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Review

Subset-based local vs. finite element-based global digital image correlation: A comparison study

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HIGHLIGHTS

- Performance evaluation of subset-based local and finite element (FE)-based global digital image correlation (DIC) is performed.
- Theoretical analyses of the standard deviation errors of the two DIC approaches are given.
- The performances of local DIC and global DIC approaches are compared with numerical tests and real experiments.
- The results revealed that subset-based local DIC outperforms global DIC when subset (element) size is larger than 11 pixels.

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ABSTRACT

Being the two primary approaches for full-field kinematics measurements, both subset-based local digital image correlation (DIC) and finite element-based global DIC have been extensively studied. Nowadays, most commercial DIC systems employ local DIC algorithm because of its advantages of straight forward principle and higher efficiency. However, several researchers argue that global DIC can provide better displacement results due to the displacement continuity constraint among adjacent elements. As such, thoroughly examining the performance of these two different DIC methods seems to be highly necessary. Here, the random errors associated with local DIC and two global DIC methods are theoretically analyzed at first. Subsequently, based on the same algorithmic details and parameters during analyses of numerical and real experiments, the performance of the different DIC approaches is fairly compared. Theoretical and experimental results reveal that local DIC outperforms its global counterpart in terms of both displacement results and computational efficiency when element (subset) size is no less than 11 pixels.

Contents

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1. Introduction

Benefiting from rapid development of industrial camera, modern computer, and image processing technique, digital image correlation (DIC) [1–3], initially emerged in 1980s, has kept booming during last three decades due to its simplicity, practicality, and wide application range. In DIC analysis, image displacements (in pixels) are first determined by matching digital images of flat surface (2D-DIC) or curved surface (stereo-DIC) using certain image registration algorithm. Then, the physical displacement can be further evaluated according to certain imaging model. Since strain estimation and identification of material parameters are generally performed on the basis of displacement fields, accurate displacement measurement is always a major focus in DIC algorithm.

Although plenty of DIC algorithms have been developed, subset-based DIC (local DIC) [4–21] and finite element-based DIC (FE-based global DIC) [22–35] are the two most commonly used ones. Local DIC allocates separate reference subset centered at each calculation point at first, then traces the corresponding deformed subset in target images using a local shape function. As such, local DIC processes a calculation point at a time independently without displacement continuity enforcement applied to the global displacement fields. Alternatively, global DIC usually discretizes the specified region of interest (ROI) into elements connected by nodes, and then traces all these elements in the target image simultaneously to evaluate all the nodal displacements. In this sense, displacement continuity can be explicitly ensured between adjacent elements by the shared nodes.

In retrospect of the historical development of DIC technique, it is seen that subset-based local DIC emerged first and has been widely applied. Initially proposed to realize full-field displacement measurement in 1982 [1], local DIC can only reach integer-pixel accuracy. Motivated by improving both accuracy and efficiency, various local optimization algorithms, such as gradient-based method [4,5], correlation coefficient curve-fitting method [6,7], Newton–Raphson (NR) algorithm [8–10], and quasi-Newton algorithm [11,12], were successively developed during the following 20 years. To unify the disagreement on algorithm selection, Pan et al. [13] experimentally demonstrated that NR algorithm outperforms other methods in terms of displacement accuracy and precision, which makes it become the standard DIC algorithm. Subsequently, to further satisfy the accuracy and efficiency requirement in diverse time-critical applications, researchers gradually focus on algorithm details and parameter selection, such as shape function [14,15], correlation criterion [16,17], interpolation scheme [18,19], and subset size [20]. Recently, inspired by the inverse compositional matching algorithm widely adopted in computer vision, Pan et al. [21] proposed the inverse compositional Gauss–Newton (IC-GN) algorithm, which offers higher accuracy and efficiency than classic NR algorithm, and is highly recommended as a new standard algorithm.

At the beginning of the 21st century, in the meantime of rapid development of local DIC method, several researchers attempted to combine DIC with the finite element method (FEM). Bspline-based [22], four-node FE-based [23,24], and eight-node FE-based global DIC approaches [25] were successively proposed to ensure global continuity of displacement field. To allow more complex cases during the analysis of fracture, bending and discrete geometry, various algorithm improvements, such as extended DIC (X-DIC) [26,27], non-uniform rational B-spline (NURBS) [28], quasi-3D FE-DIC [29], and single-element X-DIC [30], were put forward. However, the inherent drawback of global DIC is the compromise between spatial resolution and displacement uncertainty. Specifically, higher spatial resolution requires denser mesh, resulting in larger displacement fluctuation (i.e., displacement uncertainty or random error). As such, to enhance displacement precision in the case of high spatial resolution, a series of regularization strategies, such as temporal regularity [31], Tikhonov regularization [32], and proper generalized decomposition [33], were applied to global DIC. Alternatively, to balance the tradeoff between spatial resolution and displacement uncertainty, p-adaptive global DIC [34] and h-adaptive global DIC [35] were developed by adaptively selecting higher-order element and refining element, respectively.

Due to its outstanding advantages such as easy implementation, high accuracy, and high efficiency, local DIC has been applied in most commercial systems and practical applications up to now. Nevertheless, recent works [36] claim that global DIC may lead to better displacement results due to the displacement continuity constrain, thus posing an important issue of evaluating and comparing the performance of local and global DIC algorithms. Therefore, a detailed examination of their respective performances becomes attractive and pressing. Here, we summarize our recent research results on the performance evaluation of local and global DIC. In the following, the fundamental principles of local and global DIC are first briefly reviewed to ensure fair comparison. Then, the governing formulas of random errors associated with local DIC and two global DIC algorithms are derived. Finally, by using both numerical and real experiments, the measurement errors and computational efficiency of local DIC, four-node FE-based DIC (Q4-DIC), and eight-node FE-based DIC (Q8-DIC) are thoroughly compared. Experimental results demonstrate that local DIC outperforms global DIC in the case of relatively large element (subset) size and matched (or overmatched) shape function.

2. Basic principles and algorithmic details

To make the performance comparison fair enough, the same algorithm details including correlation criteria, subpixel registration algorithm, interpolation scheme, initial guess, and convergence condition employed in local and global DIC should be carefully defined. Though the basic principles of the two DIC techniques have been fully characterized in the literature [8–10, 23–25], the algorithm details in the two DIC approaches are briefly reviewed for clarity.

2.1. Basic principles

Both local and global DIC employ certain matching algorithm to obtain initial displacement with integer-pixel accuracy, and then adopt specific subpixel registration algorithm (such as, nonlinear optimization algorithm or curve fitting algorithm) to further improve displacement accuracy. As illustrated in Fig. 1, however, the