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ELECTRONIC SPECKLE PATTERN SHEARING INTERFEROMETER WITH A PHOTOPOLYMER HOLOGRAPHYC GRATING

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Abstract

A photopolymer holographic grating is used to produce the two sheared images in an electronic speckle pattern shearing interferometer. A ground glass screen following the grating serves the purpose of eliminating unwanted diffraction orders and to remove the requirement for the CCD camera to resolve the diffraction grating's pitch. The sheared images on the ground glass are further imaged onto the CCD camera. The fringe pattern contrast was estimated to be above 90%. A validation of the system was done by comparing the theoretical phase difference distribution with the experimental data from the three point bending test.

OCIS codes: 120.6160 Speckle interferometry; 090.7330 Volume holographic gratings.

1. INTRODUCTION

Electronic speckle pattern interferometry (ESPI) can only directly measure displacement. Electronic speckle pattern shearing interferometry (ESPSI) enables direct measurements of displacement derivatives to be made. ESPSI using a diffraction grating as a shearing element is an attractive alternative to other shearographic systems[1,2] using gratings as it provides observation of real-time fringe formation and the possibility of phase-stepping analysis. The basic restriction in the application of holographic gratings in ESPSI systems comes[3] from the requirement for the CCD camera to resolve the pitch of the diffraction grating (50 l/mm). Joenathan & Bürkle suggested[4] an introduction of a ground glass in the ESPSI system to overcome the limitation for the grating frequency to be low. This idea is of interest for further experimental development.

We suggest a new application of a photopolymer holographic grating in ESPSI. Self-processing acrylamide based photopolymer[5] is used as a recording medium for recording holographic gratings. The optimized photopolymer material gives good diffraction efficiencies up to 94% for an exposure of $80 mJ/cm^2$ and it performs well in the transmission mode of hologram recording.

2. THEORY

2.1. Conventional shearography

When two light waves interfere, the following equation[6] relates their relative phase Φ at a location to their relative geometrical path length L:

$$\Phi = \frac{2\pi}{\lambda} nL - \beta \tag{1}$$

where λ is the wavelength of the laser light, n is the refractive index of the medium through which the laser light is transmitted, and β is a constant phase. The change in the relative phase $\Delta = \delta\Phi$ or phase change, which manifests as visible fringes, can be effected by an incremental change in any of the three parameters λ, n, and L. Thus,

$$\Delta = \frac{\partial \Phi}{\partial \lambda}\delta\lambda + \frac{\partial \Phi}{\partial n}\delta n + \frac{\partial \Phi}{\partial L}\delta L = -\frac{2\pi L n}{\lambda^2}\delta\lambda + \frac{2\pi L}{\lambda}\delta n + \frac{2\pi n}{\lambda}\delta L \qquad (2)$$

where $\delta\lambda$, δn, and δL denote respectively, the incremental change in wavelength, in refractive index, and in relative geometrical path length of the interfering waves.

If the same wavelength is used and the test environment is still air ($n = 1$), only δL term in Eq. (2) is nonzero, resulting in the following equation for the phase change[7]:

$$\Delta = \frac{2\pi}{\lambda}\left[A\,\delta u + B\,\delta v + C\,\delta w\right] \qquad (3)$$

where u, v and w are the displacement components of the neighboring point $P'(x+\Delta x, y, z+\Delta z)$ relative to point P (x, y, z) on the test surface, and A, B, and C are sensitivity factors that are related to the optical arrangement. For small image shearing Δx, the displacement terms in Eq. (3) can be expressed in terms of partial derivatives:

$$\Delta = \frac{2\pi}{\lambda}\left[A\frac{\partial u}{\partial x} + B\frac{\partial v}{\partial x} + C\frac{\partial w}{\partial x}\right] \qquad (4)$$

In our case (Figure 1) the object beam lies in the (x, z) plane, so there is no displacement along y axis. The phase change is:

$$\Delta = \frac{2\pi}{\lambda}\left[A\frac{\partial u}{\partial x} + C\frac{\partial w}{\partial x}\right] \qquad (5)$$

Consider the situation of an ESPSI system with one holographic grating in front of the CCD camera and small image shear Δx. The phase difference Δ can be expressed as[3]

$$\Delta = \frac{2\pi}{\lambda}\left[\frac{\partial u}{\partial x}\sin\theta + \frac{\partial w}{\partial x}(1+\cos\theta)\right]\Delta x \tag{6}$$

The dark fringes correspond to $\Delta = 2n\pi$, where n is the fringe order. In this case:

$$\frac{\partial u}{\partial x}\sin\theta + \frac{\partial w}{\partial x}(1+\cos\theta) = \frac{\lambda n}{\Delta x} \tag{7}$$

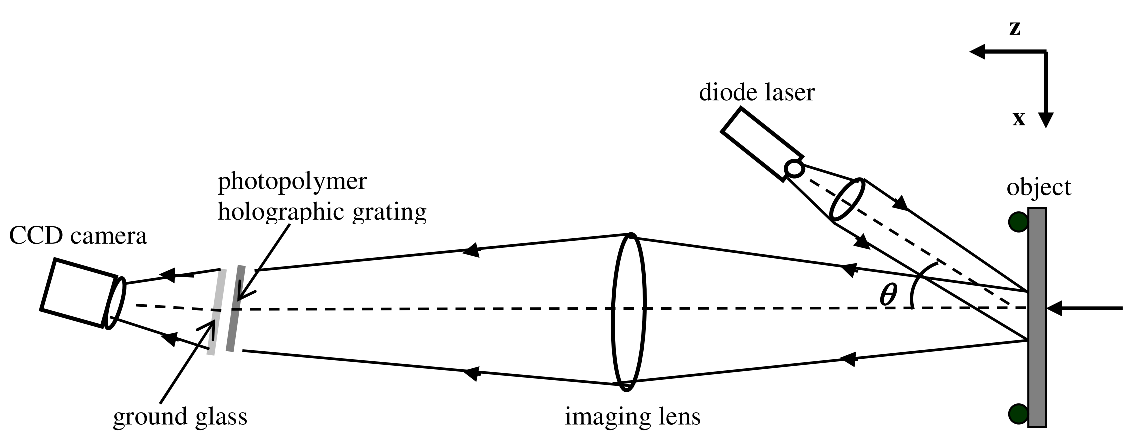

Fig.1. An optical set-up of the ESPSI system with a photopolymer grating

2.2. Pure bending

We consider the case of a beam with a constant bending moment along its length, which we will refer to as a beam in *pure bending*. There is a horizontal plane in the beam that does not change in length – this is known as the neutral surface and denoted NS in Figure 2. Using the definition of strain[8]

$$\varepsilon = \frac{\partial u}{\partial x} = \frac{z}{R} \tag{8}$$

where R is the radius of curvature of neutral axis of the bent beam; z is the distance between the neutral surface and any surface PP'; z is positive below the neutral surface, where the material is streched and negative above the neutral surface, giving negative strain.

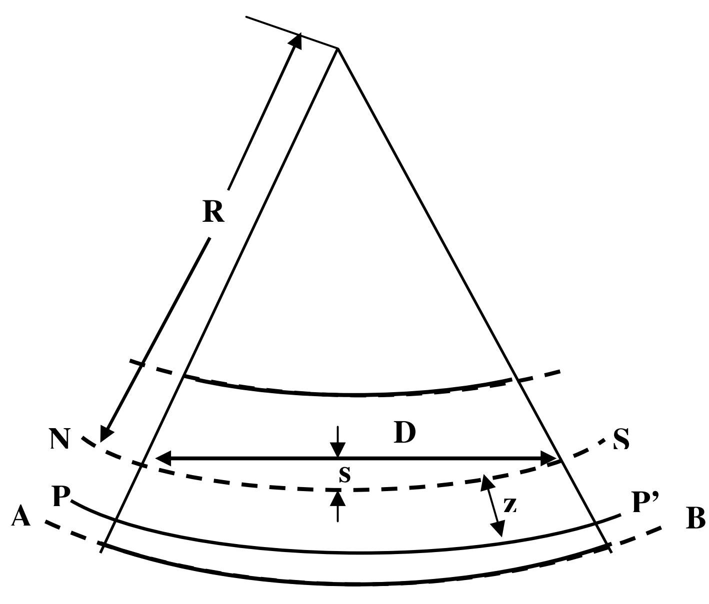

Fig. 2. Deformation of a symmetric beam subjected to pure bending in its plane of symmetry

The height of a curve measured from the chord (the sag formula) is:

$$s = R - \sqrt{R^2 - \left(\frac{D}{2}\right)^2} \qquad (9)$$

where *D* is the diameter of the optical surface; we assume that the radius of the curvature of the surface of interest is *R* as the degree of bending is of the order of microns (R>>z).

Using Eq. (8) and Eq. (9)

$$\varepsilon = \frac{\partial u}{\partial x} = \frac{4ds}{D^2 + 4s^2} \qquad (10)$$

where d is the thickness of the beam. As the ESPSI fringes are observed on the outer stretched surface of the beam, $z = \frac{d}{2}$.

For calibration of the system the well-known formulas[8] for the slope (Eq. 11 and Eq. 12) have been used:

$$\frac{\partial w}{\partial x}(x) = -\frac{P\left(L^2 - 4x^2\right)}{16EI} \qquad 0 \le x \le \frac{L}{2} \qquad (11)$$

$$\frac{\partial w}{\partial x}(x) = -\frac{P(3L - 2x)(2x - L)}{16EI} \qquad \frac{L}{2} \le x \le L \qquad (12)$$

where P is the constant uniform load per unit length, L is the length of the beam, EI is the bending modulus.

3. EXPERIMENT

The arrangement of the electronic speckle pattern shearing interferometric system with a single photopolymer holographic grating is presented schematically in Figure 2. A laser diode, with wavelength 785 nm and a maximum output power of 50 mW, is used as the light source. A laser beam illuminates the object at an angle $\theta = 30°$ to the normal to the object surface. A lens images the object onto a ground glass. A holographic photopolymer diffraction grating is placed in front of the ground glass, which acts as a diffusing screen. A holographic grating with spatial frequency 500 lines per mm was recorded using the second harmonic of NdYAG laser - λ=532nm. The diffraction efficiency of the grating is 60%. The intensities of the zero and the first order of diffraction were equalized by rotation of the grating. The rotation of the grating leads to slight off-Brag angle reading and decreases the intensity of the first order thus offering the possibility for fine adjustment of both image and sheared image intensities.

4. RESULTS AND DISCUSSION

Figure 3 and Figure 4 show the results from the test of the ESPSI system using a photopolymer holographic grating to introduce the shear. Fringe patterns presented on Figure 3 were recorded during cooling of an aluminium tin filled with hot water. The fringe pattern characteristic of the derivative of the displacement of the deformed object is displayed on the computer monitor. A filter with a 3x3 window was used to remove the speckle noise in the images. The fringe pattern contrast was estimated to be above 90%.

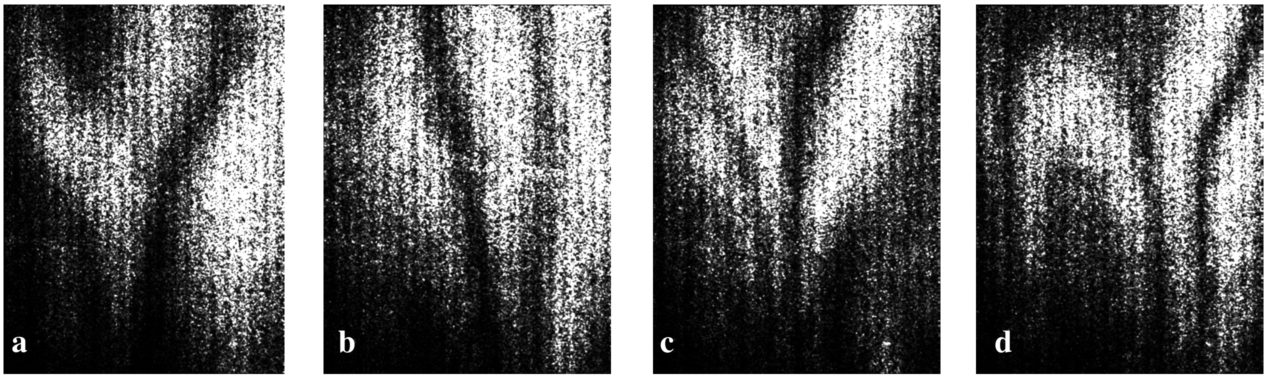

Fig. 3. ESPSI fringes in aluminium tin filled with hot water recorded during cooling:

a) at the beginning; b) after 3s; c) after 6s; d) after 9 s. The field of view is 20mm x 26mm

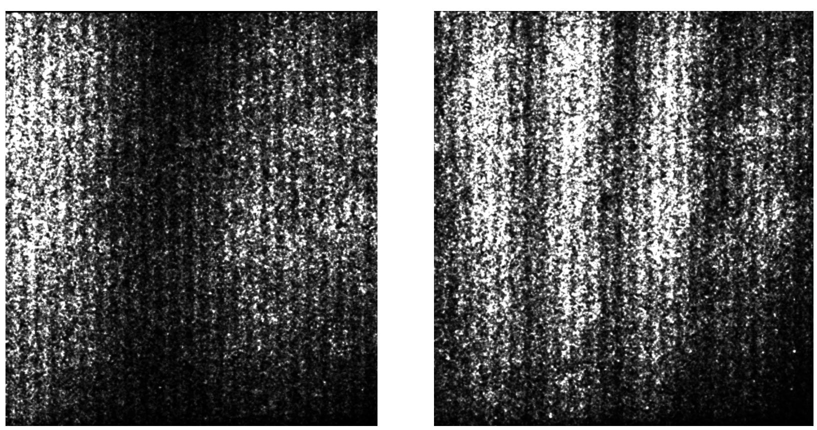

Fig. 4. ESPSI fringes on PVC during pure bending under deflection of:

a) 5 µm; b) 20µm. The field of view is 19 mm x 22 mm. The shear is Δx = 6 mm.

Fringe patterns presented in Figure 4 were recorded during pure bending of an polyvinylchloride (PVC) beam with following dimensions: length - L = 130 mm; width – d = 6 mm and height – h = 27 mm. The deflection was introduced using a vernier support and a step of 5 μm.

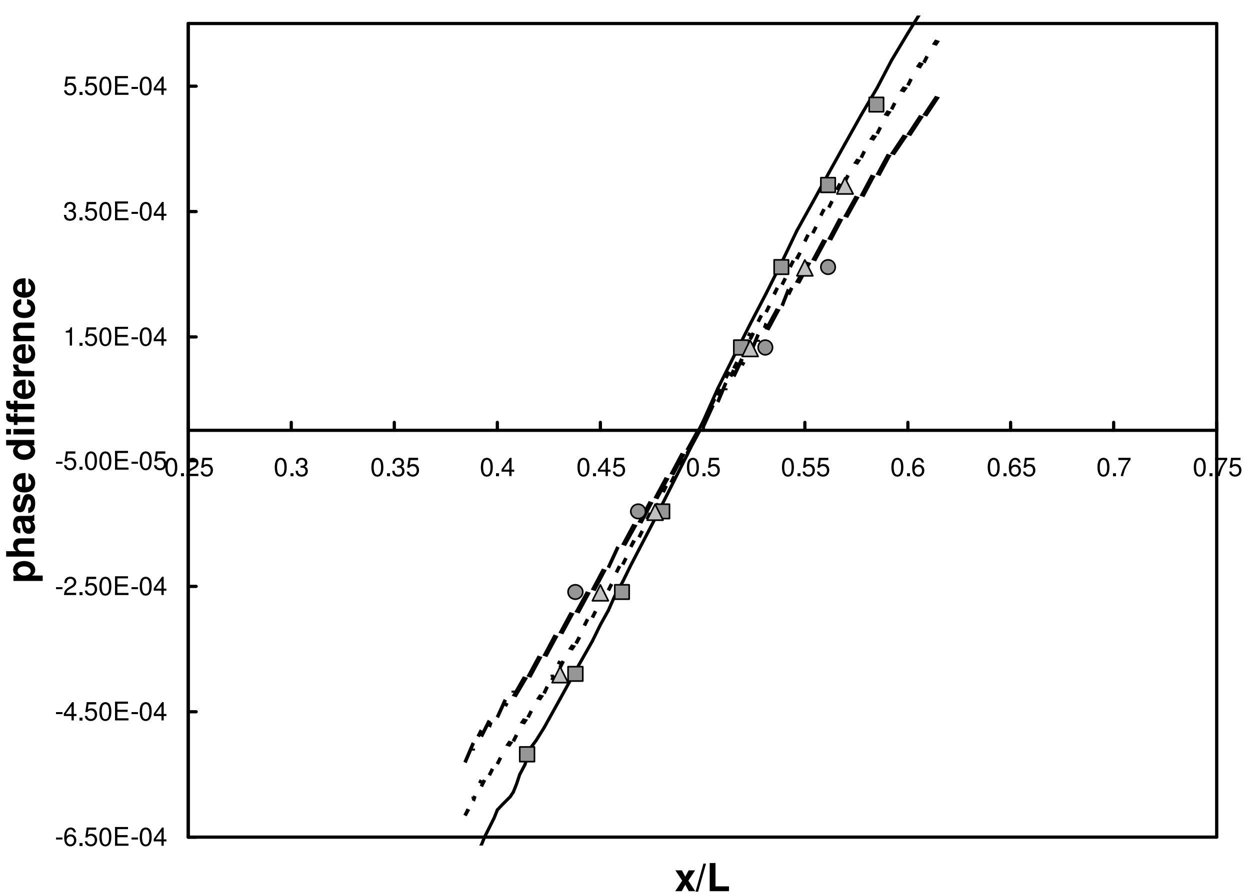

Fig. 5. Distribution of the phase difference vs. distance on the *x*-axis:

- - - - 30 μm deflection - theory; ● 30 μm deflection - experiment;

.... 35 μm deflection - theory; ▲ 35 μm deflection - experiment;

—— 40 μm deflection - theory; ■ 40 μm deflection - experiment;

Figure 5 presents the calibration curves of the ESPSI system with a single photopolymer holographic grating and a ground glass. After substitution of the theoretical formulas for the strain (10) and the slope (11) and (12) in the left part of Equation (7) we calculated the phase difference distribution in *x* direction. From the experimental results for the position of the fringes with order n = 0, 1, 2… we calculated the same phase difference distribution - right part of Equation (7). The three different distributions (for deflections: 30 μm, 35 μm and 40μm) show a good agreement between the theoretical prediction and the experimental data.

5. CONCLUSIONS

A new application of a photopolymer diffractive optical element in electronic speckle pattern shearing interferometer (ESPSI) is presented. We improve the fringe pattern contrast in a simple ESPSI scheme proposed by Jonathan & Bürkle[4] utilising a photopolymer phase diffraction grating as a shear-introducing element. The holographic grating is recorded using a self-developing acrylamide based photopolymer material. The holographic grating is used to shear the two images on a sheet of ground glass. The distance between the grating and the ground glass can be used to control the amount of the shear. The sheared images on the ground glass are further imaged onto a CCD camera. The introduction of the ground glass in the ESPSI system removes the limitation for the grating spatial frequency to be low in order to be resolved by the CCD camera.

A validation of the system was done by comparing the theoretical phase difference distribution with the experimental data from the three point bending test.

The ESPSI system using a diffraction grating as a shearing element is compact, offers a simple way to introduce discrete shear steps between two images by changing the distance between the grating and the imaging plane. An additional advantage is the low cost of such a system.

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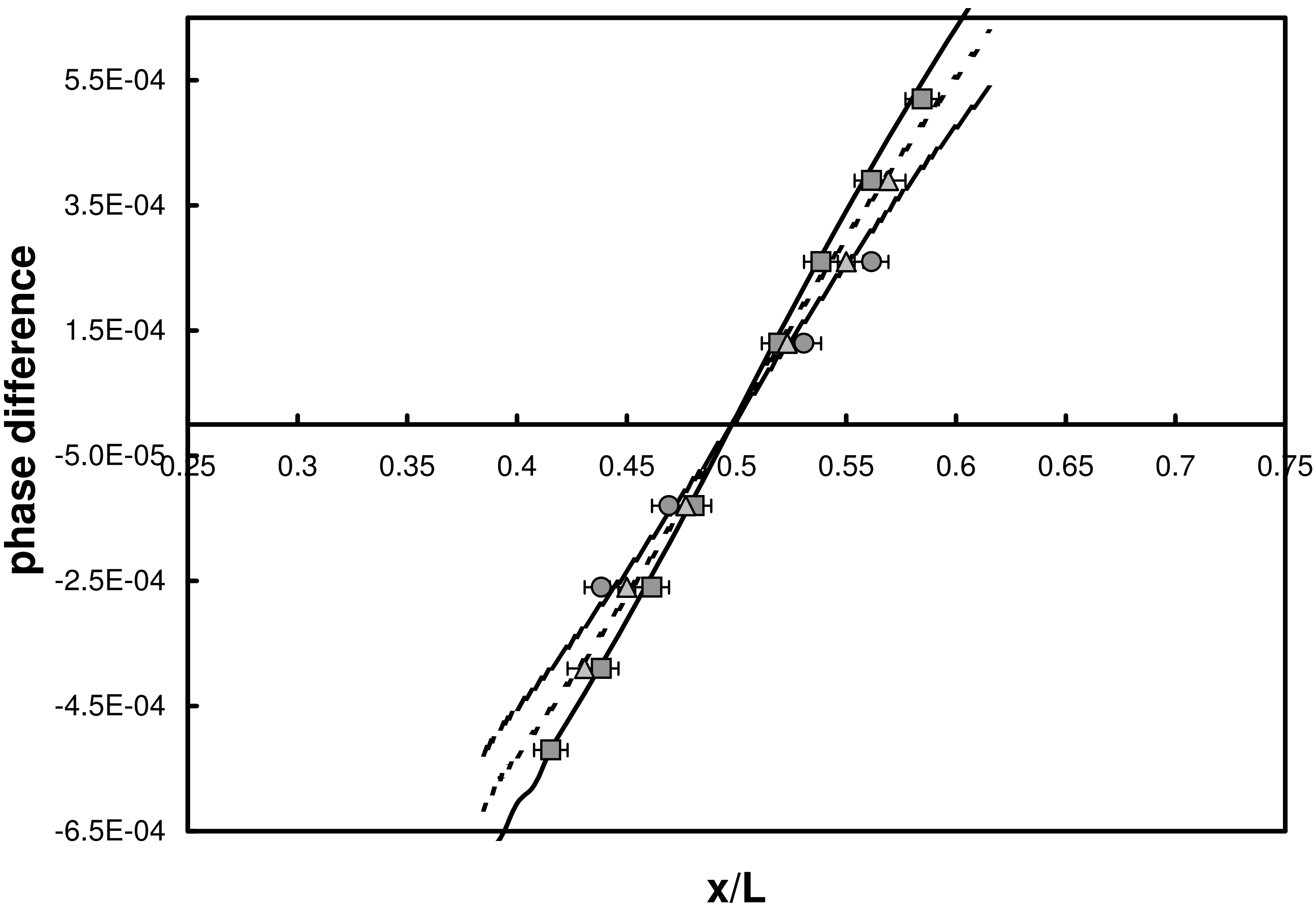

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0.35
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0.5
0.55
0.6
0.65
0.7
0.75
phase difference
x/L

Fig. 5