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A new optical configuration in speckle interferometry for contouring of three-dimensional objects

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Abstract

A novel optical configuration for contouring of three-dimensional objects is presented. In this configuration (referred to as image plane speckle interferometry) an object point is viewed symmetrically with respect to the surface normal and combined coherently at the image plane of the imaging system. This configuration is simple to implement and provides the possibility to vary the sensitivity over a wide range. Detailed theory and experimental results are presented. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Coding of an object surface by its contour lines has been by far the most prevalent way of characterizing the depth variations of a three-dimensional surface [1]. The earlier methods of contour generation were based on two-wavelength techniques [2], altering the refractive index of the medium surrounding the object [3] and displacing the object and the illumination beams [4]. All these methods are directly implemented in speckle interferometry from holographic interferometry, and have many constraints thereby limiting their applications. Later some new methods [5,6] of contouring have been reported in Electronic/Digital Speckle Pattern Interferometry (ESPI)/(DSPI) to overcome some of the drawbacks suffered by the earlier methods. The interferometer developed by Ganesan and Sirohi [6] uses Leendertz's [7] two-beam illumination configuration for measuring the in-plane displacement and the contour fringes are generated by giving a small rotation to the object perpendicular to the plane of the illumination beams. Joenathan et al. [8] have further extended this technique by incorporating phase shifting techniques. However, this method yields low contrast fringes when recorded on a photographic plate due to the presence of high dc component in the irradiance distribution [9]. The dc term is conveniently removed and implemented in ESPI/DSPI in the subtraction mode of operation. Ganesan and Sirohi [6] reported that the contour interval obtainable is 5–6 mm and for large angles of object rotation the fringes disappear due to large decorrelation.

In this paper we present a new optical configuration for depth contouring based on in-plane displacement sensitive configuration. Unlike the Leendertz configuration, the proposed configuration uses single beam illumination and dual directions of observation but the sensitivity is large and is equal to that of Leendertz's method. In this configuration an object point is viewed symmetrically with respect to the surface normal and combined coherently at the image plane of the imaging system. Contour fringes are generated by rotating the object perpendicularly to the plane of the illumination beam between the double exposures. Experimental results show that the decorrelation is rather slow in this setup and therefore even a very small contour interval can be obtained. Experimental results on a domestic light bulb are presented with the detailed theory.

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2. Experimental arrangement and theory

The optical arrangement for the image plane speckle interferometric configuration is shown in Fig. 1. The object to be contoured is illuminated normally with a collimated laser beam. The scattered speckle fields are observed symmetrically at an angle u on either side of the surface normal via a pair of mirrors (M_1 and M_3) and (M_2 and M_4) placed in front of the imaging system. The angle between the inner mirrors (M_3 and M_4) fixed at 90°. The outer mirrors (M_1 and M_2) are used to align and vary the symmetric observation angle $2u$. The outer mirrors are adjusted such that the observed scattered wave fronts via mirrors M_1 and M_2 enter each half of the lens segment independently and combined coherently at the image plane of the lens. At the image plane two images overlapped with identical magnification are formed. A two aperture mask is placed in front of the lens and hence at the image plane each speckle is modulated by a grid structure running orthogonally to the line joining the apertures. The aperture mask is not required in the present arrangement, however it acts as a pre-filtering arrangement and improves the contrast of the fringes in the interferogram [10].

An exposure is made on the photographic plate with the object in its original position. Then the object is rotated by a small angle and another exposure is made on the same plate. The total recorded intensity I_T at the recording plane can be expressed as

$$I_T = 2\left[I_1 + I_2 + 2\sqrt{I_1 I_2}\,\cos(f + 2pmx + d_{21}/2) = \cos(d_{21}/2)\right], \tag{1}$$

where I_1 and I_2 are the intensities recorded on the photographic plate before and after the object rotation, respectively, d_{21} the phase change introduced due to object rotation, m the grating frequency formed due to two apertures, f the random phase of the speckle field.

After processing, the specklegram (processed double exposed plate) is whole-field filtered [11]. Three halos are formed at the Fourier transform plane including the zeroth order; filtering through one of the first order halos results in an interferogram. The phase change d_{21} can be expressed as

$$d_{21} = (\mathrm{K}_2 - \mathrm{K})\mathrm{PL} - (\mathrm{K}_1 - \mathrm{K})\mathrm{PL} = (\mathrm{K}_2 - \mathrm{K}_1)\mathrm{PL}, \tag{2}$$

where K is the propagation vector along the direction of illumination, K_1 and K_2 are the propagation vectors along the directions of observation, $\mathrm{L}(u,v,w)$ is the deformation vector at any point on the object with $\mathrm{L} = u\hat{i} + v\hat{j} + w\hat{k}$; u, v and w are the displacement components along x, y and z directions, respectively.

Assuming that the illumination beam lies in the x–z plane, we obtain d_{21} which is responsible for fringe formation as

$$d_{21} = \frac{2p}{l} = 2u\sin u. \tag{3}$$

The concept of contouring is based on the fact that for very small angles of rotation, points at the same depth along the viewing direction (z-direction) undergo equal in-plane displacements (along x-direction) and this displacement is directly proportional to the depth of those points [6]. Since the object is given a small rotation of $\mathrm{D}j$

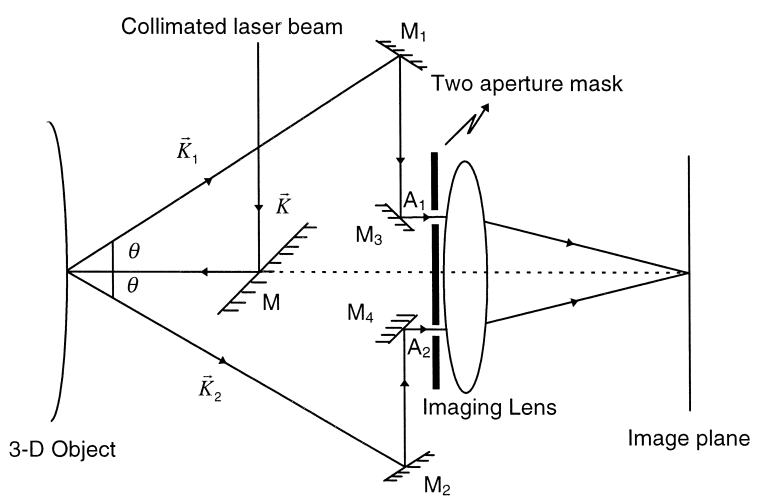

Fig. 1. Experimental arrangement for an image plane speckle interferometric configuration for three-dimensional contouring.

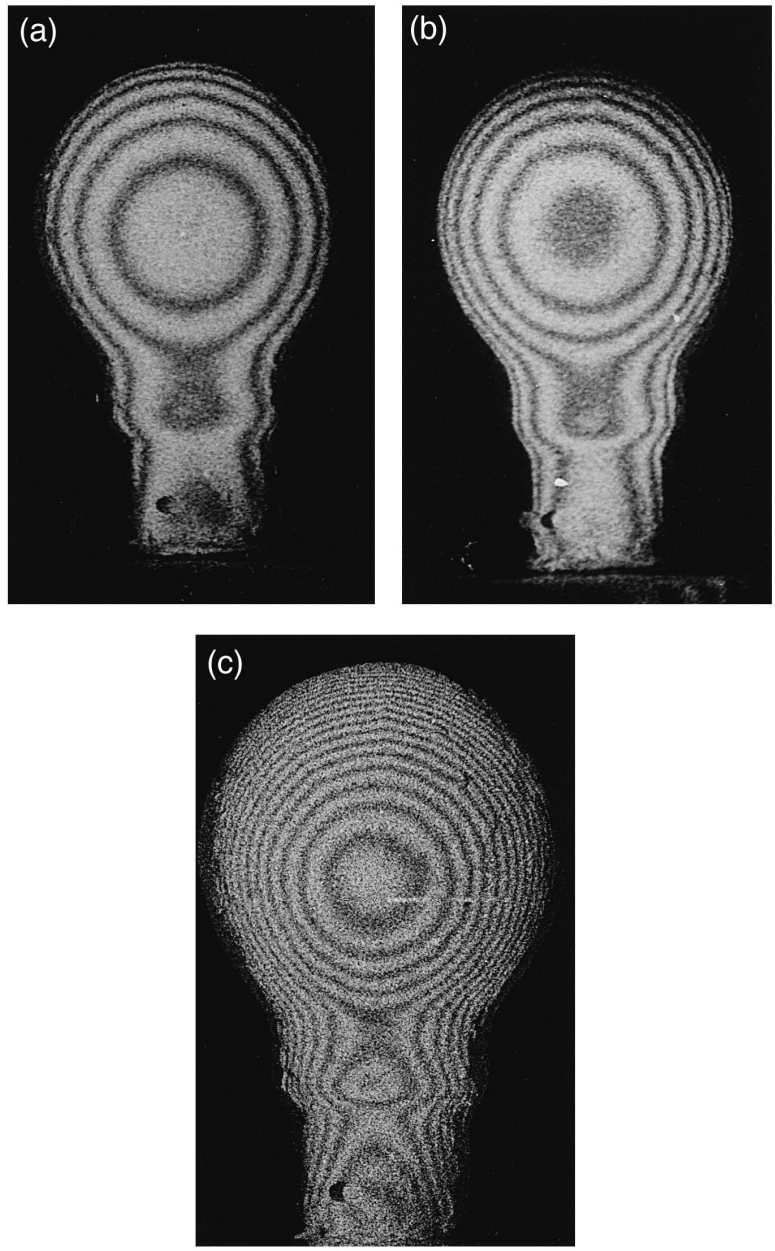

Fig. 2. Contour fringes of a light bulb obtained via one of the first order halos for: (a) $\Delta\varphi = 0.44$ mrad; (b) $\Delta\varphi = 0.66$ mrad; and (c) $\Delta\varphi = 1.32$ mrad.

in between the exposures we can write the u-component of the in-plane displacement as

$$u = z\Delta\varphi \,. \tag{4}$$

Substituting Eq. (4) into Eq. (3) the phase change becomes

$$\delta_{21} = \frac{2\pi}{\lambda} = 2z\Delta\varphi \sin u. \tag{5}$$

Bright fringes are formed when

$$\frac{2\pi}{\lambda} = 2z\Delta\varphi \sin u = 2m\pi$$

or

$$z = \frac{m\lambda}{2\Delta\varphi \sin u}. \tag{6}$$