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Sub-pixel displacement algorithm in temporal sequence digital image correlation based on correlation coefficient weighted fitting

Wenxin Hu, Hong Miao*

CAS Key Laboratory of Mechanical Behavior and Design of Materials, Department of Modern Mechanics, University of Science and Technology of China, Hefei, Anhui 230027, China

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ABSTRACT

Digital image correlation (DIC) is a non-contact technique that is used widely for deformation measurement, but it has problems due to the large amount of calculations required, which make it time consuming. Sub-pixel displacement methods are usually based on spatial correlations, which only consider the spatial continuity of the deformation and ignore temporal continuity. This study proposes a DIC algorithm to calculate sub-pixel displacement combining spatial and temporal correlations. A fast integer-pixel displacement algorithm is employed to calculate full field integer-pixel displacement at different deformation times. Then the moving least squares fitting technique with a weighted function based on the correlation coefficient is used to fit each point's integer-pixel displacement along the time axis, allowing the full field sub-pixel displacement to be calculated for every moment. Experimental results demonstrated the accuracy and efficiency of the proposed algorithm. This achieved the same accuracy as tradition spatial correlation algorithms. Computation efficiency was improved almost 8 fold compared with the IC-GN algorithm, largely due to the integer-pixel displacement calculation; sub-pixel displacement computation only accounted for approximately 2.7% with 41 pixel subsets. Computational efficiency could be further enhanced if a faster integer-pixel displacement calculation method was developed or parallel processing was incorporated.

1. Introduction

Digital image correlation (DIC) is an optical measurement method first proposed by Yamaguchi [1] and Peters and Ranson [2] in the 1980s. Subsequent studies have improved this method greatly. DIC is suitable to obtain field measurements because it is non-contact and achieves high precision, and it has been successfully employed in a wide range of applications.

The method employs feature matching to find an area in a deformation image that corresponds to the calculated area in a reference image, and hence obtain the displacement field on the surface of the object. The calculation is usually divided into two stages: integer-pixel displacement and sub-pixel displacement. Common integer-pixel displacement methods include neighborhood search [3], coarse-fine search [4], and cross search [5]. Sub-pixel displacement methods include NR iteration [6], curved surface fitting [7], genetic algorithms [8,9], amongst others [10]. The basic DIC principle has been described in many previous studies [6,11].

2. Principle of the algorithm

Digital image correlation methods can achieve high accuracy but they require a large amount of calculations and hence can be somewhat time consuming. Traditionally, DIC uses the space continuity of deformation, which assumes that the deformation of a nearby point along the space axis is similar. i.e., there is no jump in the displacement field, so the correlation coefficient between the deformed and reference subsets can be used to determine the location of the deformed subset. However, the deformation is also continuous along the time axis, i.e., deformation of a nearby point along the time axis is also similar. Thus, the time continuity could also be used to determine the deformation field, fitting the deformation and hence avoiding calculation of a large number of correlations. Considering deformation continuity in space and time, we propose a method to calculate sub-pixel displacement that combines spatial correlation and time continuity. The proposed algorithm incorporates integer-pixel displacement and sub-pixel displacement calculations. A fast integer-pixel displacement algorithm is employed to calculate the full field integer-pixel displacement at different deformation times along the time axis, and then moving least squares (MLS) fitting with a weighted function based on the correlation coefficient is employed to fit each calculation point's integer-pixel displacement along the time axis. Thus, the full field sub-pixel displacement at every time can be obtained.

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* Corresponding author.
E-mail address: miaohong@ustc.edu.cn (H. Miao).

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2.1. Fast integer-pixel displacement search algorithm

Integer-pixel displacement is usually calculated by neighborhood or full field search, but these are relatively time consuming processes due to their redundant search scheme. The integer-pixel displacement at different deformation times along the time axis is required by our algorithm, hence the number of calculations means traditional methods are unsuitable. However, a seed point can be used as the initial value for neighboring points to reduce computational time for spatial deformation continuity. A neighborhood search scheme is applied to the seed points to ensure calculation accuracy and avoid errors in the neighboring points.

Therefore, we propose a fast integer-pixel displacement searching algorithm based on seed points. First, a seed point (x_0, y_0) is selected (or several points, depending on the complexity of the deformation) and the integer-pixel displacement (u_0, v_0) of (x_0, y_0) is calculated using neighborhood or full field search schemes. If the search radius is S_r, then the search scope is $(x_0 - S_r, y_0 - S_r)$ to $(x_0 + S_r, y_0 + S_r)$.

For spatial displacement continuity, the integer-pixel displacements of other points should be similar to the displacement of the seed point. Therefore, the integer-pixel displacement of a seed point can be regarded as a rigid body displacement, hence the displacement of other points can be calculated by searching around $(x + u_0, y + v_0)$ with incremental search radius I_r, where I_r is larger when the deformation gradient is larger, and is determined based on the deformation difference between neighboring seed points. It is usually sufficient to use 3–5 pixels more than the deformation difference.

Thus, the search scope for point (*x, y*) ranges from $(x + u_0 + I_r, y + v_0 + I_r)$ to $(x + u_0 + I_r, y + v_0 + I_r)$. In general, $I_r \ll S_r$, which greatly reduces the number of calculations, significantly improving computational efficiency.

2.2. Moving least squares fitting based on weighted correlation coefficients

A temporal sequence DIC algorithm has been developed, but it has some problems. The method is used to analyze a sequence of images, where the expected displacement field temporal regularity in the image sequence can be used to determine sub-pixel displacement. For example, Xi et al. used a single basis function to fit the complete integer-pixel displacement on the time axis to determine sub-pixel displacement [12]. The algorithm is effective when the displacement field gradient is low, but is unsuitable for high gradient or piecewise continuous displacement fields. Therefore, we propose a weighted MLS (WMLS) with high adaptability and flexibility in a local sub-domain of the fitting region, using a polynomial as the WMLS basis function. Compared with the MLS algorithm [13], all integer-pixel displacement data are included in the domain of influence, defined by the radius, *r*, and center, t_i, which are weighted based on the correlation coefficient before being used to obtain the fitted curve of sub-pixel displacement. The location of the point that needs to be solved is t_i and the influence of *r* should not be excessively small, to prevent the coefficient matrix being irreversible or ill-conditioned; nor excessively large, ensuring all local features are included while reducing the required computational time.

Previous studies [12] have generally considered all integer-pixel displacements to have equal precision, hence the least squares algorithm was employed. However, accuracy differs among points in practice, and Integer-pixel displacement is closer to the real displacement, with higher accuracy and reliability. The correlation coefficient is a simple representation of reliability, where larger correlation coefficient indicates that the integer-pixel displacement is a better approximation of the actual displacement. Therefore, we generate a weighted function based on the difference between the correlation coefficient and the minimum, such that a point's weight is larger for larger correlation coefficient, and vice versa. The parameters can be obtained using MLS, and the sub-pixel displacement is calculated based on the fitted results.

3. Experiments

The speckle patterns used in this study were based on the results of finite element calculations for two experiments: a tensile experiment using mild steel, and a fatigue tensile experiment using duralumin. We used ANSYS to establish finite element models of the specimens, and forces were applied to simulate the experiments: axial tensile force in the first experiment, and sinusoidal periodic load in the second experiment.

Displacement gradient increases with increasing load speed and amplitude, requiring larger search fields to determine integer-pixel displacement, hence calculation speed is reduced to ensure the same accuracy level. However, with the development of high speed cameras, deformation progress can be well and slowly recorded, ensuring deformation between successive images is relatively small, hence the proposed method's accuracy and efficiency will be little affected by load speed and amplitude. The proposed sub-pixel displacement calculation will also not be influenced because sub-pixel displacement can be easily calculated once each point's integer-pixel displacement and correlation coefficient are determined.

The current study presents results calculated for the elastic stage. The plastic stage was relatively complex, and subsequent results from that stage will be presented in subsequent reports. The displacement–time curve and strain–time curve for each point could be obtained from the ANSYS simulation, providing the displacement field for each time. Displacement for each point was determined by its location and deformation time, hence displacement fields along space and time axes were determined quantitatively. The whole displacement field can be described analytically after discretization according to the row number in the pixel matrix of each image and the time series number for the image.

Pixel displacement for the low carbon steel tensile test was

$$v(n,h) = 1.5 \times 10^{-1} \cdot n + 5.0 \times 10^{-5} \cdot n \cdot h \tag{1}$$

where *h* is the row number for the pixel matrix in each image, *n* = 1, 2, …, 100 is the time series number for the image, and *v* is expressed as pixels. Similarly, pixel displacement for the fatigue tensile experiment using duralumin was

$$\begin{aligned} v(n,h) &= 5.0 + 5.0 \cdot \sin\left(\frac{2.0\pi}{75.0} \cdot n - \frac{\pi}{2.0}\right) \\ &\quad + \left(1.5 \times 10^{-3} + 1.5 \times 10^{-3} \cdot \sin\left(\frac{2.0\pi}{75.0} \cdot n - \frac{\pi}{2.0}\right)\right) \cdot h \end{aligned} \tag{2}$$

Fig. 1 shows speckle patterns generated from (1) or (2), as appropriate, to allow computational accuracy and efficiency to be calculated and quantitatively evaluated. The reference image was obtained from the real experiment, and deformed images were generated by adding a displacement pattern to the reference image. The images included environmental noise and were similar to the actual situation. The speckle patterns comprised 400 × 600 pixels. Experiment 1 employed 100 speckle patterns and experiment 2 employed 375. Speckle pattern 0 was the reference image.

4. Results and discussion

4.1. Computational accuracy

The effectiveness and feasibility of the algorithm were verified by analyzing the experiment errors.

Table 1 shows the algorithm accuracy, determined by comparing with results obtained using NR algorithm. The proposed method computation accuracy was of the same order as NR algorithm, usually within 0.005–0.1 pixels [14]. Average error for experiments 1 and 2 was within 0.03 pixel for both cases, standard error was within 0.04 and 0.06 pixel respectively. And in experiment 2, the average error was about 0.03 pixels and the standard error was about 0.06 pixels.

Fig. 2 shows that the computed and actual displacement–time curves agree well, verifying the proposed method is highly accurate.