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A novel approach to determine decorrelation effect in a dual-beam electronic speckle pattern interferometer

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

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

A novel approach to determine decorrelation effect in a dual-beam electronic speckle pattern interferometer. An intrinsic decorrelation effect in a dual-beam ESPI system for contouring application is quantified by simple image processing techniques incorporating experimental data of speckle patterns. Practical limits for the range of application on contouring an object are also considered from the point of view of automatic fringe analysis. An acceptable degree of decorrelation due to the tilt of illuminating beams has been established.

Ein neuer Weg zur Bestimmung des Dekorrelationseffektes in einem elektronischen Zweistrahl-Speckle-Interferometer. Mit Hilfe einer einfachen Bildverarbeitungstechnik und experimentellen Daten von Speckelmustern wird der intrinsische Dekorrelationseffekt in einem Zweistrahl-ESPI-System für die Erzeugung von Höhenlinien quantifiziert. Praktische Grenzen bei der Anwendung zur Höhenlinienerzeugung werden aus der Sicht der automatischen Streifenanalyse diskutiert. Ein akzeptabler Dekorrelationsgrad bei der Verkippung der Beleuchtungsstrahlen wurde definiert.

Introduction

A foundational factor limiting the performance of an electronic speckle pattern interferometer is an intrinsic speckle pattern decorrelation effect. Therefore it is important to investigate speckle decorrelation effect in order to achieve an optimal performance of a speckle interferometer and to determine practical limits for the range of application by taking this effect into account. Except for speckle decorrelation effect, the condition for obtaining the best performance from an ESPI are also interrelated function of TV camera characteristic, input laser power, the type of interferometer and the mode of operation [1]. These effects have been discussed elsewhere [2–3].

The decorrelation effect for the plane strain sensitive and out-of-plane sensitive speckle interferometers was first investigated by R. Jones and C. Wykes [4–5]. For a plane strain sensitive speckle interferometry, the relationship between the decorrelation factor of speckle patterns and the rigid-body translation, the out-of-plane rotation of the object was investigated [4]. In parallel the reduction in fringe visibility of a speckle pattern due to decorrelation of two-wavelength contour fringes obtained by ESPI was also studied in detail [5]. In these studies analytical expressions describing the dependence of decorrelation of speckle pattern either on the object translation, out-of-plane rotation, or on the change of wavelength were derived theoretically to predict the limitation on the performance of speckle pattern interferometer concerned due to the decorrelation effect. However these analytical expressions could be obtained only in some special case and under many assumptions and simplifications. It might usually be difficult, if it is not impossible, to obtain more general analytical expressions which describes the decorrelation effect in a given speckle interferometer. In addition these theoretical expressions might not be satisfied to give an accurate prediction to the real decorrelation effect in speckle interferometers. This would be attributed to those assumptions and simplification which have been made in theoretical approaches. For instance, it has been found that one could observe fringes at theoretically very low visibility, i.e. towards the limits of object displacement sufficient to cause fringe extinction [4]. Therefore it should be necessary to have a more efficient way to predict speckle decorrelation effect in order to get more insight into the performance of a given speckle interferometer. It should also be noted that while the discussion has been concerned with the visual appearance of the fringes, it is equally important to consider the suitability of the fringe pattern for automatic analysis.

In this paper, an alternative method for predicting the decorrelation effect of speckle patterns will be suggested. The decorrelation effect in a dual-beam electronic speckle pattern interferometer will be investigated in detail. This type of speckle interferometer has recently been used for generating contour fringes of an object [6–7] and vibration analysis [8]. We investigate decorrelation effect in a way which uses image processing techniques incorporating experimental data rather than in the way of deriving an analytical expression predicting decorrelation effect of speckle patterns. Although the analysis is onto a specified dual-beam ESPI, the method discussed in this paper should also be adaptable to other type of speckle interferometer. A suitability of the approach here to the fringe pattern for automatic analysis will also be considered.

Experiment description

A diagrammatic arrangement of a specified dual-beam electronic speckle pattern interferometer is shown in fig. 1. A He-Ne laser with 10 mw is used as a light source. The laser beam is collimated by lens L and then divided

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Xiang Peng, H. Y. Diao, Y. L. Zou, and H. Tiziani, Institut für Technische Optik, Universität Stuttgart, Pfaffenwaldring 9, D-7000 Stuttgart 80.

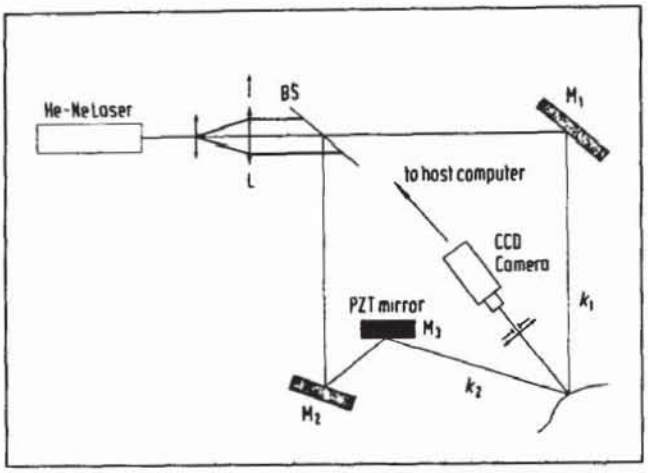

Fig. 1. **Schematic diagram of a dual-beam ESPI arrangement.**

into two illuminating beams via a beam splitter *BS*. The collimating lens *L* is mounted on a movable device, a tilt to both illuminating beams is then introduced by shifting lens *L*. The shifts of collimating lens are provided by a precision, kinematically coupled micrometer drive. A viewing system is arranged so that the *f*/number of imaging lens is set to be able to give fully resolved speckles. The contour fringe patterns corresponding to the surface geometry of the object are obtained by subtracting the state 1 and state 2 speckle pattern. The output of CCD camera is processed with help of an Epson computer, and FG-100 software is employed for subtraction of the digitized speckle patterns and for evaluation of correlation coefficients. In other words, correlation fringes with approprete visibility are obtained by applying a small shift to collimating lens (or equivalent a small tilt to both illuminating beams), sufficient to produce about five fringes across the object. It has been found, from the experiment, that this is a suitable case for automatic fringe analysis.

For a dual-beam ESPI, it is easily to show that the intensity at a point in the image plane is given by

$$I = I_{S1} + I_{S2} + 2\langle I_{S1} I_{S2}\rangle^{0.5}\cos(\phi_{S1} - \phi_{S2} + \delta\phi/2). \quad (1)$$

The mean subtracted and rectified signal *S* is given by

$$S = 8\langle I_{S1}\rangle\langle I_{S2}\rangle\sin^2(\delta\phi/2) \quad (2)$$

where $\delta\phi$ is the phase change which generates the speckle correlation fringes. I_{S1} and I_{S2} are intensities of speckle patterns generated by each illuminating beams, respectively. Eq. (2) is deduced under an assumption that the object light amplitude, A_S, and its phase ϕ_S remain unchanged when the phase change $\delta\phi$ is introduced. If this is not the case, the visibility of fringes is reduced since the two speckle patterns will no longer be fully correlated. When this specified dual-beam ESPI is used to generate contour fringes of an object, the exact form of phase change $\delta\phi$ varied as surface geometry of the object has been derived in our another recent paper [7].

Procedures of determining speckle decorrelation effect in a dual-beam ESPI by using image processing techniques incorporating experimental data

In the following discussion we fix our attention on a specified electronic speckle pattern interferometer shown in fig. 1. This type of interferometer has been used to investigate surface geometry of an object. It is also assumed that laser power used as a light source in the interferometer is sufficient large so that the intensities of speckle pattern generated by two illuminating beams, and a suitable *f*/number of viewing system can be controlled within the sensitivity range of a CCD camera which is used as a photosensor in the interferometer (i.e. below the saturation level of the camera). In this case the non-linearity of the TV camera is not necessary to be considered. In addition the ratio of intensity of one illuminating beam to another has been adjusted to give maximum fringe visibility. With these conditions, it would be reasonable to assume that any reduction in visibility of fringe pattern is due to the decorrelation effect, while two illuminating beams are tilted for generating contour fringes of an object.

A correlation coefficient *C* has been defined [9] and could be used to analyze the decorrelation effect

$$C_{kl} = \frac{|\langle A_k A_l^*\rangle|^2}{[\langle|A_k|^2\rangle\langle|A_l|^2\rangle]} \quad (3)$$

where A_k and A_l are the complex amplitudes of the light before and after the change of state. Clearly when $A_k = A_l$, the correlation coefficient $C = 1$, and in this case maximum visibility of fringes are obtained. As the value of *C* decreases the visibility of fringe drops. The relationship between visibility and correlation coefficient is complicated and depends on the type of interferometer, but a significant drops in the value of *C* gives a significant drop in visibility, and when $C = 0$ the fringes vanish. An illustration of decorrelation effect in a dual-beam ESPI is shown in fig. 2(a)–(d). To quantify the decorrelation effect by using image processing techniques and experimental data, the intensity distribution of speckle pattern is better to be represented in a discrete form

$$[I(m,n)]_{MN} = \begin{bmatrix} I_{11} & I_{12} & \dots & I_{1N} \\ I_{21} & I_{22} & \dots & I_{2N} \\ \dots & \dots & \dots & \dots \\ I_{M1} & I_{M2} & \dots & I_{MN} \end{bmatrix}$$

where $[I(m,n)]_{MN}$ is an image matrix representing speckle intensity distribution, $I(m,n)$ is the intensity value of speckle pattern at the point (m,n) which represents coordinate of each pixel in vertical and horizontal direction, respectively. $M \times N$ is the dimension of a portion of speckle pattern selected to be analyzed.

Small shift of collimating lens, and therefore a small tilt to both illuminating beams, produce a change in the relative phase of the two wavefronts. This phase change is proportional to the variation of surface shape and will cause a spatial variation in the correlation of speckle pattern as observed before (state 1) and after (state 2)

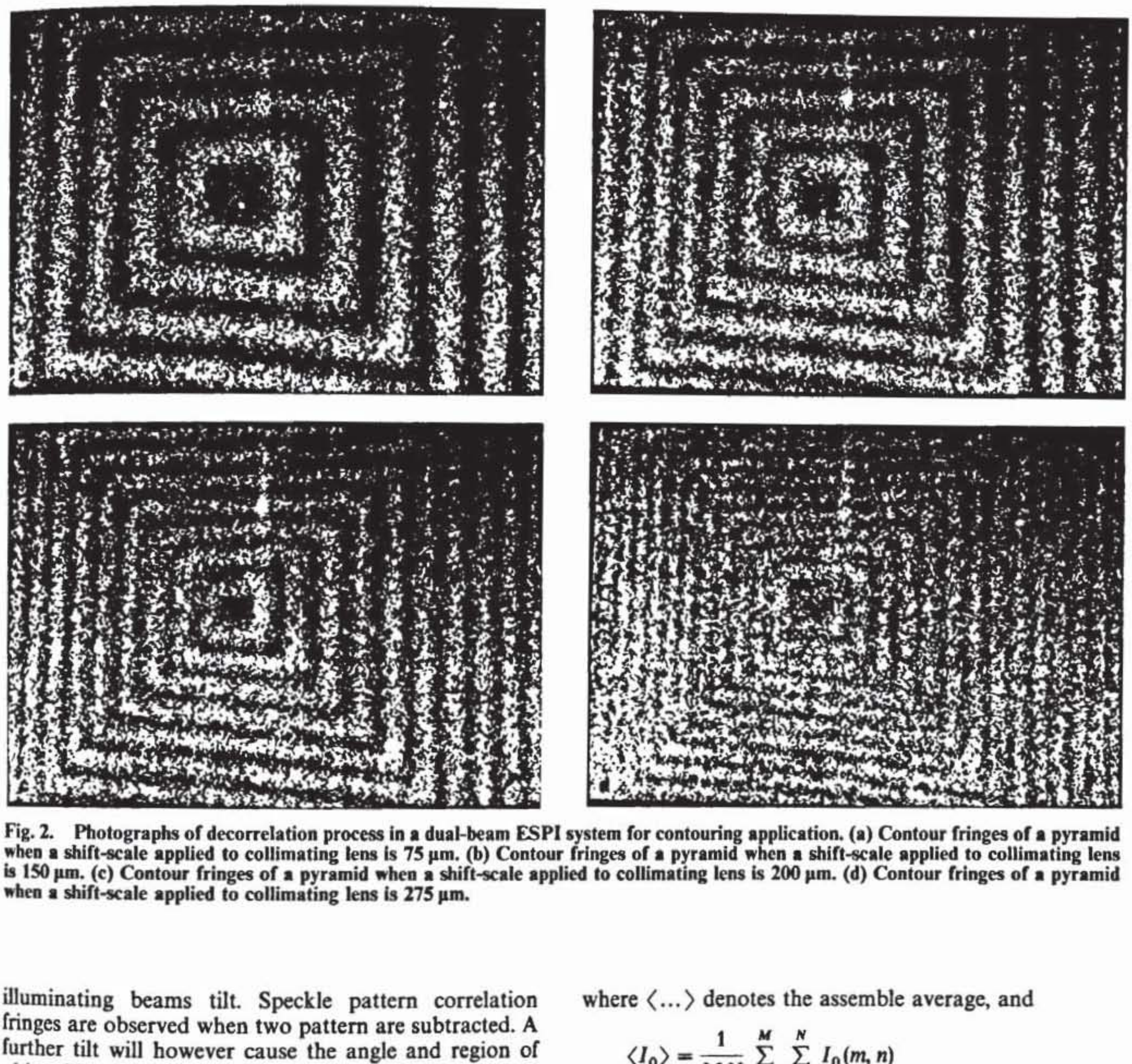

Fig. 2. Photographs of decorrelation process in a dual-beam ESPI system for contouring application. (a) Contour fringes of a pyramid when a shift-scale applied to collimating lens is 75 µm. (b) Contour fringes of a pyramid when a shift-scale applied to collimating lens is 150 µm. (c) Contour fringes of a pyramid when a shift-scale applied to collimating lens is 200 µm. (d) Contour fringes of a pyramid when a shift-scale applied to collimating lens is 275 µm.

illuminating beams tilt. Speckle pattern correlation fringes are observed when two pattern are subtracted. A further tilt will however cause the angle and region of object illumination to change to a great extent between states and it is argued that this effect should result in speckle pattern decorrelation.

An original speckle pattern $I_0(m, n)$ (state 1) is acquired by an image grabber and stored in the frame memory. Then successive speckle patterns, $I_i(m, n)$ $i = 1, 2, \dots L$, which correspond to different amount of shift applied to the collimating lens (or equivalent amount of tilt to both illuminating beams) are acquired and stored separately. 256 × 256 area in each pattern has been chosen to be analyzed. Now the correlation coefficients between $I_0(m, n)$ and $I_i(m, n)$ may be evaluated numerically from following formula

$$C_i = \frac{\sum_{k=1}^{N} \sum_{l=1}^{N} [I_0(m, n) - \langle I_0 \rangle] [I_i(m, n) - \langle I_i \rangle]}{\left\{ \sum_{k=1}^{M} [I_0(m, n) - \langle I_0 \rangle]^2 \sum_{l=1}^{M} [I_i(m, n) - \langle I_i \rangle]^2 \right\}^{0.5}} \quad (4)$$

where $\langle \dots \rangle$ denotes the assemble average, and

$$\langle I_0 \rangle = \frac{1}{MN} \sum_{k=1}^{M} \sum_{l=1}^{N} I_0(m, n)$$

$$\langle I_i \rangle = \frac{1}{MN} \sum_{k=1}^{M} \sum_{l=1}^{N} I_i(m, n) \quad (5)$$

It can be easily seen that the value of correlation coefficient depend on the average intensity of speckle patterns.

The analysis above and the algorithm indicated by eq. (4) and eq. (5) layout a simple procedure for analyzing decorrelation effect in a specified dual-beam electronic speckle pattern interferometer shown by fig. 1.

Results and discussion

Fig. 3 shows the results for the evaluation of correlation coefficients for twelve frame images of speckle patterns with 256 × 256 dimension which correspond to different

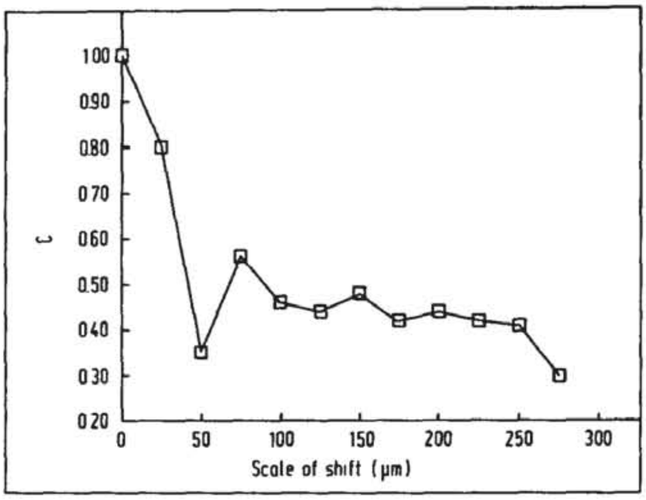

Fig. 3. The variation of correlation coefficient, C_t, as a function of shift scale applied to collimating lens (twelve speckle patterns with 256 × 256 dimension have been used to evaluate correlation coefficients).

small shifts applied to collimating lens. The scale of shifts are controlled and adjusted by a micrometer drive in a range from zero to 275 μm. An original speckle pattern corresponding to zero shift is taken to be as a sample speckle pattern and it is used to be correlated to successive speckle patterns with different shifts. A speckle pattern with 150 μm shift is digitally subtracted from original speckle pattern and a contour pattern with seven fringes across the object can be observed as shown in fig. 2(b).

Experimentally we have found that this is a case best for automatic fringe analysis in the dual-beam ESPI specified here. Fig. 4(a)–(b) show the results according to the calculation by using phase-shifting algorithm. However it is also interesting to note, from fig. 3, that correlation coefficient do not vary seriously in a range around the position of 150 μm shifting (from 100 μm to 225 μm). Two different shifts with 100 μm and 200 μm respectively have been chosen for testing the result of automatic fringe analysis, and both of them give reasonable results although slight noise is introduced due to small drop of the correlation coefficient value. This would be an encouraging result, which implies that one might be able to obtain good results for automatic fringe analysis in a suitable dynamic range.

Conclusion

In conclusion we have investigated intrinsic speckle decorrelation effect in a dual-beam electronic speckle pattern interferometer. In particular we have evaluated correlation coefficients by using simple image processing techniques supported by experimental data. This approach provides with a more effective way to access the performance of dual-beam ESPI and should also be applicable to other types of ESPI systems. Practical limits for the range of application from the point of view of automatic fringe analysis are also discussed. An acceptable degree of decorrelation of illuminating beams tilt has been established. Finally the method described here does not require many assumptions and simplifications as those used by a theoretical approach. Therefore, it would be able to estimate decorrelation effect in a speckle pattern interferometer more objectively. The numerical approach and experimental results are in reasonable agreement within the limit of experimental error.

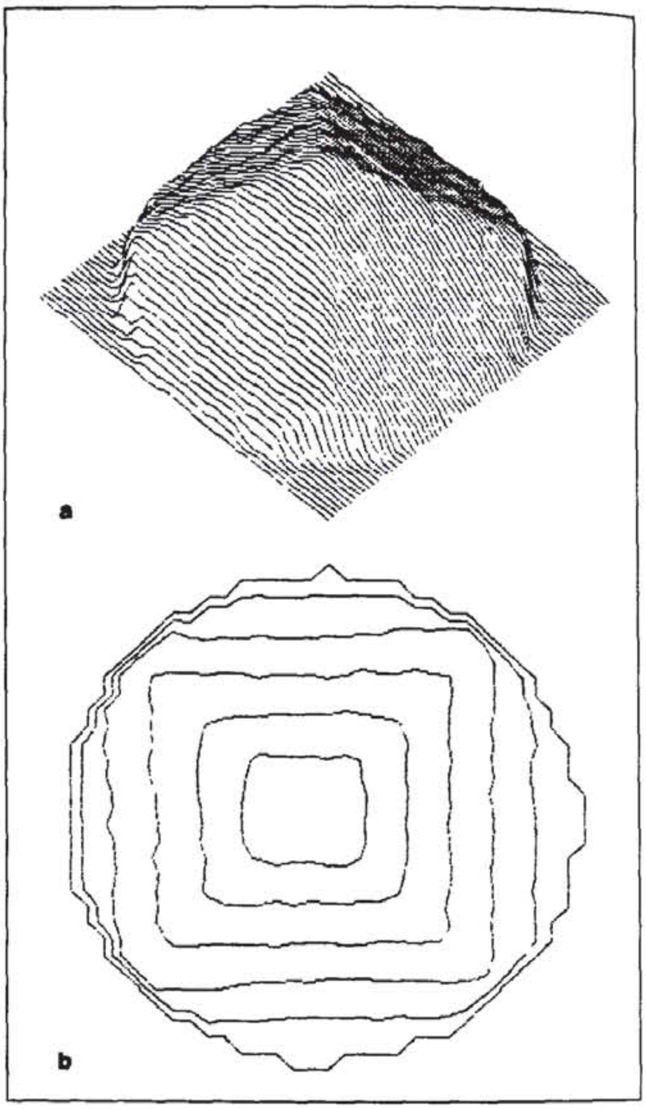

Fig. 4. Results of automatic fringe analysis using phase-shifting algorithm. (a) 3-D plot according to phase calculation. (b) Contour map.

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