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Dynamic two-beam speckle interferometry

Mansour A. Ahmadshahi
Sridhar Krishnaswamy
Siavouche Nemat-Nasser

Department of Applied Mechanics and Engineering Sciences
University of California, San Diego, La Jolla, CA 92093.

ABSTRACT

The feasibility of two-beam speckle interferometry for the study of time-varying mechanical deformation of diffusely reflecting bodies is demonstrated. A sequence of speckle patterns produced by a vibrating cantilever beam was recorded photographically by means of a high-speed camera. These speckle photographs were subsequently digitized using a CCD camera for input into an image processing computer. By gray-level subtraction of carefully registered pairs of speckle images, fringes corresponding to the relative surface displacements were obtained. A sequence of these fringe patterns was reconstructed to obtain the time-history of deformation. These are compared with time-frozen (strobed) patterns for the same body.

1. INTRODUCTION

When a coherent light beam is scattered by a diffuse surface, a random speckle pattern is observed. If the surface is now deformed, the resulting speckle pattern could be correlated with the original pattern to obtain a fringe pattern representing the relative displacement of the surface[1]. Many types of speckle interferometers have been configured to provide either out-of-plane or in-plane displacement-sensitive devices[2]. These interferometers have been so successful that many systems are commercially available today. However, speckle interferometry has been thus far confined to the study of *static* deformation, or at most, periodic deformation in a time-average or time-frozen sense. It has been stated as recently as 1989 that "dynamic speckle pattern interferometry is not possible"[3]. While there are in principle no physical limitations that would necessarily preclude the use of dynamic speckle techniques, a number of technical difficulties had to be overcome before dynamic speckle interferometry could be established as a viable technique. Among these were insufficient light intensity for the extant photographic recording media, resolution of typical high-speed camera systems, and perhaps most importantly, image registration.

In this paper, we present preliminary results demonstrating that dynamic two-beam ("holographic") speckle interferometry can be successfully used to study dynamic, mechanical deformation of diffusely reflecting bodies. This work was motivated in part to remove the misconception that speckle interferometry is unsuitable for dynamic studies, but more importantly because there is a pressing need for such a technique. Currently available full-field optical techniques can be used to study dynamic deformation in only certain classes of materials. For instance, the method of photoelasticity[4] works only with transparent materials that are birefringent. In moire techniques,[5,6] typically a grating has to be ruled or etched on to the specimen surface. Michelson and grating shearing interferometry[7] require that the material be either transparent or opaque but highly polishable. However, most of the advanced materials that are being actively pursued by the technological community today are either composites or ceramics, and it is expected that time-varying deformation in such materials may be more amenable to high-resolution optical scrutiny through the dynamic two-beam speckle interferometer described in this paper.

2. PRINCIPLE OF TWO-BEAM SPECKLE INTERFEROMETRY

The details of dynamic holographic speckle interferometry are given in a forthcoming report[8]. Here, only the basic principles are described. As shown in Figure 1, the diffuse surface of a test object is in the xy plane, and two collimated laser beams W_1 and W_2 are incident on it along the xz plane making angles $2\theta_1$ and $2\theta_2$ to the normal respectively.

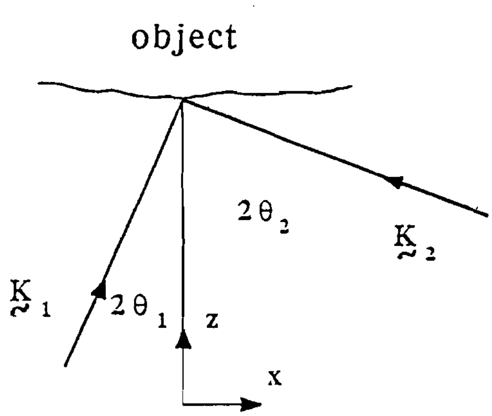

FIGURE 1: Schematic representation of double illumination of the test object, and the corresponding propagation vectors.

The diffusely scattered light from the test object is then collected by a lens system and the resulting speckle pattern is imaged in a camera. As in conventional speckle correlation interferometry, the electric field at the film plane of the camera can be expressed as the sum of the fields E_1 and E_2 due to the two illuminations, where:

$$E_1(x,y,t) = A(x,y)e^{i\psi_{T1}(x,y,t)}, \quad (1)$$

$$E_2(x,y,t) = B(x,y)e^{i\psi_{T2}(x,y,t)}. \tag{2}$$

Here $A(x,y)$ and $B(x,y)$ are possibly spatially varying amplitudes, and the phases are:

$$\psi_{T1}(x,y,t) = \hat{\psi}_1(x,y) + \frac{2\pi}{\lambda}(\mathbf{K}_1 - \mathbf{K}_0).\mathbf{d}(x,y,t), \tag{3}$$

$$\psi_{T2}(x,y,t) = \hat{\psi}_2(x,y) + \frac{2\pi}{\lambda}(\mathbf{K}_2 - \mathbf{K}_0).\mathbf{d}(x,y,t), \tag{4}$$

where λ is the wavelength of the laser light; $\hat{\psi}_1(x,y)$ and $\hat{\psi}_2(x,y)$ are related to the randomness of the test object surface; $\mathbf{d}(x,y,t)$ is the possibly time-varying test object surface displacement vector; $\mathbf{K}_1, \mathbf{K}_2$ are the unit propagation vectors in the direction of the incident wavefronts W_1 and W_2 respectively; and $\mathbf{K}_0$ is the unit vector in the observation direction (specimen to camera). The intensity at the film plane is therefore a time-varying function given by:

$$I(x,y,t) = \{E_1 + E_2\}\{E_1 + E_2\}^*, \tag{5}$$

where $*$ denotes complex conjugation.

In dynamic two-beam speckle interferometry, the time varying displacement field is to be monitored by recording (in a high-speed camera) the above intensity distribution over a series of frames each separated by a certain frame interval T. The total exposure in each frame of the sequence should be obtained by integrating the intensity given in equation (5) over the exposure time T_{exp} of the frame. However, if the exposure time is sufficiently small such that the displacement vector can be treated as essentially constant during this interval, then the intensity recorded on the film is proportional to that given by equation (5) itself. Note, however, that in the time interval T between one frame of the sequence and the next, the test object displacement vector could have changed appreciably and it is this change that is to be monitored. Thus, on the film plane, a total of $(N+1)$ exposures are made, each of intensity:

$$\mathcal{I}(x,y;nT) = A^2 + B^2 + 2AB\cos\left[\hat{\psi} + \frac{2\pi}{\lambda}(\mathbf{K}_1 - \mathbf{K}_2).\mathbf{d}\right], \quad n = 0,1,2...,N \tag{6}$$

where the arguments of the various functions are omitted for clarity. Here, $\hat{\psi}(x,y) = \hat{\psi}_1(x,y) - \hat{\psi}_2(x,y)$ is a spatially random phase variation.

The information regarding the specimen surface displacements at any instant can be extracted from (6) by subtracting the recorded speckle pattern at that instant from a reference pattern. Letting the first ($n = 0$) pattern in the sequence correspond to the reference, we can take the displacement vector at this time to be zero (ie., the specimen displacements are to be measured relative to the position when $n = 0$). Subtracting subsequent images from the reference image results in a sequence of intensity distributions:

$$q(x,y;nT) = \mathcal{I}(x,y;nT) - \mathcal{I}(x,y;0), \quad n = 1,2,3...N. \tag{7}$$

This process of subtraction is done by digitizing in a CCD camera the sequence of images recorded in the high-speed camera (as described in the following section). Finally, the absolute value of $q(x, y; nT)$ is obtained. Using equation (6) in (7) results in:

$$|q(x,y;nT)| = 4AB\left|\sin[\hat{\psi} + \frac{2\pi}{\lambda}(\mathbf{K}_1 - \mathbf{K}_2).\mathbf{d}]\right|\left|\sin[\frac{\pi}{\lambda}(\mathbf{K}_1 - \mathbf{K}_2).\mathbf{d}]\right|, \qquad (8)$$

Since $\hat{\psi}(x, y)$ is a randomly varying function, and $A(x, y)$ and $B(x, y)$ are typically spatially slowly varying functions, it can be seen that speckle correlation fringe maxima occur when

$$\frac{\pi}{\lambda}(\mathbf{K}_1 - \mathbf{K}_2).\mathbf{d}(x,y;nT) = (2m+1)\frac{\pi}{2}, \quad m = 0, 1, 2... \qquad (9)$$

where m is the fringe order. Equation (9) relates fringe order to that component of the displacement vector that lies along the direction $(\mathbf{K}_1 - \mathbf{K}_2)$. By suitably choosing the illumination directions, fringes corresponding to any desired component of the object surface displacement vector can be obtained. In particular, if a symmetric illumination is chosen such that $\theta_1 = \theta_2$, then fringes corresponding to in-plane x-direction displacement components are obtained in this setup.

3. EXPERIMENT

To demonstrate the feasibility of the proposed technique, the evolution of the time varying displacements of a vibrating cantilever beam at resonance was monitored. Figure 2 shows a schematic of the experimental setup.

The test object was an aluminum cantilever beam, 15.2 cm long, 5 cm wide, and 0.4 cm thick. A Hewlett-Packard function generator was used to obtain a sinusoidal signal which was amplified to drive an electro-magnetic shaker. The shaker was mechanically coupled to the specimen whose plate-mode resonance at a frequency of 3125 Hz was excited.

A continuous wave Coherent Innova-70 argon-ion laser (1.2 Watts in green) was used as the light source. The beam was routed through an acousto-optic modulator controlled by an RF driver which was in turn modulated by an arbitrary waveform generator. The acousto-optic modulator was essentially used as a shuttering device for the high-speed camera. The output (first-order) beam of the bragg-cell was spatially filtered, expanded and collimated to provide a beam of 2.4 cm diameter. This beam was split into two through use of a partial mirror, and a system of mirrors was used to provide two illuminations on the diffuse surface of the cantilever beam. These incident wavefronts made angles of $2\theta_1 = 20^o$ and $2\theta_2 = 55^o$ with the normal respectively. Thus, the speckle interferometer was sensitive to a combination of in-plane and out-of-plane displacements. Since the purpose of these experiments was to only demonstrate the feasibility of

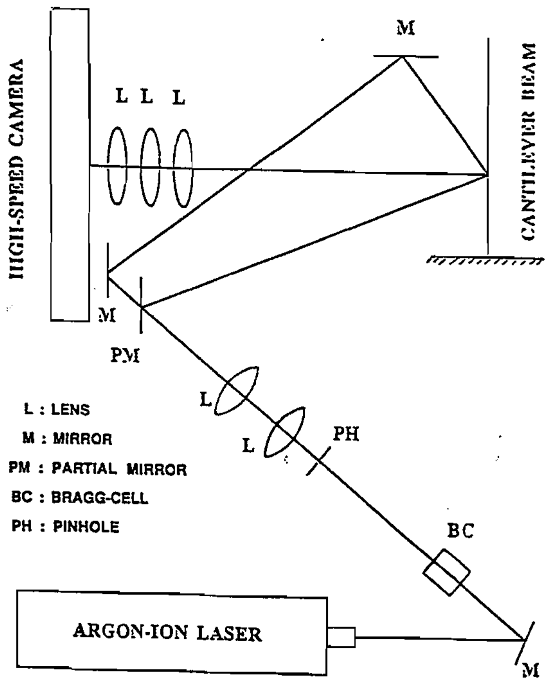

FIGURE 2: Schematic of the experimental setup.

dynamic two-beam speckle interferometry, no attempt was made to quantitatively separate the displacement information.

The diffusely scattered light from the specimen was collected by means of a series of lenses and imaged into a partially modified Cordin 330 high-speed camera. This camera is of the three-sided rotating mirror type. A framing rate of 25,000 frames per second (40 μs between frames) was used such that there would be about eight frames per cycle of vibration of the beam for a total of eighty frames. T-Max P3200 black and white film was used to record a sequence of speckle patterns from the vibrating cantilever beam. The exposed film was then processed with T-MAX developer.

The developed negatives were back-illuminated on a light table and the sequence of speckle photographs were digitized into an Imaging Technology Series 151 image processing system using a Pulnix TM545w CCD camera. Care was taken to accurately register the images using pre-marked alignment spots on the specimen and digital image correlation techniques. Subtraction of pairs of these speckle photographs provided fringe patterns corresponding to the relative displacements of the vibrating beam. As explained in a forthcoming report[8], spatial filtering operations were used to enhance fringe contrast.

4. RESULTS

The time varying surface displacement vector of the vibrating cantilever beam may be expressed as:

$$\mathbf{d}(x, y, t) = \cos\{2\pi\Omega t\}\mathbf{f}(x, y), \tag{10}$$

where $\Omega = 3125$Hz is the frequency of vibration, and $\mathbf{f}(x, y)$ is the mode shape vector which includes a combination of both in-plane and out-of-plane displacements, since the illumination used was not symmetric.

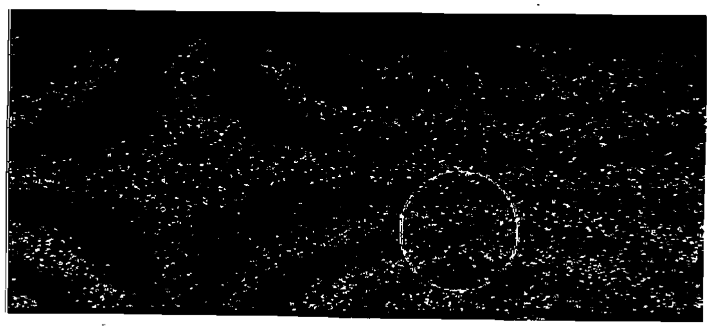

FIGURE 3: Time frozen fringes using strobed ESPI; the evolution of displacements in the highlighted region is monitored using dynamic holographic speckle interferometry.

Figure 3 shows a time-frozen (strobed) fringe pattern for this setup, but obtained with a conventional two-beam ESPI technique. The time-frozen fringe pattern shown corresponds to the maximum deflection position, with the reference being the *rest* position. The dynamic (time-varying) displacements in the subregion shown in the same figure were then experimentally monitored using the dynamic two-beam speckle interferometery described in this paper.

As the beam vibrates from its maximum positive position at time $t = 0\mu$s, a series of holographic speckle patterns was recorded at discrete 40μs intervals as shown in Fig. 4. A sequence of the *processed* dynamic two-beam speckle interferograms (Fig. 5) was then extracted from the recorded speckle patterns by the image digitization and processing methods described in the previous section. Further details of the contrast enhancement procedure which included spatial filtering and normalization using the Hilbert transform are described elsewhere[9]. Here, only the processed results are given. As can be seen from the figure, the number of fringes increases from 2 at 40μs to about 6 at 160μs when the cantilever is at its maximum negative position, with the reference corresponding to the maximum positive position of the beam.

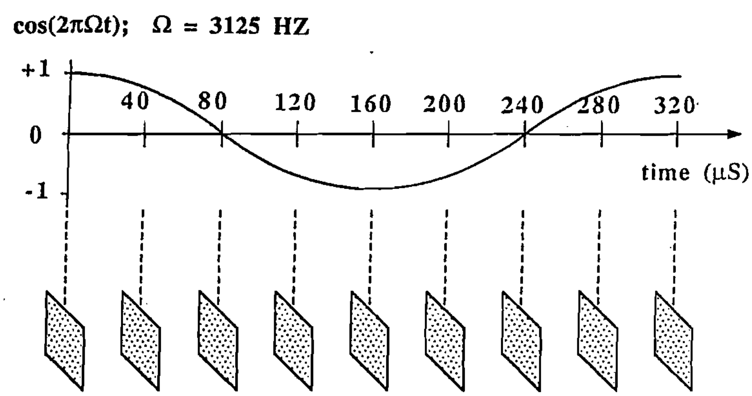

FIGURE 4: Time-varying amplitude of the mode function; dotted parallelograms are schematic representations of the holographic speckle patterns obtained at discrete times using a high-speed camera.

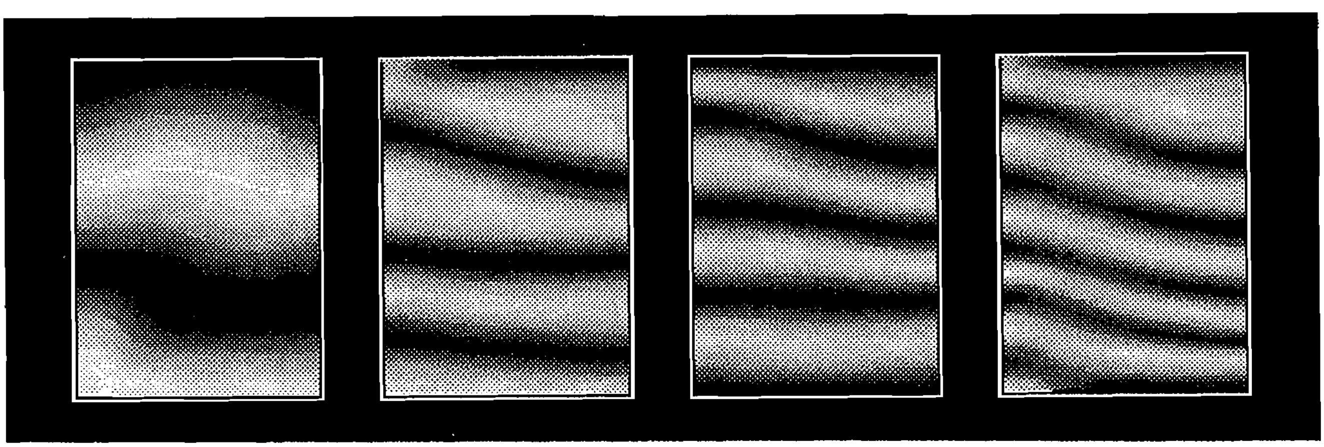

FIGURE 5: Evolution of displacement fringes in the highlighted subregion of the vibrating cantilever beam. These are the final processed results for time $t = 40, 80, 120$ and $160\mu s$.

5. CONCLUSION

To summarize, it has been shown in this paper that dynamic two-beam speckle interferometry is currently feasible. It is a two-step process whereby a sequence of speckle patterns corresponding to the time-varying deformation of a test object is recorded in a photographic high-speed camera. The developed negatives are then digitized and processed in a computer to obtain fringe sequences related to the time-varying mechanical displacements of the object. Some modifications to the current set-up that would greatly extend its applicability readily suggest themselves. In particular, a more powerful pulsed laser system synchronized with the camera shutter could be used to deliver greatly increased light intensity thereby allowing for larger test areas. It is expected that dynamic two-beam speckle interferometry would have important applications in the study of high-strain rate and impact phenomena of diffuse bodies such as advanced ceramics and composite materials.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. J.C. Dainty, Laser Speckle and Related Phenomena, Springer-Verlag, Berlin, 1975.

2. C.A. Sciamerella and J.A. Gilbert, "A Holographic-Moire Technique to Obtain Separate Patterns for Components of Displacement," *Experimental Mechanics,* vol. 16, No.6, pp.215-220, 1976.

3. R. Jones and C. Wykes, Holographic and Speckle Interferometry, Cambridge University Press, Cambridge, 1989.

4. J. Dally, W.F. Riley, and A.J. Durelli, "A Photoelastic Approach to Transient Stress Problems Employing Low-Modulus Materials," *Journal of Applied Mechanics,* vol. 26, pp.245-620, 1959.

5. W.F. Riley and A.J. Durelli, "Application of Moire Method to the Determination of Transient Stress and Strain Distribution," *Journal of Applied Mechanics,* vol. 29, pp.23-29, 1962.

6. J.M. Huntley and J.E. Field, "High Resolution Moire Photography: Application to Dynamic Stress Analysis," *Optical Engineering,* vol. 28, No. 8, pp.926-933, 1989.

7. S. Krishnaswamy, H.V. Tippur, and A.J. Rosakis, "Measurement of Transient Crack-Tip Fields Using the Method of Coherent Gradient Sensing," GALCIT SM-Report 90-1, California Institute of Technology, (to appear in the *Journal of Mechanics and Physics of Solids.*

8. M.A. Ahmadshahi, S. Krishnaswamy, and S. Nemat-Nasser, "Dynamic Holographic-Electronic Speckle Pattern Interferometry," University of California, San Diego, (forthcoming), 1991.

9. M.A. Ahmadshahi, "Computer Based Techniques for Holographic Fringe Pattern Information Detection," Ph.D Thesis, Illinois Insitute of Technology, Chicago, 1988.