Measurement of Three-Dimensional Deformations by Phase-Shifting Digital Holographic Interferometry

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ABSTRACT

Out-of-plane deformations of a cantilever were measured using phase-shifting digital holographic interferometry (PSDHI) and the Fourier transform method (FTM). The cantilever was recorded in two different states, and holograms were stored electronically with a charge-coupled device (CCD) camera. When the holograms are superimposed and reconstructed jointly, a holographic interferogram results. The three-dimensional (3D) surface deformations were successfully visualized by applying FTM to holographic interferogram analysis. The minimum surface displacement measured was 0.317 μm. The processing time for the digital reconstruction and visualization of 3D deformation took about 1 minute. The technique was calibrated using Michelson interferometry setup.

INTRODUCTION

Non-contact measurement of surface deformations is much demanded in areas of science and engineering. Conventional holographic techniques coupled with automatic fringe analysis provide a sensitive and reliable method for deformation analysis (Almoro & Daza, 1998). Traditionally, photographic films were used to record the holograms. Photographic films have a very high resolution, but have the disadvantage of needing wet chemical processing. After recording a hologram on such films, a physical reconstruction of the recorded wave field by illumination of the film with a laser is required. Added to this, the intensity distribution of the reconstructed object still needs to be imaged for phase evaluation and processing. The procedure is time consuming. In digital holography, holograms are recorded by a CCD camera and image reconstruction is performed by a computer (Schnars & Jûptner, 1994). To increase the fringe spacing and to obtain the desired image of high quality, phase shifting technique is used (Yamaguchi & Zhang, 1997). A more detailed discussion on the principles and experimental results on digital phase-shifting holography are presented in reference (Almoro et al., 2001).

Digital holography has spawned into various imaging (Zhang & Yamaguchi, 1998) and optical measurement applications (Yamaguchi et al., 2001; Yamaguchi, 2001; Pedrini et al., 1999; Pedrini et al., 1998; Schnars & Jûptner, 1994). Evidently, this technique is better suited to an industrial environment than photographic films.

This study will demonstrate the sensitivity of PSDHI in measuring microscopic (sub-micron) out-of-plane displacements. Displacement calculations using PSDHI and FTM will be compared to Michelson interferometry (MI). This study will show that digital holographic interferometry, coupled with FTM, is a fast, sensitive, and reliable technique for measurement and

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visualization of 3D out-of-plane deformations of real objects.

Theoretical background: Digital holographic interferometry

The approach to obtain the interference phase distribution $\Delta\Phi(x,y)$ and displacement distribution $d(x,y)$ in digital holographic interferometry is summarized in Fig. 1 (Kreis, 1996). In the same way that holography can be extended to double-exposure holographic interferometry, digital holography can be employed to perform digital holographic interferometry. Two holograms with amplitude transmittances $\tau_1(k,l)$ and $\tau_2(k,l)$ corresponding to different states of the object are recorded and stored subsequently and then added point wisely. Since the Fresnel transform is essentially a Fourier transform and, thus is linear, it reconstructs the sum of the two wave fields. The resulting intensity exhibits the cosine-shaped interference pattern called "holographic interferogram". This interferogram may be evaluated by one of the various interference phase determination methods like the FTM and phase unwrapping techniques (Kreis, 1986). The continuous phase distribution obtained is proportional to the out-of-plane displacement distribution when the illumination and observation directions are nearly anti-parallel. The displacement distribution is then given by (Kreis, 1986)

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

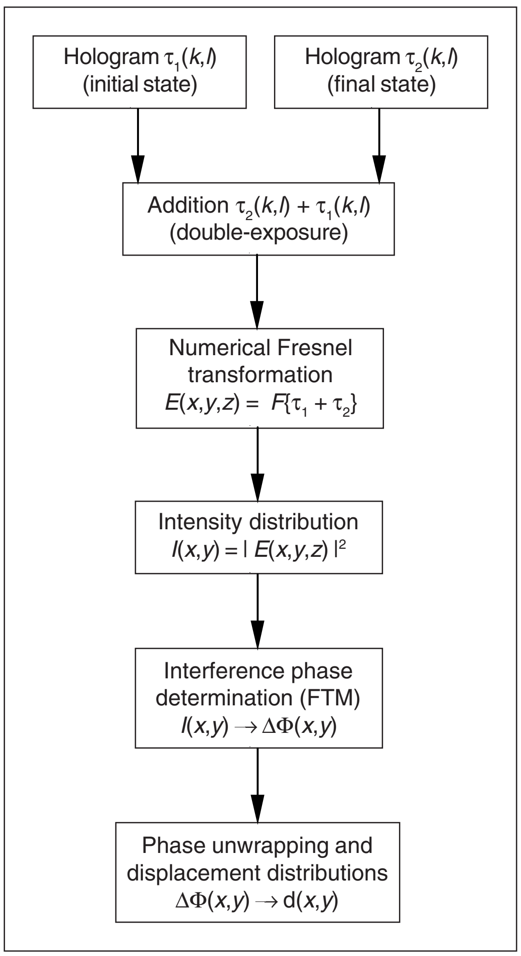

Fig. 1. Digital holographic interferometry for measurement of out-of-plane displacements.

METHODOLOGY

The experimental set-up is shown in Fig. 2. The laser used was a 1 mW frequency stabilized Helium-Neon laser (ë = 632 nm). The split beams are expanded and collimated. One of the beams illuminates the test object in a direction that is almost anti-parallel with the line from object to CCD camera. This makes the setup sensitive only to out-of-plane (perpendicular to object surface) direction. The other beam, which is reflected back from the mirror 1 attached to the piezoelectric transducer (PZT1), forms the reference plane wave at normal incidence to the CCD. The PZT1 was utilized to phase-shift the reference beam. The diffracted light from the object is collected by lens L1 onto the CCD

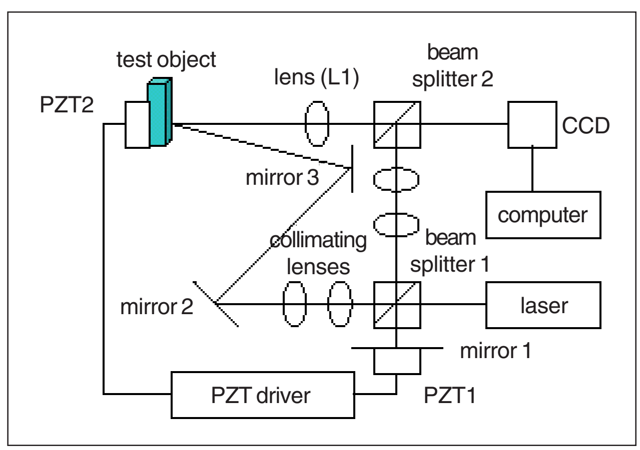

Fig. 2. Experimental setup.

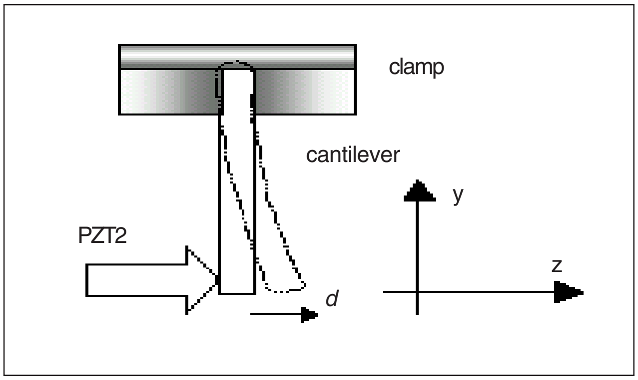

Fig. 3. Cantilever and displacement, d.

array. The distance from L1 to the CCD is beyond the image plane of the test object, and as far as possible to increase the fringe spacing. The optimum distance from object to CCD in this experiment is 1.3 m. As a rule of thumb on the beam ratio, the object and the reference beams must form visible interference fringes on the CCD plane as seen from the computer monitor.

Fig. 3 shows the cantilever and the out-of-plane displacement actuated by the PZT2. The cantilever was an aluminum sheet (1.5 cm x 2.0 cm x 0.05 cm) clamped from the top. PZT2 was attached to the free end of the cantilever to effect an out-of-plane displacement (*d*). A 5 V step increase in the voltage difference was applied to PZT2. The CCD and a frame-grabber capture the interference pattern (between object and reference beams) and store it as the hologram. Four frames (phase-shifted by $\pi/2$) are obtained for each deformation state to obtain the complex amplitude at the CCD plane using the fourbucket algorithm (Yamaguchi & Zhang, 1997). The holographic interferograms are evaluated using the FTM to yield a phase distribution wrapped in 2π. After phase-unwrapping, the displacement distribution is obtained using Eq. (1). In comparing digital holographic interferometry with MI, the optical path difference in MI is calculated using

$$d = \frac{n\lambda}{2} \qquad (2)$$

where *n* is the fringe shift as the voltage applied to the PZT2, while attached to the movable mirror in MI setup, is increased.

RESULTS AND DISCUSSION

The reconstructed object without any deformation is shown in Fig. 4a. The image is free from holographic interferogram (Note: The bright curved pattern on the center of the image is not a fringe pattern but a strong reflection of light on the metal surface. Note also that the dark square image on the lower left region is the beam splitter that stood on the path of the object beam). Fig. 4b to 4f are samples of the digitally reconstructed objects covered with holographic interferograms, obtained for a voltage difference of 10 V, 30 V, 35 V, 40 V, and 50 V, respectively. The number of fringes increased as the voltage difference is increased. Notice also that the slope of the fringes become uniformly horizontal as the voltage is increased. This means that for increased voltage difference the cantilever undergoes uniform out-of-plane deformation, which is attributed to increased tension. An increase in the tension removes the slackening of the cantilever, thereby making the

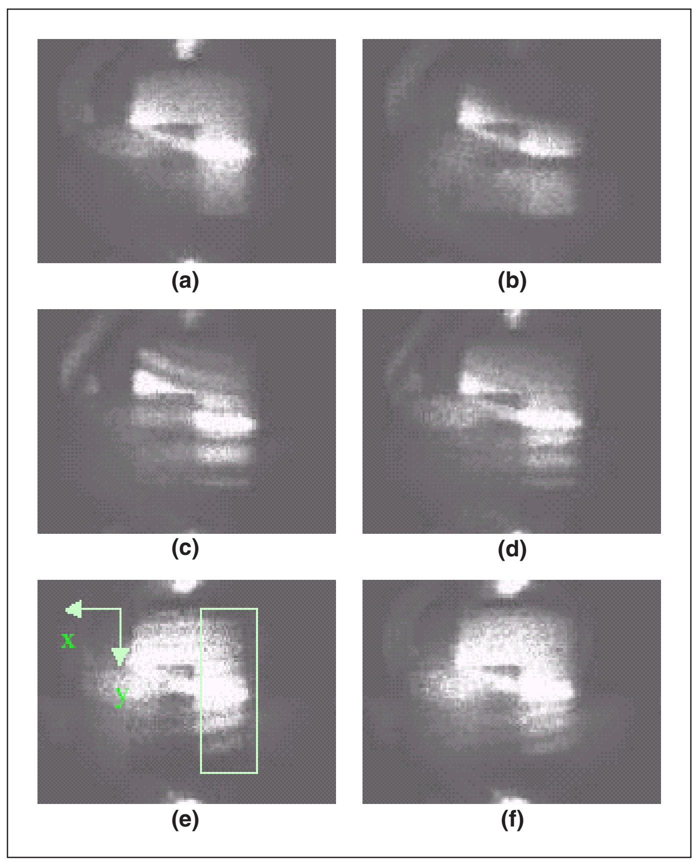

Fig. 4. (a) Reconstructed object without deformation. Holographic interferograms obtained for a voltage difference of (b) 10 V, (c) 30 V, (d) 35 V, (e) 40 V, and (f) 50 V.

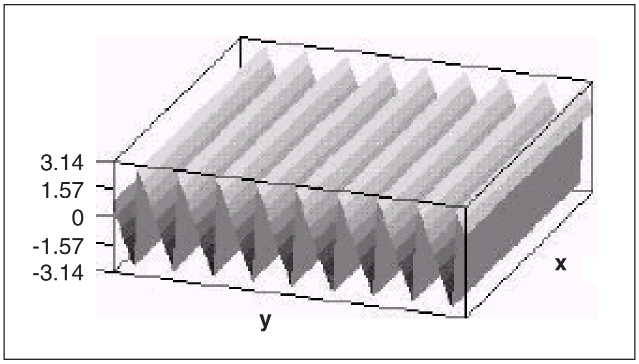

Fig. 5. Phase distribution (wrapped in 2π) obtained after applying the FTM (Fourier transform method) on the rectangular region in Fig. 4 e.

surface deformation uniform. For still greater displacements, the fringes become more closely spaced and difficult to resolve. The processing time for the digital reconstruction of the images and visualization of 3D deformation by the FTM took about 1 minute. Note that this is a vast improvement compared to wet chemical processing in conventional films, which take at least 3 minutes to develop and bleach, plus a few more minutes for optical reconstruction and image processing. The total processing time involving holographic films take at least 5 minutes (Almoro & Daza, 1998).

Since the intensity distributions are already in digital format, the 3D deformations can be visualized directly by applying the FTM to the holographic interferogram analysis. As a demonstration, FTM was applied to the rectangular region in Fig. 4e, chosen because it is free from spurious artifacts. The phase distribution wrapped in 2π is shown in Fig. 5. The filtering process in the FTM removes the high frequency noise and yields the desired phase distribution. Fig. 6 is the 3D plot obtained after unwrapping the phase distribution in Fig. 5 and then applying Eq. (1). From this plot it is clear that for a voltage difference of 40 V the out-of-plane displacement is 2.53 microns.

Table 1 lists the values of the out-of-plane displacements for different PZT voltages obtained using PSDHI and MI. The displacements obtained are consistent for the two techniques. Using the PSDHI, the smallest displacement measured was 0.317 µm (l/2) and the largest was 4.414 µm. This shows that PSDHI, coupled with FTM, is a sensitive, fast, and reliable technique in measuring 3D deformations of real objects.

CONCLUSIONS

Phase-shifting digital holographic interferometry was used to measure 3D out-of-plane deformations of a cantilever. The smallest displacement measured was 0.317 µm and the largest displacement was 4.414 µm. The digital reconstruction, instead of the wet chemical processing in conventional films, greatly reduced the processing time from 5 minutes to about 1 minute. The measured displacements of the cantilever, for a given voltage difference applied to the PZT, were consistent with those obtained using MI. Therefore, phase-shifting

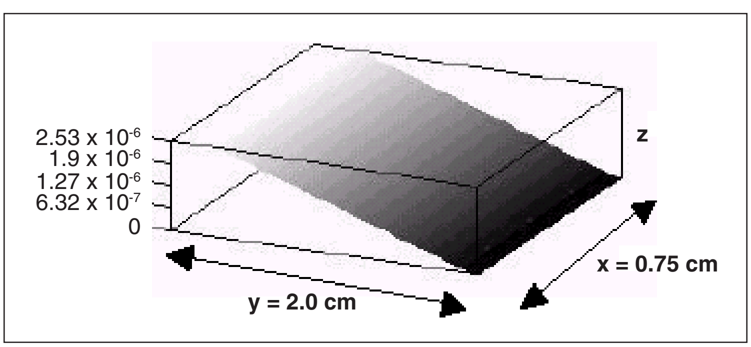

Fig. 6. 3D plot of the surface deformation for a voltage difference of 40 V (z-axis is in meter).

Table 1. Calculated displacements using digital holography and Michelson interferometry.

Voltage Difference (V)	Displacement (µm)	
	PSDHI	Michelson
6.0	0.317	0.317
11.4	0.633	0.633
16.1	0.950	0.950
21.0	1.266	1.266
24.9	1.583	1.583
29.3	1.899	1.899
34.1	2.216	2.216
38.8	2.532	2.532
42.9	2.849	2.849
47.0	3.165	3.165
50.4	3.482	3.482
55.4	3.798	3.798
59.9	4.414	4.414

digital holographic interferometry can be used as a fast, sensitive, and reliable technique in measuring 3D deformations of real objects.

ACKNOWLEDGMENTS

The authors would like to thank the DOST-PCASTRD for the equipment grant. M. Cadatal would like to thank DOST-SEI for the scholarship grant.

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