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Three-step interferometric method with blind phase shifts by use of interframe correlation between interferograms

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A B S T R A C T

A new three-step interferometric method with blind phase shifts to retrieve phase maps (PMs) of smooth and low-roughness engineering surfaces is proposed. Evaluating of two unknown phase shifts is fulfilled by using the interframe correlation between interferograms. The method consists of two stages. The first stage provides recording of three interferograms of a test object and their processing including calculation of unknown phase shifts, and retrieval of a coarse PM. The second stage implements firstly separation of high-frequency and low-frequency PMs and secondly producing of a fine PM consisting of areal surface roughness and waviness PMs. Extraction of the areal surface roughness and waviness PMs is fulfilled by using a linear low-pass filter. The computer simulation and experiments fulfilled to retrieve a gauge block surface area and its areal surface roughness and waviness have confirmed the reliability of the proposed three-step method.

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1. Introduction

In order to retrieve desired information about a spatial phase distribution in a surface testing, numerous phase shifting interferometry (PSI) algorithms are used. In spite of relatively large level of errors in reconstructed phase maps (PMs), three step algorithms with given phase shifts are also used due to their simplicity in comparison with other multistep algorithms [1]. But the desire to simplify the three step PSI by refusal from calibrated phase shifters has stimulated the development of new algorithms with blind phase shifts between reference and object waves.

A generalized PSI method developed by Greivenkamp [2] promoted creation of new generalized PSI techniques with arbitrary unknown and unequal phase shifts. Cai et al. have proposed the method of the generalized PSI with arbitrary unknown and unequal phase steps [3]. This method is usable for N frame numbers ($N \geq 3$). However, the necessity to measure intensity of a reference wave that should possess the constant amplitude along the full aperture complicates its practical application. Besides, the supposition that the averaging of difference interferogram intensity distributions have the same value leads to high errors of the reconstructed object wavefront for some angular ranges of arbitrary phase shifts. Let's note that the proposed method is fulfilled by using time-consuming iterative procedures. Xu et al. [4,5] also used the generalized PSI approach in two methods containing noniterative algorithms for extraction of unknown phase shifts. The first method [4] was proposed for a blind searching of the unknown phase shifts and wavefront reconstruction by using several formulas including the equation obtained by Zhang [6] and a mean error function. However, intensity distributions of reference and object wavefronts should be preliminary known. In addition, the used averaging procedure initiates errors of unknown phase shift extraction and wavefront reconstruction, which are partially suppressed by additional introducing of error function. In this connection, its practical use is rather labour-consuming. The second method [5] requires measuring of the reference wave intensity that should be constant. It also uses averaging procedure that causes increase of the phase shift extraction errors, especially in angular ranges from 0 to 0.1 rad and from 2.8 to π rad. Efficient phase shift extraction method for generalized PSI that extracts the unknown phase shift and retrieves the PM with low level of errors was proposed by Xu et al. [7]. However, the necessity to use amplitude and intensity distributions of object and reference waves for final calculations restricts its practical application. The generalized

Abbreviations: PM, phase map; PSI, phase shifting interferometry; TSM, three-step interferometric method with two blind phase shifts of the reference wave; M1, two-frame interferometric method with a blind phase shift of a reference wave; M2, two-step interferometric method for a surface relief retrieval; MM2, modified two-step interferometric method for a surface relief retrieval; LP, low-pass; LPF, low-pass filter; GS3 approach, Gram–Schmidt algorithm without the background filtering; GRF, Gaussian regression filter; ACF, autocorrelation function.

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iterative algorithm for extraction of random phase shifts that simultaneously eliminates tilt-shift errors was proposed by Xu et al. [8]. This algorithm is useful for working with large-aperture interferometers. Besides, it practically compensates the waviness in a reconstructed PM. However, using at least four interferograms and several iteration cycles, and assuming that the background intensity and the modulation amplitude do not have frame-to-frame variation complicate the practical use of this algorithm.

Several phase shifting methods for reconstruction of phase maps by using exclusively three interferograms recorded with blind phase shifts were also proposed [9–15]. Guo et al. [9] have developed two blind self-calibrating algorithms to estimate two unknown phase shifts δ_2 and δ_3 from three interferograms in assumption that the first interferogram was recorded without a phase shift, i.e. $\delta_1 = 0$, and the second and third interferograms were recorded with the phase shifts δ_2 and δ_3 concerning the first one. To extract the phase shifts, a phase φ to be measured and a reference wave I_r are recovered, and a minimal value of spatial correlations between φ and I_r is defined. But the second order correlation initiated a cross power spectrum cannot describe nonlinear correlations between these two signals, because their spectra are overlapped weakly. To overcome this lack, Guo [10] have proposed to use the third-order correlation between φ and I_r that is estimated by a cross-bispectrum. The developed blind self-calibrating algorithm allows estimating random phase shifts from three fringe patterns. However, the computational procedure for searching of random phase shift values is sophisticated. Besides, computer simulations are possible only for those phase shifts that are used for the conventional three-step algorithms (for example, $\delta_i = 0,\ 2\pi/3,\ 4\pi/3$), and estimation of peak-to-valley and RMS errors can be fulfilled also only for those shifts. Meneses Fabian [11] has proposed a non-iterative algorithm for phase retrieval with the help of PSI of three unknown and unequal phase steps that is based on geometric concept of volume enclosed by a surface. The algorithm allows reaching the low errors of blind phase shifts extraction and object phase retrieval. However, some specific demands to interferograms that should have at least several fringes considerably restrict the possibilities of this algorithm. Another approach of Menenes Fabian [12] based on the modulation light estimation by applying the least squares iterative method demands high spatial variation in the illumination and the object phase. Wang et al [13] have proposed a phase retrieval method based on the normalized difference maps induced by three interferograms with unknown phase shifts. In this method, two difference PMs without background determined as the sum of an object and reference wave intensity distributions are achieved due to subtraction operation between interferograms. To eliminate amplitude unequality between two difference maps, the normalizing approach is used to produce two normalized difference maps. These maps are used for retrieval of the searched PM with the help of the two-step Gram–Schmidt algorithm [16]. The background elimination without the normalization procedure was also used in the phase-shift extraction algorithm for the blind phase-shifting holography based on the quotient of inner products [14]. But this algorithm requires the additional acquiring of the reference wave in addition to three holograms with arbitrary unequal phase shift values.

The similar approach to background elimination implemented in Ref. [13] was proposed for realization of two-step interferometric methods with a blind phase shift of the reference wave for a surface relief retrieval [17,18]. However, to retrieve the searched PM by these methods, it is necessary to record the reference and object wave spatial distributions and two interferograms I_1 and I_2 differed by the blind phase shift α_{12} of the reference wave, and further to produce two differences between I_1 and I_2 and background. Normalization of these difference maps is not necessary, since simultaneously the phase shift α is defined by using interframe correlation between interferograms (ICI) that allows calculating the correlation coefficient between two recorded interferograms and defining the phase shift angle as an inverse cosine of this coefficient [17,18].

If three interferograms with different arbitrary phase shifts between the object and reference waves are recorded, it is enough to produce two difference PMs, in which the background is excluded. In this case, the separate registration of the object and reference wave intensity distributions is removed. Besides, if two arbitrary phase shifts are defined preliminary, the searched PM can be retrieved with the help of a simple equation without any additional operations. This principle is used in a proposed three-step interferometric method (TSM) with two blind phase shifts of the reference wave. The TSM implements the preliminary extraction of blind phase shifts from three recorded interferograms with the help of the ICI and further retrieval of the PM of a test object. The ICI can be used for extraction of the blind phase shifts at the range from 0 to π with a low level of systematic error, as it has been shown in Refs. [17–19]. Thus, if phase shifts of a reference wave will not exceed π, the TSM can be successfully used. Except of the test object PM retrieval, it also contains procedure of high-frequency and low-frequency PMs separate extraction, which are the constituent parts of the test object PM. If the studied test object is a smooth or a low-roughness engineering surface, the TSM can be used not only to retrieve the total surface relief of a studied surface area, but also its areal surface roughness and waviness. The fulfilled computer simulations and experimental results have confirmed the reliability of the proposed method to retrieve test objects if they represent smooth or low-roughness surfaces.

2. Three-step interferometric method with two blind phase shifts

The TSM contains two stages. The first stage provides processing of three interferograms I_1, I_2 and I_3 of a test object and retrieval of a coarse PM. The second one implements a separate extraction of areal surface roughness and waviness PMs and producing of a fine PM. Some operations that fulfills by this method are similar to the operations that are presented in the two-frame interferometric method with a blind phase shift of a reference wave (M1) [17] and two-step interferometric method for a surface relief retrieval (M2) [18] that is modified in Refs. [20,21] (MM2). These Methods are dedicated for processing of two interferograms differed only by an arbitrary phase shift of the reference wave. The proposed TSM is adapted to processing of three interferograms that are differed by two arbitrary phase shifts of the reference wave. Let's consider separately two stages of the TSM fulfilment.

2.1. First stage of the TSM

At the first stage, three digital interferograms $I_1(k,l)$ $I_2(k,l)$ and $I_3(k,l)$ with the blind phase shifts δ_1, δ_2 and δ_3 of the reference wave are recorded in a two-beam interferometer. These interferograms are used for retrieval of the PM $\varphi(k,l)$ of a given test object in each its k,l^{th} pixel. They can be expressed by the next fundamental equations for the temporal three-step PSI:

$$\left.\begin{aligned} I_1(k,l) &= I'(k,l)\left\{1 + V(k,l)\cos\left[\varphi(k,l)+\delta_1\right]\right\} \\ I_2(k,l) &= I'(k,l)\left\{1 + V(k,l)\cos\left[\varphi(k,l)+\delta_2\right]\right\} \\ I_3(k,l) &= I'(k,l)\left\{1 + V(k,l)\cos\left[\varphi(k,l)+\delta_3\right]\right\} \end{aligned}\right\}, \tag{1}$$

where $I' = I_o + I_r$ is the average (background) intensity, I_o is the object wave intensity distribution, I_r is the reference wave intensity distribution, $V = \frac{2\sqrt{I_o I_r}}{I_o + I_r}$ is the fringe visibility. Here and in following symbols and Eqs. the pixel coordinates (k,l) are omitted for brevity.

If the blind phase shifts δ_1, δ_2 and δ_3 are unknown, the equation set (1) can't be solved and the PM can't be calculated. To define these phase shifts, we propose to use the same ICI that was named as "correlation approach" and applied to extraction of the reference wave blind phase shift in the methods M1 and M2 [17,18]. According to this approach, phase shift differences $\alpha_{21} = \delta_2 - \delta_1$, $\alpha_{31} = \delta_3 - \delta_1$ can be expressed as

$$\alpha_{21} = \arccos\frac{\left\langle\left[I_1 - \langle I_1\rangle\right]\left[I_2 - \langle I_2\rangle\right]\right\rangle}{\sigma_{I_1}\sigma_{I_2}}, \tag{2}$$

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