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A simplified multi-wavelength ESPI contouring technique based on a diode laser system

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A simplified multi-wavelength ESPI contouring technique based on a diode laser system. A simplified multi-wavelength ESPI contouring technique using a diode laser source has been demonstrated to be a useful tool in the shape measurement of an object. Unlike other type of two-wavelength ESPI contouring systems, the technique described in this paper does not required a master-wavefront illumination and the conjugate condition imposed on the reference beam, the experiment procedure is, therefore, considerably simplified. Instead of modulating the injection current of the diode laser, the alternation of wavelength is achieved by adjusting the temperatures applied to the laser diode so that the problem of visibility reduction due to intensity variations of speckle pattern can be overcome. In addition, the decorrelation effect due to the wavelength change in this specific ESPI contouring system is also analyzed quantitatively in order to show the limitations of this technique on practical applications. Contour fringes of a pyramid, as an example, are obtained from experiments, which are in agreement with the theoretical analysis.

Ein auf dem Laserdiodensystem basierendes vereinfachtes ESPI-Konturlinienverfahren mit Multiwellenlängen. Es wird ein vereinfachtes ESPI-Konturlinienverfahren mit Multiwellenlängen, das eine Laserdiode als Lichtquelle verwendet, gezeigt und bei Oberflächenmessungen eingesetzt. Das in diesem Artikel beschriebene Verfahren braucht keine Musterwellenfrontbeleuchtung und keine konjugierte Bedingung für Referenzwellenfront, was aber die anderen ESPI-Konturlinienverfahren mit Doppelwellenlängen verwendet haben. Dadurch ist der Versuchsprozeß weitgehend vereinfacht. Anstatt der Modulation des Laserdiodenstroms wird die Wellenlänge durch Änderung der Laserdiodentemperatur variiert, so daß die durch Intensitätsänderung der Speckle-Muster verursachte Kontrastreduzierung vermieden werden kann. Ferner wird der durch Wellenlängenänderung verursachte Dekorrelationseffekt in diesem spezifischen ESPI-Konturlinienverfahren quantitativ analysiert, um die Begrenzung des Verfahrens auf praktische Anwendungen zu zeigen. Als Beispiel sind Konturlinienstreifen einer Pyramide aufgenommen und diskutiert, welche mit theoretischer Analyse übereinstimmt.

1. Introduction

Electronic speckle pattern interferometry can be applied to compare the shape of test object with a master wavefront [1, 2]. To produce speckle contours, the test object is illuminated at wavelength λ_1 by a wavefront that matches the master shape exactly. An image of the object is formed on the vidicon together with the usual reference beam. A speckle pattern is then obtained at λ_2 and subtracted from the first pattern. The fringes obtained represent the difference in depth along the view direction between the master wave front and test object. When such a technique is used, the role of the master wave front is fundamental to ESPI shape measurement. However, several drawbacks exist in these systems such as the master wave that may be derived from conventional optical components limit the object to those having plane, spherical, or cylindrical surface geometries. The object with more complex geometry would be inspected in the same way but with the illumination wave front formed by hologram recorded from a specular master component [3]. The procedure of generating a master wave front from holographically recording a specular master component is usually a tedious procedure, and therefore is a serious limitation on practical applications in many cases. In addition, to obtain shape-difference fringes, the point to which the master wave front converges must be located at the centre of the viewing lens of an ESPI system and a smooth reference beam must satisfy the conjugate condition. This would impose another difficulty on aligning the arrangements.

Laser diodes (LD's) are useful light sources for an interferometer because they permit single-mode operation and frequency tenability. Recently some new techniques for using laser diodes in the interferometers have been reported [4–6]. In these techniques, the alternation of the wavelength (or the frequency) of a diode laser has been achieved by modulating the injection current of the laser diode [4]. When this method is applied to a two-wavelength ESPI system, the speckle intensities corresponding to different wavelength will be changed and thus the visibility of interferogram will be degraded.

In this paper, we present a new arrangement of multi-wavelength ESPI for contouring applications, which is based on using a diode laser system. It can be used to generate contours of a pyramid without having to produce corresponding master wave front and the conjugate condition to the reference beam can also be eliminated, this would considerably simplify the experiment procedure and release the requirement for optics alignment. Wavelength alternation is achieved by adjusting the temperature applied to the laser diode instead of by modulating the injection current as made by another work [4], so that the problem of the variations in the intensities of speckle patterns due to the current change could be overcome and permit relatively good fringe visibility. Contour fringes of a pyramid at various sensitivities are obtained from experiments which agree well with theoreti-

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cal analysis. The decorrelation effect due to the wavelength change for this specific arrangement is also analyzed quantitatively by simple image processing technique incorporating with experimental data of speckle patterns.

2. Theoretical background

Fig. 1 shows the arrangement used for generating contour fringes of a test object. The object is illuminated by a normal incident wave front. A speckle reference wave front generated by a ground diffuser G is arranged to combine with object wave at the second beam-splitter BS_2. Both object and reference wave are aligned to be on-axis to simplify the analysis. However, it is important to note that this geometry does not require that the point of divergence of the reference beam be conjugate with that of the original object illumination as assumed in previous research [3].

It will be assumed that P is an arbitrary reference plane which is across and parallel to the test object. The phase ϕ_0 of the light at a point in the image plane (in the absence of reference beam) is given by the following expression

$$\phi_0 = (2\pi/\lambda)[l_1 + 2l_2 + l_3] + \phi_{0s} + (4\pi/\lambda)h, \qquad (1)$$

where l_1 is the optical path of the object beam from the first beam-splitter to the second one; l_2 is the distance from the second beam-splitter to an arbitrary reference plane P; l_3 is the optical path from the second beam-splitter to the image plane. ϕ_{0s} is the random phase associated with speckle pattern at wavelength λ, and h represents the height variation of the object surface about reference plane P (normal to the optical axis). h is measured in the direction of the optical axis. The phase ϕ_r of the speckle reference beam may be written as

$$\phi_r = (2\pi/\lambda)(l_{r1} + l_3) + \phi_{rs}, \qquad (2)$$

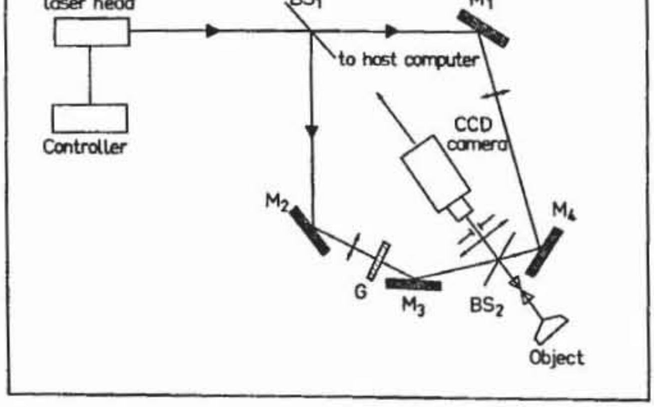

Fig. 1. Experiment set-up.

where l_{r1} is the optical path of the reference beam from the first beam-splitter to the second beam-splitter; ϕ_{rs} is the random phase associated with speckle pattern due to scattering from a ground diffuser. It is evident that $(2\pi/\lambda)(l_1 + 2l_2 + l_3)$ is a constant phase ϕ_{0c} and $(2\pi/\lambda)(l_{r1} + l_3)$ also a constant phase ϕ_{rc}. The image speckle pattern interferes with the speckle reference beam and the amplitude at a point in the image plane is given by the equation

$$U = U_0 + U_r = |U_0|\exp(\phi_0) + |U_r|\exp(\phi_r). \qquad (3)$$

The intensity at a point in the image plane is then given by

$$I = I_0 + I_r + 2\sqrt{I_0 I_r}\cos[\phi + \phi_s + (4\pi/\lambda)h], \qquad (4)$$

where $\phi = \phi_{0c} - \phi_{rc}$, $\phi_s = \phi_{0s} - \phi_{rs}$.

The intensities corresponding to two different wavelengths λ_1 and λ_2 can be written as follows

$$I_1 = I_{01} + I_{r1} + 2\sqrt{I_{01} I_{r1}}\cos[\phi_1 + \phi_{s1} + (4\pi/\lambda_1)h] \qquad (5a)$$

$$I_2 = I_{02} + I_{r2} + 2\sqrt{I_{02} I_{r2}}\cos[\phi_2 + \phi_{s2} + (4\pi/\lambda_2)h]. \qquad (5b)$$

It is assumed that the intensities of the object beam and the reference beam keep unchanged approximately and the phases of speckle patterns also approximately remain constant, when the illuminating wavelength is changed. Then we have $I_{01} = I_{02}$, $I_{r1} = I_{r2}$, $\phi_{s1} = \phi_{s2}$. If the intensity on the screen is averaged over many speckles, then the brightness B is proportional to $\langle (I_1 - I_2)^2 \rangle$. It is easy to show that

$$I_1 - I_2 = 4\sqrt{I_0 I_r}\sin[\alpha + \phi_s + (8\pi/\lambda_1)h] \cdot \sin[\beta + (2\pi/\Gamma)h], \qquad (6)$$

where $\alpha = (\phi_1 + \phi_2)/2$, $\beta = (\phi_1 - \phi_2)/2$, and $\Gamma = \lambda_1\lambda_2/(2\lambda_1 - 2\lambda_2)$ is the fringe contour interval and

$$B = \langle (I_1 - I_2)^2 \rangle = 8\langle I_0 \rangle \langle I_r \rangle \sin^2[\beta + (2\pi/\Gamma)h]. \qquad (7)$$

In derivating eq. (7), we have assumed that I_0 and I_r are statistically independent, and ϕ_s is statistically independent of the intensity fluctuations, as well as that ϕ_s is a uniformly distributed random variable. As h varies, the value of B fluctuates between zero and $8\langle I_0 \rangle \langle I_r \rangle$ and dark fringes will therefore be observed when h changes by an amount of Γ. Thus the departure of object surface from an arbitrary reference plane P is contoured at intervals of Γ. The sensitivity of the fringes obtained (the contour interval) is determined by the wavelength difference.

It should be pointed out that there is no conjugate condition imposed upon the reference beam and the shape difference between an arbitrary reference plane, rather than the master, and test object may be determined from the fringe pattern described by eq. (7).

The analysis above provides a theoretical basis for contouring objects with more complex geometries in the absence of master wave front illumination.

3. Experiment

3.1 Arrangement and results

The basic experimental technique is shown in fig. 1. The input laser beam is divided by the first beam-splitter BS_1 into a reference beam and an object beam. The object beam illuminates the test object and is imaged using a lens and an aperture combination on to the face of a CCD camera. The speckle reference beam is generated by a ground diffuser G and is introduced from the second beam-splitter BS_2. The object beam and the reference beam are aligned being coaxial. Contour fringes are obtained by illuminating the test object at λ_1 and then at λ_2, the first image is acquired and recorded by a frame grabber and the second is digitally subtracted from it to give correlation fringes by subtraction. In this arrangement, a high power diode laser (30 mW) is used as a light source. The diode laser system used consists of a Melles Griot diode laser head (06DLL407) in conjunction with a PROFILE laser diode controller (LDC 700A). For this specific diode laser system, the dependence of the wavelength on the temperature applied to LD system is measured and given in fig. 2, which shows a linear region from 20 °C to 27 °C. The differences of wavelengths corresponding to this region are also given in fig. 2. It has been shown from fig. 2 that emission wavelength of this diode laser system can be altered continuously from 781.66 nm to 783.40 nm, and a range of contour sensitivities from 3.8 mm to 0.7 mm may be achieved, when the temperature applied to the LD system is adjusted from 20 °C to 27 °C. The advantage of shifting wavelength by adjusting the temperatures instead of by modulating the injection current is that the variations in the intensities of speckle patterns due to the current change may be minimized so that relatively good visibility should be obtained [4]. A pyramid, chosen as a test object, is inspected at several contour sensitivities. The resultant interferograms obtained at these sensitivities are shown in figs. 3(a)–3(e) respectively. This result has proved the possibility of contouring a test object with more complex geometry without having to produce a special master wave front; on the other hand, this result also indicates that the technique gives consistent and repeatedly results. In addition, the decorrelation effect due to the wavelength change for this specific ESPI contouring arrangement may also be observed from figs. 3(a)–3(e).

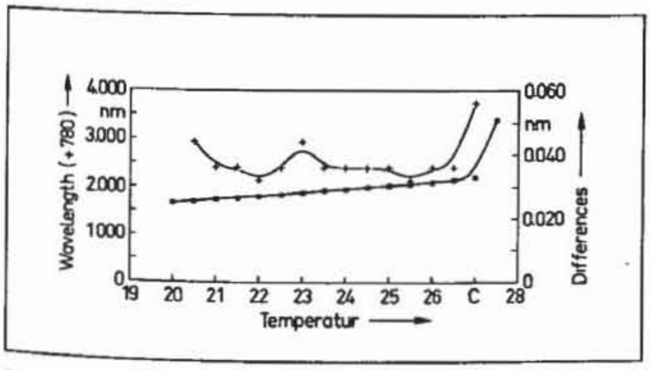

Fig. 2. Experimental curve of wavelength variation vs. temperature applied to the diode laser at constant optical power. For technical details see text. –●– Series 1, –+– Series 2.

3.2 Decorrelation effect and limitations of the technique

When high sensitivity contours are observed, speckle decorrelation is likely to occur leading to the visibility reduction of contour fringes, this has been seen from figs. 3(a)–3(e). The fine scale detail of the speckle patterns I_1 and I_2 change with wavelength, which explains why the conditions $I_{01} = I_{02}, I_{r1} = I_{r2}$ and $\phi_{s1} = \phi_{s2}$ can only be approximately satisfied. The performance of this multi-wavelength ESPI contouring technique is limited by the intrinsic speckle pattern decorrelation effect. To quantify this effect, the correlation coefficients of speckle patterns corresponding to the wavelength change are evaluated by simple image processing technique incorporating experimental data of speckle patterns. This method has been used for determining the decorrelation effect in a dual-beam ESPI contouring system with single wavelength illumination [7]. Fig. 4 shows the results for the evaluation of correlation coefficients with eight frame images of speckle patterns corresponding to different temperatures applied to the diode laser (therefore the different wavelength changes). It can be seen from fig. 4 and fig. 3 that the correlation of speckle patterns decreases as the temperature applied to the diode laser varies (or the illuminating wavelength varies). When the value of the correlation coefficient of speckle patterns drops to 0.278, the contour fringes tends to be vanished, or equivalently, the visibility of the correlation fringes goes towards zero. It should be noted that the decorrelation of speckle is also a function of surface roughness except for being a function of the wavelength change. However, in our case, the surface roughness is a constant and the condition $\Gamma > 8\sigma$ is satisfied, where σ is the surface roughness [8]. Furthermore, we have assumed that all other variables of the interferometer such as reference beam/object beam ratio, camera focus and gain, input laser power etc., are optimized, so that any loss in fringe visibility may be attributed to the wavelength only.

By the quantitative analysis above, we could determine that the correlation coefficients of speckle patterns corresponding to the wavelength change (or temperature adjustment) should be in the range of 0.418 to 0.314 in order to ensure a reasonable visibility of the contour fringes, which is an acceptable degree of decorrelation in this technique.

4. Conclusion

In conclusion, we have demonstrated a new multi-wavelength ESPI contouring technique from which an object with more complex surface geometry could be inspected directly without having to produce a corresponding master wave front, this would much simplify the experimental procedure. The conjugate condition imposed upon the reference beam, as required in other type

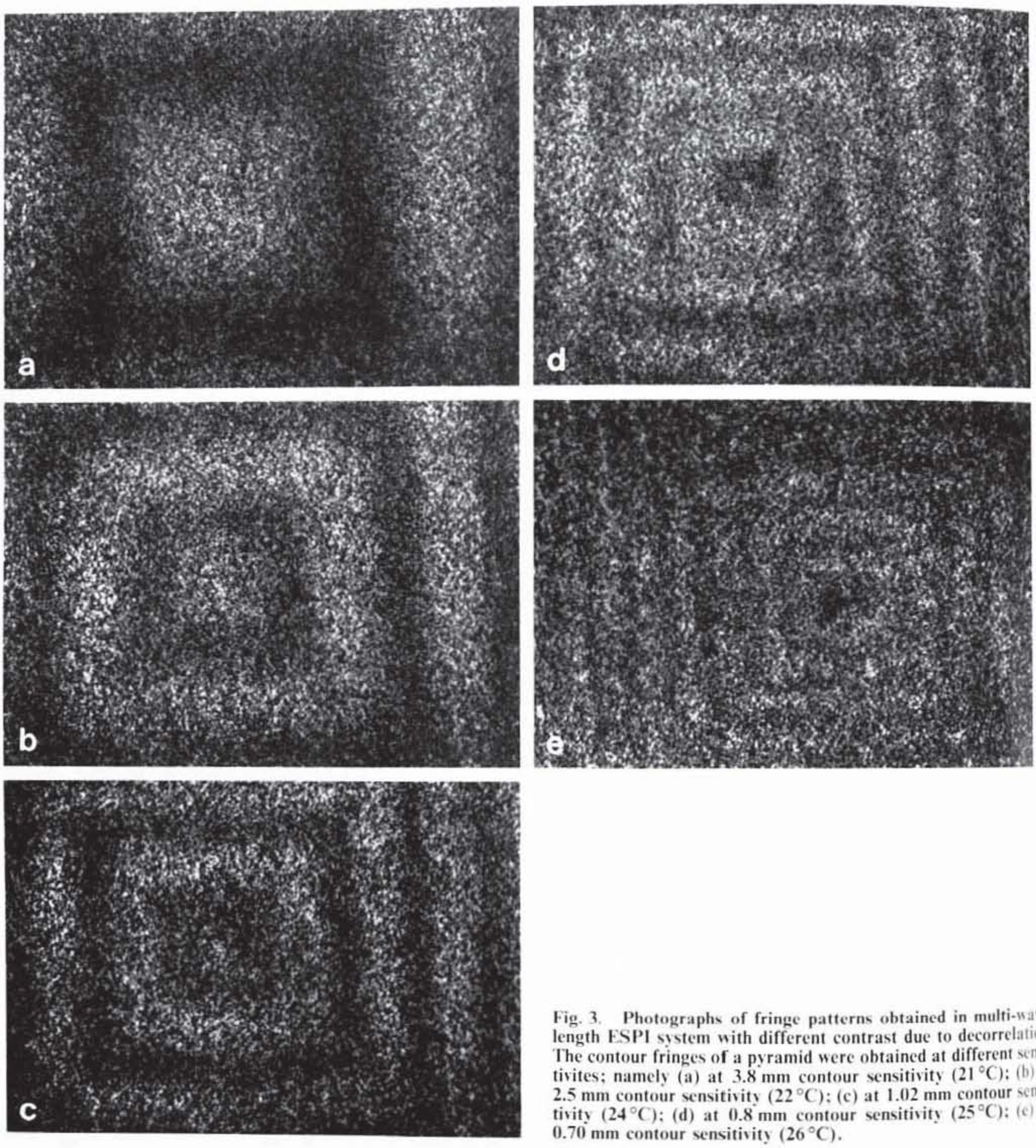

Fig. 3. Photographs of fringe patterns obtained in multi-wavelength ESPI system with different contrast due to decorrelation. The contour fringes of a pyramid were obtained at different sensitivites; namely (a) at 3.8 mm contour sensitivity (21 °C); (b) at 2.5 mm contour sensitivity (22 °C); (c) at 1.02 mm contour sensitivity (24 °C); (d) at 0.8 mm contour sensitivity (25 °C); (e) at 0.70 mm contour sensitivity (26 °C).

of two-wavelength ESPI system, has been eliminated so that optics alignment would become easier. In comparison with using the Argon laser or tuneable dye laser, a special range of contour sensitivities of 0.7–3.8 mm could be achieved by using a diode laser system, which may extend the measurement range of ESPI contouring techniques. The alternation of illuminating wavelength has been performed by adjusting the temperature applied to the laser diode instead of by modulating the injection current in order to remain the intensities of speckle patterns corresponding to temperature variation unchanged and therefore permit a reasonable visibility of fringe patterns. The speckle reference beam has been used in this arrangement so that the requirement of precisely aligning the configuration is released. In addition, the intrinsic decorrelation effect due

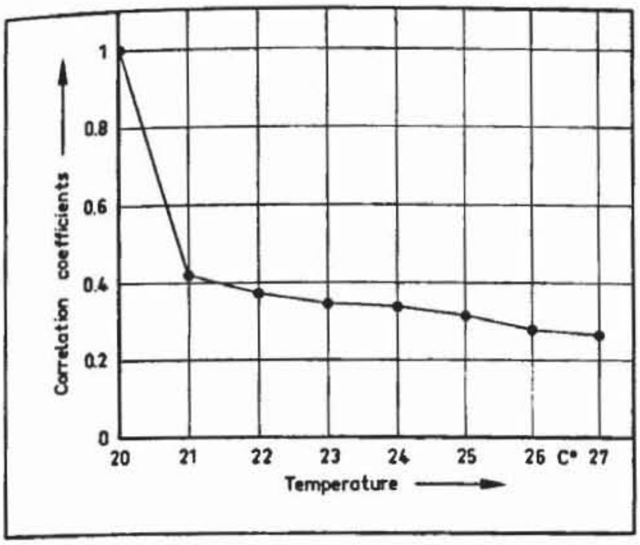

Fig. 4. The variation of correlation coefficient is plotted as a function of the temperatures (or the wavelength change) applied to the diode laser (eight speckle patterns have been used to evaluate the correlation coefficients).

to the wavelength change in this special arrangement has been analyzed quantitatively and practical limits for the range of application of this technique have been determined.

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