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**APPLICATION OF PHOTOPOLYMER HOLOGRAPHIC GRATINGS
IN ELECTRONIC SPECKLE PATTERN SHEARING INTERFEROMETRY**

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ABSTRACT

Two optical set-ups for electronic speckle pattern shearing interferometry (ESPSI) using photopolymer diffractive optical elements are presented. Holographic gratings are recorded using an acrylamide based photopolymer material. Since the polymerisation process occurs during recording, the holograms are produced without any development or processing. In both ESPSI systems the photopolymer gratings are used to shear the image. In the first ESPSI system only one grating is used in combination with 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. In the second ESPSI system two gratings are used to shear the image. The gratings are placed between the object and an imaging lens in front of the CCD camera. The distance between the two gratings controls the size of the shear. The ESPSI system with two photopolymer holographic gratings is compact and suitable for industrial applications. Introducing photopolymer holographic gratings in ESPSI gives the advantage of using high

aperture optical elements at relatively low price. Both of these interferometric systems are simple and flexible.

KEYWORDS: ESPSI, shearing interferometry, holographic gratings

INTRODUCTION

Electronic speckle pattern shearing interferometry (ESPSI) enables direct measurements of displacement derivatives to be made with variable sensitivity¹⁻⁸. A common approach to generate two sheared images of the object in ESPSI systems is to use a Michelson interferometric optical set-up. The images are generated via the two mirrors and the shear is introduced and controlled by tilting one of the mirrors. The idea of using a holographic grating for shearing of the two images in speckle shearing interferometry is not new⁵⁻⁹, but ESPSI using gratings to shear the image is an attractive alternative to the other shearographic systems⁵⁻⁷ using gratings as it provides observation of real-time fringe formation and the possibility of phase-stepping analysis. The ESPSI system presented by Joenathan & Bürkle⁹ is of interest for further development as the introduction of the ground glass removes the limitation for the grating frequency to be low.

We suggest new applications of photopolymer holographic gratings in two ESPSI optical set-ups. Self-processing acrylamide based photopolymer¹⁰ 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 80mJ/cm² and it performs well in the transmission mode of hologram recording. In both ESPSI systems the photopolymer gratings are used to shear the image. In the first ESPSI system only one grating is used in combination with a sheet of ground glass. The

distance between the grating and the ground glass can be used to control the amount of the shear. In the second ESPSI system two gratings with identical spatial frequency are used to shear the image. The distance between the two gratings controls the size of the shear. Introducing photopolymer holographic gratings in ESPSI gives the advantage of using high aperture optical elements at relatively low price and makes the system compact. Both of these interferometric systems are simple and flexible.

THEORY

When two light waves interfere, the following equation¹¹ relates their relative phase Φ at a location to their relative geometrical path length L :

$$\Phi = \frac{2\pi}{\lambda} nL - \beta \quad (1)$$

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,

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

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 the δL term in Eq. (2) is nonzero, resulting in the following equation for the phase change¹²:

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

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:

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

In our case (Fig. 1 and Fig. 2) the object beam lies in the (x, z) plane, so there is no displacement along y axis. The phase change is:

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

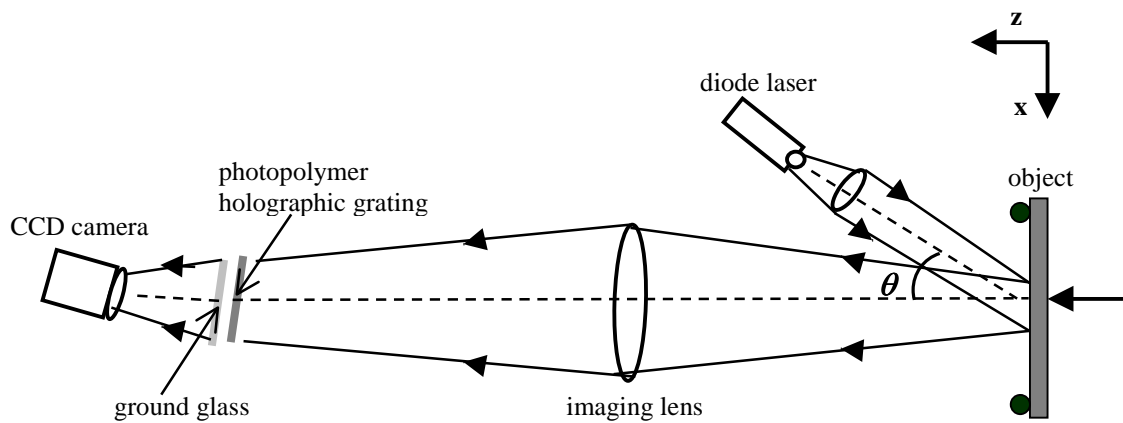


Fig.1. An optical set-up of the ESPSI system with one photopolymer grating

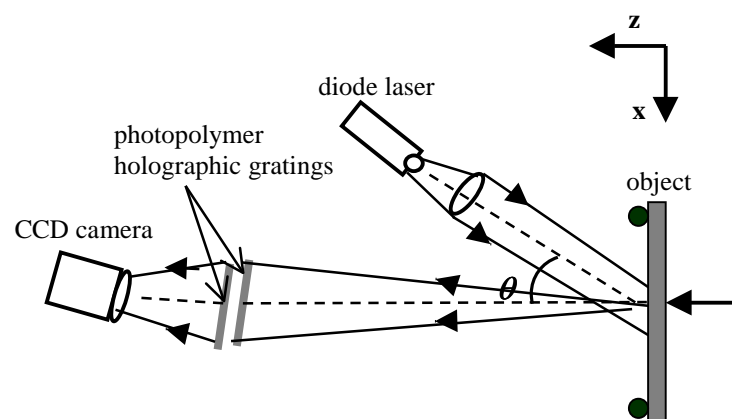


Fig.2. An optical set-up of the ESPSI system with two photopolymer gratings

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 as⁸

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

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

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

EXPERIMENT

Holographic gratings with three different spatial frequencies 200, 500 and 1000 lines per mm were recorded using the second harmonic of a CW Nd-YVO₄ laser ($\lambda = 532\text{nm}$). Recording time and intensity were 20s and 3.5mW/cm² respectively. The diameter of the gratings is 40mm. Diffraction efficiency in the +1 order of diffraction is 60%.

The arrangement of the electronic speckle pattern shearing interferometric system with a single photopolymer holographic grating is presented in Figure 3. 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 $\theta = 30^\circ$ 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. 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-Bragg angular adjustment and decrease in the intensity of the first order thus offering the possibility for fine adjustment of both image and sheared image intensities.

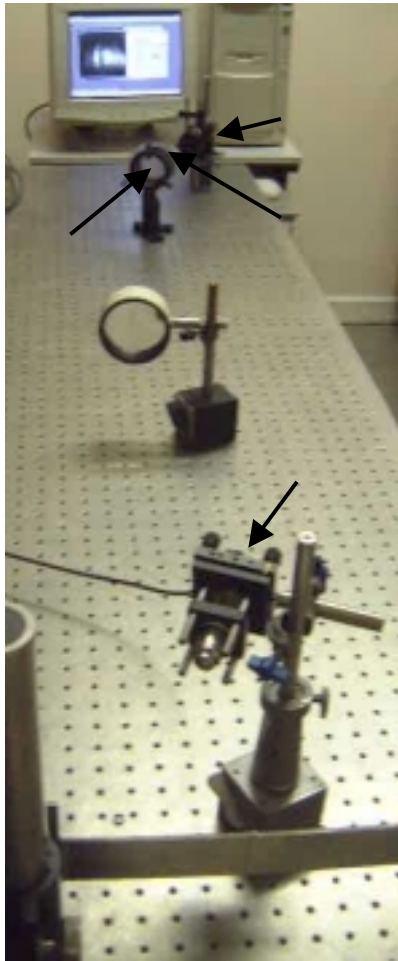


Fig. 3. Experimental set-up of the ESPSI system with a photopolymer grating

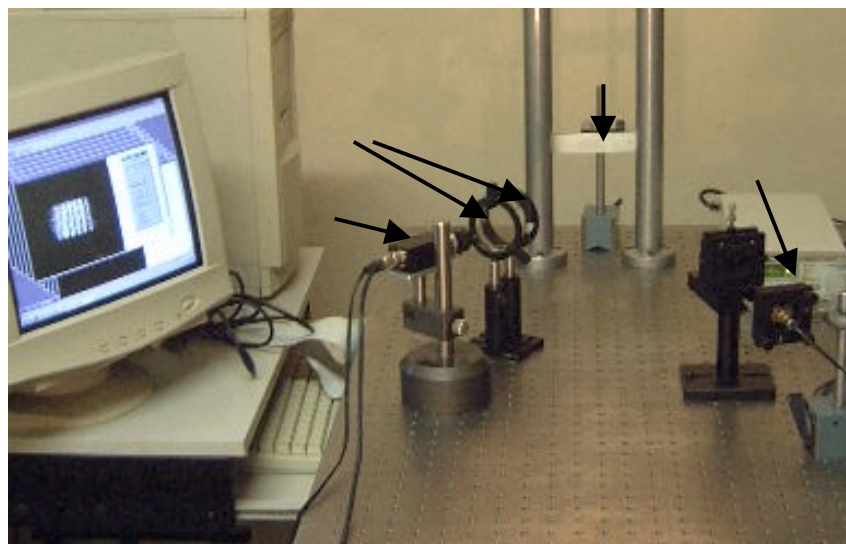


Fig. 4. . Experimental set-up of the ESPSI system with two photopolymer gratings

The arrangement of the electronic speckle pattern shearing interferometric system with two photopolymer holographic gratings is presented in Figure 4. 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 $\theta = 30^\circ$ to the normal to the object surface.

In the shearography system with two holographic gratings (Fig. 5) two pairs of beams can be used - (00, 11) or (10, 01). The intensities for the beams in the each of the pairs can be equalized by rotation of the gratings after which the CCD camera is realigned.

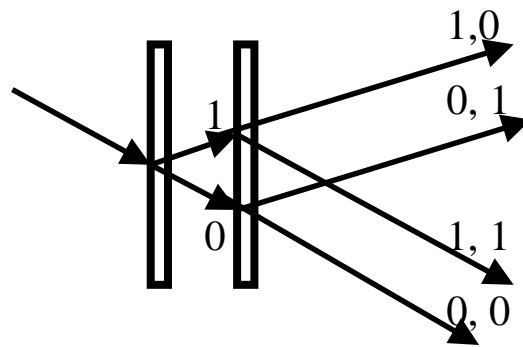


Fig. 5. Propagation of the beams through the shear introducing diffraction gratings.

RESULTS AND DISCUSSION

Figure 6 and Figure 7 show the results from the test of the ESPSI system using one photopolymer holographic grating and ground glass to introduce the shear (first ESPSI system). Fringe patterns presented in Figure 6 were recorded during cooling of an aluminium tin filled with hot water. A filter with a 3x3 window was used to reduce the speckle noise in the images.

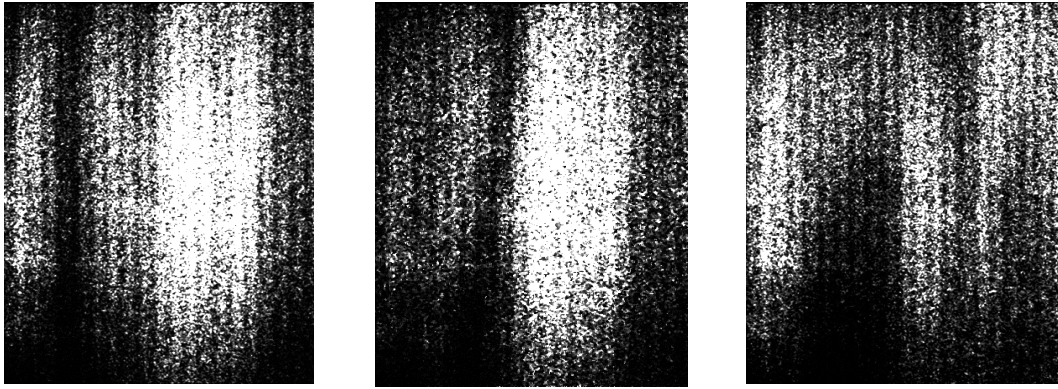


Fig. 6. ESPSI fringes in aluminium tin filled with hot water recorded during cooling with first ESPSI system: a) at the beginning of data acquisition; b) after 3 s; c) after 6 s. The field of view is 19mm x 26mm.

Fringe patterns presented in Figure 7 were recorded during pure bending of a 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 $5 \mu\text{m}$.

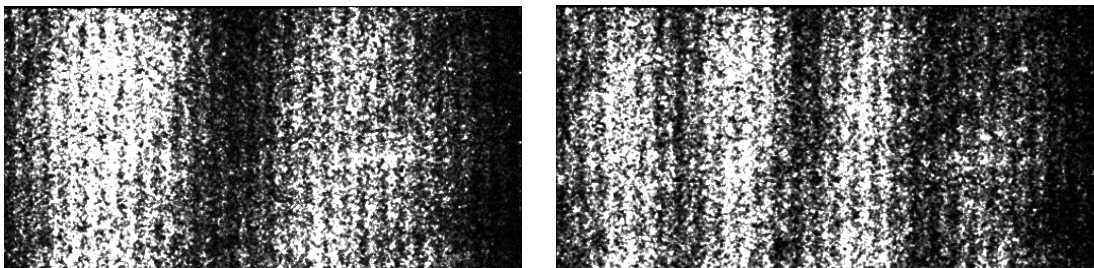


Fig. 7. ESPSI fringes on PVC during pure bending, recorded with ESPSI system with one photopolymer holographic grating and ground glass, under deflection of:

a) $10 \mu\text{m}$; b) $20 \mu\text{m}$. The field of view is 22 mm x 11 mm. The shear is $\Delta x = 6$ mm.

For characterisation of the ESPSI system with two holographic gratings, three different sets of gratings with different spatial frequencies were investigated. At the lowest spatial frequency - 200 l/mm , the beams from the two couples (01, 10) and (11,

00) shown in Fig. 2 were overlapped with higher orders of diffraction of the beams scattered outside the investigated part of the object. As a result the fringe pattern contrast was poor. When gratings with spatial frequency of 1000 l/mm were used the field of view corresponding to the investigated part of the object was reduced due to high angular selectivity of the gratings. The relative intensities of the two images were optimised only in the middle of the field of view and decreased very rapidly outside the central part. It was possible to enlarge the field of view by decreasing the photopolymer layer thickness and reducing gratings angular selectivity respectively. The optimum performance was achieved in the system that consists of two gratings with spatial frequency of 500 l/mm and thickness of half the standard. In this case the field of view was 50 mm and the fringe contrast was higher than 90 %.

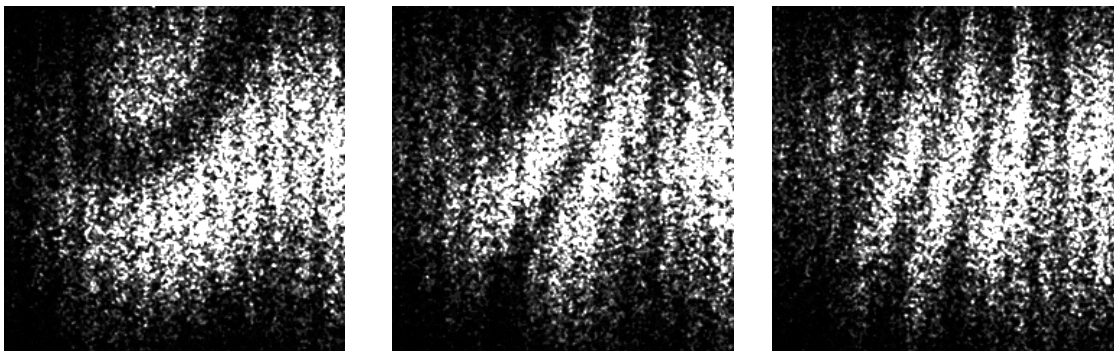


Fig. 8. ESPSI fringes in aluminium tin filled with hot water recorded during cooling with ESPSI system with two photopolymer holographic gratings: a) at the beginning of data acquisition; b) after 3 s; c) after 6 s. The field of view is 23mm x 23mm.

Figure 8 and Figure 9 show the results from the test of the ESPSI system using two photopolymer holographic gratings with spatial frequency of 500 l/mm (second ESPSI system). Fringe patterns presented in Figure 8 were recorded during cooling of

an aluminium tin filled with hot water. Again a filter with a 3x3 window was used to remove the speckle noise in the images.

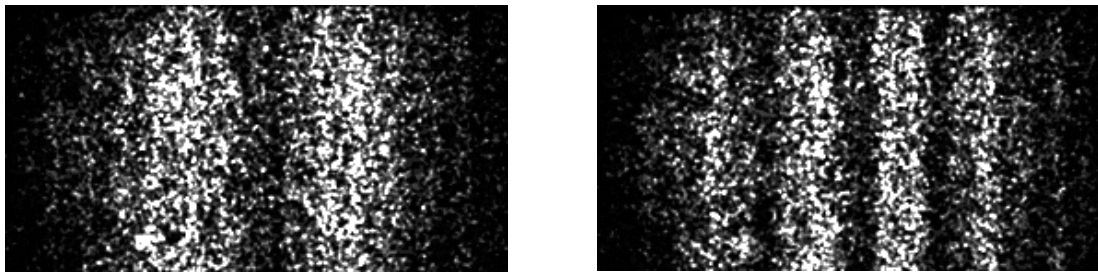


Fig. 9. ESPSI fringes on PVC during pure bending, recorded with ESPSI system with two photopolymer holographic gratings under deflection of: a) 10 μm ; b) 20 μm . The field of view is 44 mm x 24 mm. The shear is $\Delta x = 6$ mm.

Fringe patterns presented in Figure 9 were recorded with the second ESPSI system during pure bending of the same PVC beam as for the experiments with the first system. The deflection was introduced using a vernier support and a step of 5 μm .

The fringe pattern contrast for both systems was estimated to be above 90%. Both ESPSI systems using photopolymer diffractive optical elements are simple and flexible and offer a simple way to introduce discrete shear steps between two images: by changing the distance between the grating and the ground glass for the first system and by changing the distance between the two gratings for the second system.

CONCLUSIONS

New applications of photopolymer diffractive optical elements in electronic speckle pattern shearing interferometry are presented. Holographic gratings are recorded using an acrylamide based photopolymer material. Two optical set-ups for electronic speckle pattern shearing interferometry (ESPSI) using photopolymer diffractive optical elements are presented.

In both ESPSI systems the photopolymer gratings are used to shear the image. In the first ESPSI system only one grating is used in combination with 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. We improve the fringe pattern contrast in a simple ESPSI scheme proposed by Jonathan & Bürkle⁹ utilising a photopolymer phase diffraction grating as a shear-introducing element.

In the second ESPSI system two gratings are used to shear the image. The gratings are placed in front of the CCD camera. The distance between the two gratings controls the size of the shear. In order to have a large field of view and a good fringe contrast the spatial frequency and the thickness of the gratings in relation to their angular selectivity must be optimised.

The ESPSI systems using diffraction gratings to shear the image have some advantages compared to the commercially available systems based on a combination of a beam splitter and two mirrors (modified Michelson interferometer). They are simple and flexible and offer a simple way to introduce discrete shear steps between two images. An additional advantage is the low cost of such a system. The ESPSI system with two photopolymer holographic gratings is compact and suitable for industrial applications.

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