Optics and Laser Technology 107 (2018) 72–79

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

Quantification of nanoscale deformations using electronic speckle pattern interferometer

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ARTICLE INFO

Article history:
Received 11 November 2017
Received in revised form 6 March 2018
Accepted 13 May 2018

Keywords:
Nanoscale mechanical deformation
Electronic speckle pattern interferometer (ESPI)
Phase shifting method

ABSTRACT

Quantification of deformations using electronic speckle pattern interferometer is a well known technique. Usually, deformation size probed by this technique ranges in tens of microns. This paper reports quantification of nanoscale mechanical deformations in metal plates using a low cost optical phase shifter in an electronic speckle pattern interferometer.

1. Introduction

Electronic speckle pattern interferometer (ESPI) is a non-destructive testing technique for characterization of various sample surfaces [1–5]. In this method, sample surface under study gets illuminated by a laser source for obtaining its speckle image [6,7]. Any minute deformation in the surface of the sample, results in the phase variation of the speckle pattern. Changes in the surface of the sample can be studied by superimposing two speckle patterns taken before and after deformation. By subtracting speckle images taken before and after deformation, autocorrelation fringe pattern can be obtained. Autocorrelation fringe pattern reveals the degree of correlation of the two speckle patterns taken before and after deformation. However, getting quantitative information of deformation directly from this correlation fringe pattern is impossible. There are number of methods developed over the years to get quantitative information from speckle images. They are Fourier transform methods [8–10], Phase shifting methods [11,12], Digital image correlation (DIC) methods [13–15] and Moiré's method [16,17].

In 1986 Kreis [18], reported the Fourier transform method to extract the phase information from the interference pattern. In this method, speckle pattern from spatial domain is transformed into frequency domain and first order frequency is obtained by subsequently applying band-pass filter. Later on, phase information is achieved by transforming it again from frequency domain into spatial domain by applying the inverse Fourier transform. Judge et al. [19], reported the Fourier transform method for the measurement of holographic deformations with automatic phase unwrapping. Quan et al. [20] inspect the nanoscale deformation on the surface by combining the Fourier transform and phase shifting method. Kaufman et al. [21] compared the performance of Fourier transform method with temporal phase shifting method. Phase shifting method is seems to be popular method among all the phase retrieval techniques. Quantitative information regarding deformation of the sample surface using the phase shifting method can be achieved via temporal phase shifting method or spatial phase shifting method [22]. In the temporal phase shifting method, known phases in the speckle pattern is introduced sequentially by the optical phase shifter located in the path of reference beam and speckle patterns are captured by digital camera accordingly. Four step [23] and five step temporal phase shifting method [24,25] are generally used for the extraction of phase information from the correlation fringe patterns. Later technique is more effective and invites lesser errors and hence it is used in this paper. In the spatial phase shifting method several cameras are used to capture spatially shifted speckle images to obtain phase information [26].

Digital image correlation (DIC) is another popular and powerful technique used to calculate the deformation and shape measurement [14]. The basic principle used in this technique is tracking the same subset located in the image before and after deformation of the sample. Moiré's interferometer is first used by Post et al. [16], in this method, specimen grating and reference grating are overlap for the generation of Moiré's pattern. This Moirés pattern

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https://doi.org/10.1016/j.optlastec.2018.05.019
0030-3992/

can be used to measure the in-plane deformation of the sample surface [17].

This paper reports measurement of nanoscale surface deformation of metal plates subjected to mechanical stress using temporal phase shifting ESPI technique. Previous attempts in measurement of surface deformation restricted up to micron scale using ESPI technique [27,28]. Measurement of nanoscale deformation up to 220 nm has been reported [21] via combination of Fast Fourier Transform (FFT) and phase shifting method. In this work, peak surface deformation up to 124 nm and below is reported using only temporal phase shifting method.

2. Theory: Five step temporal phase shifting technique

In ESPI method, speckle pattern from the un-deformed and deformed sample surface is subtracted to get correlation fringe pattern. Larger the applied deformation, denser the correlation fringe pattern will become. Intensity equation for correlation fringe pattern is given by Eq. (1) [29],

$$I(x,y) = I_a(x,y) + I_b(x,y) + 2\sqrt{I_a(x,y)I_b(x,y)}cos(\delta + \phi) \tag{1}$$

where I_a (x, y) and I_b (x, y) are the intensities of two interfering light waves. δ is the phase difference between these two waves which is completely random and depends upon the local deformation. φ is the additional constant phase shift introduced by the phase shifter. Our aim is to find δ at each location of the sample surface. This equation represents the correlation fringe pattern for out-of-plane surface displacement. It contains large noise and phase ambiguity due to which we cannot obtained phase information from this equation. To remove large noise, digital filters can be used [30]. Phase shifting methods are used to extract phase information and subsequently to get amplitude of deformation. Optical phase shifter is used in the experiment in order to add a constant phase difference between object and the reference beam. For the five step phase shifting method which is used in this paper, optical phase (δ) can be calculated by using Eq. (2) [24],

$$\delta = tan^{-1}\left[\frac{2*(I_4(x,y) - I_2(x,y))}{I_1(x,y) - 2*I_3(x,y) + I_5(x,y)}\right] \tag{2}$$

Eq. (2) gives wrapped phase map which has phase discontinuity from −π to +π. Hence it is not possible to obtain the phase information from this. To obtain continuous phase map quickly from wrapped phase map, two-dimensional phase-unwrapping algorithm[31] is commonly used. Displacement (D) of the object from the unwrapped phase map (UP) can be calculated using Eq. (3) [32],

$$D = UP * \frac{\lambda}{4\pi} \tag{3}$$

where λ is the wavelength of the laser light.

3. Experimental setup

Experimental set up of ESPI is as shown in Fig. 1. Light from the He: Ne laser (λ = 632.8 nm, Power = 5 mW, coherence length ~10 cm) was first divided into two half using a beam splitter. One beam was used to illuminate the object surface in the full-field manner using spatial filter assembly. The illuminated object thus forms speckle pattern which contains information about the surface of test object. In our experiment, circular metal plate discs of aluminium, brass and iron were used as test objects. The speckle pattern was then collected with a zoom lens (f number ~ 2.8) and imaged on to the digital camera. The digital camera was having following specifications; 1/4-inch CMOS sensor, Array element: 1280 × 1024, Image area: 3.6 × 2.9 mm, Pixel sizes: 2.8 × 2.8 µm and Maximum frame rate: 7.5 fps. Second beam (reference beam), after reflecting from series of mirrors whose paths are matched with the first beam, was made to diverge and superimposed with the light reflected from the object via beam splitter on the camera. The path length difference between the object beam and reference beam is adjusted in such a way that it is much below the coherence length of the laser used. One mirror from the path of reference beam is piezoelectric transducer [PZT] mirror as shown in the Fig. 1. In a

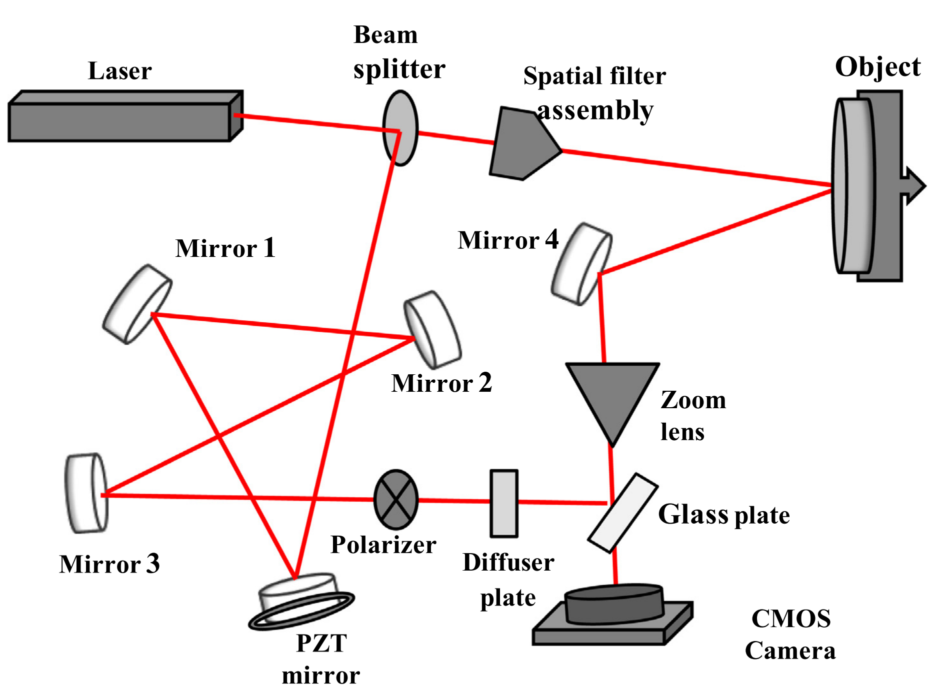

Fig. 1. Experimental setup of electronic speckle pattern interferometer.