Theoretical & Applied Mechanics Letters 6 (2016) 162–166

Contents lists available at ScienceDirect

Theoretical & Applied Mechanics Letters

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

Letter

Instantaneous phase-stepping interferometry based on a pixelated micro-polarizer array

Satoru Yoneyama *, Shuichi Arikawa

Department of Mechanical Engineering, Aoyama Gakuin University, 5-10-1 Fuchinobe, Sagamihara 252-5258, Japan

HIGHLIGHTS

- A camera equipped with micro-polarizer array is used in a polarization interferometer.
- Phase values of interference fringes can be obtained from a single image.
- This method can be applied to the measurement of time-varying phenomena.

ARTICLE INFO

Article history:
Received 12 November 2015
Received in revised form
22 March 2016
Accepted 14 May 2016
Available online 2 June 2016

Keywords:
Instantaneous phase-stepping method
Mach–Zehnder interferometry
Micro-polarizer array
Polarization
Fringe
Crack

ABSTRACT

In this paper, we propose an instantaneous phase-stepping method for determining phase distribution of interference fringes utilizing a camera that is equipped with a micro-polarizer array on the sensor plane. An optical setup of polarization interferometry using a Mach–Zehnder interferometer with two polarizers is constructed. Light emerging from the interferometer is recorded using a camera that has a micro-polarizer array. This micro-polarizer array has four different optical axes. That is, an image obtained by the camera contains four types of information corresponding to four different optical axes of the polarizer. The four images separated from the image recorded by the camera are reconstructed using gray level interpolation. Subsequently, the distributions of the Stokes parameters that represent the state of polarization are calculated from the four images. The phase distribution of the interference fringe pattern produced by the Mach–Zehnder interferometer is then obtained from these Stokes parameters. The effectiveness of the proposed method is demonstrated by measuring a static carrier pattern and time-variant fringe patterns. It is emphasized that this method is applicable to time-variant phenomena because multiple exposures are unnecessary for sufficient data acquisition in the completion of the phase analysis.

Several interferometric techniques, such as moiré, Twyman–Green, Mach–Zehnder, holographic and speckle pattern interferometries, have long been used for studying mechanical deformation of solids and the mechanics of fracture [1–4]. Several techniques exist for the analysis of fringe patterns obtained by these methods. Among them, phase-stepping (or phase-shifting) method is the most important and widely accepted techniques [5]. Phase-stepping interferometry is a simple and precise method for converting interferograms into phase maps. However, it is known that a temporal phase-stepping method has the disadvantage of a time lag during phase stepping and acquisition between phase steps.

Morimoto and co-workers [6–8] developed a high-speed temporal phase-shifting method for real-time measurement and applied it to analyses of time-varying Twyman–Green, moiré, and photoelastic fringes. Their method is applicable to slowly varying problems, but it is fundamentally difficult to analyze time-variant problems by their method because the multiple phase-stepped images cannot be obtained simultaneously. Another approach to real-time measurement or instantaneous recording of phase-stepped images is a spatial phase-stepping method. The spatial phase-stepping method generates simultaneous phase-stepped interferograms using polarization optics or diffraction grating [5]. Several researchers have developed an instantaneous spatial phase-stepping method that uses multiple cameras for the acquisition of phase-stepped interferograms [9–13]. Others have applied it to measurements of crystal growth [14] and supercritical flow [15]. The major drawback of this technique is the high complexity of the experimental setup, which requires perfect alignment and calibration of the pixels of multiple cameras. On the other hand, Novak et al. [16] proposed a method for recording

* Corresponding author.
E-mail address: yoneyama@me.aoyama.ac.jp (S. Yoneyama).

http://dx.doi.org/10.1016/j.taml.2016.05.004

multiple phase-stepped images using a camera with micro-polarizers. Similarly, one author [17,18] proposed instantaneous phase-stepping interferometry and photoelasticity using a camera equipped with a micro-retarder array. Furthermore, this technique has been used for evaluating the stress fields around a propagating crack tip in a glass plate under thermal load [19]. Recently, on the other hand, a high-speed camera that is equipped with a micro-polarizer array on the sensor plane is available [20–22]. Whereas this camera has been developed for the measurement of birefringence, it is considered that the instantaneous recording of phase-stepped interference fringes is possible using this camera, similar to the Novak's method [16].

In this paper we propose an instantaneous phase-stepping method for determining phase distribution of interference fringes utilizing a camera equipped with a micro-polarizer array on the sensor plane. An optical setup of polarization interferometry using a Mach–Zehnder interferometer with two polarizers is constructed to analyze the distribution of the thickness change of the transparent sample, i.e., the sum of principal stresses in the case of the plane stress state. Light emerging from the interferometer is recorded using a camera that has a micro-polarizer array on a sensor plane. This micro-polarizer array has four different optical axes. That is, an image obtained by the camera contains four types of information corresponding to four different optical axes of the polarizer. The four images separated from the image recorded by the camera are reconstructed using gray level interpolation. Subsequently, the distributions of the Stokes parameters that represent the state of polarization are obtained from the four images. The phase distribution of the interference fringe pattern produced by the Mach–Zehnder interferometer is then obtained from these Stokes parameters.

Figure 1 portrays the outline of the camera equipped with the micro-polarizer array on the sensor plane. As shown in this figure, many sets of four (2 × 2) micro-polarizers whose optical axes subtend four different angles, 0, $\pi/4$ rad, $\pi/2$ rad, $3\pi/4$ rad, form the large array the sensor. The size of a single micro-polarizer is equivalent to a single pixel of the sensor. The micro-polarizer position is aligned with the sensor. A single sensor detects the intensity of a light that passes through a single polarizer with a specific angle of the optical axis. Then, the four light intensity distributions corresponding to the four optical axes are obtained as a single image. Spatial resolution of each light intensity distribution is reduced to one-fourth of the CCD's resolution. In addition, the spatial positions of the four light intensity distributions do not mutually correspond. Therefore, light intensities other than the angle of the polarizer at the point are determined from light intensities at the neighboring points using interpolation such as bilinear or bicubic interpolation methods. Then, the four light intensity distributions whose respective sizes are equivalent to the original image are obtained by a single exposure. The four light intensity distributions are therefore phase-stepped images, similar to those obtained in other phase-stepping methods.

The interferometer used in this study is shown in Fig. 2. This interferometer consists of a Mach–Zehnder interferometer, two polarizers, and a quarter-wave plate. Light emitted from a point light source is collimated using a collimator lens. Then, a beam splitter divides the light. The light beam reflected by the beam splitter passes through a polarizer whose optical axis is vertical and a transparent specimen. Meanwhile, the light that passes through the beam splitter passes a polarizer whose optical axis is horizontal. In the case of an ordinary Mach–Zehnder interferometer, the two light beams interfere at the beam splitter. Then, the interference fringe pattern is observed. On the other hand, no interference fringe pattern is observed for the interferometer shown in Fig. 2 because polarization directions of the two light beams cross at the right angles. The Stokes vector of the light emerging from the beam splitter is expressed as follows

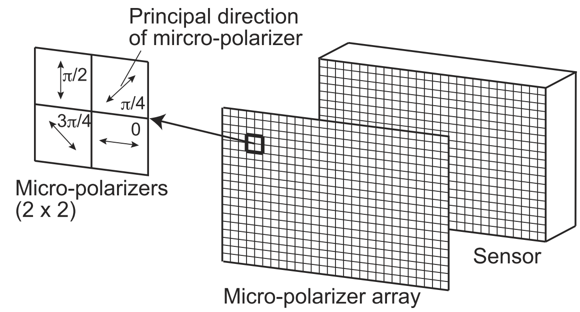

Fig. 1. Configuration of the micro-polarizer array on the sensor plane.

$$\boldsymbol{s} = \begin{Bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{Bmatrix} = \begin{Bmatrix} A_x^2 + A_y^2 \\ A_x^2 - A_y^2 \\ 2A_xA_y\cos\delta \\ 2A_xA_y\sin\delta \end{Bmatrix}. \tag{1}$$

Therein, s_0, s_1, s_2, and s_3 are the Stokes parameters, A_x and A_y are the amplitude components, δ represents the phase difference. The light beam passes through a quarter-wave plate and the polarizer attached on the sensor plane whose optical axis is θ. The Stokes vector of the light beam at the sensor plane is expressed as

$$\boldsymbol{s}' = \boldsymbol{P}_\theta \boldsymbol{Q}_{\pi/4} \boldsymbol{s}$$
$$= \begin{bmatrix} \frac{1}{2} & 0 & \cos\theta\sin\theta & -\frac{1}{2}\cos 2\theta \\ \frac{1}{2}\cos 2\theta & 0 & \frac{1}{4}\sin 4\theta & -\frac{1}{2}\cos^2 2\theta \\ \cos\theta\sin\theta & 0 & \cos^2\theta\sin^2\theta & -\frac{1}{4}\sin 4\theta \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{Bmatrix}. \tag{2}$$

Therefore, the four light intensities, I_0, I_1, I_2, and I_3, corresponding to the four different angles of the polarizers, $\theta = 0$, $\pi/4$ rad, $\pi/2$ rad, $3\pi/4$ rad are obtained as

$$\begin{Bmatrix} I_0 \\ I_1 \\ I_2 \\ I_3 \end{Bmatrix} = \begin{bmatrix} \frac{1}{2} & 0 & 0 & -\frac{1}{2} \\ \frac{1}{2} & 0 & \frac{1}{2} & 0 \\ \frac{1}{2} & 0 & 0 & \frac{1}{2} \\ \frac{1}{2} & 0 & -\frac{1}{2} & 0 \end{bmatrix} \begin{Bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{Bmatrix}. \tag{3}$$

Then, the Stokes parameters s_2 and s_3 of the light emerging from the interferometer are obtainable as

$$s_2 = I_1 - I_3, \quad s_3 = I_2 - I_0. \tag{4}$$

Therefore, the phase value of the interference fringe is obtained as follows

$$\tan\delta = \frac{s_3}{s_2}. \tag{5}$$

Using the above interferometer and the camera, the wrapped phase map is obtainable from an image obtained by a single exposure. A phase unwrapping procedure can be introduced to obtain the unwrapped phase map. Then, the sum of principal stresses is obtained for plane stress specimen as [23]

$$\sigma_1 + \sigma_2 = \frac{\delta f_s}{2\pi d}, \tag{6}$$

where σ_1 and σ_2 are the principal stresses, f_s is the material constant, and d expresses the thickness of the specimens. It is noted