Advances in Engineering Software 116 (2018) 80–88

Contents lists available at ScienceDirect

Advances in Engineering Software

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

Incremental digital volume correlation method with nearest subvolume offset: An accurate and simple approach for large deformation measurement

Wang Bo, Pan Bing*

Institute of Solid Mechanics, Beihang University, Beijing 100191 China

ARTICLE INFO

Keywords:
Digital volume correlation
Large deformation
Nearest subvolume offset

ABSTRACT

Digital volume correlation (DVC) has been widely accepted as an effective experimental technique for quantifying full-field internal 3D deformation of solid materials and structures under external loading. However, conventional DVC using a fixed reference volume image generally fails when serious decorrelation occurs in deformed volume images due to large deformation or other reasons. In this work, an accurate and simple incremental DVC method with nearest subvolume offset is proposed for large deformation measurement. Specifically, the reference subvolumes in the updated reference volume images are translated to nearest integer-voxel positions, rather than being interpolated at subvoxel locations. The translated reference subvolumes, within which all correlation points locate at integer-voxel positions, are then tracked in the rest deformed volume images to retrieve incremental displacement fields. The obtained incremental displacement fields are then accumulated to previously obtained displacement fields to determine the overall displacements. By using the simple nearest subvolume offset approach, subvoxel intensity interpolation for the updated reference subvolumes is entirely avoided, thus not only eliminating the bias error associated with imperfect subvoxel intensity interpolation, but also increasing the computational efficiency of incremental DVC calculation by approximately 2.5 times. The accuracy, efficiency and practicality of the presented incremental DVC are demonstrated by analyzing two sets of volume images with large deformation generated in numerically simulated and real-world experiments.

1. Introduction

Digital volume correlation (DVC) was expanded from the well-established two-dimensional digital image correlation technique [1,2] by Bay et al. in 1999 [3]. It has been widely accepted as a useful tool for retrieving true 3D internal deformation of solid materials under external loading [4-6]. During the last two decades, plentiful research efforts have been dedicated to improving the accuracy and efficiency of DVC technique by developing approaches that can minimize CT artifacts [7-10], introducing advanced subvoxel registration algorithms [11-13] and optimizing correlation calculation parameters [14]. With the aid of advanced volumetric imaging facilities (e.g., X-ray micro-/nano-CT, synchrotron radiation micro-CT), DVC-measured kinematics fields can not only benefit for better understanding the relationship between material microstructure and macroscale mechanical behavior under external loading [15], but also contribute to cross-validation of 3D finite element modeling and simulation [16-17].

When using DVC, a reference volume image is specified first, and then the deformed volume images recorded at different states are compared with the reference counterpart to extract the encoded deformation. Conventional DVC approaches generally specify a fixed reference volume image, which can ensure high-accuracy measurement in most cases, but are not generally applicable. Particularly, when test samples with low stiffness (e.g., soft materials, biological tissues, polymeric materials) undergo large non-uniform deformation [18-22], serious image decorrelation effect may occur to the deformed volume images. The local decorrelation effect generally causes a failure of DVC analysis that cannot be well remedied by even the most robust subvoxel registration algorithm.

To realize large deformation measurement, incremental DVC analysis using intermediate volume images as updated reference volume images has been introduced to track incremental displacements between consecutive volume images [19-22]. As schematically shown in Fig. 1, the computed incremental displacement vector (i.e., $\mathbf{p}_{12}$) at a measurement point is accumulated to its previously obtained displacement vectors (i.e., $\mathbf{p}_{01}$) to determine the overall displacements (i.e., $\mathbf{p}_{02}$). However, in the updated reference volume images, reference subvolumes generally are centered at subvoxel positions. To reconstruct

* Corresponding author.
E-mail address: panb@buaa.edu.cn (B. Pan).

https://doi.org/10.1016/j.advengsoft.2017.12.004
Received 23 September 2017; Received in revised form 20 November 2017; Accepted 11 December 2017
Available online 19 December 2017
0965-9978/ © 2017 Elsevier Ltd. All rights reserved.

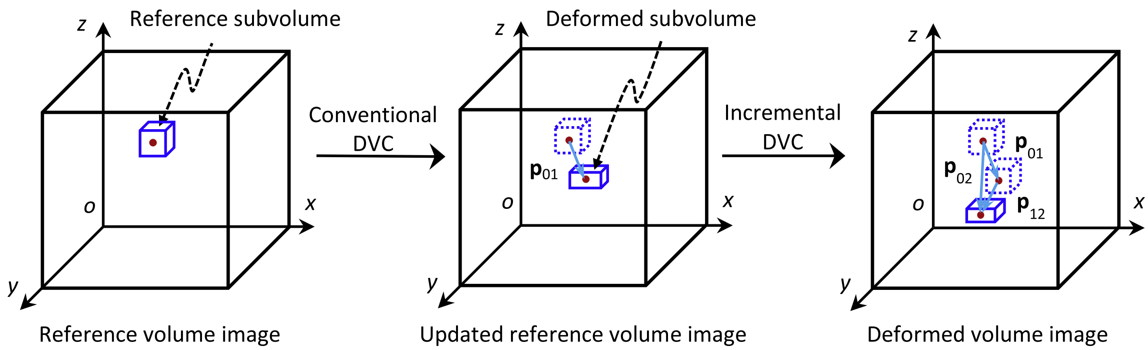

Fig. 1. Schematic of incremental DVC analysis for large deformation measurement.

the intensities of the subvoxel correlation points within the renewed reference subvolumes, tricubic polynomial interpolation or tricubic B-spline interpolation is therefore required. However, as demonstrated by various studies [23-26], subvoxel intensity interpolation is not only computational intensive, but also cause considerable bias error in DVC measurement. For this reason, a more simple, accurate and efficient incremental DVC free of subvoxel interpolation of renewed reference subvolumes is highly desirable.

In this work, an accurate and simple incremental DVC method, which adopts an easy-to-implement but effective nearest subvolume offset approach, is proposed for large deformation measurement. In the proposed incremental DVC, the calculation points within the renewed reference volume images are automatically translated to their nearest integer-voxel locations. Afterwards, these translated reference subvolumes with all correlation points locating at integer-voxel positions, are tracked in the deformed volume images using an advanced 3D inverse-compositional Newton-Gauss (IC-GN) algorithm [13,27]. After retrieving incremental displacement fields, the calculated displacements are transferred to the actual subvoxel position of each updated calculation point to estimate its incremental displacements. By this means, intensive computation and systematic errors due to intensity interpolation of updated reference subvolumes are eliminated, leading to more accurate, efficient and simple incremental DVC analysis. To verify the accuracy and efficiency of the proposed incremental DVC method, both numerically simulated and experimentally recorded volume images subjected to large deformation were processed. The results demonstrate the efficacy and practicality of the proposed incremental DVC approach in practical applications.

2. Incremental digital volume correlation with nearest subvolume offset

2.1. Digital volume correlation

By comparing two volume images recorded in different loading stages, DVC can retrieve 3D internal displacement and strain fields of the test specimen. As shown in Fig. 2, routine DVC analysis generally specifies the initially captured volume image as a reference, and defines a series of discrete calculation points within the volume of interest (VOI) first. Afterwards, the 3D coordinates of these calculation points are tracked in the deformed volume image sequences using certain subvoxel registration algorithm to extract the encoded full-field displacements. By differentiating the obtained displacement fields with proper numerical differentiation algorithm (e.g., 3D pointwise least square algorithm [12]), 3D full-field strain maps can be estimated.

To realize accurate and efficient full-field internal displacement tracking, a flexible and accurate DVC method, which combines the advanced 3D IC-GN algorithm [13] with layer-wise reliability-guided displacement tracking (LW-RGDT) scheme [27], is adopted in this work. For each measurement point, the 3D IC-GN algorithm aims to optimize the robust zero-mean normalized sum of squared difference (ZNSSD) criterion defined below to determine displacement components with subvoxel accuracy.

$$C_{ZNSSD}(\Delta\mathbf{p}) = \sum_{\xi}\left\{\frac{[f(\mathbf{x}+\mathbf{W}(\xi;\Delta\mathbf{p}))-f_m]}{\sqrt{\sum_{\xi}[f(\mathbf{x}+\mathbf{W}(\xi;\Delta\mathbf{p}))-f_m]^2}}-\frac{[g(\mathbf{x}+\mathbf{W}(\xi;\mathbf{p}))-g_m]}{\sqrt{\sum_{\xi}[g(\mathbf{x}+\mathbf{W}(\xi;\mathbf{p}))-g_m]^2}}\right\}^2 \tag{1}$$

where $f(\mathbf{x})$ and $g(\mathbf{x})$ denote the gray values at point $\mathbf{x} = (x, y, z)^T$ within the reference and deformed subvolumes, respectively. $\boldsymbol{\xi} = (\Delta x, \Delta y, \Delta z)^T$ is the local coordinates of each integer-voxel point in the cubic reference subvolume with a size of $N \times N \times N$ voxels. f_m and g_m represent the average gray level of reference and deformed subvolumes; $\mathbf{W}(\boldsymbol{\xi}; \mathbf{p})$ is the warp function used to approximate the encoded deformation of the target subvolume with $\mathbf{p}$ representing the linear deformation vector; $\mathbf{W}(\boldsymbol{\xi}; \Delta\mathbf{p})$ the incremental warp function exerted on the reference subvolume with $\Delta\mathbf{p}$ denoting the corresponding incremental deformation vector.

A flowchart of the 3D IC-GN algorithm is schematically shown in Fig. 3. To solve the incremental deformation vector $\Delta\mathbf{p}$, Gauss-Newton algorithm is first employed to optimize the defined ZNSSD function. Then the incremental warp $\mathbf{W}(\xi; \Delta\mathbf{p})$ of the reference subvolume can be estimated, which is further inverted and composed with the current estimate $\mathbf{W}(\boldsymbol{\xi}; \mathbf{p})$ to determine the updated warp function of the target subvolume. The iterative calculation of incremental deformation vector $\Delta\mathbf{p}$ is repeated until the preset convergence conditions are reached. Finally, the deformation parameter $\mathbf{p}$ of the target subvolume can be extracted from the final estimate $\mathbf{W}(\boldsymbol{\xi}; \mathbf{p})$ [28,29].

The 3D IC-GN algorithm can be further combined with the recently proposed LW-RGDT scheme [27] to realize full-field displacement tracking from slice to slice. In the practical implementation of LW-RGDT strategy, a seed point specified in the top or bottom layer of the VOI is first analyzed by the 3D IC-GN algorithm. Then, all the calculation points within current layer are calculated in parallel by using 3D IC-GN algorithm along the most reliable calculation path guided by the intra-layer RGDT strategy. By use of the inter-layer initial guess transfer (IGT) strategy, the most reliable deformation vector is transferred between adjacent calculation layers. In this manner, the LW-RGDT scheme is repeated from layer to layer until all the calculation points within the VOI are processed. Interested reader can find more details regarding the state-of-the-art DVC algorithm in [13,27].

2.2. Incremental digital volume correlation

As described above, when severe decorrelation effect occurs to the deformed volume image undergoing large deformation/rotation, routine DVC analysis using a fixed reference volume image cannot yield reliable displacement measurement or even fails. To address this challenge, incremental DVC analysis can be performed by updating the

Download English Version:

https://daneshyari.com/en/article/6961408

Download Persian Version:

https://daneshyari.com/article/6961408

Daneshyari.com