lost from the emulsion with some other substance, the result being no net emulsion shrinkage.

(iii) Use a thicker photographic plate, a thinner (less shrinking) emulsion, and/or a smaller hologram plate size.

(iv) Use a different, non-distorting, hologram recording medium.

The potential of each of the above items for solving our particular distortion problem is being investigated. It is felt that this distortion can be reduced at least to a level of introducing no more than $\lambda/2$ wavefront error into the system. One should then be able to detect wavefront errors due to distortions of the test piece with a $\lambda/10$ accuracy even in the presence of a $\lambda/2$ residual error.

Conclusions

If the exposed and processed hologram is completely dry and if it is mounted firmly in a rigid holder, then it will retain its shape indefinitely. If the distortion has been reduced to some reasonable level (less than $\lambda/2$ wavefront error) the remainder of the distortion can be removed by calibration, that is, by quantitative measurement of the wavefront error introduced by the hologram. This is done with conventional interferometers and the calibration procedure should here be the same, except that high quality mirrors are not needed. All that is required is stability of the mirrors M_1 and M_2 between readin and readout on the order of the calibration accuracy desired.

Assuming the hologram distortion problem can be adequately solved, it appears that the fundamental feasibility of optical testing by holographic interferometry has been established.

Applications

The most immediate application which comes to mind is for direct interferometric evaluation of mirror deformation due to thermal or mechanical causes. Ordinarily one would have to make two interferograms of a mirror under test, each with respect to some independent reference mirror, and then compute differences between the two interferograms. With holography, one can now produce interference directly between a deformed test mirror and its undeformed self, without need for an independent, high quality reference mirror.

Since there is no requirement for the surfaces of mirrors M_1 and M_2 to be specularly reflecting (indeed M_1 and M_2 can be any arbitrary objects), the technique can easily be used to test unpolished, diffusely reflecting surfaces. That this is feasible will be demonstrated in a later memo.

For such a test, one of the mirrors would be replaced by the unpolished optic to be tested. Since the light received by the hologram from this surface would now be substantially less, some form of attenuation of the light from the other mirror might be required during readout in order to achieve good fringe contrast.

In such diffuse reflection interferometry rather accurate point-for-point superposition of the test surface and the image of the test surface is required. This fact might make the effects of hologram distortion more critical. It must then be concluded that a major effort aimed at reducing this distortion is in order.

It is not intended that actual optical tests be performed using the configuration of figure 1 without any modifications. Functional configurations for testing both plane and curved surfaces are given in reference 4.

Initially, applications of holographic testing will be confined to those tests which cannot easily be performed using more conventional interferometry. Ultimately, since a hologram can be used to replace both the beam splitter and the reference mirror of a conventional interferometer, it is anticipated that the technique will be able to compete favorably with conventional interferometry for the same tests.

Additional possible applications can also here be cited:

(1) Use holographic interferometry to provide an accurate measure of grinding and polishing rates and effects using the unique difference measuring capability of holographic testing. The technique can be used ultimately for quantitative in-process testing.

(2) Provide a real-time readout during thermal cycling, or as a check for distortions introduced into a lens or mirror figure by the mounting. Another possibility would be for real-time readout during certain kinds of optical figuring.

(3) Provide a "tuning" capability for component mount assemblies, figure control devices, and even entire systems where element tilts and spacings are control variables difficult to assess quantitatively.

(4) Vibration location and measurement applied to any arbitrary surface.

(5) Replacement of beam splitters and reference mirrors by their holographic equivalents in practically any interferometer, thereby freeing these optics for other use.

In short, the technique appears to have enormous potential in interferometric testing.

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