How knowledge about speckle intensity and phase gradients can improve electronic speckle pattern interferometry

H. Helmers, J. Burke, Carl von Ossietzky Universität Oldenburg, FB Physik, 26111 Oldenburg, Germany
Mail: helmers@uwa.physik.uni-oldenburg.de / *Internet*: http://www.physik.uni-oldenburg.de/Docs/holo

Abstract. As is well known, the spatial coherence in a speckle field is limited to an area called the mean speckle size. Throughout this area, the coherence decays smoothly from the centre to the margin of a speckle, and the degree of coherence between two points (x_1,y_1) and (x_2,y_2) determines the probable amount of deviations between their intensities I_1, I_2 and phases φ_1, φ_2. These deviations are of special importance when spatial phase shifting (SPS)[1,2] is applied in electronic speckle pattern interferometry (ESPI). We demonstrate that the knowledge about the intensity and phase gradients in the object speckle pattern can be used to reduce the noise in measured deformation maps significantly.

Intensity gradients. In ref. 3, it is proven that the bright speckles essentially all have the same shape and size, independent of their maximum brightness. Only in the very centre of the speckles the intensity is nearly constant and decreases with nearly constant gradient to the margins. The greater the speckles' brightness, the greater the gradients. Furthermore, within the speckle field the intensity gradients in one spatial direction (no more is usually used in SPS) have been shown to be Laplace distributed[4]. The similarity between the negative exponential distribution of the intensities and the Laplacian one of its gradients is readily explained: Because most speckles are similar in shape, their intensity distribution determines the intensity gradient's distribution over a major part of the intensity scale. Hence, intensity gradients occur even within the bright speckle areas and the assumption of constant intensity across one speckle, that is often made in SPS, is violated everywhere. If, however, the intensity distribution in the object speckle field is measured once at the beginning of the measuring process, it can be considered in a modified phase reconstruction formula[1]. By this approach, the noise in ESPI sawtooth maps was reduced significantly by some 28 %.

Phase gradients. In ref. 5, the joint probability density function $p(I,\varphi,I_x,\varphi_x,I_y,\varphi_y)$, with $I_x = \partial I/\partial x$ etc. is given, from which the joint density function of the phase gradients, $p(\varphi_x,\varphi_y)$ is obtained, being roughly a bell-shaped function. In ref. 6, the second-order joint probability density function $p(I_1,I_2,\varphi_1,\varphi_2)$ is given, with all the quantities I_1, I_2, φ_1, and φ_2 being mutually dependent. The relationships between these quantities are investigated in terms of mean values and variances in ref. 7. $p(\varphi_2|I_1,I_2,\varphi_1)$ is shown to yield high variance for φ_2 when I_1 and/or I_2 are low, i.e. high phase deviations are found in dark regions of the speckle pattern. This is confirmed by Freund[8] , who showed that $p(I,\nabla\varphi)$ exhibits an anticorrelation between I and $\nabla\varphi$. In ref. 9, the average phase gradient in a speckle field is calculated to be 172° per speckle diameter. For the bright speckles themselves, a mean phase gradient of 50° per diameter is found at the centres of the speckles. This confirms that the bright speckles lie in regions of slower phase variations. But still the typical phase variation across the FWHM of a bright speckle is determined to be 45° to 90°.

These theoretical predictions about the phase gradients in speckle fields were confirmed by own measurements. A speckle field was imaged on the target of a CCD camera with 1024*768 pixels of 7.5*7.5 μm^2 size each. SPS was applied with a carrier fringe spacing of 3 pixels and the mean speckle size was set to about 45 pixels. Therefore errors caused by varying intensity and phase across the speckles could be neglected and the phase could be measured with a sufficient resolution. Fig. 1 shows an experimental result. The familiar bright-and-dark intensity features have been measured directly without superposition of the reference wave. The overlaid network of phase isolines has been generated from a grey-scale phase map by an appropriate look-up-table. As can be seen in fig. 1, in a first approximation the phase gradients in one direction can be assumed to be constant over the set of pixels used for phase calculation in SPS[1]. Treating the phase gradients in this way is equivalent to assuming local linear miscalibrations of the phase shift, a problem that has been treated extensively in temporal phase shifting (TPS). Therefore, the well known averaging and error compensating algorithms[10] for phase calculation can be applied. By this approach, together with the correction of varying intensity mentioned above, the noise in ESPI sawtooth maps was reduced by approximately 39 %.

Phase singularities. Beside the phase gradients, the phase structure of a speckle field contains the so-called phase singularities or screw dislocations, appearing at points of zero amplitude. These features are very frequent in speckle patterns; their statistical density has been shown to be one per two speckles[11]. Many of them can be discerned in fig. 1, recognisable by junctions of all eight phase isolines. At these locations, the phase is undefined. Moreover, the phase shows large statistical errors at locations with very low object light intensity, because here the interferogram modulation depth is very low as well.

Both kinds of locations form "bad points", which are responsible for the "salt and pepper" noise in ESPI phase maps. However, when depolarising objects are investigated, the number of such "bad points" can be reduced significantly.

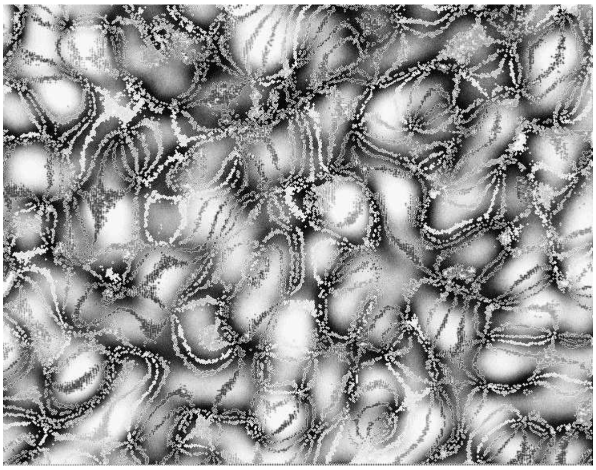

Fig. 1: Speckle field with phase isolines in 45° steps

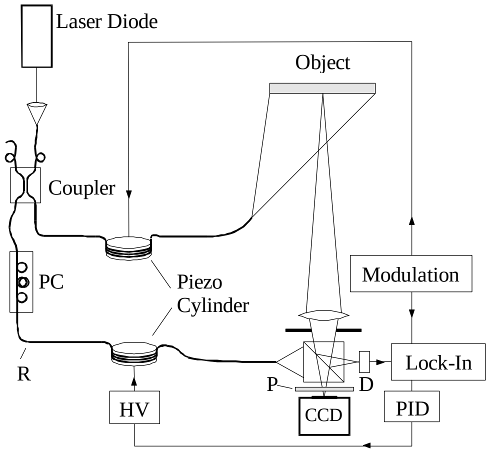

Fig. 2: Phase stabilised ESPI set-up

Merging of polarisation states. Consider an object illuminated with, e.g., vertical linearly polarised light. If the state of polarisation (SOP) of the scattered light differs from the SOP of the incident light, the object is said to be depolarising. The depolarisation coefficient ρ is the ratio of cross- to copolarised intensity of the scattered light. If the scattered light is split into two orthogonal linearly polarised states (vertical, v, and horizontal, h), two speckle patterns $S_v(x,y)$ and $S_h(x,y)$ are generated with a correlation coefficient c. Freund et al. have shown theoretically[12] that ρ is the parameter with the most important influence on the correlation coefficient c. The larger ρ is, the smaller is c. We will concentrate ourselves on strongly depolarising materials (e.g. $\rho > 0.5$), for which the speckle field correlation coefficient is low (e.g. $c < 0.2$)[13]. Caused by this low speckle field correlation, the "bad points", where the phase is undefined or uncertain, frequently occur at different locations. Therefore, by suitable merging of the corresponding phase maps on the basis of a modulation depth analysis, the number of "bad points" in the phase map can be minimised.

Fig. 2 shows the schematic experimental set-up of an fiber-optical ESPI system used for this purpose. The object showed a strong depolarisation ($\rho \approx 0.78$) so that the measured correlation coefficient for the speckle fields $S_v(x,y)$ and $S_h(x,y)$ was $c \approx 0.02$. The polariser P in front of the CCD camera was used to select the orthogonal linearly polarised states of the interferogram between the object wave and the reference wave R. The SOP of R was set to 45° linear by means of the polarisation controller PC. As long as one single camera is used, an active phase stabilisation system is required, by which the phase is kept constant during the time period necessary for the acquisition of the two orthogonally polarised interferograms in every object deformation state. In a previous version of the system[14], a separate path of rays for the stabilisation purpose was introduced in the set-up with the well known disadvantage of possible optical path differences between the measuring and the stabilisation set-up. Meanwhile, a PID controlled synthetic heterodyne system is used with a highly sensitive detector (D) of about 50 μm aperture diameter. This system allows for a phase stabilisation with respect to a reference area of the same size in the recorded interferograms. In the result, by this merging process a noise reduction in ESPI sawtooth maps by some 23 % was achieved.

References

[1] Bothe, T., Burke, J., Helmers, H., Appl. Opt. **36** (1997) 5310

[2] Sirohi, R. S., Burke, J., Helmers, H., Hinsch, K., Appl. Opt. **36** (1997) 5787

[3] Freund, I., Opt. Comm. **128** (1996) 315

[4] Ebeling, K. J., Opt. Act. **26** (1979) 1505

[5] Ochoa, E., Goodman, J. W., J. Opt. Soc. Am. **73** (1983) 943

[6] Goodman, J. W. in: Laser Speckle and related Phenomena, J. C. Dainty (Ed.), Springer-Verlag, Berlin (1984) 35

[7] Donati, S., Martini, G., J. Opt. Soc. Am. **69** (1979) 1690

[8] Freund, I., Phys. Rev. **51** (1995) 3770

[9] Shvartsman, N., Freund, I., Opt. Comm. **117** (1995) 228 and *Erratum*, Opt. Comm. **120** (1995) 369

[10] Schwider, J., Falkenstörfer, O., Schreiber, H., Zöller, A., Streibl, N., Opt. Eng. **32** (1993) 1883

[11] Berry, M. V., J. Phys. A **11** (1978) 27

[12] Freund, I., Kaveh, M., Berkovits, R., Rosenbluh, M., Phys. Rev. B **42** (1990) 2613

[13] Adams, M., Hinsch, K.D., Lange, F., Wolff, K., Opt. Eng. **36** (1997) 2225

[14] Brozeit, A., Burke, J., Helmers, H., Sagehorn, H., Schuh, R., Opt. Las. Technol., in press