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Comparison of phase recovery methods in spiral speckle pattern interferometry correlation fringes

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ABSTRACT

Spiral interferometry can be used as a solution to the problem of sign ambiguity presented in the conventional speckle pattern interferometric technique when the optical phase needs to be reconstructed from a single closed fringe system. Depressions and elevations of the topography corresponding to the object deformation are distinguished by the direction of rotation of the local spiral fringe pattern. In this work, we implement and compare several methods for optical phase reconstruction by analyzing a single image composed of spiral speckle pattern interferometry correlation fringes. The implemented methods are based on contour line demodulation, center line demodulation, Spiral Phase Quadrature Transform and the 2D Riesz transform with multivector structure. Contour line and center line demodulation approaches are exclusively dedicated to images containing a fringe system with spiral structure. The others are based on the 2D Riesz transform, these being well known approaches in conventional interferometry. We examine simulated experiments and analyze some of the emerging drawbacks for solving the phase reconstruction problem by using different mean values of speckle size and background noise levels. We also discuss several numerical procedures that may well improve the efficiency and robustness of the presented numerical implementations. The performance of the implemented demodulation methods is evaluated by using a universal image quality index and therefore a quantitative comparison is also presented.

1. Introduction

In optical metrology, full-field measurement techniques with parallel data acquisition and the processing for all object points imaged onto the 2D matrix sensor can deliver the output in the form of a fringe pattern. Single frame techniques are highly desired because they can be implemented using simpler experimental hardware, consequently increasing robustness with respect to environmental disturbances and facilitating the investigation of transient events. However, simplified setup configurations introduce the need of more sophisticated algorithmics to provide the demanded measurement accuracy. When adopting these measurement conditions, fringe analysis becomes an important topic and constantly deserves special attention due to the new advantages that are introduced by using novel mathematical tools developed in the field of harmonic analysis. By virtue of this, the automated fringe analysis enables optical methods to be user friendly, reliable and accurate.

A plethora of fringe analysis methods have been documented in a quite extensive specialized bibliography (see Ref. [1] and the references therein to quote a few original contributions). As is well known, the situation becomes even more complex when dealing with closed fringe systems, where the direction of the deformation in the phase recovery process cannot be determined from a single fringe system obtained by means of a conventional interferometric optical setup. However, this drawback can be overcome by using a spiral interferometry approach. Therefore, the improvement of the accuracy in the phase recovery problem by analyzing a single Spiral speckle pattern interferometry Correlation Fringe (SCF) image presents a new challenge and according to our knowledge it has not been actually addressed.

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In this work, we implement and compare several phase recovery methods by demodulating a single SCF image. We analyze and discuss the main issues on this topic with the aim to improve its understanding and to favor its use in optical metrology applications, due to the fact that this technique can be easily adopted in most industrial processes. It is also convenient to remark that the demodulation processing of SCF images is not straightforward due to considerable variation of the background and modulation intensity, both perturbed by high speckle noise.

Spiral interferometry can be used as an alternative to conventional digital speckle pattern interferometry to solve the problem of the sign ambiguity presented in the optical phase reconstruction from a single closed fringe system [2]. This enhanced optical setup can be obtained by placing a vortex filter system in the beam path of a standard two beam interferometer. The resulting interferogram contains spiral fringes instead of the closed fringes observed in conventional interferometry. Therefore, it is possible to distinguish between elevations and depressions present in the topography corresponding to the object deformation according to the rotation sign of the associated local spiral. It is important to note that this approach favors faster interferometric measurements than the usual phase-shifting technique and consequently reduces the need to have environmental stability.

We focus on the analysis of digital SCF images. Two interferometric speckle pattern images of the object under test are taken, one before and one after a deformation takes place, changing the optical phase profile detected by means of an interferometer with out-of-plane sensibility and vortex filtering. A spiral speckle fringe pattern is obtained by using a multiplicative correlation procedure between the two successive acquired speckle pattern interferograms. Due to the high content of speckle noise presented in the SCF images, they need to be denoised. For denoising, we use a wave atom basis decomposition approach obtaining a high filtering performance [3]. This noise removal approach favors the optical phase profile reconstruction using simple techniques of line demodulation. The denoised spiral interferogram fringes can be connected by computing associated contour or center lines to obtain one single curve $\mathcal{C}$. By evaluating the local tangential direction and the number of revolutions of $\mathcal{C}$, the optical phase distribution map can be reconstructed. To finally gain a major insight into the obtained performance of the optical phase map reconstruction from a single SCF system, we tested phase recovery methods based on the 2D Riesz transform by using the usual procedure proposed by Larkin et al., named as Spiral Phase Quadrature Transform (SPQT) [4], and a novel isotropic estimation technique given by Bülow et al. (2D Riesz transform assisted with orientation unwrapping procedure [5]). For all these approaches, we examine simulated experiments and remark some of the major existing drawbacks. We also analyze, implement and discuss a number of numerical procedures to improve the efficiency and robustness in the presented optical phase reconstruction methods.

This paper is organized in the following way. In Section 2, a theoretical description is briefly presented divided into two subsections that focus on the generation of synthetic SCF images and on the optical phase recovery methods. Results of simulated experiments comparing the different optical phase recovery methods are presented in Section 3. Finally, conclusions are given in Section 4.

2. Theoretical description

We are interested in optical phase recovery processes when a system of digital SCF is codified for whole-field measurement of out-of-plane deformations. One advantage of this technique is that it allows rough object surfaces to be monitored with high sensitivity in a non-contact mode and favors fast interferometric measurements. The optical phase changes produced by different states of the specimen under study are characterized via the acquisition of speckle interferograms, which in turn are specifically correlated to generate SCF images. The estimate of the optical phase distribution, coded in the spiral correlation fringes, is of primary concern. These fringe patterns are images mainly characterized by low information content and the local fringe density is one of the main features. Nevertheless, the different fringe densities are strongly affected by speckle noise. Therefore, a speckle noise removal method that takes into consideration the local quality of the fringe should be applied. The use of an adequate noise removal method is an important requirement in phase recovery processes. The challenge is the determination of the optical phase distribution from the analysis of a single one SCF image. Below, we discuss the construction of synthetic SCF images by introducing a multiplicative correlation method that is well adapted to a speckle denoising method via the use of a thresholding technique when the fringe system is decomposed into a wave atoms basis. Finally, we briefly describe the phase recovery methods implemented in this work.

2.1. Preliminary descriptions

2.1.1. Out-of-plane speckle pattern interferometry

In speckle interferometry, out-of-plane interferometers combine the optical field scattered by a rough object surface with a uniform optical reference field [6]. Therefore, the measurement is an intensity image described by a speckle pattern interferogram $I_0(x,y)$ given by the expression

$$I_0(x,y) = I_s(x,y) + I_r(x,y) + 2[I_s(x,y)I_r(x,y)]^{1/2}\cos[\psi_0(x,y)], \tag{1}$$

where $I_r(x,y)$ and $I_s(x,y)$ represent the intensities of the reference and the object beams, respectively. $\psi_0(x,y) \in (-\pi,\pi]$ is a random phase corresponding to an initial state of the object deformation and (x,y) are usually coordinates in $\mathbb{R}^2$. As the phase $\psi_0(x,y)$ varies randomly across the image, Eq. (1) does not directly display any fringe pattern. To produce a fringe system, a correlation procedure is usually employed between the speckle pattern interferogram intensity measurements corresponding to the initial state of the object under test and its deformation state $I_f(x,y)$, that is expressed by

$$I_f(x,y) = I_s(x,y) + I_r(x,y) + 2[I_s(x,y)I_r(x,y)]^{1/2}\cos[\psi_f(x,y)], \tag{2}$$

where $\psi_f(x,y)$ is the optical phase of the modified object state. Note that the main assumption in speckle interferometry is that the object phase information is associated with its deformation [6]. By comparing Eq. (1) with its analogous equation (2), only the phase $\psi_D(x,y) = \psi_f(x,y) - \psi_0(x,y)$ varies between the two object deformation states.

2.1.2. Multiplicative correlation of speckle pattern interferograms

The required fringe pattern can be obtained by using a correlation operation. Usually, the correlation is done by subtracting or adding the intensities of the two speckle pattern interferograms corresponding to the initial and final deformation states. The subtraction operation is more widely used due to the acceptable values of contrast and visibility of the resultant fringe patterns. However, mutiplicative operation has been shown to produce better results than the subtraction or addition operation applied to speckle pattern interferograms [7,8]. This procedure combines the addition and subtraction operations by taking an average of both quadratic correlations

$$I_P(x,y) \equiv \frac{I_D^{(HI)}(x,y)^2 + (-1)I_A^{(HI)}(x,y)^2}{2} = -I_0^{(HI)}(x,y)I_f^{(HI)}(x,y), \tag{3}$$