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Contouring by modified dual-beam ESPI based on tilting illumination beams

X. Peng, H. Y. Diao, Y. L. Zou, and H. Tiziani

University of Stuttgart, Institut für Technische Optik, Stuttgart, FRG

Contouring by modified dual-beam ESPI based on tilting illumination beams. A new contouring method by modified dual-beam electronic speckle pattern interferometry is proposed. Instead of tilting test object as used in previous single wavelength techniques by ESPI, we introduce a tilt to the illuminating beams in order to obtain the contour fringe patterns. The most attractive feature of this technique is the possibility of contouring a stationary object so that it would be a more promising method in practical engineering metrology. The theoretical and experimental results show good agreement.

Konturing mit einem modifizierten Zweistrahl ESPI mit geneigtem Beleuchtungsstrahl. Eine neue Konturing-Methode mit einem modifizierten elektronischen Zweistrahl-Speckle-Interferometer wird vorgeschlagen. Anstatt wie bei den üblichen Einwellenlängen-Techniken beim ESPI das Testobjekt zu verdrehen, neigen wir zur Erzeugung von Konturstreifen den Beleuchtungsstrahl. Der attraktivste Vorteil dieser Technik ist die Möglichkeit, ein stationäres Objekt zu konturieren. Damit wird diese Methode in der praktischen Meßtechnik sehr vielversprechend. Theorie und Experiment zeigen eine gute Übereinstimmung.

Introduction

One of important application aspects using electronic speckle pattern interferometry is to generate contours of a diffuse object in order to provide data for 3-D shape analysis and topography measurement. Various contouring techniques by conventional ESPI have been developed for these applications. Two typical examples are single wavelength techniques with tilting the object to be contoured, and two-wavelength techniques. The basic principle of a conventional ESPI and its application on contouring are well known and can be found in various books in the literature [1]–[2].

Recently some new techniques for contouring an object by using ESPI have been reported [3]–[5]. The aim of these new techniques is to overcome some drawbacks suffered by already existing methods. A specific electronic speckle pattern interferometry with dual-beam illumination has been proposed for generating contours of an object [5]. A dual-beam ESPI has several advantages: 1) economy of light usage, 2) it was found to be stable, 3) the image system does not have to resolve the fine structure. However a small tilt has to be introduced to the object to be tested when one uses such a dual-beam ESPI to obtain the contour fringe pattern.

In this paper, we present a modified dual-beam ESPI arrangement and make a detailed study on the contour phase analysis and on the optimal determination of the contour plane orientation. In this modified dual-beam ESPI, we introduce a lateral shift to the collimating lens and, therefore, a tilt to the illumination beams instead of a tilt to the object to be contoured. Hence the technique described in this paper appeared to be a more promising method from the point of view of practical engineering applications. The results with phase-shift and fringe analysis are also presented in this paper.

Modified dual-beam ESPI with tilting illumination beams

Fig. 1 shows the experimental set-up of modified dual-beam electronic speckle pattern interferometer. The laser beam is collimated and then split into two illuminating beams via a beam splitter *BS*. An additional mirror M_3 is added in the optical configuration. A tilt to both incident wavefronts is introduced by shifting collimation lens *L*. The subtracted speckle pattern is displayed on the monitor, and the contour fringe pattern corresponding to the shape of the object being tested are obtained by subtracting the intensities of two speckle patterns before and after shifting of collimation lens *L*. We shall show that the necessity of the mirror M_3 in the next section. It will be demonstrated that the function of mirror M_3 plays an

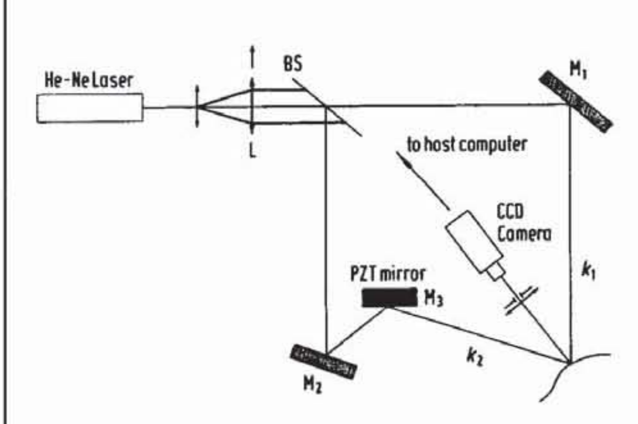

Fig. 1. Experiment arrangement.

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X. Peng, H. Y. Diao, Y. L. Zou, and H. Tiziani, Institut für Technische Optik, Universität Stuttgart, Pfaffenwaldring 9, D-7000 Stuttgart.

important role in obtaining a suitable contour fringe pattern and keep the orientation of contour planes in the optimum direction.

Theoretical analysis

a. Contour phase analysis

The optical vector geometry for the modified electronic specle pattern interferometer is shown in fig. 2, where $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ are unit vectors representing the directions of each illuminating beam; $\delta\boldsymbol{k}_1$ and $\delta\boldsymbol{k}_2$ are vectors corresponding to the tilt direction of each incident beam; $\boldsymbol{a}$ is a unit vector standing for a rotation axis about which both incident beams are rotated due to the shift of collimating lens. P_1 and P_2 are two points on the object to be contoured and vectors $R_1\boldsymbol{r}_1$ and $R_2\boldsymbol{r}_2$ are two vectors from the observation point O to the two arbitrary position points on the object surface. The vector $\boldsymbol{r}_2$ has been chosen to be the sight direction, and the direction of optical axis are also chosen to be in this direction in order to simplify the analysis. $I\boldsymbol{i}$ is a position vector defined by observation point O and rotation axis.

In such an optical geometry, there is no surface displacement and any change of phase is thus due to the rotation of wavefronts incident on the object. In addition, the amount of tilt for each illuminating beam is exactly same, i.e. $\delta\theta_1 = \delta\theta_2 = \delta\theta$, in this arrangement. Where $\delta\theta$ represents tilt angle for each incident beam. Since the rotations of incident wavefronts are so small that we could write

$$\delta\boldsymbol{k}_1 = \delta\theta\cdot(\boldsymbol{a}\times\boldsymbol{k}_1)$$
$$\delta\boldsymbol{k}_2 = \delta\theta\cdot(\boldsymbol{a}\times\boldsymbol{k}_2)\,. \tag{1}$$

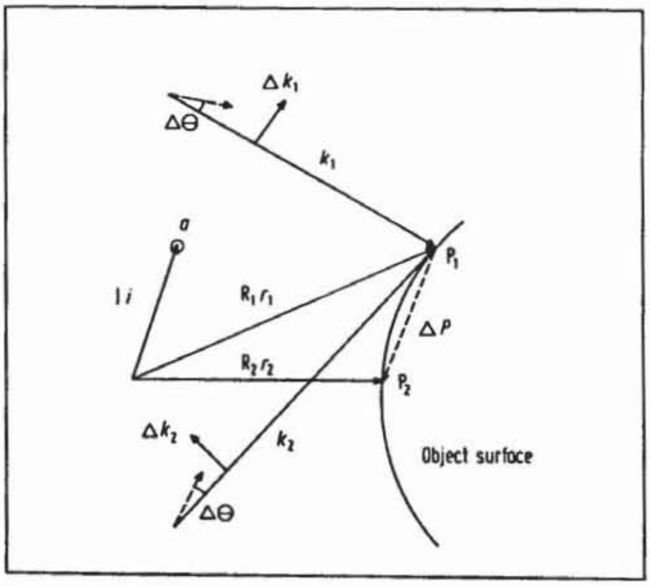

Fig. 2. Optical vector geometry.

For a given line of sight direction $\boldsymbol{r}_1$, the phase advance from resultant wavefront to the observation point O can be evaluated as

$$\Phi(P_1) = (2\pi/\lambda)\,\{[K_1 + R_1 + (R_1\boldsymbol{r}_1 - I\boldsymbol{i})\cdot\boldsymbol{k}_1] - [K_2 + R_1 + (R_1\boldsymbol{r}_1 - I\boldsymbol{i})\cdot\boldsymbol{k}_2]\} \tag{2}$$

where K_1, K_2 and R_1 are scalar magnitudes. By taking the derivative of eq. (2), we obtain the phase variation at the point P_1 before and after incident wavefronts tilt.

$$\delta\Phi(P_1) = (2\pi/\lambda)\,[(R_1\boldsymbol{r}_1 - I\boldsymbol{i})\cdot\delta\boldsymbol{k}_1 - (R_1\boldsymbol{r}_1 - I\boldsymbol{i})\cdot\delta\boldsymbol{k}_2]\,. \tag{3}$$

Inserting eq. (1) into eq. (3), we have

$$\delta\Phi(P_1) = (2\pi/\lambda)\delta\theta[(R_1\boldsymbol{r}_1 - I\boldsymbol{i})\cdot(\boldsymbol{a}\times\boldsymbol{k}_1) - (R_1\boldsymbol{r}_1 - I\boldsymbol{i})\cdot(\boldsymbol{a}\times\boldsymbol{k}_2)]\,. \tag{4}$$

For the reference point P_2, we have a similar expression

$$\delta\Phi(P_2) = (2\pi/\lambda)\delta\theta[(R_2\boldsymbol{r}_2 - I\boldsymbol{i})\cdot(\boldsymbol{a}\times\boldsymbol{k}_1) - (R_2\boldsymbol{r}_2 - I\boldsymbol{i})\cdot(\boldsymbol{a}\times\boldsymbol{k}_2)]\,. \tag{5}$$

The relationship between the contour phase and shape difference of the object to be contoured is of great interest. For this reason we consider the difference of phase variations at the point P_1 and P_2

$$\delta\Phi(P_1, P_2) = \delta\Phi(P_1) - \delta\Phi(P_2)\,. \tag{6}$$

Substituting for eq. (2) and eq. (4) in eq. (6), we obtain

$$\begin{aligned}\delta\Phi(P_1, P_2) &= (2\pi/\lambda)\delta\theta\{(R_1\boldsymbol{r}_1 - R_2\boldsymbol{r}_2)\cdot[(\boldsymbol{a}\times\boldsymbol{k}_1) - (\boldsymbol{a}\times\boldsymbol{k}_2)]\}\\ &= (2\pi/\lambda)[(R_1\boldsymbol{r}_1 - R_2\boldsymbol{r}_2)\cdot(\delta\boldsymbol{k}_1 - \delta\boldsymbol{k}_2)]\\ &= (2\pi/\lambda)(\delta\boldsymbol{P}\cdot\boldsymbol{d})\,.\end{aligned} \tag{7}$$

As mentioned above, there is no surface displacement any change of the phase is due to the tilt of wavefront incident on the object. It can be seen from eq. (7) that contour phase $\delta\Phi(P_1, P_2)$ depends on the alternation of each incident wavefront, which is represented by vector $\boldsymbol{d}$, and on the shape difference of the object surface which is implied by vector $\delta\boldsymbol{P}$. The argument in the square bracket of eq. (7) indicates the projection of difference position vectors onto the difference vector of incident beam alternation. When taking this term to be the values of a half the integral number of illuminating wavelength, we obtain dark contour fringes. Eq. (7) indicates, then, that $\Phi(P_1, P_2)$ determines the distance between these points in terms of the contour interval $\lambda/\delta\theta$ as project onto the direction of $\boldsymbol{d}$.

b. Orientation of contour planes

The optical determination of the orientation of contour planes plays an important role in designing the optical system described in this paper. We suggest a criterion of determining the orientation of contour planes in order to achieve an appropriate contour pattern of the object.

At first we introduce an orthogonal vector $\boldsymbol{b}$, which is perpendicular to the vector $\boldsymbol{d}$ in eq. (7), to indicate the direction of contour orientation. The vector $\boldsymbol{b}$ may be

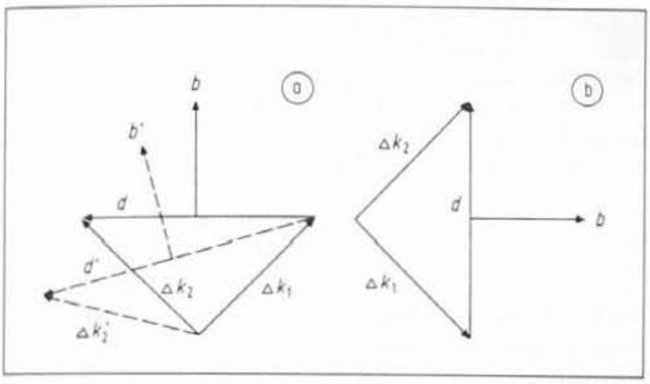

Fig. 3. Vector geometry for contour planes orientation. (a) Illuminating beams tilt in the same direction. (b) Illuminating beams tilt in different direction.

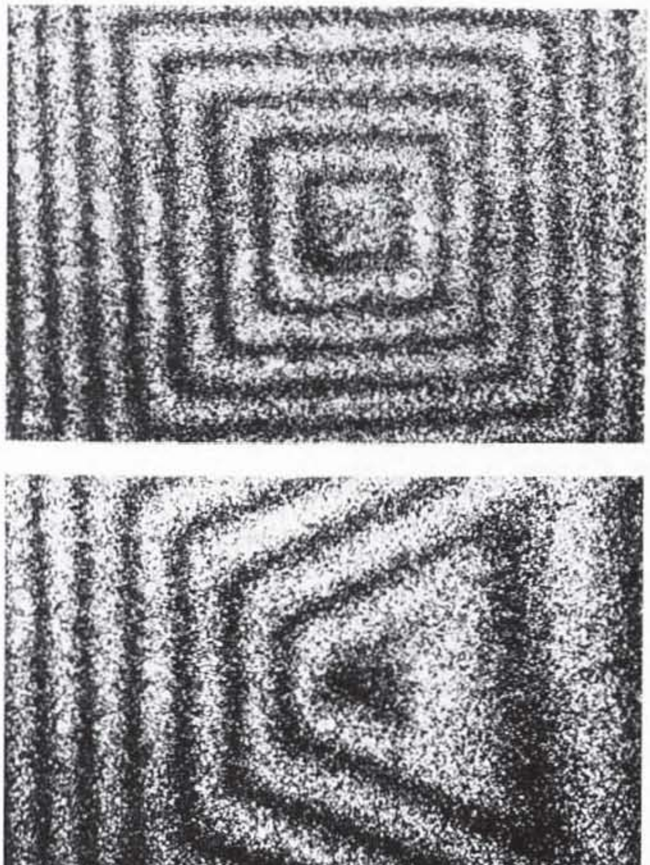

Fig. 4. Photographs of contour fringes. (a) The contour planes are perpendicular to the optical axis. (b) The contour planes are inclined when illuminating beams tilt with a different amount.

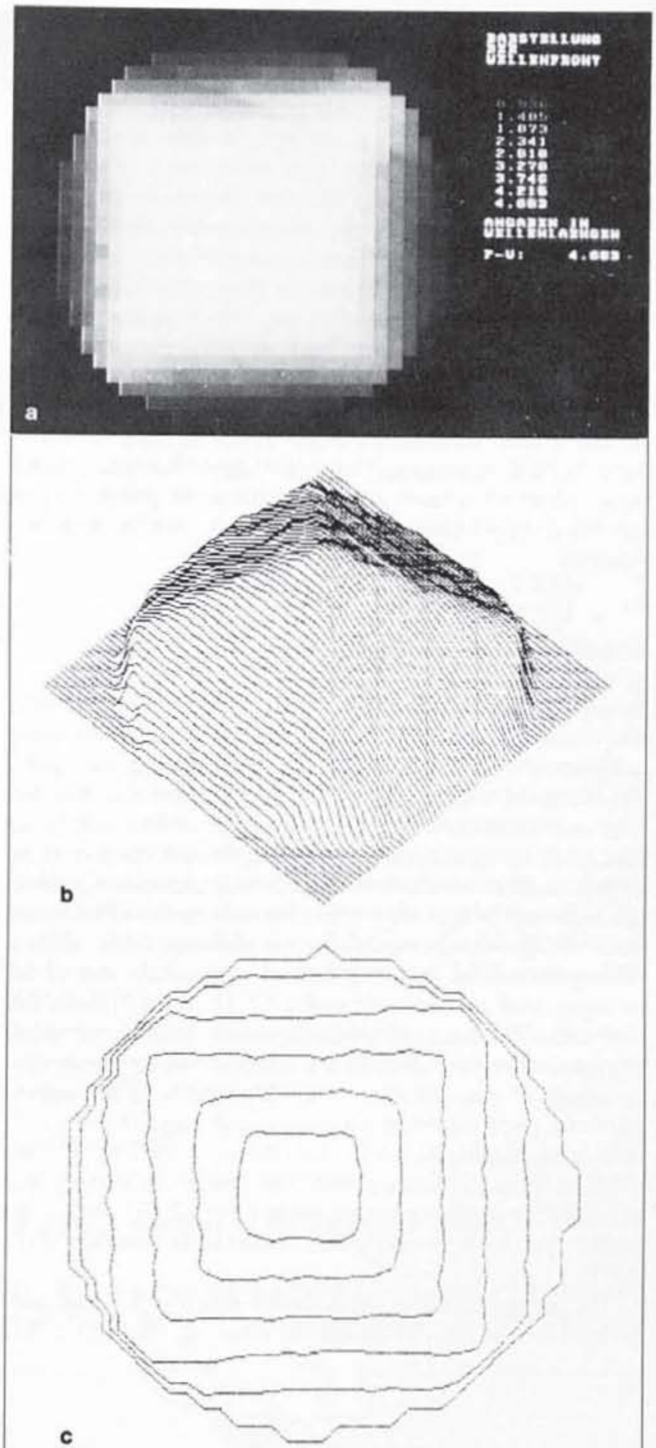

Fig. 5. Results obtained with three interferogram method for the pyramid with the interferogram shown in fig. 4(a). (a) Phase map. (b) 3-D plot. (c) Plot of the contour maps.

referred as an orientation vector, and the geometry of vector relationships is shown in fig. 3. By using the orientation vector $\boldsymbol{b}$ defined and eq. (7), we could analyze the alternation of contour planes when tilting illuminating beams. Fig. 3 shows that the orientation vector $\boldsymbol{b}$ is dependent on the differential vector $(\delta \boldsymbol{k}_2 - \delta \boldsymbol{k}_1)$, and any change of either $\delta \boldsymbol{k}_2$ or $\delta \boldsymbol{k}_1$ will result in the rotation of orientation vector $\boldsymbol{b}$. If two incident beams rotate in the same direction about the axis $\boldsymbol{a}$, we have $\boldsymbol{d} = \delta \boldsymbol{k}_2 - \delta \boldsymbol{k}_1$ as inferred by eq. (7), and orientation vector $\boldsymbol{b}$ would approach to the direction perpendicular to the optical axis. This vector geometry is shown in fig. 3(a). If incident beams rotate with different direction about axis $\boldsymbol{a}$, we get $\boldsymbol{d} = \delta \boldsymbol{k}_2 - \delta \boldsymbol{k}_1$ and the orientation vector $\boldsymbol{b}$ would lie nearly in the direction of the optical axis as shown in fig. 3(b). For two situations the orientation of contour planes appear to be totally different. In contouring applications we might usually wish to generate contour planes which would be perpendicular to the sight direction, thereby, it is necessary to ensure that both illumination beams rotate in the same direction about an axis. Otherwise, an inclined contour pattern will appear when a stationary object is contoured. This phenomenon is due to the alternation of contour plane orientation. A thumb of rule is that we need to adjust optical configuration to keep both illuminating beams tilting in the same direction and with the same amount of tilt when designing this modified dual-beam electronic speckle pattern interferometer.

Experimental set-up and results

In this section we present preliminary measurements with the technique described above. The diagram of the optical system is shown in fig. 1. As a light source we used a He-Ne laser with 10 mW. The laser beam was divided into two illuminating beams by a beam splitter. A pyramid with an apex angle of 120 degree was chosen as an object to be contoured. In the optical arrangement, both illuminating beams were tilted by shifting the collimating lens which was mounted on a moving table with a micrometer. The viewing system was composed of an imaging lens, an aperture and a CCD camera (PULNiX TM-745). The diameter of the aperture was so controlled that the averaging speckle size was set to be approximately equal to the cell size of CCD camera. The speckle patterns were digitized on a host computer (Epson PC-AX) and displayed on a TV monitor (SONY PVW-122CE). To introduce a phase shift, one of the mirrors was attached to a piezoelectric transducer (PZT), and controlled by the host computer through an interface (DT-2801).

The fringe analysis with phase-shifting [6] was performed for the interferogram shown in fig. 4(a). 5×5 and 7×7 median window were used to smooth the speckle pattern data and evaluate the phase, and fig. 5(a)–(c) show the phase, 3-D plot and the contour map, respectively. The fringes for an object where contour planes are inclined is shown in fig. 4(b). The theoretical and experimental results show good agreement.

Conclusion

We have demonstrated a new contouring method by developing a modified dual-beam electronic speckle pattern interferometer. Because of introducing a tilt to the illuminating beams, instead of the object tilt, the technique described here appears to be a more promising method from the point of view of practical applications and the technique has more flexibilities to generate contour patterns of an object. For example, two mirrors in the optical configuration could be tilted sequentially to get contour fringes. On the other hand, we could more easily obtain inclined contour planes by tilting one of the mirror in the optical arrangement when different perspective view of the object is required. The phase contour of the object shape have been determined by phase-shifting techniques. This allows the shape of the object to be measured accurately.

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