Optics and Lasers in Engineering 52 (2014) 66–74

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Simultaneous in-and-out-of-plane displacement measurements using fringe projection and digital image correlation

Luis Felipe-Sesé [a,*], Philip Siegmann [b], Francisco A. Díaz [a], Eann A. Patterson [c]

[a] Departamemto de Ingeniería Mecánica y Minera, Campus las Lagunillas, Universidad de Jaén, 23071 Jaén, Spain
[b] Departamento de Teoría de la Señal y Comunicaciones, Universidad de Alcalá, 28871 Alcalá de Henares, Madrid, Spain
[c] School of Engineering, University of Liverpool, The Quadrangle, Brownlow Hill, Liverpool L69 3GH, UK

ARTICLE INFO

Article history:
Received 16 May 2013
Received in revised form
31 July 2013
Accepted 31 July 2013
Available online 25 August 2013

Keywords:
Fringe projection
Digital image correlation
Displacement analysis

ABSTRACT

The combination of fringe projection (FP) and two-dimensional digital image correlation (2D–DIC) has been proposed in previous work [1] as an alternative method to obtain displacement maps in the three spatial directions. However, if a telecentric lens is not employed in the experimental setup, the in-plane displacements obtained with 2D–DIC are influenced by the out-of-plane displacements occurring during deformation. Nevertheless, this error can be corrected if the out-of-plane displacements are known, for instance from measurements using the FP technique. In this paper a novel methodology based on the combination of FP and 2D–DIC is employed to perform the correction of the in-plane displacements, and is applied to several experimental examples. Results are compared and validated with those obtained using a commercial 3D–DIC system showing an average displacement error of 4% for *X*-displacements and 6.5% for *Y*-displacements.

1. Introduction

Mechanical testing using full-field optical techniques has been the focus of attention for many researchers during the last few decades. At present, the decrease in the price of digital cameras and the continuous improvement of image processing techniques have contributed to the development of more computationally and cost efficient experimental techniques [2]. One of these techniques is Digital Image Correlation (DIC). DIC makes it possible to obtain displacement maps at the surface of a deformed object by tracking the displacement of groups of pixels from a sequence of images acquired during deformation. [3–6]. If only one camera is employed, the DIC technique (known as 2D–DIC) allows the measurement of displacements on a plane perpendicular to the optical axis (in-plane displacements). When two cameras are employed, the DIC technique (known as 3D–DIC) enables the measurement of displacements experienced by the object in the three spatial directions. However, in this case a precise synchronization between the cameras is required as well as a calibration procedure. The calibration procedure consists of acquiring a large number of images of a calibration object to compute the intrinsic and extrinsic parameters required to perform a stereo reconstruction.

Fringe Projection (FP) is an alternative full-field optical technique that can be used to determine displacements in the direction of the camera optical axis (i.e. out-of-plane displacements) for a deformed object. This technique has been widely used for establishing the shape of objects, for metrology and other mechanical applications [6–11].

The combination of both 2D–DIC and FP techniques seems to provide a low-cost alternative to 3D–DIC for measuring in- and out-of-plane displacements maps with only one CCD camera and a fringe projector.

This approach has been adopted in several previous studies [1,12–19]; however, as highlighted by [1], if a telecentric lens is not employed, the combination of both techniques is not a straightforward task, since the 2D–DIC results are sensitive to the out-of-plane displacements experienced by a non-planar object during deformation [15]. Thus, in-plane displacements measured using 2D–DIC should be corrected using the out-of-plane displacements inferred using FP technique.

Barrientos et al. [12] combined these two techniques to measure the evolution of the surface displacements on a model of the Earth's crust. In this case, the model was deformed relatively slowly, so that the fringe images and speckle images corresponding to same level of deformation could be acquired separately. Images were captured with a time interval of 1 s, making the technique invalid for high deformation rates. Tay et al. [13] and Quan et al. [16] measured the in-plane 3D rigid body displacement of a coin and the 3D deformation of a cantilever beam respectively, using a single image with fringes and speckle superimposed. They were able to separate fringes and speckle by filtering the fringe frequency with the aid of the Fourier transform. However, fringe–speckle separation using Fourier transform may not

* Corresponding author. Tel.: +34 953 2123 53.
E-mail address: lfelipe@ujaen.es (L. Felipe-Sesé)

0143-8166/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.optlaseng.2013.07.025

be possible for large object displacements for which low carrier frequencies have to be used since for successful fringe–speckle separation the carrier frequency of the projected fringes has to be larger than the maximum signal frequency. Recently, Shi et al. [14] implemented a new method to extract the texture of the specimen surface from the phase shifted images captured to perform the fringe projection. Then, the texture information was used to perform 2D–DIC. An alternative method for fringe and speckle separation is to employ a color camera for image acquisition. This idea was implemented by Mares et al. [1] and Siegmann et al. [17]. They employed a CCD color camera to separate fringes and speckle using red and blue channels on a single RGB image. This methodology was inspired by previous work conducted by Weber et al. [18] who implemented 2D–DIC and FP using two different colors for the projected fringes and speckle pattern, namely red for speckle and blue for fringes. To apply both techniques simultaneously, they used a color encoding technique in which a red and a blue filter were placed in front of two black and white cameras to separate the fringe and speckle information, so that in-plane and the out-of-plane displacements on the same object surface could be obtained. However, in this case the influence of the out-of-plane displacements on the in-plane displacements measured using 2D–DIC was not considered and consequently no correction of the in-plane displacements was performed. In the more recent investigations, Nguyen et al. [19,20] digitized the specimen shape using the fringe projection technique to identify the location along the camera axis of planes in the specimen surface before applying and attempting to measure any deformation. Subsequently, they used the 2D –DIC technique to obtain the in-plane displacements during deformation at the different planes previously detected using fringe projection technique. Thus, the error in the in-plane displacements resulting from the change in the distance from the specimen to the plane of the CCD was eliminated. Although, this method made it possible to employ 2D–DIC to measure in-plane displacements on a non-planar object, one major limitation of the method was that the measurement planes had to be parallel to each other and parallel to CCD plane. Thus, the proposed methodology could not be directly used to infer in-plane displacements on curved objects.

In the present paper the color encoding technique proposed by Siegmann et al. [17] is developed to combine 2D–DIC and FP techniques using a single color CCD camera. The combination of both techniques will be employed to measure simultaneously in-plane and out-displacements on various non-planar objects subject to deformation. A novel calibration procedure is introduced to correct for the influence of the out-of plane displacements on the in-plane displacement. The results will be compared with those obtained using 3D–DIC to illustrate the potential and accuracy of the proposed method.

2. Color encoded combined FP and 2D–DIC technique

Fig. 1 illustrates the optical arrangement for both FP and 2D–DIC techniques. The camera optical axis must be perpendicular

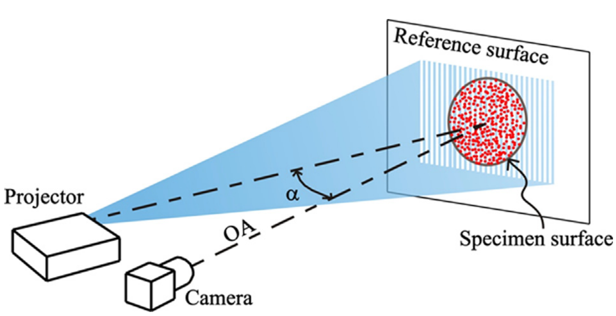

Fig. 1. Scheme of the experimental setup.

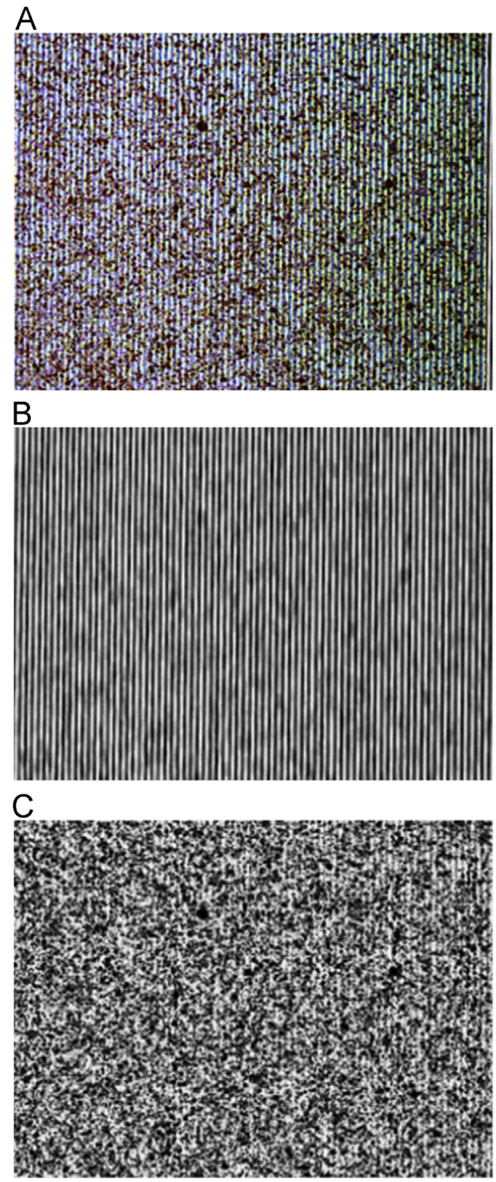

Fig. 2. Examples of filtered speckle and fringe patterns (a) RGB-image, (b) R-image, and (c) B-image.

to a reference surface in which the in-plane displacements (x- and y-displacements) are measured and from which the out-of-plane displacements (z-displacements) are evaluated.

For the 2D–DIC technique, the specimen surface was prepared by painting on it a random red speckle pattern. In the case of the FP technique, blue straight fringes were projected with a non-zero incidence angle (α) relative to the optical axis (OA) of the camera. Thus, when the surface is deformed, the 2D–DIC is employed to compute the speckle displacements while FP is used to quantify the deviation of the fringes from their initial straight condition. Therefore, the patterns have to be separated in order to employ both techniques independently.

2.1. Color encoding of the fringe and the speckle information

The technique proposed by Siegmann et al. [17] was used to separate the patterns by employing a color camera as a Bayer filter [21], as shown in Fig. 2, such that the red channel provides the fringe pattern (Fig. 2(b)), while the blue channel gives the speckle