Optics and Lasers in Engineering 73 (2015) 22–32

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Some practical considerations in finite element-based digital image correlation

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ARTICLE INFO

Article history:
Received 20 December 2014
Received in revised form
12 March 2015
Accepted 12 March 2015
Available online 20 April 2015

Keywords:
Digital image correlation
Finite element
Displacement measurement

ABSTRACT

As an alternative to subset-based digital image correlation (DIC), finite element-based (FE-based) DIC method has gained increasing attention in the experimental mechanics community. However, the literature survey reveals that some important issues have not been well addressed in the published literatures. This work therefore aims to point out a few important considerations in the practical algorithm implementation of the FE-based DIC method, along with simple but effective solutions that can effectively tackle these issues. First, to better accommodate the possible intensity variations of the deformed images practically occurred in real experiments, a robust zero-mean normalized sum of squared difference criterion, instead of the commonly used sum of squared difference criterion, is introduced to quantify the similarity between reference and deformed elements in FE-based DIC. Second, to reduce the bias error induced by image noise and imperfect intensity interpolation, low-pass filtering of the speckle images with a 5×5 pixels Gaussian filter prior to correlation analysis, is presented. Third, to ensure the iterative calculation of FE-based DIC converges correctly and rapidly, an efficient subset-based DIC method, instead of simple integer-pixel displacement searching, is used to provide accurate initial guess of deformation for each calculation point. Also, the effects of various convergence criteria on the efficiency and accuracy of FE-based DIC are carefully examined, and a proper convergence criterion is recommended. The efficacy of these solutions is verified by numerical and real experiments. The results reveal that the improved FE-based DIC offers evident advantages over existing FE-based DIC method in terms of accuracy and efficiency.

1. Introduction

Digital image correlation (DIC) [1–3] is an easy-to-use but versatile optical technique for full-field displacement and strain measurements. It is no longer necessary to emphasize the importance of DIC techniques here, as its capabilities and merits have been well demonstrated in numerous works for diverse applications [4,5]. As a typical non-interferometric optical metrology based on digital image processing, the implementation of DIC requires an image matching (or tracking) algorithm to register the same physical points recorded in two different images, which has been considered as a key to achieving high-accuracy deformation measurement.

In the past three decades, various image matching algorithms have been developed in DIC, among which the most widely used two algorithms are subset-based DIC [6,7] and finite element-based (FE-based) DIC [8–10]. The subset-based DIC processes calculation points one by one to determine their deformation parameters. For each measurement point, it first selects a reference subset centered at the point, and aims to find its target counterpart with maximum similarity in the deformed image. Towards this end, a robust correlation criterion [11,12], combined with a proper displacement mapping function [13,14] that depicts the position and shape of the target subset, should be pre-defined as an objective function to quantify the similarity degree between these two subsets. Then, the correlation criterion is optimized using an iterative optimization algorithm [15–18] to determine the desired displacements and displacement gradients of the considered point. The same procedure can be automatically extended to other points of interest to obtain full-field displacements using the robust reliability-guided displacement-tracking scheme [19]. Due to its advantages of simple principle, easy programming, high efficiency and high accuracy, subset-based DIC has been popularly used in most academic research and almost all commercial DIC packages [20–23]. However, in subset-based DIC, each subset is tracked separately and does not influence the others, and there is no requirement of inter-subset continuity enforced during correlation process, which has been considered as the main deficiency of subset-based DIC.

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http://dx.doi.org/10.1016/j.optlaseng.2015.03.010
0143-8166/

By considering the deformation continuity of solid materials, a finite element framework [8] has been introduced into DIC for the determination of full-field image displacements. Different from subset-based DIC approach, the entire region of interest (ROI) is first discreticized into finite elements linked by nodes. Then a correlation function is defined for evaluating the similarity between all the elements in the reference image and the corresponding target elements in the deformed image. Next, the displacements of all nodes are computed simultaneously by minimizing the pre-defined correlation function using a non-linear optimization algorithm. Since a four-node FE-based DIC (Q4-DIC) [8] first proposed by Sun et al. [8], FE-based DIC method has attained increasing attention and refined continuously by various researchers [10,24,25] by adopting various types of elements, introducing different basis functions or utilizing high-order shape functions. As a consequence, B-spline-based DIC [26], NURBS-DIC [27] and XFEM-DIC [28,29] have been developed. Nevertheless, one common feature in these DIC approaches is that the displacements of all nodes are obtained at one time, thus displacement continuity between adjacent elements is explicitly imposed, which has been deemed as an advantage of FE-based DIC over subset-based DIC.

Despite that FE-based DIC approach has been continuously refined and successfully used by a number of investigators, the literature survey conducted by the authors reveals that some important issues have not been well addressed in published works. Accordingly, this work aims to point out a few important considerations in the practical algorithm implementation of the FE-based DIC method, along with simple but effective solutions that can effectively tackle these issues. Specifically, three improvements inspired by the advances in subset-based DIC have been made. First, to better accommodate the possible intensity variations of the deformed images practically occurred in real experiment, a robust zero-mean normalized sum of squared difference (ZNSSD) criterion, instead of the commonly used sum of squared difference (SSD) criterion, is introduced to evaluate the similarity between reference and deformed elements. Second, to effective reduce the bias error due to imperfect interpolator and image noise, smoothing using a 5×5 pixels Gaussian filter is applied to all the images prior to correlation analysis as suggested in [30]. Finally, to ensure that the iterative procedure of the FE-based DIC method converges correctly and rapidly, an efficient subset-based DIC method [18], instead of simple integer-pixel displacement searching, is used to provide accurate initial guess of deformation for each node. Besides, the effects of various convergence criteria on the efficiency and accuracy of FE-based DIC are carefully examined, and a proper convergence criterion is recommended. With the proposed considerations and solutions, the accuracy, robustness and efficiency of the FE-based DIC can be substantially improved, which is demonstrated by processing real experimental images.

2. Basic principles of finite element-based DIC

In FE-based DIC, the ROI specified in the reference image is first discretized into finite elements linked by nodes as schematically illustrated in Fig. 1, which ensures the displacement continuity among adjacent elements. Assume that the ROI is discretized into M quadrilateral elements that are connected by N nodes (Note that the number of nodes defined for each element depends on the particular shape function used). The aim of FE-based DIC is to determine the entire nodal displacement vectors $\mathbf{p}$ containing $2N$ displacement components (each node has two displacement components, u and v) at a time by maximizing the grayscale similarity (or equivalently minimizing the grayscale difference) between all the elements in the reference image and the corresponding target elements in the deformed image.

Just like the subset-based DIC approach, a correlation criterion must be defined first to quantify the similarity or difference between these elements. It is found, in almost of all the existing works regarding FE-based DIC, that a simple SSD criterion was widely used. Thus, the overall correlation criterion is written as

$$C_{SSD,\Omega}(\mathbf{p}_{\Omega}) = \sum_{m=1}^{M} C_{SSD,\Omega_m} = \sum_{m=1}^{M} \sum_{\Omega_m} [f(\mathbf{x}) - g(\mathbf{x} + \mathbf{u}(\mathbf{x}, \mathbf{p}_{\Omega_m}))]^2 \quad (1)$$

where Ω represents the whole ROI of the speckle image, and it contains M elements and N nodes; Ω_m denotes all the pixels within the mth element; $\mathbf{p}_{\Omega_m}$ is the displacement vector of the mth element; $\mathbf{p}_{\Omega}$ is the global displacement vector containing $2N$ displacement components to be determined. According to the finite element theory, the displacement components of each pixel located in an element, e.g., the mth element, can be approximated using shape function

$$u_{\Omega_m}(\mathbf{x}, \mathbf{p}_{\Omega_m}) = \sum_{i=1}^{K} N_i(\mathbf{x}) u_{mi} = \sum_{i=1}^{K} N_i(\xi, \eta) u_{mi}$$
$$v_{\Omega_m}(\mathbf{x}, \mathbf{p}_{\Omega_m}) = \sum_{i=1}^{K} N_i(\mathbf{x}) v_{mi} = \sum_{i=1}^{K} N_i(\xi, \eta) v_{mi} \quad (2)$$

where $\xi \in [-1,1]$ and $\eta \in [-1,1]$ are the local coordinates of the element; u_{mi} and v_{mi} are the x- and y-directional displacement components of the ith node in the mth element. N_i is the related shape function of the ith node, and K is the total number of the nodes in a single element. According to the number of nodes defined for

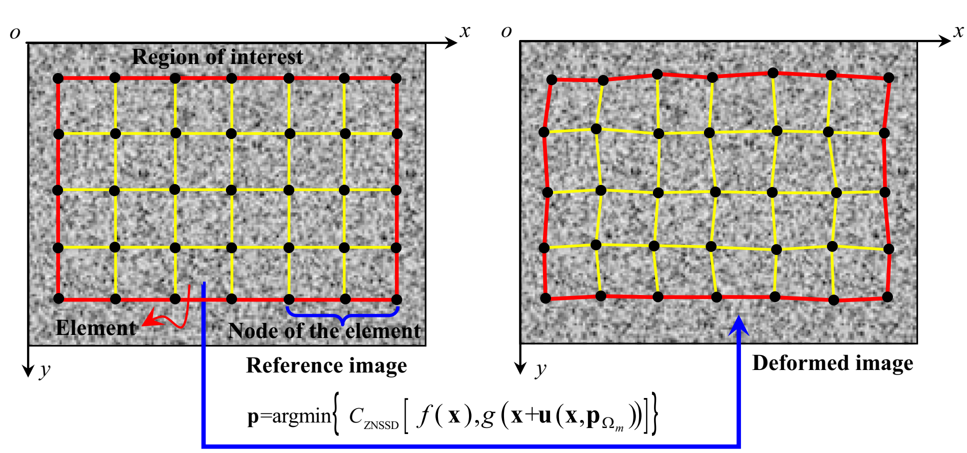

Fig. 1. Schematic showing the principle of FE-based global DIC approach.