High precision deformation measurement by digital phase shifting holographic interferometry

Ming Chang, Ching-Piao Hu, Philip Lam, and James C. Wyant

A digital phase shifting technique capable of quantitatively determining the phase of holographic interferometric displacement fringes is presented. This technique uses computer control to take data and calculate surface deformation. The phase value at each detector point can be calculated by taking four successive intensity data frames with the reference phase shifted between each frame. The displacement fringe order number can be assigned by adding or subtracting 2π from a data point until the phase difference between adjacent data points is less than π. Experimental results show that this technique can precisely determine a fraction of a fringe with an accuracy of $\pm 1°$.

I. Introduction

Holographic interferometry is a precise method for measuring surface displacement and deformation of objects. The main sources of errors in the measurements can be divided into two categories: the errors associated with measuring geometry and those associated with measuring phase. Usually, redundant measurements[1,2] and careful experimental techniques can significantly improve the accuracy of system geometry, and the fringe order numbers can only be assigned by counting or scanning the interferogram with a microdensitometer. When higher precision is required, especially when strains need to be decided from the derivatives of surface displacement, electronic phase detection methods[3–6] have proved successful for estimating fractional fringes. The phase at each point in the holographic interferogram is either measured electronically or the intensity at each point is detected electronically and fed into a computer which calculates the phase. However, while these methods give extremely accurate values of optical phase, the heterodyne holographic interferometry[3,4] is limited to point-by-point measurements, and the phase stepping system of real time holographic interferometry built by Hariharan *et al.*[6] requires the calibration of the phase shifter, generally a piezoelectric transducer (PZT). Calibration of the phase shifter can be a problem if any vibration is present or if the phase shift varies across the beam.

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This paper describes the use of phase stepping and phase shifting techniques[7–9] in holographic interferometry. Experiments were carried out using the phase shifting method. The calculation of phase is carried out without having to calibrate the phase shifter. The phase of a real time holographic interferogram can be determined with an accuracy of $\pm 1°$.

Experiments made included deflection measurements of a cantilever beam and nondestructive tests of a disbonded honeycomb structure. These show the application of this technique to diffuse objects. Very precise data can be obtained both in small and large deformations.

II. Theory

$U_o(x,y)$ and $U_r(x,y)$ are expressed as the complex amplitudes of object wave and reference wave, respectively, for constructing a real time hologram. A single holographic exposure is made of the test object in its initial static configuration, and the irradiance at the film plane is

$$I(x,y) = (U_o + U_r)(U_o + U_r)^*. \tag{1}$$

On reconstruction of the image, the instantaneous object wave will have complex amplitude $U_o(x,y) \exp[i\phi(x,y,t)]$, where ϕ is the phase change due to displacement or deformation of the object at any time t and can be expressed as the equation $\phi = K \cdot L$. A phase shift δ is induced into the reference wave so the combined instantaneous irradiance of the reconstructed image and the deformed object is

$$I_t(x,y,t) = I_1 + I_2 \cos[\phi(x,y,t) - \delta],$$

where I_1 and I_2 can be estimated from the intensities of object wave and reference wave.

For the phase stepping method, the irradiance at each point is measured at four phase steps. These four frames of intensity data are recorded with the phase of the reference beam changed by an amount 2α between each readout. According to Eq. (2), we have

$$\begin{aligned}
A(x,y) &= I_1 + I_2 \cos[\phi(x,y) - 3\alpha], \\
B(x,y) &= I_1 + I_2 \cos[(\phi(x,y) - \alpha], \\
C(x,y) &= I_1 + I_2 \cos[\phi(x,y) + \alpha], \\
D(x,y) &= I_1 + I_2 \cos[\phi(x,y) + 3\alpha].
\end{aligned} \tag{3}$$

As shown by Carre,[7] ϕ at each detection point (x,y) in the real time holographic interferogram is given by

$$\phi(x,y) = \arctan\left\{\frac{\sqrt{[(A-D)+(B-C)][(3B-C)-(A-D)]}}{(B+C)-(A+D)}\right\}, \tag{4}$$

For the phase shifting method, the only difference from the above technique is to integrate the intensity, while the phase of the reference wave is shifted linearly with time over a range of -2δ to $+2\delta$. If the integrated intensities over four successive quarter periods are taken as

$$\begin{aligned}
A(x,y) &= \int_{-2\delta}^{-\delta} \{I_1 + I_2 \cos[\phi(x,y) + \alpha(t)]\} d\alpha t, \\
B(x,y) &= \int_{-\delta}^{0} \{I_1 + I_2 \cos[\phi(x,y) + \alpha(t)]\} d\alpha t, \\
C(x,y) &= \int_{0}^{\delta} \{I_1 + I_2 \cos[\phi(x,y) + \alpha(t)]\} d\alpha t, \\
D(x,y) &= \int_{\delta}^{2\delta} \{I_1 + I_2 \cos[\phi(x,y) + \alpha(t)]\} d\alpha t,
\end{aligned} \tag{5}$$

the measuring phase $\phi(x,y)$ can also be obtained from Eq. (4).

The phase value $\phi(x,y)$ of each data point can be determined modulo 2π. Since the calculation of Eq. (4) is independent of the amount of the constant phase shift between each frame of intensity data, both of these techniques eliminate the need for calibration of the phase shifter and can more accurately calculate the phase than methods which depend on how much the phase is shifted. It is easier to take data using the phase shifting method, since the phase of the reference wave varies linearly with time rather than in discrete steps. When using discrete steps a sufficient delay must exist between changing the phase and taking data for any phase ringing to damp out. Owing to the modulo 2π of the fringe pattern, the holographic displacement fringe order can be assigned by adding or subtracting 2π from a data point until the phase difference between adjacent data point is $<\pi$. The calculation restricts the total number of resolvable fringes since the phase difference between adjacent detector elements should not vary by more than π. After the displacement fringe order numbers have been assigned, the quantity of the object deformation can be calculated from the known sensitivity vector and the value of measured phase.

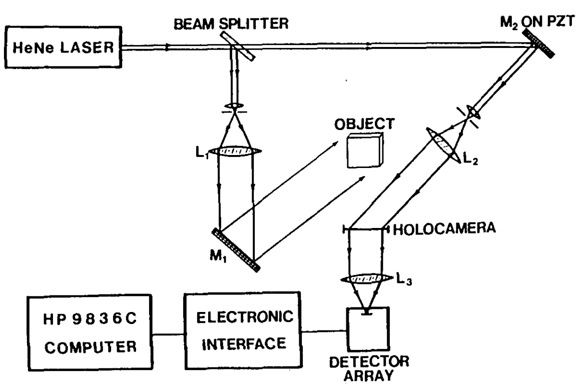


Fig. 1. Schematic of experimental setup used for deformation measurement using digital phase shifting holographic interferometry.

III. Experimental Setup

Figure 1 is a schematic of the experimental setup. The beam from a 15-mW He–Ne Laser is divided at a variable beam splitter. The collimated reference beam reflects off a mirror M_2 mounted on a PZT. The object beam was collimated or diverged to cover the whole object. After the hologram was made using a Newport HC 310 holographic camera, a set of real time holographic displacement fringes was induced by mechanically or thermally deforming the object. The holographic displacement fringes were imaged by a variable-magnification lens L_3 onto a Reticon 1-D 1728 linear and a 2-D 100 × 100 photodiode array for 1-D and 2-D measurements. The intensity on each pixel of the diode array is integrated while moving the reference mirror linearly to introduce a constant rate of change of phase in the reference beam. The phase at each pixel was calculated by a Hewlett-Packard 9836C desktop computer. The integration time is chosen to offer a suitable illumination power for the detector array.

For this kind of digital technique, an electronic interface unit is needed to control the movement of the PZT while synchronously digitizing and storing the integrated intensity frames. The detector output is digitized by an 8-bit analog-to-digital converter (ADC) for the 2-D array and a 10-bit ADC for the 1-D array, and the results are put into computer storage using a direct memory access (DMA) interface. The microcomputer then solves for the phase values after the successive four measurements according to the algorithm described earlier. The computer program for the HP8936C computer was written to perform several operations as follows:

(1) Communicate with the electronic interface unit for data acquisition.
(2) Detector output plotted on color computer display.
(3) Phase calculation and fringe order assignment.
(4) Allowing for subtraction of tilt rigid body motion.
(5) One-dimensional display of deformation maps.
(6) Two-dimensional display of phase contours.
(7) Three-dimensional display of phase maps.
(8) Printed output.

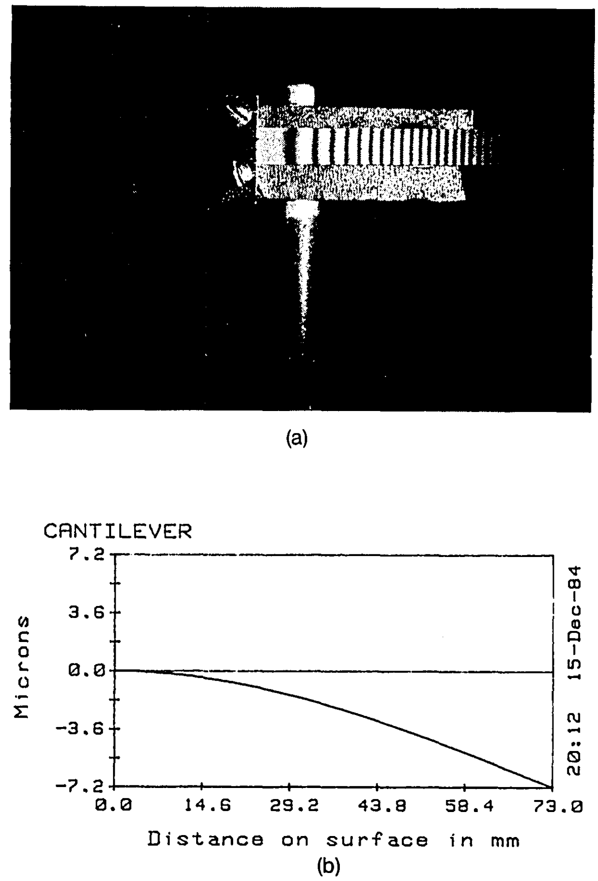


Fig. 2. Display of experimental results to show beam deflection measurement by using phase shifting technique: (a) holographic interferogram of a cantilever beam forced at the free end; (b) relative experimental deflection data of a horizontal line along the center of the beam.

(9) Disk storage and retrieval of phase data.
(10) Repeatability measurements.

IV. Experimental Results

For simplicity, a single observation direction was used in each measurement. Experiments were carried out with two objects. A Reticon RC1728H linear photodiode array was used to measure the real time deflection under different force conditions of a cantilever beam 73 mm long and 10 mm wide. A Reticon MC521C solid-state image sensor of 100 × 100 array was used to measure the thermal expansion of a large piece of honeycomb structure brazed to an aluminum plate and to determine the size of the surface defect on the panel.

Figure 2(a) is a photograph of the displacement fringes of a cantilever beam forced at one end. The relative phase values for a horizontal line along the center of the deformed cantilever beam are shown in Fig. 2(b). The phase values matched the theoretical deflection equation $Y = -9.242 \times 10^{-9}(219X^2 - X^3)$ with a residual variation caused by the different observation angle from the imaging lens to the different parts of the object.

Other measurements were carried out to show the

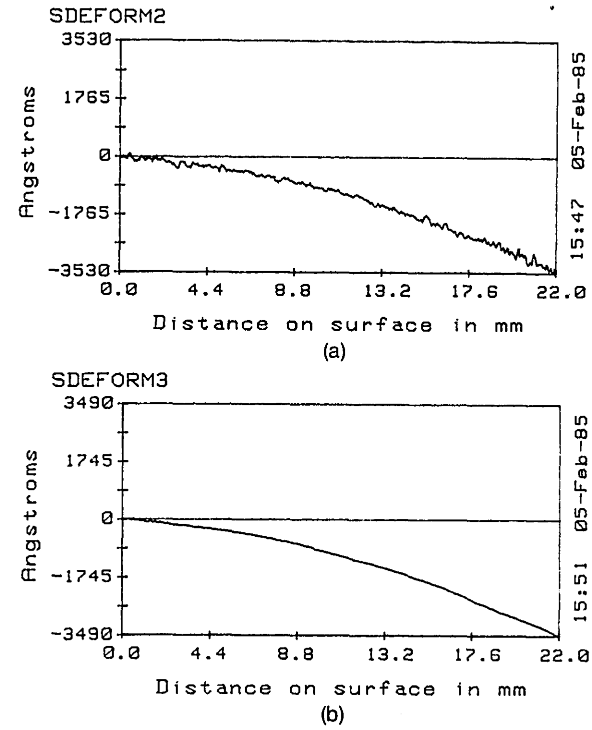


Fig. 3. Data display of small deformation measurement to show the precision of this technique: (a) Deformation data shows the influence of noise. (b) Result obtained using a rotating diffuser to average speckle pattern.

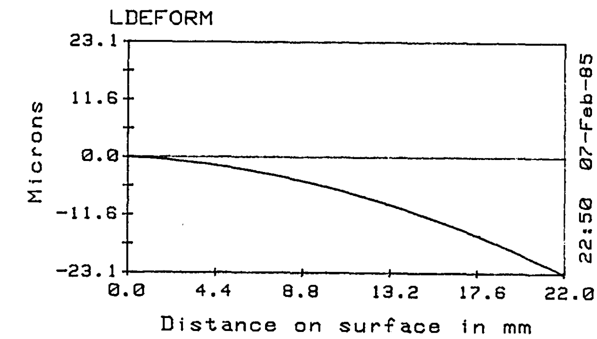
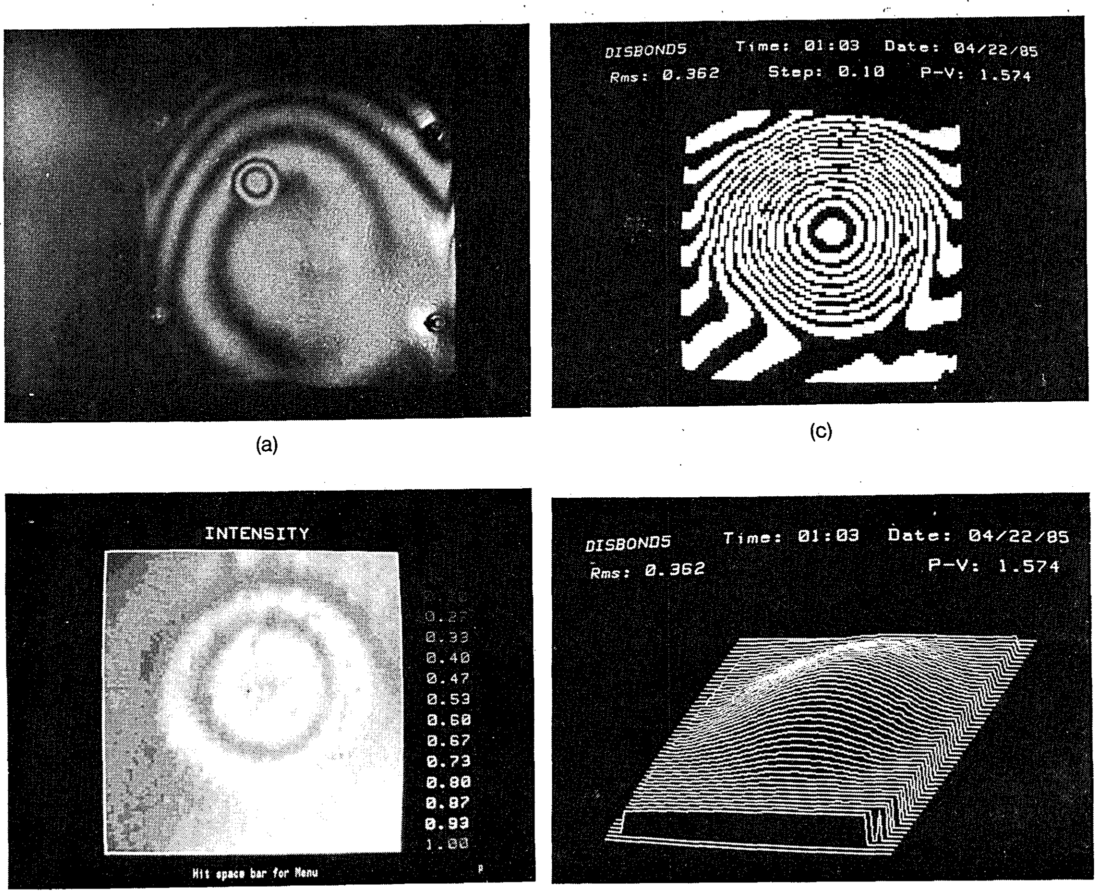


Fig. 4. Data display of large deformation measurement to show the ability for high resolution.

wide deformation measurement range. Figure 3(a) is a display of a small deformation map on the left end of the object. Figure 3(b) shows the results of removing speckle noise using a rotating diffuser to cause a time varying random speckle pattern that averages out during the integration period. The noise level is decreased to <20 Å which offers a measuring accuracy of ±1°. Figure 4 is a display of a larger deformation on the same small region to show the ability of high resolution. To get better results, a high quality camera lens is needed for large deformation measurements. Also these high spatial frequency displacement fringes should be imaged exactly on the detector array to achieve the best SNR.



(a) (b) (c) (d)

Fig. 5. Detection of disbond area in a honeycomb structure brazed to an aluminum plate by using a 100 × 100 detector array: (a)HNDT of the honeycomb structure under thermal stress; (b) real time intensity display of the deformation interferogram of the disbond area; (c) 2-D display of phase contour of the disbond area; (d) 3-D display of the phase map.

The same principle of deformation measurement can also be used in holographic nondestructive testing (HNDT). Figure 5(a) is a photograph of the holographic deformation fringes of a panel of honeycomb structure. The interferogram was formed by heating the aluminum skin on a honeycomb structure. The contour on the left upper region nearby center shows the existence of a surface disbond. Because there is no need to do the full interferogram analysis for locating the defect region, this flaw was imaged as large as possible on a 100 × 100 detector array. Figure 5(b) is the real time intensity display of this area. Figure 5(c) is a 2-D display of phase contour calculated using the phase shifting technique. Figure 5(d) shows the 3-D display of the phase map. The location, size, and shape of the disbond region can be determined quantitatively from the output data.

V. Conclusion

Displacements can be quantitatively determined using the holographic digital phase shifting technique with an accuracy of $\pm 1°$. These data can be differentiated to determine strains for stress analysis. With this technique, a holographic nondestructive testing system was developed to locate defects, and, due to the fast measurement speed, a real-time site observation can be effectively executed. Diffuse objects, specular surfaces, and transparent phase objects can be measured. The resolution for large deformation is dependent on the number of the pixels in the detector array and the quality of the imaging lens. The ultimate limitation to the number of fringe that can be measured by this technique is the requirement that the phase between any two adjacent detector points must be $<\pi$.

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