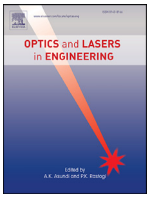
Optics and Lasers in Engineering 98 (2017) 31–36

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Enhancement of vibration desensitising capability of iterative algorithms for phase-shifting interferometers

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ARTICLE INFO

Keywords:
Metrology
Phase-shifting interferometry
Iterative algorithm
Vibration desensitisation

ABSTRACT

The sensitivity of phase-shifting interferometers (PSIs) to vibration impairs their application in unsteady environment. Iterative algorithms were developed to desensitise the effect of vibration on PSIs, but their desensitising capability is restricted by the estimated initial value. In this paper, a spatial carrier-assisted method is proposed, in which a wavefront phase retrieved from an additional spatial-carrier interferogram is used as the initial value. Because of the benefits of spatial carrier, vibration immunity and sign determination, iteration could converge to accurate value even when interferometers are under severe vibration. To reduce the possibility of transverse movement of the measured surface, subsampling strategy is further proposed to decrease the required tilt angle, with the additional benefit of decreasing the calculation time of iteration. Computer simulations and experiments are performed to verify the effectiveness of the proposed method. Results indicate that the vibration desensitising capability of an iterative algorithm is significantly enhanced by the proposed method. The proposed method improves the vibration desensitising capability with low cost and is thus highly compatible.

1. Introduction

As the most important technique for optical surface measurement, phase-shifting interferometry shows excellent performance with high spatial resolution and high repeatability. Because it uses phase shifting with high precision, the disadvantage of sensitivity to vibration also arises meanwhile. The major influence of vibration on phase-shifting interferometers (PSIs) is the disturbance to preset phase shifting, in which the increment is usually tens of nanometres. Additionally, for PSIs subjected to vibration, the averaging effect of camera exposure causes variation in fringe contrast, which needs to be a constant for in optical measurements. Both the phase shifting error and contrast variation introduce measurement error for PSIs [1]. To overcome this problem, many vibration desensitisation methods have been proposed, including the feed-back method, spatial-carrier (SC) method, parallel phase-shifting method and general phase retrieval method. The feed-back method detects phase variation and compensates the error by controlling the optical path difference [2–3]. Thus, a detailed optical configuration and high-cost hardware are required in for the feed-back method. In SC method, wavefront phase is modulated by a spatial carrier and retrieved from one-shot interferogram [4–6]. The SC method can be implemented easily, but suffers from low spatial resolution and significant error [7]. The parallel phase-shifting method realises phase shifting simultaneously, which freezes the effect of vibration [8–10]. However, complicated optical configuration and specially designed camera are needed for the parallel phase-shifting method. The general phase retrieval method, which uses the relation that one fringe corresponds to 2π phase, retrieves wavefront phase by using algorithms that analyse fringe distributions [11–16]. With no modification and restriction of interferometer required, the general phase retrieval method can be easily implemented and is of low cost. Among the general phase retrieval algorithms, iterative algorithms [17–21] have achieved widespread use in PSI because there is no limitation in the amount of fringes required and high accuracy is ensured. For an iterative calculation, an initial value is required as the starting point. However, if the initial value largely deviates from the accurate value, the iteration may not converge, which manifests the failure of PSI measurement. In other words, the vibration desensitising capability of an iterative algorithm largely depends on the initial value. In practice, preset phase shift is usually selected as the initial value. However, it is predicated that iterative algorithms may not converge when PSIs are implemented in severe vibration.

To enhance the vibration desensitising capability of an iterative algorithm for PSIs, we propose a spatial carrier-assisted (SCA) method, which uses wavefront phase retrieved from an additional SC interferogram as the initial value for iteration. The conception of SCA method was briefly mentioned in ref. [21], in which the details are not presented. In this paper, we describe the SCA method in detail and propose a subsampling strategy to overcome the problems in practical implementation. We first describe the SCA method and then verify the method by

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http://dx.doi.org/10.1016/j.optlaseng.2017.05.020
Received 19 February 2017; Received in revised form 31 May 2017; Accepted 31 May 2017

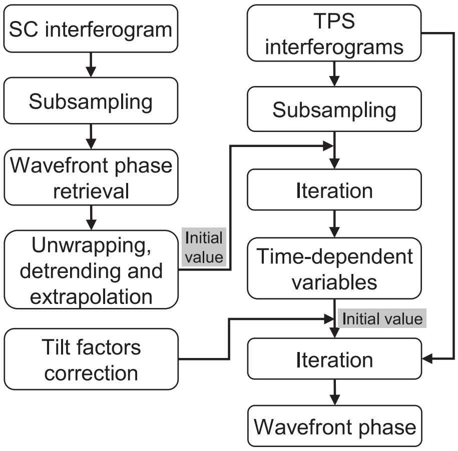

Fig. 1. Flowchart of the SCA method.

computer simulation. An experimental example is finally presented to exhibit the performance of SCA under realistic vibration.

2. Method descriptions

Spatial carrier and phase shifting are two different ways to realise phase modulation. Spatial carrier modulates phase in spatial domain and consequently results in high temporal resolution but low spatial resolution, while phase shifting modulates phase in temporal domain and consequently results in high spatial resolution but low temporal resolution.

It is necessary to briefly introduce the principle of iterative algorithm at first. Here, we use a modified three-step iterative algorithm (MTIA) [21] as an example. The temporal phase-shifting (TPS) interferogram subjected to vibration is described as follows:

$$I_j(x,y) = \alpha_j A(x,y) + \beta_j B(x,y)\cos[\varphi(x,y) + k_{xj}x + k_{yj}y + \delta_j], \tag{1}$$

where j is the temporal index. Variables in Eq. (1) could be divided into two types: space-dependent and time-dependent variables. The background A, modulation amplitude B and wavefront phase φ are space dependent, and the background variation factor α, modulation variation factor β, phase-shifting tilt factors k_x and k_y and translational value δ are time dependent. After expanding the cosine item in Eq. (1), space- and time-dependent variables are not correlated. In Eq. (1), only the interferogram grey $I_j(x,y)$ is known, and the other variables are unknown. Iterative algorithms construct algebraic equations in the form of Eq. (1) and solve unknowns using the uncorrelation between space- and time-dependent variables. The initial value could be either time- or space-dependent variables. After convergence, all the variables are obtained, including the wavefront phase.

The flowchart of the SCA method is shown in Fig. 1. When implementing the SCA method, a conflict exists between SC and TPS: the relative tilts between the reference and measured wavefronts are much different. In SC interferometry, the relative tilt between the reference and the measured wavefronts is required to be large enough to generate a sufficient carrier. Nevertheless, because of the aberration of interferometer imaging system, the relative tilt makes the reference and test rays pass through different paths in the interferometers and results in non-null error [22]. Hence, to achieve high-precision measurement in TPS interferometry, the relative tilt is adjusted to be about null. However, during the switching from nonnull status to null status, the tilting operation may result in transverse movement of the measured surface, which may make the SCA method fail. To reduce the possibility of transverse movement and ensure the measurement success, a subsampling strategy is introduced to the SCA method to decrease the required tilt angle in SC interferometry. The details are described in the following.

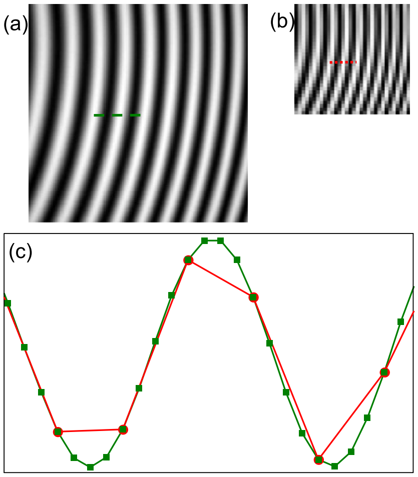

Fig. 2. Computer-generated SC interferogram: (a) the original and (b) subsampled SC interferograms and (c) the fringe profiles.

First, the SC and TPS interferograms are collected and subsampled. To generate a spatial carrier in the interferometer, the relative angle between the reference and the measured wavefront should be introduced to produce a certain amount of fringes, which is approximately proportional to the angle. In our work, the spatial-carrier phase-shifting (SCPS) algorithm [6] is used to retrieve the wavefront phase, which requires that a fringe covers four pixels. If the resolution of interferograms is 128 × 128, about 32 fringes should be introduced, and the surface should be tilted by a very large angle. Subsampling could reduce the amount of fringes required to apply the SCPS algorithm. An example is shown in Fig. 2(a), in which one fringe covers about 15 pixels in the x-direction. After 4×4 subsampling, a fringe covers about 3.75 pixels in the x-direction, which is close to the requirement of the SCPS algorithm, as shown in Fig. 2(b) and (c). In other words, with 4×4 subsampling, only about eight fringes are sufficient to meet the SCPS requirement. In addition, the same subsampling should be applied to TPS interferograms to make the resolution of the TPS interferograms equal to that of SC interferogram.

Second, the wavefront phase is first retrieved from the subsampled SC interferogram and then unwrapped, detrended and extrapolated. This phase retrieved using the SCPS algorithm contains large linear item, which is resulted from spatial carrier. However, the linear item of the wavefront phase in TPS interferograms is approximately zero because TPS interferometry works in null status. Hence, unwrapping and detrending are needed to remove the linear item. In the SCPS algorithm, the wavefront phase of one pixel is calculated from the greyscale values of its four adjacent pixels. Consequently, the size of the wavefront phase is less than the interferogram by three pixels. Therefore, extrapolation is needed to patch the absent data. In our work, a cubic polynomial fitting is used to extrapolate the wavefront phase.

Third, by using the wavefront phase from SC interferogram as the initial value, time-dependent variables are calculated from the subsampled TPS interferograms by an iterative algorithm. Owning to the different resolutions of the original and subsampled interferograms, the tilt factors should be corrected by dividing them by the subsampling ratio.

Finally, by using time-dependent variables as initial values, the wavefront phase is calculated from the original TPS interferograms by using the iterative algorithm. The resolution of the wavefront phase is the same as that of the original interferograms. The measured surface could then be reconstructed after phase unwrapping.

In the SCA method, the wavefront phase estimated from the SC interferogram is delivered to the iteration as the initial value, and thus helps in the convergence of the iteration. A precondition for the implementation of the SCA method is that no transverse movement of measured