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Strain field estimation based on digital image correlation and radial basis function

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ABSTRACT

Two methods based on digital image correlation (DIC) and radial basis function (RBF) were proposed to obtain the accurate strain field in this paper. One is a combined method. RBF was applied to remove the noisy discrete displacement data first. After that, the strain was computed by a local least-squares algorithm. The other is a partial derivative of RBF (PD-RBF) based strain estimation method which integrated denoising with differential process. The effectiveness and accuracy of the proposed methods were verified through two numerical simulation experiments. A practical application on the normal strain measurement of an aluminum alloy beam under symmetric four-point bending via an outer loading frame was also presented. The measurement results are in good accordance with the data obtained by strain gauges. Furthermore, a shape parameter selection method based on rate of convergence was suggested. The new method simplifies the choice of the good shape parameter.

1. Introduction

Digital image correlation (DIC) is an effective and practical optical metrology technique which can provide quantitative and qualitative information on full-field motion and deformation of an object. Due to the special and attractive advantages of simple experimental setup and specimen preparation, low requirements in measurement environment and wide range of measurement sensitivity and resolution, this method has been widely used in the field of experimental solid mechanics [1–6]. In general, DIC is based on the principle of comparing the reference image and deformed images recorded by CCD. Full-field displacements of the object surface to sub-pixel accuracy can be directly obtained by a correlation algorithm. Then strain components can be computed from numerical differentiation of the estimated displacement field. Unfortunately, there are some noises which contaminate the differential of the displacement. Furthermore, the numerical differentiation is an unstable and risky operation, because it can greatly amplify the noises contained in the computed displacement [7]. Thus, many research works concentrated on eliminating the noisy data of the displacement. Bicubic and bicubic-spline interpolation methods can provide improved accuracy [8]. A finite element (FE) smoothing method is a popular technique employed to reduce displacement measurement "noise" [9]. For FE, the acquired displacements are used as the displacements at the nodes of a finite element model. Then the smoothed data was differentiated to provided the estimated "noiseless" strain components. Sometimes, FE was also combined with other algorithm such as generalized cross-validation (GCV) [10], and least squares method [11]. A thin-plate spline (TPS) smooth method is another well-known global smoothing approach. It was defined as the minimizer of a variational problem whose differential operators approximate a simple notion of bending energy [12]. The parameter which controls the degree of smoothing can be automatically and optimally determined by GCV [13]. Obviously, global smoothing is useful when focusing on the deformation of complete image. However, in some cases, the object has locally deformed regions, which need more attention for improved results. As for the small part of displacement data, local smoothing methods are more suitable choices for its low computation and high adaptivity [14]. The least squares (LS) method is a typical local method. More recently, some modified LS methods, such as the iterative least-squares (ILS) method and point-wise local least-squares (LLS) fitting technique, have been utilized to obtain accurate full-field deformation because of simpleness, high accuracy and effectiveness [2,15].

Here, radial basis functions (RBFs) was applied to improve the accuracy of strain field estimation. RBF is a famous means used for the purpose of scattered data approximation. Inasmuch as they involve a single independent variable regardless of the dimension of the problem [16], RBFs have enjoyed considerable success and research as a technique for interpolating data and functions

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[17–19]. Compared with the classical method like the FE method, RBF has the meshless property, and need not to spend much time on the mesh-generation. Two methods based on RBF were proposed to obtain the accurate strain field in this paper. One is a combined method. RBF was applied to remove the noisy discrete displacement data first. After that, the strain was computed by the LLS method. The other is a partial derivative of RBF (PD-RBF) based strain estimation method which integrated denoising with differential process. It is well known that the accuracy of some RBF based interpolants, e.g. the multiquadric (MQ), depends heavily on the choice of shape parameter [20,21]. The optimal shape parameter can be picked by some ad-hoc criterion which has been published [21,22,23]. In this paper a novel convergence rate based algorithm for selecting a good value for the parameter was suggested. The optimal shape parameter is that which ensures the minimum value of the rate of convergence.

To investigate the performance and accuracy of the proposed methods for strain measurement, two numerical simulation experiments were carried out. The reason for the use of numerical function is that it has theoretical result. And as for simulated images, it can provide controlled deformation of exact values for accuracy examination purpose and can eliminate errors caused by a CCD/CMOS camera, imperfect speckle granules on the object surface, non-uniform illumination and other uncertainties. The results clearly show that the proposed methods can produce accurate measurement on strain field. Finally, as a practical application, the proposed techniques were applied to determinate the normal strain of an aluminum alloy beam under symmetric four-point bending via an outer loading frame.

2. Theory

2.1. Displacement field measurement by DIC

The basic principle of DIC is to match the same physical points between the two images recorded before and after deformation as schematically illustrated in Fig. 1. A square reference subset of $(2N+1)\times(2N+1)$ pixels centered at the interrogated point in the reference image is chosen and used to track its corresponding location in the deformed image. Once the location of the target subset in the deformed image is founded, the displacement field can be determined. Then the strain components can also be calculated by a derivative algorithm. To evaluate the similarity degree between the reference and target subsets, a certain correlation criterion should be defined in advance. The following correlation function, which is called the zero-mean cross correlation criterion (ZNCC) [2], was used in this study:

$$C=\frac{\sum_{x=-N}^{N}\sum_{y=-N}^{N}[f(x,y)-\bar{f}(x,y)][g(x',y')-\bar{g}(x',y')]}{\sqrt{\sum_{x=-N}^{N}\sum_{y=-N}^{N}[f(x,y)-\bar{f}(x,y)]^2}\sqrt{\sum_{x=-N}^{N}\sum_{y=-N}^{N}[g(x',y')-\bar{g}(x',y')]^2}} \quad (1)$$

where $f(x,y)$ is the gray value at point (x,y) of the reference image, and $g(x',y')$ is the gray value at point (x',y') of the target image. $\bar{f}(x,y)=(1/(2N+1)^2)\sum_{x=-N}^{N}\sum_{y=-N}^{N}[f(x,y)]$ is the mean intensity value of reference subset and $\bar{g}(x',y')=(1/(2N+1)^2)\sum_{x=-N}^{N}\sum_{y=-N}^{N}[g(x',y')]$ is the mean intensity value of the target subset. N is the subset size used for calculation.

For digital image, the integer displacements with one pixel accuracy can readily be computed by registration algorithms. To improve displacement measurement accuracy, various interpolation schemes, such as B-spline, bicubic spline interpolations etc., can be used. Once the displacement of a subset is determined, the coordinates of any point in the subset can be calculated using shape functions and the deformation continuity assumption. Normally, the first-order shape function which allows translation, rotation, shear, normal strains and their combinations of the subset is most commonly used:

$$\begin{aligned} x_i' &= x_i+u+u_x\Delta x+u_y\Delta y \\ y_i' &= y_i+v+v_x\Delta x+v_y\Delta y \end{aligned} \quad (2)$$

where $\Delta x=x_i-x_0$, $\Delta y=y_i-y_0$, u and v are the x and y direction displacements of the reference subset, and u_x, u_y, v_x and v_y are the first-order displacement gradients of the reference subset. In the research, the Newton–Raphson (N–R) method, a popular iterative spatial cross-correlation algorithm, was used to resolve the deformation parameters.

2.2. Strain field estimation by RBF

Strain distributions are very important in many tasks of experimental solid mechanics such as mechanical testing of material and structure stress analysis. To obtain the accurate strain field, two aspects should be considered. One is the accuracy of displacement fields, the other is the method of calculation. However, there are some noises which contaminate the displacements. Thus, it is necessary to smooth the displacement field.

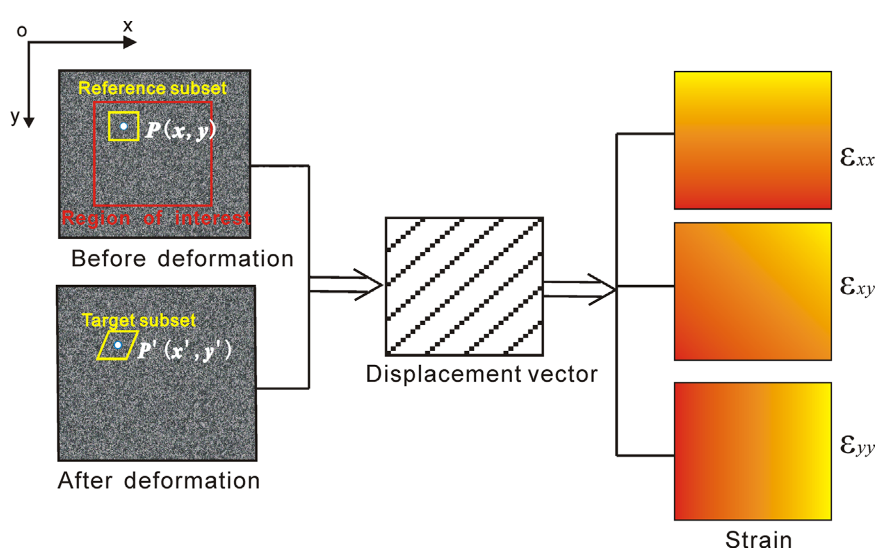

Fig. 1. Principle of DIC applied on in-plane strain measurement.