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Principle and Engineering Application of Digital Image Correlation Method

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Abstract

The digital image correlation method has the advantages of simple operation, low environmental requirements and high measurement accuracy compared with the traditional strain gauge and displacement meter because of its non-contact and full-field measurement. It is widely used in the mechanical properties test of materials. The high temperature compression tests of concrete materials and CFRP laminates are reviewed.

Keywords

Digital Image Correlation; Correlation Function; Engineering Application.

1. Introduction

In recent years, with the continuous development of science and technology, in the field of engineering mechanics, mechanics of materials, aerospace, bridge construction, the safety performance reliability of each component and its displacement deformation under load have been the focus of research. The traditional measurement of displacement deformation is contact measurement, and the commonly used methods are extensometer, resistance strain gauge and three-sphere coordinate measuring machine [1 – 3] . The principle is to make the component directly contact the measured object. With the deformation of the object, the variation is transformed into electrical information, and then the deformation is further calculated. Contact measurement has the advantages of simple operation and high precision. However, there are also some shortcomings. For example, it can only obtain local displacement deformation, and it is difficult to reflect the displacement deformation of the whole field. In recent decades, with the development of computer science, computer aided engineering has been greatly developed, and the demand of object shape and deformation measurement is more and more extensive[4-5]. Subsequently, new measurement methods have emerged, such as Digital Image Correlation. Digital image correlation method has the advantages of non-contact, simple measurement, high precision and full-field measurement.

2. Digital Image Correlation Method

The Digital Image Correlation Method was originally proposed by I. Yamaguchi[6] of Japan and Peter and Ranson[7] of the United States. The camera was used to collect the surface images of the measured object before and after deformation. The deformation information of the measured object surface was stored in the digital image with gray value, and then the displacement of each pixel was calculated for the digital image before and after deformation.

In the digital image correlation method, the digital speckle image before deformation is generally called the reference image, and the deformed image is called the target image. The basic principle of digital image correlation measurement method is based on images with a certain distribution of feature points (called speckle images). These feature points take pixels as coordinates, and take the gray level of pixels as the information carrier. Before the calculation of correlation algorithm, a square image sub-region is selected on the speckle image, and the center of this sub-region is the pixel of interest. In the process of image movement or deformation, the displacement vector at the center of the sub-region can be obtained by tracking the position of the image sub-region in the deformed image (i. e., the target image). By analyzing the displacement vector of the center point of multiple sub-regions, the displacement field of the whole analysis area is formed.

3. Matching Principle and Correlation Criterion of Digital Image Correlation Method

Digital image correlation method Using CCD industrial camera to collect the surface image of the measured object before and after deformation as shown in Figure 1. The image before deformation, the size of the subset of $(2M+1)\times(2M+1)$ with $p(x,y)$ as the center is selected as the reference subset, which is represented by $f(x,y)$. Then, the similarity matching is carried out in the deformed image to find the target subset with $p'(x',y')$ as the center, so as to maximize its correlation. Then, $p'(x',y')$ is considered to be the position after $p(x,y)$ deformation, and the schematic diagram is shown in Figure. 2.

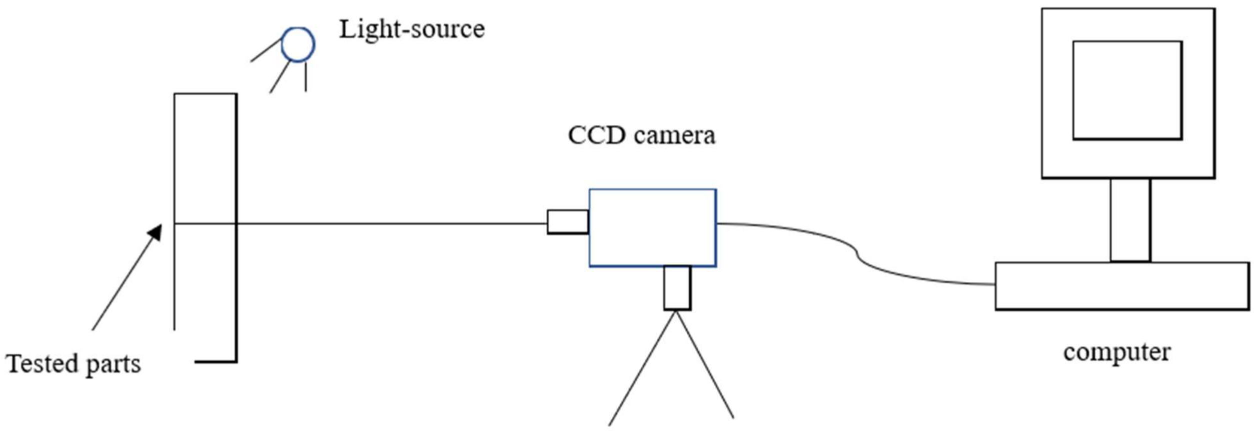

Figure 1. Schematic diagram of DIC measurement system

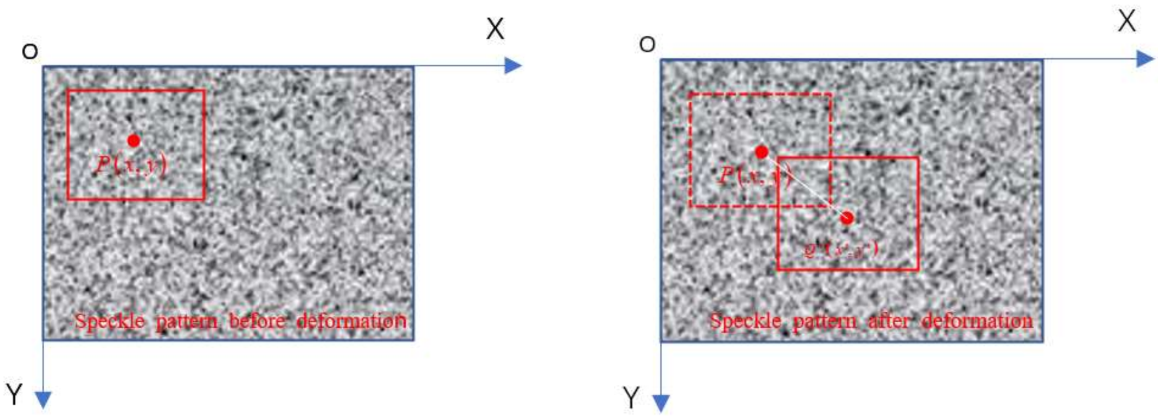

Figure 2. Schematic diagram of matching principle of digital image correlation method

In the matching process of the digital image correlation method, it is necessary to determine the accurate shape function to characterize the position of the deformed subset, so as to quickly match and improve the matching accuracy. The image after deformation is not only a rigid body displacement, but also the shape of the subset will change. Therefore, it is necessary to use the shape function to represent the position of the sub-region after deformation. The schematic diagram is shown in Figure 3.

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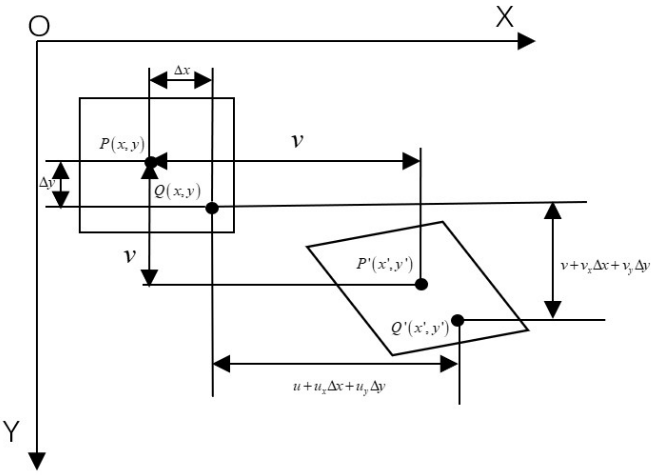

Figure 3. Shape function diagram

For the specimen with only rigid displacement, the zero-order shape function can be used:

$$\begin{cases} x' = x + u \\ y' = y + v \end{cases}$$

A first order shape function for uniform deformation of sample surface:

$$\begin{cases} x' = x + u + u_x \Delta x + u_y \Delta y \\ y' = y + u + v_x \Delta x + v_y \Delta y \end{cases}$$

where Δx , Δy represents the distance from the pixel point to the center of the subset.

Mathematically, when the gray values of $f(x,y)$ and $g(x',y')$ are closest, we think we have found the subregion corresponding to the reference image in the target subregion. Solve mathematically using the minimum value of the correlation function to solve, commonly used correlation functions are :

cross-correlation function:

$$C_{cc} = \sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[f(x,y) \times g(x',y') \right] \tag{1}$$

normalized cross correlation function:

$$C_{NCC} = \sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[\frac{f(x,y) \times g(x',y')}{\overline{f} \times \overline{g}} \right] \tag{2}$$

Square sum function of normalized difference:

$$C_{NSSD} = \sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[\frac{f(x,y)}{\overline{f}} - \frac{g(x',y')}{\overline{g}} \right]^2 \tag{3}$$

Zero-mean normalized cross-correlation function:

$$C_{ZNCC} = \sum_{x=-M}^{M} \sum_{y=-M}^{M} \frac{\left[f(x,y) - f_m \right] \times \left[g(x',y') - g_m \right]}{\sqrt{\sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[f(x,y) - f_m \right]^2} \sqrt{\sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[g(x',y') - g_m \right]^2}} \tag{4}$$

Square sum function of difference:

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$$C_{SSD} = \sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[f(x,y) - g(x',y') \right]^2 \tag{5}$$

Zero-mean normalized cross-correlation function:

$$C_{ZNSSD} = \sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[\frac{f(x,y) - f_m}{\sqrt{\sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[f(x,y) - f_m \right]^2}} - \frac{g(x',y') - g_m}{\sqrt{\sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[g(x',y') - g_m \right]^2}} \right]^2 \tag{6}$$

$f(x,y)$ represents the gray value of the subset before deformation, $g(x',y')$ represents the gray value of the subset after deformation, $\overline{f}$ represents the average gray value of the subregion before deformation, $\overline{g}$ represents the average gray value of the subregion after deformation. When the subset after deformation is most similar to the subset before deformation, the correlation function gets the minimum value, that is, the gradient of the correlation coefficient is equal to. In the above correlation functions, the calculation speed of cross-correlation function and interpolation square sum function is fast, but the accuracy is not high. The accuracy of normalized cross-correlation function and normalized interpolation square sum function is higher than that of cross-correlation function and interpolation square sum function, but the derivation calculation is complex. The square sum function of zero mean normalized cross correlation function and zero mean normalized difference is the most accurate, and its derivation calculation is also the most complex.

Taking the solution of difference square sum as an example, shape function adopts first order shape function and vector $\mathrm{p}=(u,v,u_x,u_y,v_x,v_y)$, When C_{SSD} takes the minimum value, its gradient is 0, that is, solving p at that time:

$$\nabla C_{SSD}(\mathrm{p}) = -2 \left\{ \sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[f(x,y) - g(x',y') \right] \cdot \frac{\partial g(x',y')}{\partial \mathrm{p}_i} \right\}_{i=1,2\ldots6} = 0 \tag{7}$$

Equation (7) can be solved by Newton-Raphson iteration :

$$\nabla C(\mathrm{p}^{k+1}) = \nabla C(\mathrm{p}^k) + \nabla\nabla C(\mathrm{p}^k)(\mathrm{p}^{k+1} - \mathrm{p}^k) = 0 \tag{8}$$

where p_0 represents the initial value, which can be obtained by integer pixel search ; p^k represents the value after the Kth iteration ; $\nabla C(\mathrm{p})$ is the first-order gradient vector of the correlation function ; $\nabla\nabla C(\mathrm{p})$ represents the second-order matrix of the correlation function, namely the Hessian matrix. From Eq. (8), there is:

$$\mathrm{p}^{k+1} = \mathrm{p}^k - \frac{\nabla C(\mathrm{p}^k)}{\nabla\nabla C(\mathrm{p}^k)} \tag{9}$$

The gray values of the reference subregion before and after deformation are close to those of the deformation subset. We believe that $f(x,y) \approx g(x',y')$, so $\nabla\nabla C(\mathrm{p})$ in Equation (9) can be expressed as:

$$\nabla\nabla C(\mathrm{p}) = 2 \left[\frac{\partial g(x',y')}{\partial \mathrm{p}_i} \cdot \frac{\partial g(x',y')}{\partial \mathrm{p}_j} \right]_{i,j=1,2\ldots6} \tag{10}$$

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Substituting the Hessian matrix obtained by Eq. (10) into Eq. (9), Newton-Raphson iterative calculation is carried out. The process diagram is as follows:

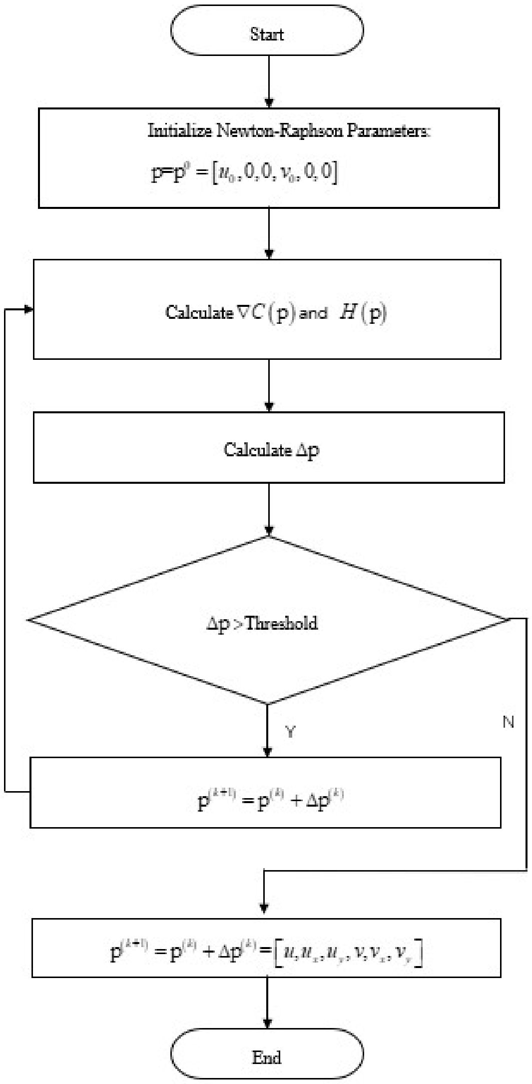

Figure 4. Algorithm flowchart

4. Application of Digital Image Correlation Method in Engineering

Reinforced concrete is the most widely used building material, and its structural durability has attracted more and more attention. Wang Xiaoxian[8] et al. used digital image correlation method to continuously track the deformation and cracking of reinforced concrete under constant potential accelerated corrosion, and obtained the corrosion current and the stress and strain of reinforcement. Under the action of seawater infiltration and constant potential accelerated corrosion device, the cracking time of reinforced concrete was judged to be about 25 h according to the corrosion current density collected by constant potential accelerated corrosion. The rust expansion stress of reinforcement makes the stress concentration at the groove on the upper surface of concrete, and the tensile stress occurs in the interface area. The tensile stress on the surface of concrete is greater than that in the interior of concrete. According to DIC, it can be determined that the time for large cracks in concrete is about 38.5 h.

The traditional displacement meter can only measure the displacement of a single point and the experiment has a direction offset, and the accuracy cannot be guaranteed. Digital image correlation method should have the advantages of non-contact, high precision and full-field measurement.

However, the traditional speckle spraying cannot control its particle size, resulting in poor quality of the speckle field and affecting the measurement accuracy. Xu Xiangyang[9] et al. used the method of water transfer printing to transfer the speckle field to the surface of the specimen and used eight cameras. The two cameras formed four sets of three-dimensional digital image correlation systems. The concrete with a length of 5000mm, a height of 600mm, a flange width of 400mm, a height of 100mm, and a web width of 100mm was measured. The single frame acquisition of specific load points was used for acquisition. The results show that the digital speckle field transferred ensures the consistency of the speckle field and the stability of the measurement results of the digital image correlation method, and the accuracy is also higher than that of the speckle field produced by the traditional spraying.

High temperature compression performance is a key mechanical parameter for composite structure design, but it is difficult to effectively measure it by traditional technical means. Digital image correlation method can make up for the shortcomings of traditional methods due to its non-contact advantages. Yang[10] et al. built a high temperature test system of digital image correlation method to test the high temperature compression performance of CFRP laminates, and obtained the compression performance, stress-strain curve and full-field strain information of related materials. Under 130 °C, the compressive strength retention rates at 0° and 90° were 70.5 % and 62.6 %, respectively, and the compression modulus retention rates were 88.0 % and 75.4 %, respectively.

5. Conclusion

Digital image correlation method has been widely used in engineering. It has good advantages in recording the deformation and failure of the specimen in the measurement test. At present, it is mainly used in the near-distance test, and the research on the long-distance test method remains to be developed. In terms of measurement accuracy, the quality of speckle field and the selection of sub-area size affect the error.

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