Optics and Lasers in Engineering 60 (2014) 32–37

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Application of the mean intensity of the second derivative in evaluating the speckle patterns in digital image correlation

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ARTICLE INFO

Article history:
Received 8 October 2013
Received in revised form
30 March 2014
Accepted 31 March 2014
Available online 22 April 2014

Keywords:
Digital image correlation
Mean intensity gradient
Mean intensity of second derivative

ABSTRACT

In this work, the mean intensity of the second derivative of speckle pattern was used to quantify the quality of the speckle patterns for digital image correlation. Numerical experimental studies were performed to justify the correctness and effectiveness of this new global parameter. The results indicate that the measured displacement error was related to the mean intensity of the second derivative of the speckle patterns when they had equal mean intensity gradients. The results also indicate that the measurement accuracy was affected by both the mean intensity gradient and the mean intensity of the second derivative. Therefore, high quality speckle patterns should have a large mean intensity gradient and a small mean intensity of the second derivative.

1. Introduction

Digital image correlation (DIC) [1–5] is an effective and practical tool for full-field deformation measurement that has been widely used in the domain of experimental mechanics. This technique is based on a comparison between pictures taken from specimen surface before and after loading. The specimen surface must be covered with random speckles, which serve as carriers of the surface deformation information. In recent years, many applications of DIC have been reported [6–10].

Measurement accuracy is an issue for the application of DIC and has been investigated by many researchers. Relevant literature reports have indicated that the measurement accuracy is affected by many factors, such as the sub-pixel registration algorithm [11], the shape function [12], the subset size [13,14], and the sub-pixel intensity interpolation scheme [15]. Furthermore, the subset speckle patterns are used to calculate the displacement and deformation fields. Therefore, the assessment of the quality of the speckle pattern is essential for the measurement accuracy of DIC. Two local parameters, subset entropy [13] and the sum of squares of subset intensity gradient [16], were proposed to evaluate the quality of the speckle patterns, and both of them significantly influenced the accuracy of the measured displacements. Recently, Pan et al. [17] introduced a global parameter, the mean intensity gradient (MIG), to evaluate speckle patterns. They indicated that a speckle pattern with a large MIG will produce small displacement measurement errors. Hua et al. [18] also proposed a similar parameter, named mean subset fluctuation, to evaluate speckle patterns. However, because the speckle pattern on the surface of a specimen can be prepared by spraying with white and/or black paints or by other non-traditional methods [19,20], different gray forms may be displayed on the surface of the specimen, which would result in an incomplete assessment of the quality of the speckle patterns.

In this paper, a new effective global parameter, the mean intensity of the second derivative (MIOSD), is proposed to evaluate the quality of the speckle patterns associated with the MIG. MIOSD was developed on the basis of the MIG. The MIOSD reflects the smoothness of the gray surface of the speckle patterns. Numerical experiments were performed to justify such a parameter for evaluating speckle patterns. The same MIG value was used for each of four different speckle patterns. The influence of the MIOSD on the systematic error of the measured displacements was studied in the first numerical experiment. The subsequent experiment indicated that the accuracy of the displacement measurements was affected by both the two parameters, and the accuracy was effectively improved by using a speckle pattern with a large MIG and a small MIOSD.

2. Principle of digital image correlation

In general, the DIC method measures the full-field displacement with sub-pixel accuracy from digital images by determining

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http://dx.doi.org/10.1016/j.optlaseng.2014.03.015
0143-8166/

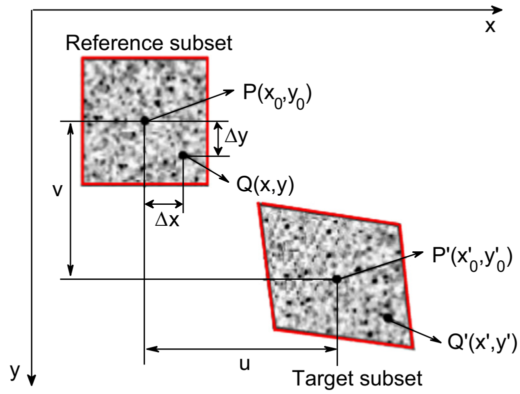

Fig. 1. Schematic of the reference square subset before deformation and the target subset after deformation in DIC.

the correspondence between matching subsets in specimen surface images before and after the loading states. The specimen surface is covered with random speckles. Fig. 1 shows the basic principle of the standard subset-based DIC method. A square subset of $(2M+1)\times(2M+1)$ pixels centered at point P from the undeformed image is chosen to find its corresponding location in the deformed image. In this paper, the cross-correlation criterion is used to evaluate the similarity between the reference subset and the target subset using the following expression:

$$C(p)=\frac{\sum_{i=-M}^{M}\sum_{j=-M}^{M}[f(x_i,y_j)-f_m][g(x_i',y_j')-g_m]}{\sqrt{\sum_{i=-M}^{M}\sum_{j=-M}^{M}[f(x_i,y_j)-f_m]^2}\sqrt{\sum_{i=-M}^{M}\sum_{j=-M}^{M}[g(x_i',y_j')-g_m]^2}} \tag{1}$$

where $f(x_i,y_j)$ is the gray level at coordinates (x_i,y_j) in the reference subset of the reference image, and $g(x_i',y_j')$ is the gray level at coordinates (x_i',y_j') in the target subset of the deformed image; f_m and g_m are the mean gray values for reference and target subsets, respectively. To accurately match the reference subset with the target subset, the first-order shape function is commonly used:

$$x_i'=x_0+\Delta x_i+u+u_x\Delta x_i+u_y\Delta y_j \tag{2}$$

$$y_j'=y_0+\Delta y_j+v+v_x\Delta x_i+v_y\Delta y_j \tag{3}$$

where u and v are the displacement components for the subset center P in the x and y directions, respectively; Δx_i and Δy_j are the distances from the subset center P to point Q in the x and y directions, respectively; u_x,u_y and v_x, v_y are the displacement gradient components for the subset. To efficiently solve parameter vector $p(u,v,u_x,u_y,v_x,v_y)$, the Newton–Raphson iteration [1] method is used to minimize the correlation coefficient (Eq. (1)). More details of the DIC principle can be found in the relevant literature [21–25].

3. Basic definition

3.1. Image entropy

According to the Merriam-Webster dictionary, "entropy" [26] is a measure of the unavailable energy in a closed thermodynamic system that is also usually considered to be a measure of the system's disorder or chaos. Image entropy is a quantity that is used to describe the 'business' of an image. Image information is expressed by each pixel. Therefore, the values of the pixel sample can be taken as the information symbols. The entropy for an eight-bit image is calculated as follows:

$$H(X)=-\sum_{j=0}^{255}P(a_j)\log\ P(a_j) \tag{4}$$

where a_j is a certain grayscale in the image, $P(a_j)$ is the probability of occurrence of symbol a_j, and the unit of H is bits/pixel. The entropy of an image can be easily calculated on the basis of the image histogram information, which is the information of the occurrence of all the intensity values (symbols) in the image. Image entropy reflects the statistical average of the bit number to a certain grayscale. In general, the higher the image entropy, the more information the image contains, and it would be more likely that the appearance of each grayscale is in a uniform probability distribution.

3.2. Mean intensity gradient (MIG)

The MIG (denoted by δ_f) proposed by Pan et al. [17] is a global parameter for evaluating the quality of the entire speckle pattern. Both the mean bias error and the standard deviation of the measured displacements are influenced by the MIG of the speckle pattern. The speckle pattern with a large MIG will produce small displacement measurement errors. The MIG is defined as follows:

$$\delta_f=\sum_{i=1}^{W}\sum_{j=1}^{H}|\nabla f(x_{ij})|/(W\times H) \tag{5}$$

where W and H (in units of pixels) are the image width and height, respectively, and $|\nabla f(x_{ij})|=\sqrt{f_x(x_{ij})^2+f_y(x_{ij})^2}$ is the modulus of the local intensity gradient. $f_x(x_{ij})$ and $f_y(x_{ij})$ are the x- and y-directional intensity derivatives at pixel (x_{ij}), respectively, which can be computed using a central difference algorithm.

3.3. Mean intensity of the second derivative (MIOSD)

A large number of numerical experiments have shown that the accuracy of a displacement measurement can be different even though the speckle patterns have an identical δ_f value. Therefore, it would be inaccurate to use a single global parameter to assess the quality of the speckle patterns. Based on the MIG, a new global parameter, namely the mean intensity of the second derivative (denoted by ω_f) is proposed to evaluate the quality of the entire speckle pattern as follows:

$$\omega_f=\sum_{i=1}^{W}\sum_{j=1}^{H}|\nabla^2 f(x_{ij})|/(W\times H) \tag{6}$$

where W and H (in units of pixel) are the image width and height, respectively, and $|\nabla^2 f(x_{ij})|=\sqrt{f_{xx}(x_{ij})^2+f_{yy}(x_{ij})^2}$ is the modulus of local intensity of second derivative.$f_{xx}(x_{ij})$ and $f_{yy}(x_{ij})$ are the x- and y-directional intensity of the second derivatives at pixel (x_{ij}), respectively. $f_{xx}(x_{ij})$ and $f_{yy}(x_{ij})$ can be computed by using a second-order difference algorithm as follows:

$$f_{xx}(x_{ij})=f(i,j-1)-2f(i,j)+f(i,j+1) \tag{7}$$

$$f_{yy}(x_{ij})=f(i-1,j)-2f(i,j)+f(i+1,j) \tag{8}$$

4. Numerical experiments

In the numerical experiments, four 8-bit (0–255 Gy level range) speckle patterns with a resolution of 401×401 pixels were introduced to study the effect of the MIOSD on the displacement measurement mean bias error. Fig. 2 shows the four speckle