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Spatial-temporal subset based digital image correlation considering the temporal continuity of deformation

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ABSTRACT

An improved digital image correlation (DIC) scheme termed spatial-temporal subset-based DIC (STS-DIC) that incorporates the temporal continuity of deformation is proposed. Provided that displacement at a certain physical point on a specimen in several successive frames is temporally continuous and can be expressed as a linear relationship over time, the STS-DIC scheme is constructed between the reference subset and spatial-temporal deformed subset consisting of several subsets from a period of successive frames. The proposed method is verified by simulated speckle images and experimental tests featuring different types of deformation. Compared to the traditional subset-based DIC, the STS-DIC proposed in this paper takes advantage of noise suppression so as to improve the accuracy, especially for speckle images with larger noise. More importantly, it is found that the computational demand of STS-DIC is much lower than that of mesh-based (global) DIC incorporating the temporal continuity, despite achieving comparable accuracy. Therefore, STS-DIC is expected to be useful as a practical and flexible tool in complex-environment measurements with low signal-to-noise-ratio speckle images.

1. Introduction

Digital image correlation (DIC) [1,2] has been widely used in various fields because of its ability to provide whole field deformation measurements and its convenience in terms of experimental preparation and data processing. To implement deformation measurement using DIC, the surface of the specimen is first marked with speckle patterns (natural texture or artificial random patterns). One speckle image captured before loading is taken as the reference image for DIC. Thereafter, the specimen is loaded and the speckle images, termed the deformed images, are captured during the loading process. Finally, the corresponding deformed images are "compared" individually with the reference image to obtain the deformation fields at different times.

Improving the measurement accuracy of DIC remains an open problem, and many studies have been reported in recent years. In addition to the errors from hardware [3] and from the experimental configurations [4,5], the errors from DIC algorithms have been systematically investigated, even various DIC schemes have been developed by introducing new mechanical mechanisms. For example, Sun et al. [6], Réthoré et al. [7] and Ma et al. [8], amongst others, incorporated spatial continuity of displacement into DIC and developed several mesh-based (global) DIC schemes to obtain improved accuracy when measuring heterogeneous deformation. Aside from spatial continuity, in most circumstances the displacement at a physical point of a specimen is also continuous along sequential time series. Currently, owing to cheap and convenient imaging equipment, *e.g.*, digital CCD or CMOS cameras, generally hundreds to thousands of speckle images can be captured during the loading procedure. Thus, the deformation extracted from an image series can be continuous even in a rapid process. However, temporal continuity of deformation is not generally considered in the traditional DIC scheme, such that the deformed images are generally analysed independently with respect to time. Actually, in most DIC analyses, only a very small percentage of the recorded images are analysed while most of the images are wasted. If the temporal continuity of displacement is introduced into the DIC scheme as an extra constraint, the accuracy of DIC would be expected to be improved and a larger number of recorded images would be utilised. Broggiato et al. [9] first introduced the temporal continuity of deformation in mesh-based DIC considering a restricted time change of the displacement within five consecutive speckle images. Besnard et al. [10] extended the ability to consider temporal continuity over the whole image series in DIC and then improved this technique to reduce the computational costs through splitting the entire 'volumetric' pixel series into multiple short series [11]. Practically, the DIC scheme

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proposed in [9–11] may suffer from great computational consumption because of its nature of mesh-based spatial representation. Indeed, comparing with mesh-based DIC, subset-DIC is slightly inferior in terms of accuracy however enables to greatly reduce computational consumption [8,12]. Furthermore, considering the fact that most DIC codes are subset-based, it makes more sense to develop a DIC scheme incorporating temporal continuity based on subset-DIC.

In this paper, a new scheme is proposed for subset-based DIC that considers the temporal continuity of deformation in a short time series. It is a modified version of the traditional subset-based DIC scheme by adding a simple assumption of temporal continuity to the model, such that termed spatial-temporal subset-based DIC (abbreviated as STS-DIC). In STS-DIC the deformation of the image subsets over several successive images is assumed to be linear with time and those subsets are 'combined' as one spatial-temporal subset. Then, the DIC model is constructed between the reference and spatial-temporal deformed subsets. The solution scheme for STS-DIC is very similar to the traditional subset-DIC, only incorporating two additional unknowns in the optimization to describe temporal continuity. To calculate deformation at any frame in an image series using STS-DIC, a sub-image series consisting of the target frame and m successive frames before and after the target image would be processed as a spatial-temporal target image and then compared with the reference image. The sub-image series consisting of $2m+1$ successive frames is then temporally slid. Therefore, the continuity over time can be guaranteed for the deformation results of the whole series. Because of the subset-based nature and the sectional processing methods, the time consumption of STS-DIC is expected to be largely reduced compared to the mesh-based DIC considering deformation continuity. This will be validated in the present paper.

In the present paper, STS-DIC model is constructed and the solving scheme is then developed in Section 2. The proposed method is verified using numerical simulation and experimental implementation considering simple and complex deformations in Section 3. In the last section, specific techniques for the method are extensively discussed.

2. Principle of STS-DIC

In traditional subset-based DIC, the reference speckle image is first divided into a number of subsets [1,2,13] (shown in Fig. 1a), each subset is tracked in the deformed image using the correlation matching algorithm, and the deformation of the subset is determined. Let f represent the processing subset on the reference images series and $g_t (t = t_1, t_2, \ldots, t_n)$ represent the subset on deformed images captured at time t. According to the constant intensity assumption, there exists an equation for each of the subset pairs, f and g_t as,

$$f(\mathbf{X}) = g_t(\mathbf{X} + \mathbf{U}(\mathbf{X}, t)) \qquad t = t_1, t_2, \ldots, t_n \tag{1}$$

where $\mathbf{X}$ is the coordinate of the pixels and $\mathbf{U}(\mathbf{X}, t)$ is the displacement of subset g_t referring to subset f, which can be expressed as (shown in Fig. 1b),

$$\mathbf{U}(\mathbf{X}, t; \mathbf{a})|_{t=t_i} = \begin{bmatrix} u \\ v \end{bmatrix}\Bigg|_{\substack{t=t_i \\ \mathbf{X}=\mathbf{X}_c}} + \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{bmatrix}\Bigg|_{\substack{t=t_i \\ \mathbf{X}=\mathbf{X}_c}} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = \mathbf{a}\begin{bmatrix} 1 \\ \Delta x \\ \Delta y \end{bmatrix} \tag{2}$$

where $\mathbf{X}_c$, coordinated at $(x_0\ y_0)$, is the centre point (point P) of the subset, x and y are the horizontal and vertical components of coordinate $\mathbf{X}$, u and v are the horizontal and vertical components of displacement $\mathbf{U}(\mathbf{X},t)\ |_{t=t_i}$, and Δx and Δy are the coordinate differences between the representative point Q and point P (see Fig. 1b). Additionally,

$$\mathbf{a} = \begin{bmatrix} u & \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ v & \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{bmatrix}\Bigg|_{\substack{t=t_i \\ \mathbf{X}=\mathbf{X}_c}} \tag{3}$$

is the unknown matrix to be solved.

In practice, the number of pixels in the subset (*e.g.*, 21×21) is much larger than the number of unknowns in the matrix $\mathbf{a}$. Thus, Eq. (1) is over-determined and can be solved using an optimization method as,

$$\min_{\mathbf{a}} C(f(\mathbf{X}), g_t(\mathbf{X} + \mathbf{U}(\mathbf{X}, t; \mathbf{a}))) \tag{4}$$

where C is the objective function, generally termed the correlation coefficient in DIC.

In this work, the image series is considered. If the $2m+1$ (m=1, 2, 3, ...) deformed subsets on the speckle images series captured between $[t_{i-m}\ t_{i+m}]$ are averaged, Eq. (1) becomes,

$$f(\mathbf{X}) = \frac{1}{2m+1}\int_{t_{i-m}}^{t_{i+m}} g_t(\mathbf{X} + \mathbf{U}(\mathbf{X}, t)\ )\, dt \tag{5}$$

The right-hand item of Eq. (5) can be regarded as a new spatial-temporal subset and denoted as,

$$\overline{\mathrm{G}_i^{(m)}(\mathbf{X}{+}\mathrm{U}(\mathbf{X}, t))} = \frac{1}{2m+1}\int_{t_{i-m}}^{t_{i+m}} g_t(\mathbf{X}{+}\mathbf{U}(\mathbf{X}, t))dt \tag{6}$$

The spatial-temporal subset in Eq. (6) could improve the quality of the speckle images at certain circumstances compared to the traditional spatial subset in subset-based DIC. For example, when U(X, t)=0, *i.e.*, there is no displacement between the $2m+1$ images, $\mathrm{G}_i^{(m)}(\mathbf{X}+0)$ represents the direct average over the "same" $2m+1$ image captured at different times. Based on probability theory, the noise of the new averaged subset will decrease by $\sqrt{2m+1}$ times compared to the original single speckle subset g_{t_i} [14]. For the images with non-zero displacement, *i.e.*, U(X, t)≠0, it is still expected that the 'average' of the compensated speckle images, $g_t(\mathbf{X}+\mathbf{U}(\mathbf{X},t))$, could reduce noise effects as well. In other words, $\mathrm{G}_i^{(m)}(\mathbf{X}+\mathbf{U}(\mathbf{X},t))$ is a high-quality "speckle image" subset, and displacement is either zero or nonzero. Therefore, improved results are expected if a new DIC scheme is developed based on Eq. (5).

Furthermore, if the new reference image created through averaging several un-deformed images captured before loading is used, the measurement accuracy of STS-DIC should be further improved. By averaging the reference images, Eq. (5) becomes as,

$$\overline{\mathrm{F}^{(m)}(\mathbf{X})} = \overline{G_i^{(m)}(\mathbf{X} + \mathbf{U}(\mathbf{X}, t))} \tag{7}$$

with

$$\overline{\mathrm{F}^{(m)}(\mathbf{X})} = \frac{1}{2m+1}\int_{i-m}^{i+m} f_i(\mathbf{X})dt$$

To solve Eq. (7), the displacement $\mathbf{U}(\mathbf{X}, t)$ should be approximately expressed by certain special functions, as is done in traditional subset-based DIC.

It is assumed that the deformed speckle images are captured continuously within a short time interval during the experiment.

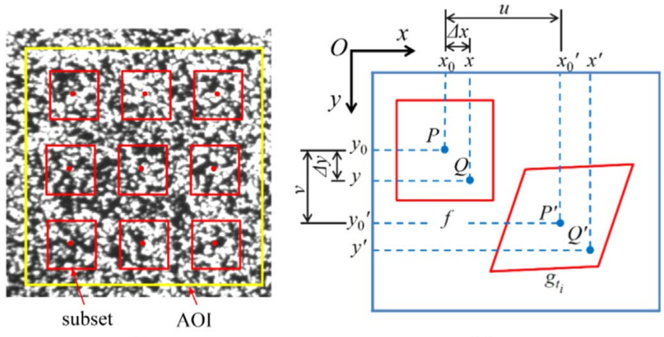

Fig. 1. Displacement field representation using rectangular subsets. (a) partitioning of the area of interest (AOI). (b) displacement representation of one subset.