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# A simplified multi-wavelength ESPI contouring technique based on a diode laser system 2: Automatic fringe analysis

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**A simplified multi-wavelength ESPI contouring technique based on a diode laser system 2: Automatic fringe analysis.** A quantitative fringe analysis of interference patterns generated by a multi-wavelength laser diode ESPI contouring system is discussed. The goal is the accurate determination of the topography of an object with steep surface. The phase change related to the surface geometry is calculated with phase-shifting techniques, and the results with different contour sensitivities are presented. Some limitations of this ESPI contouring system are also considered from the point of view of practical applications.

**Ein auf dem Laserdiodensystem basierendes vereinfachtes ESPI-Konturlinienverfahren mit Multiwellenlänge 2: Automatische Streifenauswertung.** Eine quantitative Streifenauswertung von Interferogrammen, generiert mit Multiwellenlänge, wird gezeigt. Das Ziel ist eine genaue Bestimmung der Topographie eines Objekts mit steiler Oberfläche. Die Phasenänderungen in Beziehung mit der Oberfläche wurden mit Phasenschiebungstechnik ausgewertet und die Resultate mit verschiedenen Kontour-Empfindlichkeiten werden gezeigt. Einige Beschränkungen dieses ESPI-Kontour-Systems wurden im Hinblick auf die praktische Anwendung analysiert.

## 1. Introduction

A multi-wavelength laser diode ESPI contouring arrangement has been reported in a recent paper [1]. This system has been proved to be a useful tool in the measurement of object topography. Several advances exist in such an arrangement in comparison with other type of two-wavelength techniques: (1) an object with complex surface geometry can be directly inspected without the need for producing a corresponding master wave front [2, 3], this allows the experiment procedure to be much simplified; (2) it does not require the conjugate condition imposed upon the reference beam, as required in other type of two-wavelength ESPI arrangements [3], so that optics alignment become easier; (3) a special range of contour sensitivities can be achieved by using a diode laser system, which may extend the measurement range of conventional ESPI contouring techniques; (4) the variation of illuminating wavelength is realized 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 unchanged, this permits a good visibility of fringe patterns [4].

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In this paper, we present further studies made for the automatic fringe analysis by using the new ESPI contouring arrangement mentioned above. The interferograms are analyzed by a phase-shifting algorithm. The results with different contour sensitivities are presented. We also show that some conditions must be met to obtain quantitative data from interferograms in this specific ESPI contouring arrangement. Practical limits for the range of application on contouring an object are also considered from the point of view of automatic fringe analysis.

## 2. Optical system and shape measurement

Fig. 1 shows a multi-wavelength speckle interferometer for contouring applications. A high power diode laser (30 mW) is used as the light source of the interferometer. The diode laser system used is composed of a Melles Griot laser diode head in conjunction with a PROFILE laser diode controller. The input laser beam is divided by the first beam splitter $BS_1$ into an object beam and a reference beam, and then they are recombined at the second beam splitter $BS_2$. A ground glass $G$ is used for generating speckled reference wave front. The optical path length between the object and reference beam is matched as the reference and object beam travel the same path. Both object beam and reference beam are aligned to be on-axis along the viewing system. A metal object with sloping surface is illuminated by a normal incident wave front and is imaged using a suitable lens and an aperture combination onto the photosensor plane of a CCD cam-

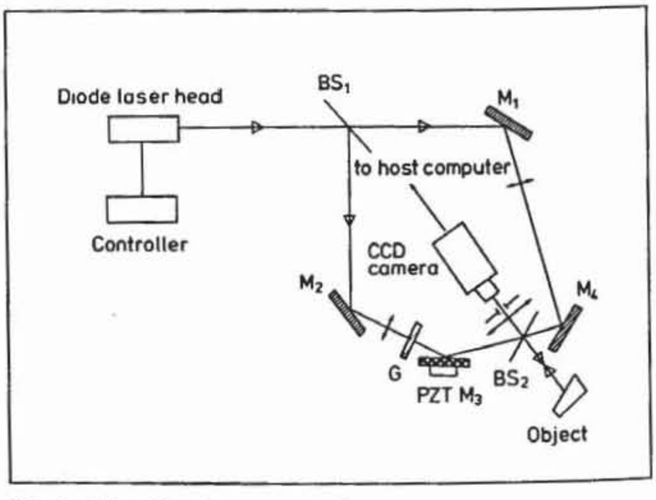
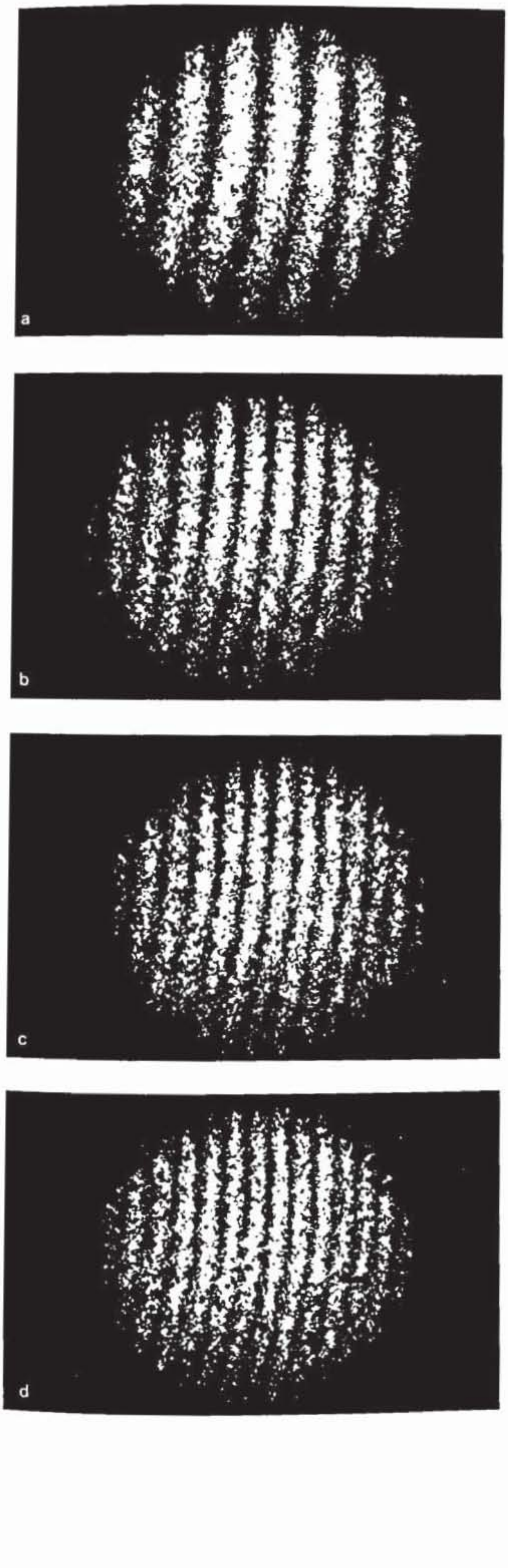



**Fig. 1. Experiment arrangement**



era. The two speckle patterns, one from the object and the other generated by the ground glass interfere at the camera sensor plane. The video analog output signal from the CCD camera is digitized in a host computer and displayed on a monitor. Contour fringes are obtained by illuminating the test object at $\lambda_1$ and then at $\lambda_2$. The first frame is acquired and stored with an image grabber and the second is digitally subtracted from the first to give correlation fringes. Speckle correlation fringes correspond to the object topography.

The variation of wavelength can be realized by adjusting the temperature applied to the laser diode. The dependence of the wavelength on the temperature in a active region of this particular LD system has been reported in a recent paper [1]. We have shown that there is a linear region existed in wavelength shifts via temperature variations. It has also been shown that the contour fringe interval is defined by the equivalent wavelength synthesized from $\lambda_1$ and $\lambda_2$ [1]. The sensitivity of the test can be therefore varied by changing the wavelength pair for illuminations. The photographs of contour fringe patterns with different sensitivities (i.e. different contour intervals) are given in figures 2(a)–(d). The surface shape of object being tested is contoured at corresponding intervals.

## 3. Quantitative fringe analysis

Speckle patterns have high frequency phase data, which make it difficult to find the absolute phase of a single speckle pattern, however, the phase of difference between two correlated speckle patterns can be determined by employing phase-shifting techniques, which will quantitatively determine the phase of double-exposure speckle measurement [6]. In fig. 1 mirror $M_3$ attached to a Piezo Electric Transducer (PZT) is applied for introducing phase steps. With this system the phase at individual pixel can be measured by three-phase shifting technique, which involves recording intensities $I_1$, $I_2$ and $I_3$ at each image point for three positions of the reference beam mirror, being 0, 90, 180 degrees. The phase calculated at each point in the interferogram is

$$\Theta = \arctan(I_3 - I_1)/(I_3 + I_1 - I_2). \quad (1)$$

After computing an initial phase $\Theta_1$, the illuminating wavelength is changed and a new phase $\Theta_2$ is computed at each image point. Subtraction of $\Theta_1$ from $\Theta_2$ gives the phase difference that is proportional to surface topography at each point.

The phase steps are calibrated for this particular arrangement. Phase evaluation is performed with this arrangement and good phase maps are obtained. Figs. 3–6 demonstrates the results of quantitative calculation carried out with this multi-wavelength ESPI contouring sys-

**Fig. 2. Photographs of contour fringes with different LD temperatures (corresponding to different contour sensitivities)**
**(a) $T = 24\,°C$ $\Delta T = 4\,°C$**
**(b) $T = 26\,°C$ $\Delta T = 6\,°C$**
**(c) $T = 27\,°C$ $\Delta T = 7\,°C$**

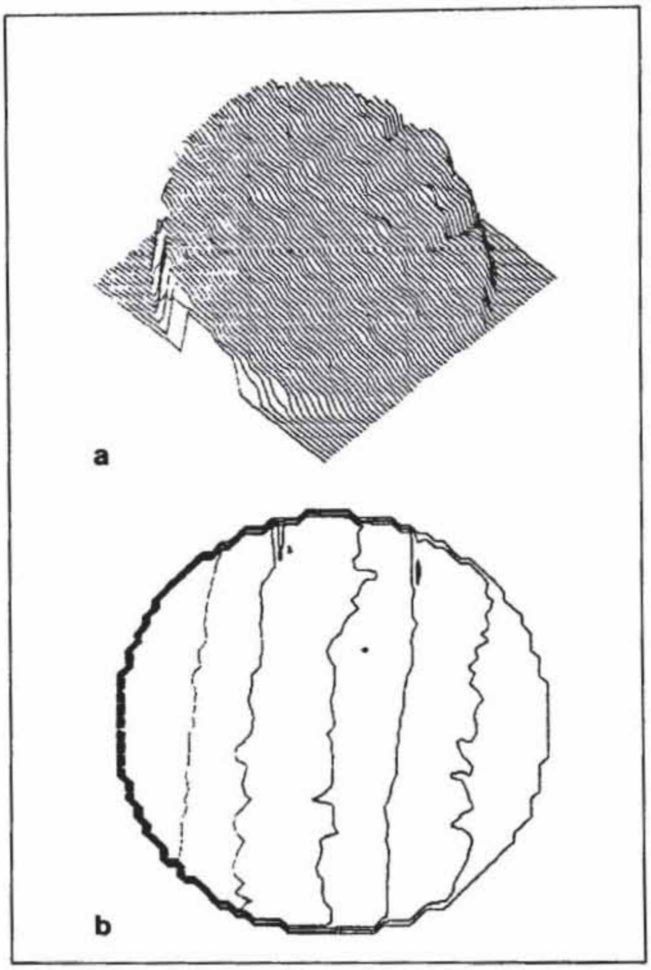



Fig. 3. $T = 24\,°C$: (a) 3-D plot, (b) contour map

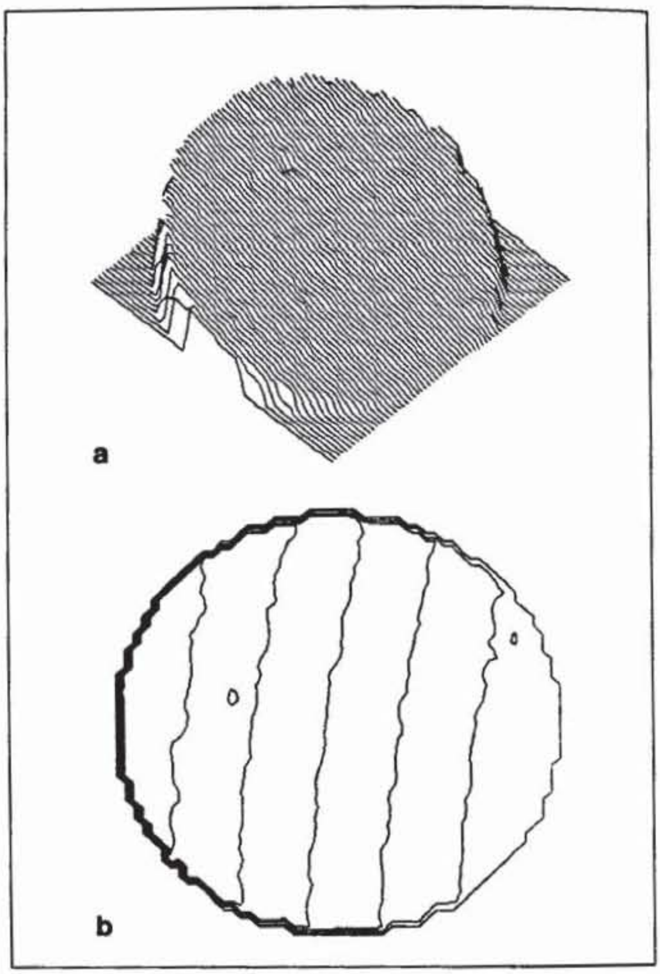



Fig. 4. $T = 26\,°C$: (a) 3-D plot, (b) contour map

Fig. 3.–Fig. 6. present quantitative evaluation results using a phase-shifting algorithm at different LD temperatures.

tem. To reduce the speckle noise, the fringes are smoothed by a $5 \times 5$ and $7 \times 7$ median window in sequence before phase evaluation.

It should be pointed out that the $2\pi$ ambiguities are not a problem when the multi-wavelength technique is applied, and the phase map of the surface does not have discontinuities present in the single-wavelength case [5].

## 4. Discussion of results

Figs. 3–6 show the quantitative calculation results with phase-shifting techniques, which give the 3-D plots and contour maps of the measured surface.

### *4.1. Temperature stability*

With LD controller, the variation of temperature applied to the laser diode head can be realized. The relationship between temperatures and wavelength changes has been obtained for this special LD system [1]. The frequency or wavelength of laser diode is controlled by the temperature provided that the injection current is kept constant. To stabilize the temperature of the laser diode, a LD controller with an automatic temperature-controlled circuit (ATC) is used. This ATC system enables the temperature control at a high-repetition rate.

### *4.2. The requirement of fringes contrast*

To simplify the discussion, we assume that laser power used in the interferometer is large enough so that the intensities of speckle patterns generated by each illuminating wavelength and a suitable $f$/number viewing system can be controlled within the sensitivity range of the CCD camera (i.e. below the saturation level of the camera). In this case the non-linearity of the camera is not necessary to be considered. It is also assumed that the ratio of intensity of object beam to reference beam has been adjusted to give good fringe visibility as well as the optical path length between the object and reference beam is matched as the reference and object beam travel the same path. With these conditions, any reduction in contrast of fringe patterns should be reasonably attributed to the decorrelation effect of speckle patterns, while illuminating wavelength is changed for generating contour fringes. The decorrelation effect can be quantified by simple image processing techniques incorporating exper-

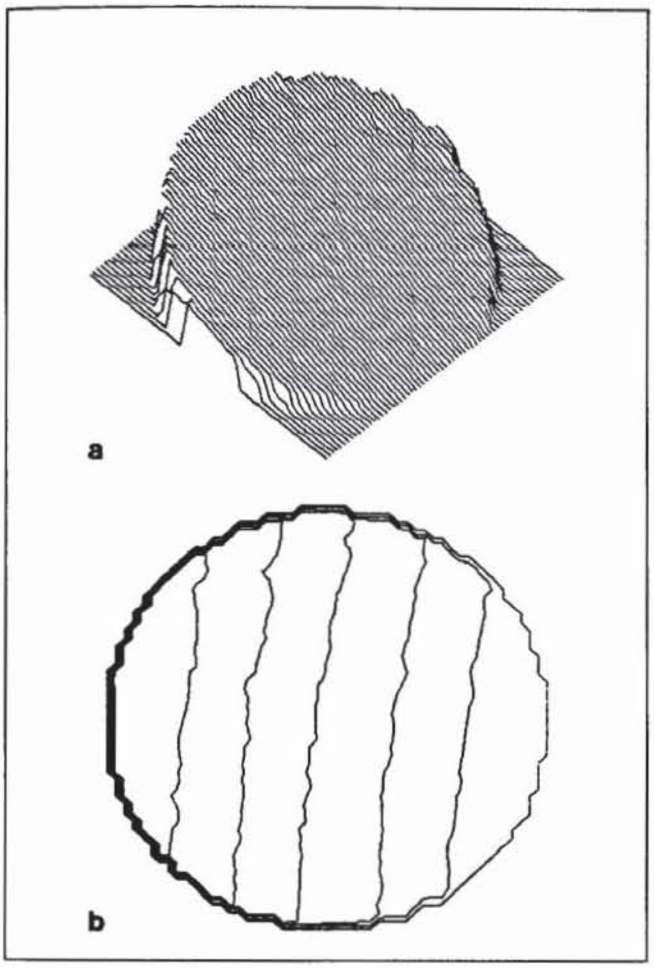


**Fig. 5.** ***T* = 27 °C: (a) 3-D plot, (b) contour map**

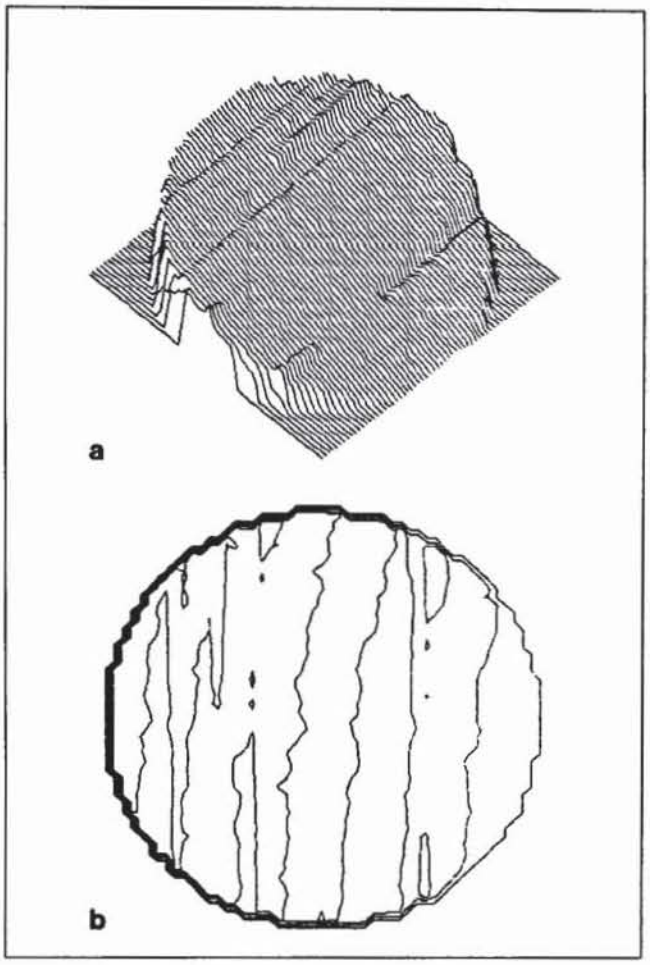


**Fig. 6.** ***T* = 28 °C: (a) 3-D plot, (b) contour map**

imental data of speckle patterns, and this technique was employed for analyzing a dual-beam ESPI contouring system recently [7]. The same approach has been used here to analyze the decorrelation effect in the multi-wavelength laser diode ESPI contouring system. Fig. 7 shows the dependence of correlation coefficients of speckle patterns on corresponding temperature variations applied to the laser diode. It can be seen from fig. 7 that the correlation coefficients are slightly different (0.54–0.50) in a temperature range of 23 to 27 degrees Cent., which indicates that the visibility of contour fringes should be good. Fig. 2 has demonstrated this prediction. When the temperature is adjusted up to 28 degree Cent., the correlation coefficient has been dropped down 0.39, yielding a large increase in the errors of quantitative calculation with the phase-shifting algorithm. This can be seen from figs. 6a) b). Figs. 3a), b) and figs. 4a), b) as well as figs. 5a), b) show the results of phase calculation with relative high correlation coefficients.

### *4.3. The requirement of fringe number in measured area*

The number of fringes in the area selected to be evaluated with a phase-shifting technique implicates the information capacity about surface topography included in this area, and therefore would be an important factor needed to be considered. In the case of setting temperature of LD to be 24 degree Cent., the corresponding contour interval is 1.02 mm. Although the correlation coefficient of speckle pattern regarding to illuminating wavelength is in a reasonable good value, the results of evaluation (figs. 3a), b)) show some errors due to insufficient of fringe numbers contained in the measured area. As the fringe number increased, the accuracy of quantitative evaluation of phase distribution has been remarkably improved as shown in figs. 4a), b) and figs. 5a), b). It should be noted that both cases have good correlation coefficient values. The best results of phase calculations in our experiment are shown in figs. 5a), b). In this case the temperature applied to LD is set to be 27 degree Cent., corresponding to contour interval of 0.57 mm, which should be an optimum condition for this particular speckle contouring arrangement.

Except for the factors causing the errors in quantitative fringe analysis discussed above, a drift of phase-step calibration resulted from adjusting wavelength to some extent might also be a potential error source, which should be carefully controlled in the experiment.

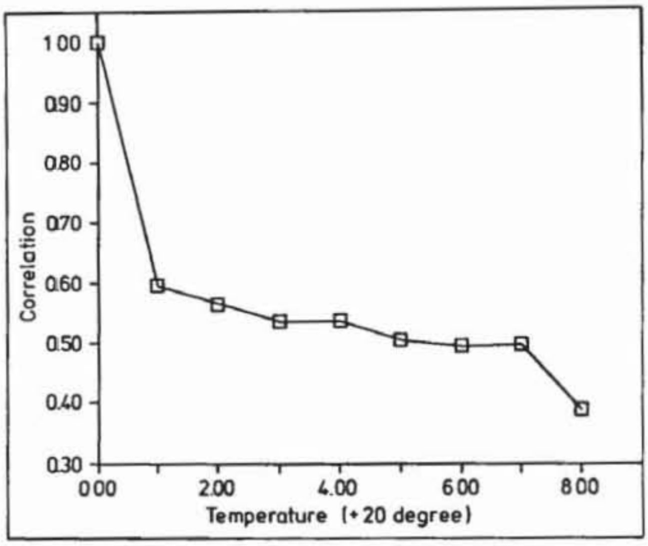



**Fig. 7.** The variation of correlation coefficient is plotted as a function of the temperature (or wavelength change) applied to the LD

## 5. Conclusion

Taken as a whole, a phase-shifting algorithm has been combined with a multi-wavelength laser diode ESPI contouring system. The phase distribution of contour fringe patterns related to the topography of an object with steep surface shape has been evaluated quantitatively under different contour sensitivities. To ensure a good result of phase calculation, three basic conditions must be met for this particular ESPI contouring system:

(i) Correlation coefficient values of speckle patterns should be high enough to have good contrast of contour fringes.

(ii) The number of fringes should be sufficient to remain reasonable information capacity in the measured area.

(iii) The alternation of temperature applied to the LD system should be limited in a range that will not cause a drift of the calibration of phase steps introduced for quantitative fringe analysis.

It should also be pointed out that $2\pi$ ambiguities are not a problem, and the phase map of the surface does not have discontinuities present in single wavelength techniques.

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