Electronic speckle pattern interferometry for simultaneous measurement of out-of-plane displacement and slope

N. Krishna Mohan

Applied Optics Laboratory, Department of Physics, Indian Institute of Technology, Madras 600 036, India

H. Saldner and N.-E. Molin

Division of Experimental Mechanics, Luleå University of Technology, S-97187 Luleå, Sweden

Received June 1, 1993

An optical configuration is presented for simultaneous measurement of out-of-plane displacement and slope change in electronic speckle pattern interferometry. Experimental results for a rectangular plate clamped along the edges and loaded at the center are presented.

Various optical configurations have been reported that use speckle interferometry and speckle shear interferometry to extract out-of-plane displacement, slope, and curvature from a single specklegram.[1-3] These techniques involve the use of a multiaperture mask with shearing elements in front of the imaging system. A reference wave is added at the image plane of the lens, either by provision of a smooth reference wave at the image plane[2] or by use of a small ground-glass reference diffuser in one of the apertures.[1] Such investigations were carried out by recording specklegrams on photographic plates, and the information was extracted by a filtering process. On the other hand, video techniques such as electronic/digital speckle pattern interferometry and TV holography eliminate the two-stage process of recording and filtering encountered in speckle interferometry and speckle shear interferometry and provide correlation fringes in real time. The technique was demonstrated by Butters and Leendertz.[4] Since then, such electronic techniques have become powerful on-line inspection tools for the measurement of displacements and displacement derivatives, vibrational analysis, shape measurement, and nondestructive testing.[5-8]

In this Letter we present an optical configuration for simultaneous observation of out-of-plane displacement and slope in real time. The technique combines the out-of-plane displacement configuration and a shearography configuration. At the CCD detector plane one half of the detector array records the out-of-plane displacement while the other half of the detector surface provides observation of slope fringes.

Figure 1 shows an optical configuration for the simultaneous measurement of out-of-plane displacement and slope change. The object is illuminated by a nearly collimated laser beam. It is imaged onto the photosensitive surface plate of a CCD camera by mirror M1 and an adjustable bimirror M2 placed in the arms of a Michelson interferometer setup. A zoom video lens in the front is used together with relay lenses before and after the Michelson interferometer. After passing through the interferometer, the beams become nearly parallel. The tilt angle between the surfaces of bimirror M2 is adjusted initially so that it acts as a plane mirror. An overlapped image that results from mirror M1 (image A) and mirror M2 (image B) is formed on the CCD camera. Mirror M1 is then tilted so that its reflected image A falls upon one half of the detector plate. Similarly the image reflected by mirror M2 is adjusted so that image B occupies the other half. A smooth in-line reference wave is added with the help of a single-mode fiber and a beam splitter to image A in one half of the detector. We introduce a shear in image B by tilting one of the arms in the bimirror along the x direction. Shear along the y direction can also be introduced by tilting one arm of the bimirror with respect to the y axis. One can see two images on the monitor, one from a conventional out-of-plane displacement configuration and the other from a shearography configuration. The average speckle size is adjusted to be within the resolution limit of the detector. The CCD camera is connected to a

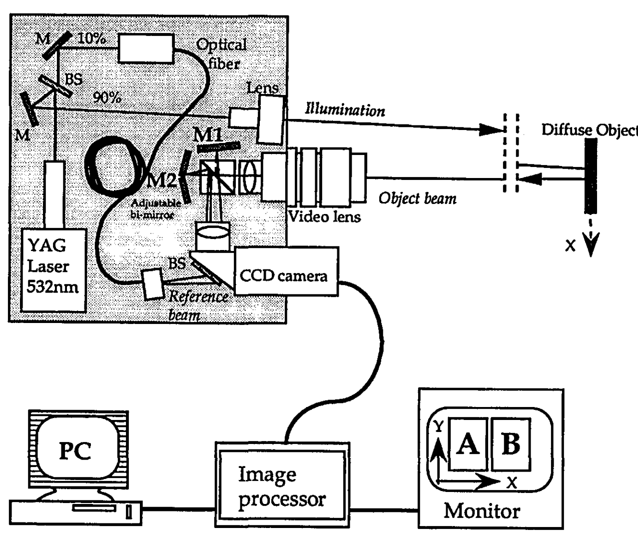


Fig. 1. Schematic for simultaneous measurement of out-of-plane displacement and slope change. M's, mirrors; BS's, beam splitters; PC, personal computer.

0146-9592/93/211861-03$6.00/0

commercially available image-processing system that is interfaced to the host computer.[6] For simplicity, we choose the system's simplest working mode, and one frame of the image is recorded with the standard ESPI version on a video store. The object is deformed, and this frame of the image is subtracted electronically pixel by pixel from the stored reference frame. The correlation out-of-plane and slope fringes are displayed on the monitor.

If I_1 and I_2 are the resultant intensities at a point on one (the out-of-plane) half of the detector, then the difference between the first and second frames that is due to image A can be written as[7]

$$\Delta I = I_2 - I_1 = \left| 4a_1a_2 \sin\left(\phi + \frac{\delta_0}{2}\right)\sin\frac{\delta_0}{2}\right|, \quad (1)$$

where a_1 and a_2 are the amplitudes of the object and reference speckle fields at that point, ϕ is the random phase between the two speckle fields, and δ_0 is the phase change introduced by the object deformation. (In the electronic holography system, developed at United Technologies Research Center, phase stepping of $\pi/2$ between successive frames can be introduced so that dark speckles carried by the random phase ϕ can be suppressed, giving high-quality interferograms. This phase-stepping facility is not used here.)

The video signals are proportional to the intensities, and hence the subtracted signal V_S is proportional to ΔI. The brightness on the monitor is then proportional to V_S. The brightness will be maximum when $\delta_0 = (2n + 1)\lambda$ and minimum when $\delta_0 = 2n\lambda$, n being an integer. All those areas where the speckles are correlated appear dark because of subtraction.

The phase change δ_0 that is due to deformation at any point (x, y) on the object is given by[9]

$$\delta_0 = (\mathbf{k}_2 - \mathbf{k}_1)\cdot \mathbf{L}(x, y), \quad (2)$$

where $\mathbf{k}_2$ and $\mathbf{k}_1$ are the propagation vectors of waves in the direction of observation and illumination, respectively, and $\mathbf{L}(x, y)$ is the deformation vector.

The phase difference δ_0 carries the information of the in-plane and out-of-plane displacements. To eliminate the in-plane component, we have the object illumination lie normally to its surface. In our experiments we study the case of out-of-plane displacement only. Therefore Eq. (2) can be expressed as[9]

$$\delta_0 = \frac{4\pi}{\lambda}\, w(x, y), \quad (3)$$

where $w(x, y)$ is the out-of-plane displacement component and λ is the wavelength of the light.

A similar expression can be obtained from the second half of the detector plane for the image B. It can be written as

$$\Delta I' = I_2' - I_1' = \left| 4a_1'a_2' \sin\left(\phi' + \frac{\delta_S}{2}\right)\sin\frac{\delta_S}{2}\right|, \quad (4)$$

where a_1' and a_2' are the amplitude contributions that are due to waves from points (x, y) and $(x + \Delta x, y + \Delta y)$ on the object at the other half of the detector plane as a result of the shearography configuration.

The phase change δ_S is

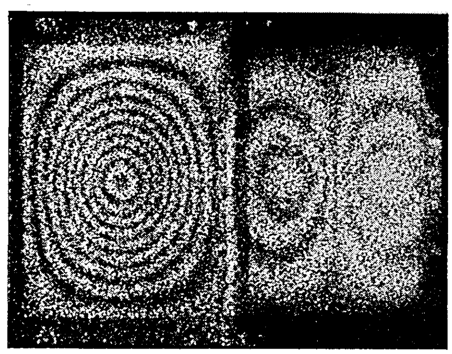
$$\delta_S = (\mathbf{k}_2 - \mathbf{k}_1)\cdot[\mathbf{L}(x - \Delta x, y - \Delta y) - \mathbf{L}(x, y)]. \quad (5)$$

Assuming a shear along the x direction, we can write the phase change δ_S for normal illumination and observation as[5]

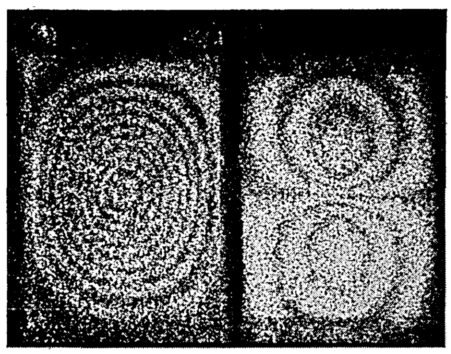
$$\delta_S = \frac{4\pi}{\lambda}\frac{\delta w}{\delta x}\Delta x. \quad (6)$$

One can observe on the monitor two sets of fringe patterns generated by individual configurations. Thus the present configuration provides real-time visualization of out-of-plane and slope fringes simultaneously.

The experiments are conducted on a rectangular aluminum plate having dimensions of 65 mm × 110 mm × 0.6 mm. The plate is clamped along the edges and loaded at the center. The specimen is sprayed with matte-white paint to scatter light uniformly and is illuminated normally with a collimated 80-mW frequency-doubled Nd:YAG laser (λ = 532 nm). The experimental arrangement is explained and shown in Fig. 1. The bimirror is tilted to introduce a shear along the x axis. The amount of shear on the object surface is 6 mm. The initial frame of the object is electronically stored.



(a)



(b)

Fig. 2. (a) Out-of-plane displacement fringes (w) and slope fringes ($\delta w/\delta x$) as seen from the monitor for a rectangular aluminum plate clamped along its edges and loaded at the center. The shear Δx is 6 mm, and the displacement $w = 2.5$ μm. (b) Out-of-plane displacement fringe pattern (w) and slope pattern ($\delta w/\delta y$) for the same object as in (a). The shear Δy is 7 mm.

The object is given an ~2.5-μm central deflection. The real-time out-of-plane displacement and slope fringes as seen from the monitor are shown in Fig. 2(a). The shear (7 mm) is also introduced along the y axis, and Fig. 2(b) shows the recorded fringe patterns. The calculated slope changes, from the out-of-plane measurements, agree within 5% to the shear measurements.

An electronic speckle pattern interferometric technique is presented in this Letter for the measurement of out-of-plane displacement and slope. This technique eliminates the use of a multiaperture configuration and recording materials and provides both components simultaneously in real time. Since the slope information is of low sensitivity, large object loading is necessary for discernible fringes to be obtained, but then the out-of-plane displacement, being very sensitive, will result in overcrowding of fringes. To some extent this problem can be solved by incorporation of an existing method, such as the speckle averaging method,[6] to produce high-quality interference patterns in real time. The other advantage of the technique is that, with the phase-shifting capabilities, it is possible to measure precisely both out-of-plane displacement and slope from a single configuration.

These experiments were performed at Luleå University of Technology when N. Krishna Mohan was a visiting scientist at the laboratory. This research was supported by the Swedish Research Council for Engineering Sciences.

References

1. R. K. Mohanty, C. Joenathan, and R. S. Sirohi, Appl. Opt. **24,** 3106 (1985).
2. D. K. Sharma, N. Krishna Mohan, and R. S. Sirohi, Opt. Commun. **57,** 230 (1986).
3. D. K. Sharma, N. Krishna Mohan, and C. Delisle, Opt. Commun. **65,** 70 (1988).
4. J. N. Butters and J. A. Leendertz, Trans. Inst. Control **4,** 349 (1971).
5. R. K. Erf, *Speckle Metrology* (Academic, New York, 1978), Chap. 4, p. 62.
6. K. A. Stetson, Opt. Eng. **26,** 1234 (1987).
7. C. Joenathan, in *Proceedings of the Spring Conference on Experimental Mechanics* (Society for Experimental Mechanics, Milwaukee, Wisc., 1991), p. 198.
8. P. K. Rastogi, J. Mod. Opt. **38,** 1251 (1991).
9. C. M. Vest, *Holographic Interferometry* (Wiley, New York, 1979), Chap. 3, p. 111.