Measurement of Microscopic Deformations Using Double-Exposure Holographic Interferometry and the Fourier Transform Method

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ABSTRACT

Microscopic deformations on the surface of a circular diaphragm were measured using double exposure holographic interferometry and Fourier transform method (FTM). The three-dimensional surface deformations were successfully visualized by applying FTM to holographic interferogram analysis. The minimum surface displacement measured was 0.317 μm. This was calibrated via the Michelson interferometry technique.

Key words: holographic interferometry, microscopic deformation measurement, Fourier transform method, double-exposure method, hologram, laser application

INTRODUCTION

Double-exposure holographic interferometry (DEHI) has been extensively applied in fields as diverse as medicine, biomechanics, geology, heat transfer, and, most notably, in the field of nondestructive testing (Rastogi, 1994). For most applications, especially in holographic nondestructive testing, the presence of interference fringes during hologram reconstruction is enough for the qualitative evaluation of microscopic surface deformations (of the order of 1 μm). Such evaluations are adequate for the purpose of detecting deformations. However, when accurate quantitative analysis is required, it is necessary that the actual three-dimensional (3-D) deformations be measured. Such measurements will rely on a fast, sensitive, and properly calibrated technique. Earlier published papers on DEHI (Pryputniewicz & Bowley, 1978; Rightley et al., 1992) were dedicated to the determination of the accuracy and precision of this technique vis-à-vis the measured values using micrometer translators. Unfortunately, micrometers are mechanical devices with poor spatial resolution, which is of the order of 10 μm. A more satisfactory approach in properly calibrating DEHI is to compare it with another technique having a higher resolution. Also, DEHI alone will not be sufficient in establishing a fast technique of 3-D deformation analysis. Each point in the interference pattern (of DEHI) has to be analyzed to obtain the 3-D

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deformation, which makes this process time-consuming. A fast analysis technique is therefore required to make the DEHI a practical nondestructive tool in the evaluation of surface deformations.

In recent years, advances in digital image processing have been changing the nature of fringe pattern analysis towards an increasing reliance on computer-based approaches. The tedium and the imprecision associated with manual extraction of quantitative data from the fringe pattern has given way to the automatic evaluation of the phase distribution encoded in the fringe pattern. One very promising technique in digital image processing is the FTM, which utilizes a single double-exposure holographic interferogram to obtain a continuous phase distribution. This phase distribution is proportional to the actual surface deformation (Kreis, 1986).

This study demonstrates the sensitivity of DEHI in measuring the out-of-plane (perpendicular to surface) sub-micron (<1 μm) deformations. Also, the calculated out-of-plane displacements generated by a piezoelectric transducer using DEHI were compared to those obtained using a Michelson interferometer (MI) setup. Furthermore, we will demonstrate that DEHI, coupled with the FTM, can be used to measure and visualize 3-D out-of-plane deformations of real objects.

PRINCIPLE OF DOUBLE-EXPOSURE HOLOGRAPHIC INTERFEROMETRY

Holographic interferometry is defined as "the interferometric comparison of two or more wave fields at least one of which is holographically reconstructed" (Kreis, 1996). In DEHI, two holograms corresponding to two states of the same object are consecutively recorded on a holographic plate. During the reconstruction stage, the two waves that correspond to the two states are reconstructed and are brought to interfere. They give rise to a diffraction pattern of an image covered with interference fringes called the holographic interferogram. DEHI allows detection of microscopic deformations that occurred between exposures. This deformation produces slightly different images recorded in the same hologram. Upon reconstruction, this slight difference results in an optical path difference which is manifested as the holographic interferogram. The contours of the interferogram represent regions of equal displacements.

To calculate the out-of-plane displacements, the static method of fringe analysis is used (Rastogi, 1994). With illumination and observation directions almost anti-parallel, the displacement distribution d(x,y), is given by:

$$d(x,y) = \frac{\Delta\phi(x,y)}{4\pi/\lambda} \tag{1}$$

where $\Delta\phi(x,y)$ is the continuous phase distribution, x, y are the spatial coordinates, and λ is the wavelength of the laser used. $\Delta\phi(x,y)$ is determined by applying the FTM to the holographic interferograms obtained from the experiment. The summary of the FTM is as follows (Kreis, 1986). The intensity distribution from the holographic interferogram is Fourier transformed and the amplitude spectrum is filtered with proper bandpass filters. The application of the inverse Fourier transform results in a phase distribution with values from $-\pi$ to π. A continuous phase distribution is obtained by performing a process called phase unwrapping. Because of the expected circular symmetry, the center displacement is obtained from the maximum value in the displacement distribution d(x,y).

In comparing DEHI with MI, we calculated the optical path difference in MI using

$$d = \frac{n\lambda}{2} \tag{2}$$

where *d* is the displacement and *n* is the number of fringes which crossed a reference point as the path length is changed (Born and Wolf, 1980).

DEHI has distinct advantages over the Michelson interferometer because it can bring to interfere two wave fields simultaneously which existed at different times and it does not require highly reflecting surfaces. Also, DEHI can be used to calculate three-dimensional deformations, which cannot be performed using MI.

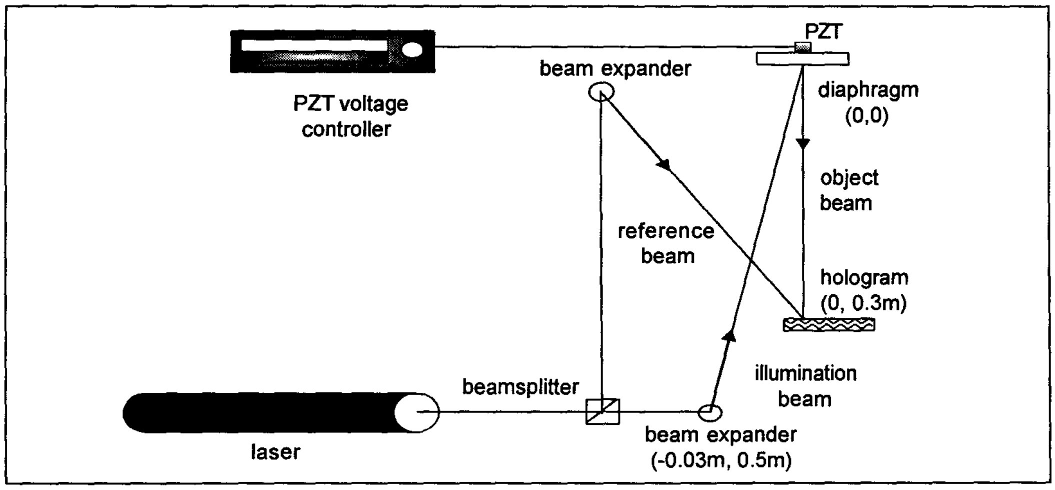

Fig. 1. Experimental recording setup for double-exposure holographic interferometry

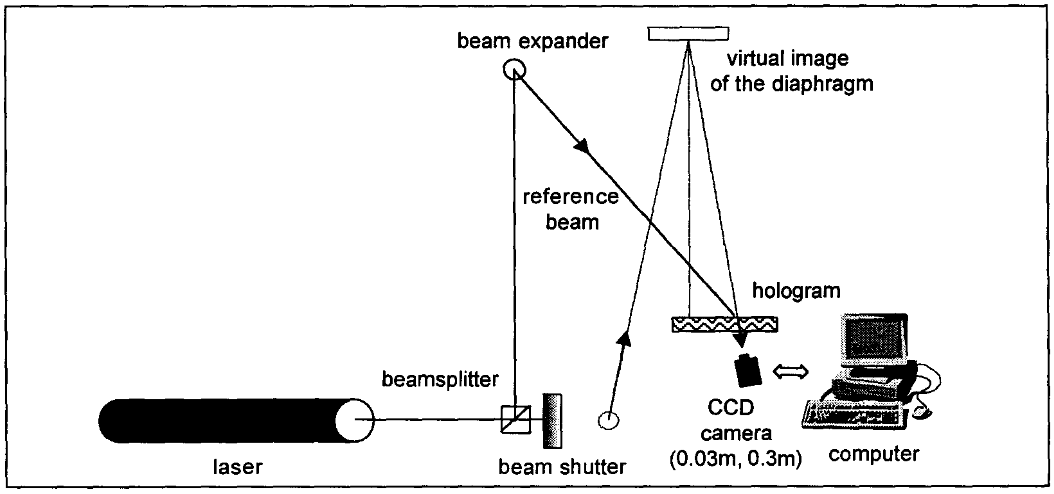

Fig. 2. Experimental setup for the hologram reconstruction

MATERIALS AND METHODS

The setup for the DEHI is shown in Fig. 1. An out-of-plane displacement at the center of the circular diaphragm (diameter of 10 cm) was generated by a PZT connected to a voltage controller. The voltage can be varied from 0 to 75V with stepsize of 0.1V. The diaphragm is a circular acetate held onto a ring holder by strips of adhesive tapes.

The holographic film used was an Agfa 8E75HD film cut into 1 cm x 5 cm strips and sandwiched between two clear glasses. The light source was a 25-mW linearly polarized Helium Neon laser with a wavelength of 0.633 μm. The intensity of the reference beam was about four times that of the object beam. Before the first exposure of the film, the holographic setup was allowed to stabilize for two minutes. The film was then exposed for one second with a voltage setting of 5V. The PZT voltage was then increased. The setup was allowed to stabilize again for another minute. Finally, the film was exposed again for one second.

The film was developed, bleached, and post treated using JD3 developer chemicals. Once thoroughly dried, the developed film was placed back to its holder for image reconstruction. The reconstruction setup is shown in Fig. 2. The diffraction patterns of the image, now covered with interference fringes, were reconstructed when the original reference beam illuminated the

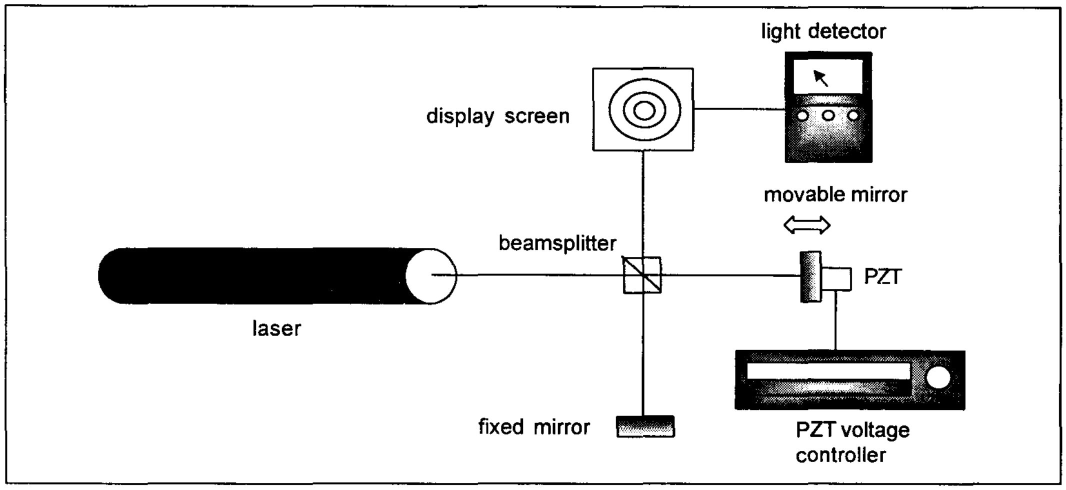

Fig. 3. Michelson interferometer setup

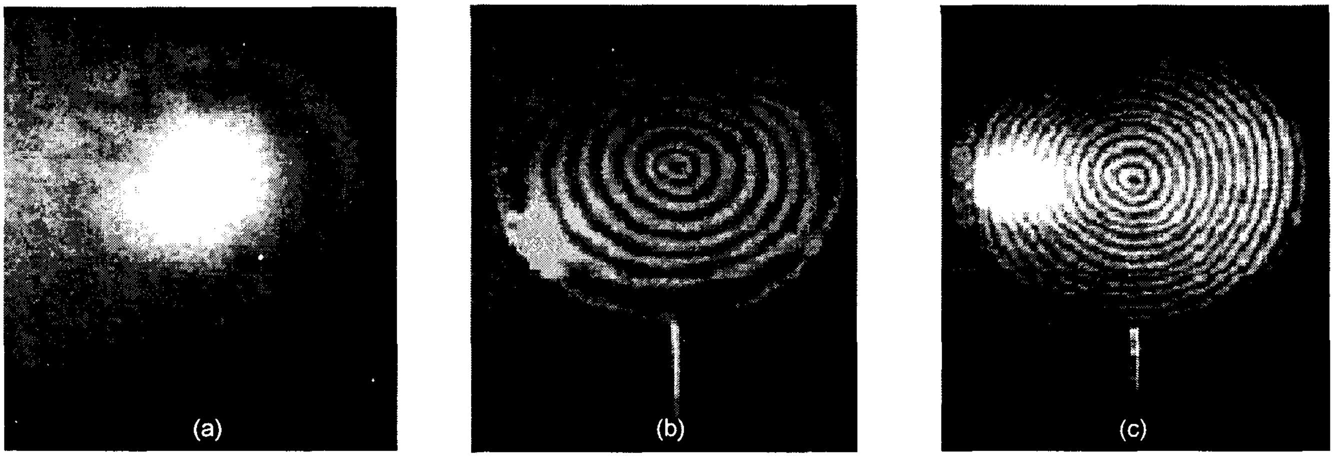

Fig. 4. Holographic interferograms obtained for a voltage difference of (a) 7V, (b) 39V, and (c) 68V. (Initial voltage reading is 5V.)

developed films. A zoom lens placed on the CCD camera images the diffraction patterns onto the detector array. A frame grabber captured the images for digital image processing. The displacement distribution was obtained using Eqn. 1. The center displacement corresponded to the maximum value in the displacement distribution.

For purposes of comparison, a Michelson interferometer (Fig.3) was used to measure the PZT response. The beam from a frequency-stabilized HeNe laser (10 mW, 0.633 μm) is split into two by a beamsplitter. A movable mirror attached to the PZT reflected one of the beams; another beam hit the fixed mirror. The two beams recombined at the beamsplitter, and then the interference patterns were projected on a display screen. To facilitate accurate fringe counting, a point detector was placed at the fringe region as the voltage was being changed. The displacement was calculated using Eqn. 2. The center displacements that were obtained holographically were compared to those obtained using the Michelson interferometer.

RESULTS AND DISCUSSION

Examples of interferograms produced in the reconstruction stage are shown in Fig. 4. Figs. 4(a), (b), and (c) correspond to PZT voltage differences of

7V, 39V and 68V, respectively, with an initial voltage reading of 5V. All holographic interferograms show nearly circular fringe patterns superimposed on the image of the diaphragm. As the voltage difference is increased, we observed an increasing number of fringes. Fig. 4 also shows increasing circular symmetry of the fringes as the voltage is increased. This can be attributed to the tension being applied by the PZT. An increase in the tension removes the slackening of the diaphragm as the voltage is increased, thereby making the surface deformation uniform. With the application of FTM, we can visualize the actual surface deformation. Using Eqn. 1, with the phase distributions obtained using the FTM and $\lambda = 0.633\mu m$, the surface deformations are shown in Figs. 5(a), 5(b), and 5(c) for voltage differences of 7V, 39V, and 68V, respectively. An increase in the PZT driving voltage leads to an increase in the PZT expansion. The PZT, in turn, exerts more pressure to the diaphragm. This directly results in an increase in the slope of the surface. The corresponding center displacements obtained are 0.317 μm, 2.219 μm, and 4.120 μm, respectively. Table 1 lists the values of the center displacements for different PZT voltages.

The same PZT is used to generate the optical path difference in the Michelson setup. A point detector measures the number of fringes for a given PZT voltage difference that crossed an arbitrary reference point. The calculated displacements, for a given PZT voltage, are also listed in Table 1. Since *n* is directly proportional to the optical path difference (see Eqn. 2) we expect a linear response of the PZT with changing voltage.

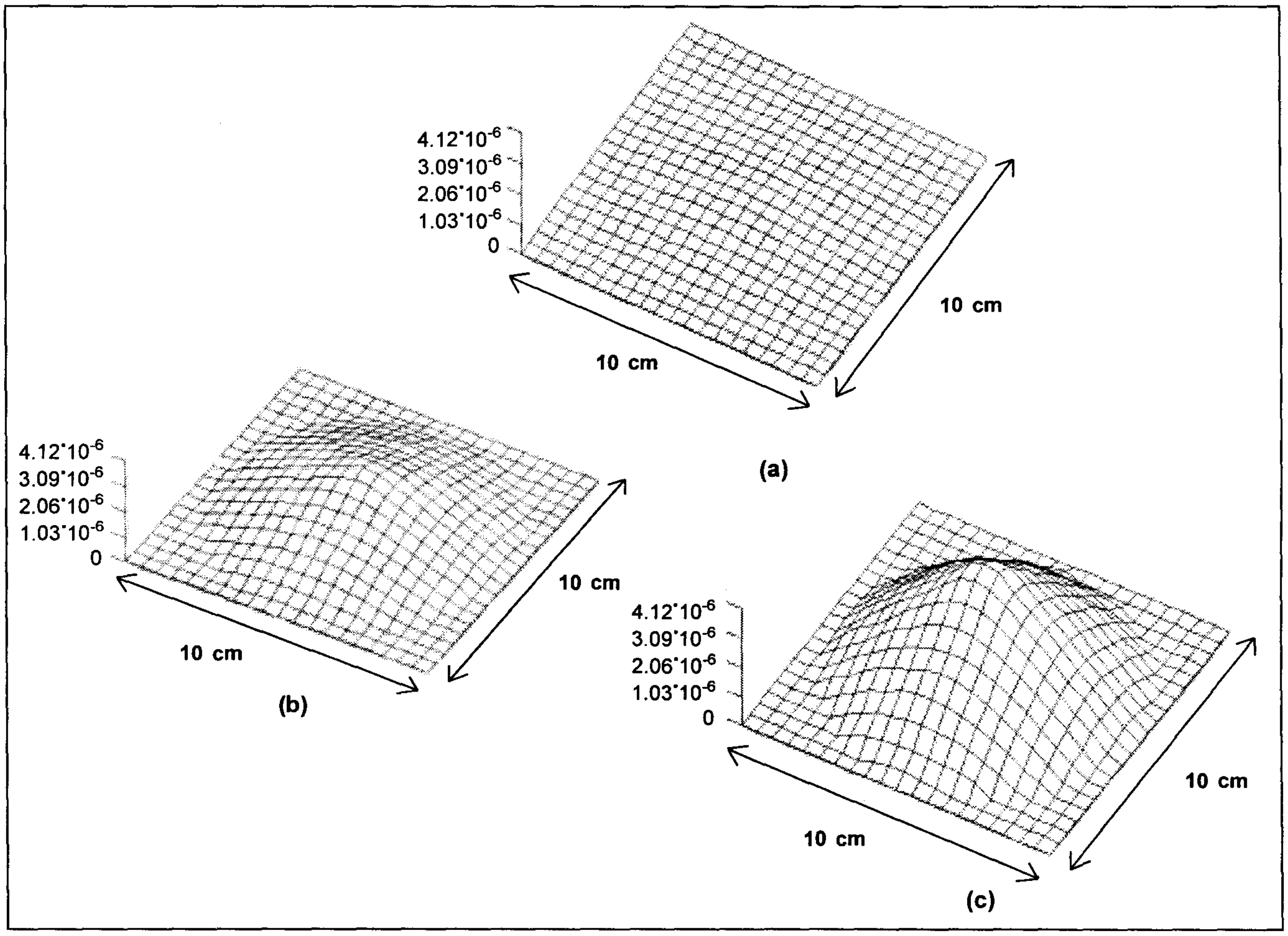

Fig. 5. 3-D plots of the surface deformations for a voltage difference of (a) 7V, (b) 39V, and (c) 68V. (The vertical axis is in meter.) The corresponding center displacements are 0.317 μm, 2.217μm, and 4.120 μm, respectively.

Table 1. Calculated displacements using DEHI and MI

Voltage Difference (V)	Displacement	
	Holographic	Michelson
7	0.137	0.137
13	-	0.633
18	0.951	0.950
23	-	1.266
29	1.585	1.583
34	-	1.899
39	2.219	2.216
44	-	2.532
48	2.852	2.849
53	-	3.165
59	3.486	3.482
63	-	3.798
68	4.120	4.114
72	-	4.431

Looking at Table 1, we can observe that the calculated displacements from the fringes obtained holographically agreed very well with those obtained using the Michelson interferometer. It can be inferred from these results that the sensitivity of the holographic interferometer approaches the sensitivity of the Michelson for a nearly anti-parallel illumination and observation vectors. The minimum surface displacement we have obtained using DEHI is 0.317 µm. This is primarily limited by the wavelength of the light source.

CONCLUSION

Double-exposure holographic interferometry was used to measure 3-D out-of-plane deformations of a circular diaphragm. A nearly anti-parallel illumination and observation vectors were used to generate interferograms having nearly circular fringes. Actual 3-D deformations were successfully visualized by applying Fourier transform method to analyze the holographic interferograms. We have measured a minimum surface displacement of 0.317 µm using the present setup. Calibration of DEHI was performed using the Michelson interferometer as a reference technique for displacement measurements.

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