Calibration of the inclined contour planes formed on ESPI and optimization of ESPI optical system for contouring

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Calibration of the inclined contour planes formed on ESPI and optimization of ESPI optical system for contouring. Instead of searching a direction vector of contour planes which is completely identical to the direction of the optical axis of a viewing system, we introduce a kind of the method of calibrating measurement values by computer so that the correct shape of the test object can be obtained when the direction vector of the contour planes deviates from the optical axis of the viewing system. The calibrating formula is derived and experimentally verified. According to the formula, the optimization of ESPI optical system is discussed. Several examples are analyzed. The theoretical and calibrated results show good agreement.

Eichung von geneigten Konturebenen von ESPI und optimale ESPI-Systeme für das Konturing. Statt einen Richtungsvektor der Konturebenen zu suchen, der vollständig identisch ist mit der Richtung der optischen Achse des Beobachtungssystems, führen wir eine Art Computer-Eichmessung ein, so daß die korrekte Form des Testobjektes bei Abweichung des Richtungsvektors der Konturebenen von der optischen Achse erhalten wird. Die Eichformel wird abgeleitet und experimentell verifiziert. Einige Beispiele werden analysiert. Theoretische und kalibrierte Resultate zeigen gute Übereinstimmung.

1. Introduction

Electronic speckle pattern interferometry (ESPI) has been widely used as the measurement techniques for contouring for a long time [1–2]. Recently some new techniques for contouring an object using ESPI have been reported to overcome some of the drawbacks suffered by the already existing methods. The typical examples are single wavelength techniques with either tilting the object [3] or shifting illuminated beams [4–6] and two-wavelength techniques which display either the shape difference between an object and a master [2, 7] or the absolute shape of the test object without a master used [8–9]. Those methods of contouring using single-wavelength techniques and two-wavelength techniques can get the normal contour planes under only the certain given conditions. How to determine these conditions is very important for optimal designs of ESPI optical system for contouring. But in general, the inclined contour planes are obtained. Especially for contouring of an opaque object using two-wavelength ESPI employing dual-beam illuminations, it is seldom possible to get the normal contour planes [8]. Therefore, the calibration of the inclined contour planes is also very important in practical engineering metrology.

In this paper, we make a detailed study on the calibration of the measured values obtained from the inclined contour planes. A kind of the method of calibrating measured values by computer is introduced in order to obtain the correct shape of the test object when the direction vector of the contour planes deviates from the optical axis of a viewing system. At the same time, two conditions which optimize ESPI optical systems are presented so that the more reasonable experimental set-ups can be established. Hence the method described in this paper appeares to be a more significant from the view of practical engineering applications.

2. Basic theory

If a test object is placed in XYZ coordination system, the schematic principle geometry using ESPI is shown in fig. 1, where N is an arbitrary point on the test surface and P is a viewing point; Q is a cross point between the optical axis Z of the viewing system and the surface of the test object; $\boldsymbol{r}_n$ is a position vector from point P to N and r_n is the scalar magnitude of $\boldsymbol{r}_n$; $\boldsymbol{d}$ locates on the XZ plane and is the unit direction vector of the contour planes which is normal to the contour planes; α is the inclined angle between the vector $\boldsymbol{d}$ and the optical axis Z and is defined as the positive angle when it is formed clockwise.

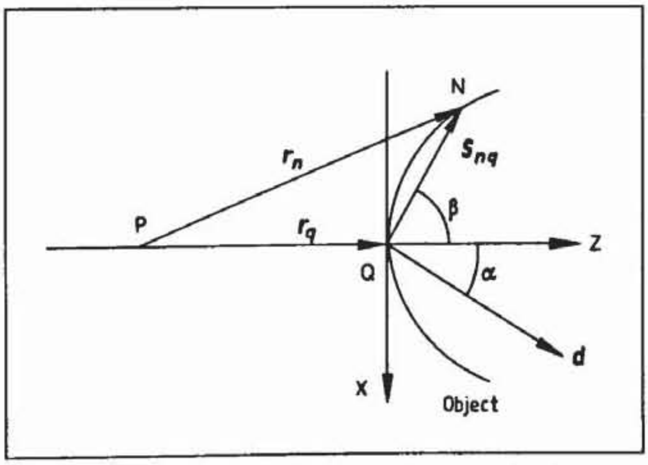

Fig. 1. The schematic principle geometry of contouring using ESPI.

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When $\boldsymbol{r}_n$ scans across the surface of the test object in such an optical geometry described above, the incremental phase difference on the viewing point P between two points N and Q on the surface of the test object is $\Delta\psi_{nq}$, then [6]

$$\begin{aligned} \Delta\psi_{nq}(\boldsymbol{r}_n, \boldsymbol{r}_q, \boldsymbol{d}) &= M\frac{2\pi}{\lambda}[(\boldsymbol{r}_n - \boldsymbol{r}_q)\cdot \boldsymbol{d}] \\ &= M\frac{2\pi}{\lambda}(\boldsymbol{S}_{nq}\cdot \boldsymbol{d}), \end{aligned} \tag{1}$$

where $\boldsymbol{S}_{nq}$ is the relative position vector between two points N and Q on the test object and S_{nq} is the scalar magnitude of vector $\boldsymbol{S}_{nq}$; λ is the wavelength or the equivalent wavelength of illumination beams and M is the magnification of the interval of the contour planes. According to eq. (1), the phase difference on the imaging plane between two points N and Q can be determined by the projection of the relative position vector $\boldsymbol{S}_{nq}$ onto the vector $\boldsymbol{d}$. When taking this projection to be the value of an integral times of λ/M we obtain correlation fringes. Therefore, the direction vector of the contour planes is identical with the vector $\boldsymbol{d}$; and the interval δ of the contour planes can be written

$$\delta = \lambda/M\,. \tag{2}$$

In general, the inclined angle α between vector $\boldsymbol{d}$ and Z axis and the constant M are related to only the construction parameters of ESPI optical system.

3. The calibration of the inclined contour planes

When the CCD camera observes along the Z axis, the quantities corresponding to the x, y coordinates in the measurement values do not change along with the direction vector $\boldsymbol{d}$ of contour planes. Only the measurement values of the depth of the test object are related to the direction vector $\boldsymbol{d}$ of contour planes. Referring eq. (1) and fig. 2, the measurement value of the relative position vector $\boldsymbol{S}_{nq}$ is the projection value QA of the vector $\boldsymbol{S}_{nq}$ onto the vector $\boldsymbol{d}$. When $\alpha \neq 0$ as shown in fig. 2, i.e. the contour planes are inclined, the measurement value QA is different from the real depth QB of the surface of the test object. Therefore, the measurement values have to be calibrated in order to get the correct contour corresponding completely to the shape of the test object.

We assume that the coordinate values of point N are (x, y, z) and the inclined angle between the position vector $\boldsymbol{S}_{nq}$ and Z axis is β. Through line NC, we can drawn a plane $NCAH$ so that the plane is vertical to the vector $\boldsymbol{d}$. According to the geometry of fig. 2, we can write

$$\sin\gamma = \frac{x}{\sqrt{x^2+z^2}} \quad \text{and} \quad \cos\gamma = \frac{z}{\sqrt{x^2+z^2}}. \tag{3}$$

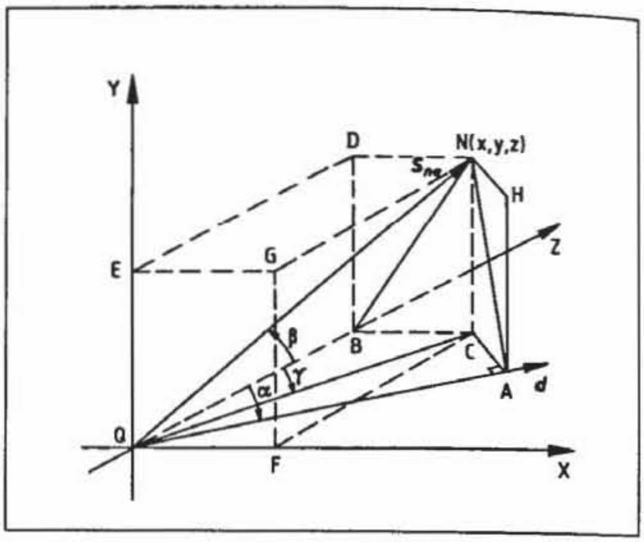

Fig. 2. The geometry for calibrating the measurement values.

The vector $\boldsymbol{d}$ is perpendicular to plane $NCAH$, so the triangles ΔQAC, ΔQAN are right. In the right triangle ΔQAC, we have

$$\begin{aligned} AC &= QC\sin(\alpha-\gamma) \\ &= (x^2+z^2)^{1/2}\sin(\alpha-\gamma) \end{aligned}$$

and
$$\begin{aligned} NA &= (NC^2+AC^2)^{1/2} \\ &= [y^2+(x^2+z^2)\sin^2(\alpha-\gamma)]^{1/2}. \end{aligned}$$

Referring to the right ΔQAN, the measurement value QA can be expressed as

$$\begin{aligned} QA &= [QN^2 - NA^2]^{1/2} \\ &= \cos(\alpha-\gamma)\,(x^2+z^2)^{1/2}. \end{aligned}$$

Therefore, the shape observed along Z axis of the test object, i.e. the coordinate value z of the test object, is expressed as

$$z = [QA^2/\cos^2(\alpha-\gamma) - x^2]^{1/2}\,. \tag{4}$$

Referring fig. 2 and eq. (3), eq. (4) is written again

$$z = \frac{1}{\cos\alpha}(QA - x\sin\alpha)\,. \tag{5}$$

After the measurement value QA is obtained from the experiments and α is obtained from the construction of ESPI optical system, the depth value QB of the test object observed along Z axis, i.e. the coordinate value z, can be calculated by eq. (5). This function can easily be performed by computer. Thus we can get the shape of the test object through the automatic calibration of the measurement values according to eq. (5).

When the measuring error of the measurement value QA is ρ, through the derivation of eq. (5), the error Δz of the calibrated result z can be expressed as

$$\Delta z = \sec\alpha\,\rho + \sec^2\alpha(QA\sin\alpha - x)\,\Delta\alpha\,. \tag{5a}$$

Because of the nonlinearity of secant function, the error Δz of the calibrated result z will increase rapidly along with α. Therefore, it is very significant to decrease and measure preciously α value.

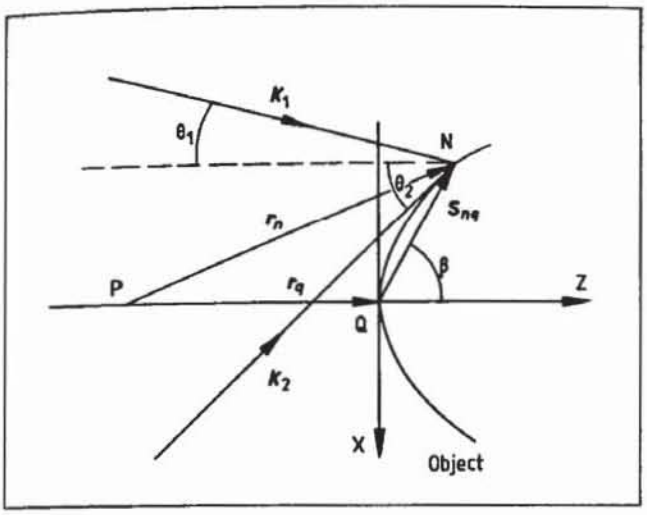

Fig. 3. The vector geometry for contouring by ESPI employing dual-beam illuminations.

4. Optimization of ESPI optical system

In certain optical arrangements, eq. (5) can be transferred into

$$z \cos\alpha = QA - x \sin\alpha\,. \tag{6}$$

When $\alpha = 90°$, the direction vector $\boldsymbol{d}$ of contour planes is normal to Z axis. According to eq. (6), the measurement value can be transferred into

$$QA = x\,. \tag{7}$$

Eq. (7) shows the measurement value QA is not related to the depth z of the test object and is the function of only x coordinate. $\Delta\psi_{nq}$ represents a series of parallel correlation fringes which are not related to the shape of the test object. If $\alpha = 0$, the direction vector $\boldsymbol{d}$ of the contour planes is identical to the Z axis and eq. (5) can be transferred into

$$z = QA\,. \tag{8}$$

Thus the measurement value QA corresponds to the shape of the object observed along Z axis. Therefore, $\alpha = 0$ is the condition to form the normal contour planes. We can optimize ESPI optical system through making α value as small as possible.

On the other hand, we notice when $M \to 0$, $\delta \to \infty$ so that the test object can not be contoured. When $M < 0$, $\delta < 0$. The direction vector of the contour planes reverses and we get the reversed shape of the test object. Therefore, selecting the suitable M value is also one of the optimal conditions of ESPI optical system.

According the conditions described above, several ESPI optical systems with dual-beam illuminations are analyzed as follows. Fig. 3 shows the geometry of the optical system for contouring.

Example 1. the optimal designs of ESPI optical system for contouring by two-wavelength ESPI employing dual-beam illuminations.

Seeing reference 8, α and M can be expressed as

$$\alpha = 90° + \tfrac{1}{2}(\theta_1 - \theta_2) \tag{9}$$

$$M = 2\sin\left(\frac{\theta_1 + \theta_2}{2}\right), \tag{10}$$

where θ_1 and θ_2 are the illumination angles of two illumination beams, respectively. From eq. (9), one find α will decrease when θ_1 decreases and θ_2 increases. When two illumination beams are located the same side of the Z axis and $|\theta_1| + |\theta_2| = 180°$, we can get the normal contour planes. This geometry is available only for contouring of a transparent object. For most of opaque objects, only the inclined contour planes can be achieved. The only method to optimize ESPI optical system is to decrease α value. At the same time, M need hold positive and suitable value so that the direction vector and the interval of the contour planes meet the requirements. We notice that $M \to 0$ when $\theta_1 \to -\theta_2$, i.e. the test object is illuminated from the same direction. Therefore, the suitable difference of the illumination angles of both illumination beams is very important. In the design of our experimental set-up, we have to consider: 1) keeping the same side illuminations of the optical axis of a viewing system and $|\theta_1| + |\theta_2| \to 180°$; 2) keeping the suitable difference of the illumination angles of both illumination beams; 3) keeping $|\theta_1| < |\theta_2|$.

Example 2. the optimal designs of ESPI optical system for contouring by ESPI with tilting dual-beam illuminations.

Case a: Two illumination beams whose illumination angles are θ_1 and θ_2, respectively, are tilted symmetrically the same angle $\Delta\beta$. If the illumination beam $\boldsymbol{K}_1$ is tilted anticlockwise and the illumination beam $\boldsymbol{K}_2$ is tilted clockwise, seeing reference 5, α and M are expressed as

$$\alpha = -[90° + \tfrac{1}{2}(\theta_1 - \theta_2)] \tag{11}$$

$$M = 2\sin\left(\frac{\theta_1 + \theta_2}{2}\right)\Delta\beta\,. \tag{12}$$

Eq. (11) and eq. (12) are similar to eq. (9) and eq. (10), respectively. Therefore, we can get the same conclusions as example 1 except for $|\theta_1| > |\theta_2|$.

Case b: Two illumination beams with θ_1 and θ_2 illumination angles, respectively, are tilted anti-symmetrically the same angle $\Delta\beta$. If the illumination beams $\boldsymbol{K}_1$ and $\boldsymbol{K}_2$ are tilted anticlockwise, seeing reference 5, α and M can be expressed as

$$\alpha = \tfrac{1}{2}(\theta_1 - \theta_2) \tag{13}$$

$$M = 2\sin\left(\frac{\theta_1 + \theta_2}{2}\right)\Delta\beta\,. \tag{14}$$

Eq. (13) shows that the normal contour planes can be achieved when $\theta_1 = \theta_2$. At this time, the interval of the contour planes is

$$\delta = \lambda/[2\Delta\beta\sin\theta]\,. \tag{15}$$

The sensitivity is determined by the tilting angle and the illumination angles of two illumination beams. We can optimize the sensitivity through selecting the suitable illumination angles of both illumination beams.

Case c: One of two illumination beams is tilted the angle $\Delta\beta$. If the illumination beam K_1 is tilted anticlockwise, seeing reference 5, α and M can be expressed as

$$\alpha = \theta_1 - 90^\circ \tag{16}$$

$$M = \Delta\beta, \tag{17}$$

where θ_1 is the illumination angle of the tilted illumination beam. Eq. (16) shows that the normal contour planes can be achieved when $\theta_1 = 90^\circ$. The interval of the contour planes is related to only the tilting angle. The measurement values are independent of the illumination angle of another illumination beam.

5. Experiments and results

In this section, we present calibration of measurement values obtained from geometry of case c in example 2

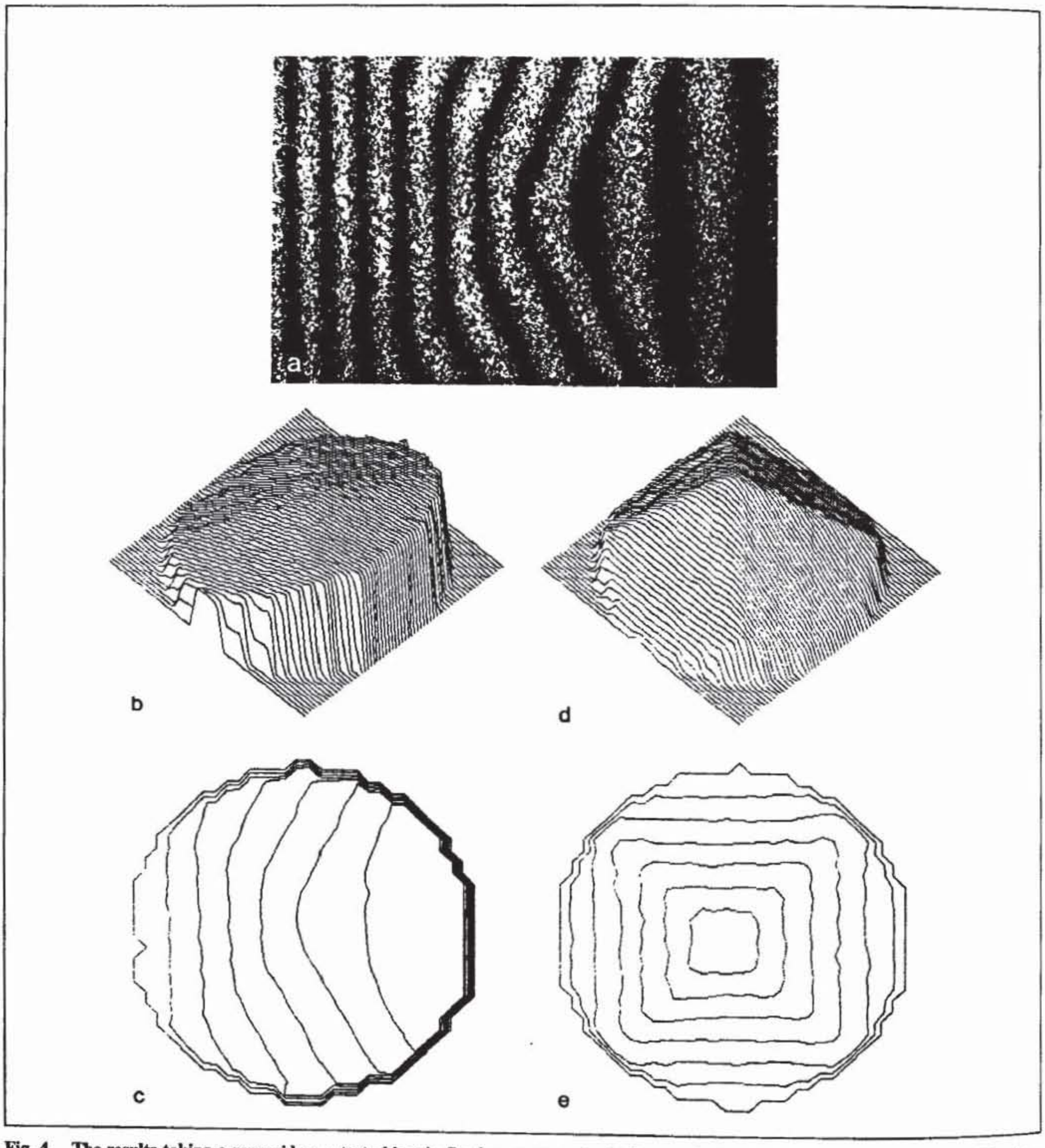

Fig. 4. The results taking a pyramid as a test object in fig. 3 arrangement. a) The correlation fringes. b) 3-D plot before calibration. c) The contour map before calibration. d) 3-D plot after calibration. e) The contour map after calibration.

with the method described above. Fig. 3 shows the geometry. In the optical arrangement, a He–Ne laser with 10 mW was used as a light source. A pyramid with an apex angle of 120 degree was chosen as an object to be contoured. One of two illumination beams was tilted $\Delta\beta$ angle. The illumination angle of the tilted illumination beam was θ_1 angle and the illumination angle of another illumination beam through a mirror attached to a PZT was arbitrary. In order to introduce a phase shift, the PZT was controlled by the host computer through an interface.

The correlation fringes are shown in fig. 4(a) when one of two illumination beams was tilted. 5×5 and 7×7 median window were used to smooth the speckle pattern data and evaluate the phase. Fig. 4(b)–(e) show 3-D plots and the contour maps before and after calibration, respectively. The theoretical and calibrated results show good agreement.

6. Conclusion

We have demonstrated a calibrating method of the measurement values obtained from the inclined contour planes by computer automatic calibration program. The method described in this paper appeared to be more significant from the view of practical engineering applications. The error of the calibrated results will rapidly increase along with α. At the same time, as the optimal conditions of ESPI optical system, α value as small as possible and the suitable M value are necessary. According to the optimal conditions of ESPI optical system, the more reasonable experimental set-up can be established.

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