A REVIEW ON SURFACE DISPLACEMENTS AND STRAINS USING DIGITAL IMAGE CORRELATION TECHNIQUES

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Abstract

In the earlier days, the displacement and strain were being measured by conventional techniques. The most useful and efficient tool put in practice with the implementation of advances in technology to measure displacements and strains on the region of interest of the object is full field optical measurement technique. This technique is a non-contact optical method known as digital image correlation (DIC), which compares the images captured before and after deformation and stores in a computer for the measurement of displacements and strains. These can be determined considering the displacement of speckles deposited on the surface of object. In this paper, the two-dimensional digital image correlation (2D-DIC) and three-dimensional digital image correlation (3D-DIC) are presented and its fundamental concepts are discussed.

Keywords: Digital image correlation, Displacement, Strain, Error

I. Introduction

The use of modern structures and machinery with great complexity has been increasing day to day to meet the societal needs than before. The structural and machine parts are subjected to several forces during their functioning by physical interaction. These forces produce deformations and thereby strains in the elements. The deformations and strains are restricted to the allowable limit in the design point of view to avoid failure. Hence, the measurement of deformations and strains induced in the components is of great importance for engineering applications to evaluate the problems of structures or machines. In the earlier days, the deformations and strains

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were being measured by conventional techniques with less accuracy. For example, surface deformations and strains [I] are measured by using extensometers, LVDT and strain gauges. The engineers have improved the measuring tools with advances in technology to compute the displacements and strains accurately. The high and informatics method is a non-contact and optical method known as digital image correlation (DIC). In recent days, DIC technique is widely used for reducing complexity and high accurate deformation measurement for different applications

II. Digital Image Correlation (DIC)

The digital image correlation is an adaptable widely used technique in experimental solid mechanics for different applications such as temperature strain mapping, fracture propagation studies, material characterization and structural deformations. It is employed to evaluate the non-contact surface displacements and strains for the entire sample during testing. The measurement of surface deformation caused by various mechanical or thermal loads is a vital task in experimental mechanics of solids.

In DIC, the image matching is paying attention on the surface of the image before and after deformations. Image matching is a discipline of computer vision that is of central significance to a great number of applications [II]. Digital image correlation discusses the primary issues in image matching with an attention on resolving the motions on the surface of deforming structures. There are numerous concepts and approaches such as aperture problem and speckle pattern. Aperture problem involves in coordinating a point on first image to a random point in the second image. The surface of image should exhibit certain properties which will correct the aperture problem. The DIC method is to correlate different types of patterns such as grids, dots, lines and random patterns. Speckle patterns are used because correlation loss is nil and which occur under large deformations and translations. A good speckle pattern gives high information content and few speckle patterns as shown in Fig. 1.

![Fig. 1: Typical speckle patterns](image)

The surface of specimen is painted to form arbitrary speckle pattern on which DIC works by relating two images of the specimen in un-deformed and deformed states. The images recorded before and after deformation are digitized and stored in the computer. According to pattern matching principle, the images are compared to identify the displacements. Single pixel and subsets containing multiple pixels are used to analyze the image to identify the matched points. The displacement field at various locations in the region of interest is evaluated using image matching rule [III].
This is a simple rule used to correlate both images by comparing various zones and it will provide in-plane displacement fields (such as \( u \) and \( v \) displacements). The matching of pattern images obtained in un-deformed and deformed states is shown in Fig. 2. Pan et al. [IV] published describing how the DIC algorithms are developed.

![Fig. 2: Matching of images a) un-loaded and b) loaded states](image)

**III. Two Dimensional Digital Image Correlation (2D DIC)**

In the beginning, two dimensional digital image correlation (2D DIC) technique was employed for the measurement of displacements and strains on the surface of the member in two orthogonal directions. In this method, only one camera is used to capture the images for analyzing in-plane deformations and out-of-plane deformation are not possible by this method. A line diagram of 2D DIC setup is shown in Fig. 3.

![Fig. 3: 2D DIC set-up](image)

The specimen containing speckle pattern gets deformed in loading state. The images consisting of displacement subsets before and after deformation are captured by the camera and preserved in the computer. These images are processed in the
region of interest (ROI) to measure displacement and strain. The subsets before and after deformation are shown in Fig. 4.

**Fig. 4: Subsets before and after deformation**

**Correlation Principle**

A reference image, \( f \) on ROI may be considered [V]. Define the displacement field, \( u(x) \). The texture, \( f \) by the displacement field creates a deformed image, \( g \) such that

\[
g(x + u) = f(x) + b(x)
\]

In the above expression, \( b(x) \) is noise induced by image acquisition.

For determining a sub-pixel displacement, interpolations are required and the preferable choices are bilinear, bi-cubic and spline functions to interpolate the texture. It has a direct impact on the behavior of the correlation algorithm [VI]. The further options are related to the optimization algorithm and the required displacements, \( v(x) \) for the ROI [VII]. After selecting the ROI, first pixel correction and FFT correlation are done. After extracting the image, the sub pixel correlation and displacement correction are done based on the parabolic interpolation. Then the images are intersected to calculate the displacement and strains on the surface. After calculating the displacements, strains are computed then the next image is considered as deformed image.

**Measurement of Displacement**

For achieving sub-pixel accuracy, the 2D DIC requires accurate initial deformation. For measuring the displacement, the most commonly used correlation algorithm is Newton-Raphson method, which converges to a given initial guess. The peak-finding algorithm is used to detect the highest location of the local discrete correlation coefficient matrix (3x3 pixels) with maximum cross correlation coefficient or minimum sum of squared differences (SSD) coefficient. Chen et al. [VIII] suggested a bi-parabolic least-squares fitting of the local highest and defined the highest location as the extremum of the obtained polynomial. Sjodahl et al. [IX] used the algorithm by intensifying the discrete correlation relation in terms of a Fourier series followed by a numerical searching system for finding the precise peak. The cross correlation coefficient is represented by the equations given below [V].
\[ C(u, v) = \frac{\sum_{i=1}^{m} \sum_{j=1}^{m} f(x_{i,j}) - \bar{f}}{\sum_{i=1}^{m} \sum_{j=1}^{m} g(x_{i,j}) - \bar{g}} \]  \tag{2}

In the above expression, 
\( \bar{f} \) = mean intensity value of reference subset and \( \bar{g} \) = mean intensity value of deformed subset

\[ x' = x + u_0 + \frac{\partial u}{\partial x} dx + \frac{\partial u}{\partial y} dy \]

\[ y' = y + v_0 + \frac{\partial v}{\partial x} dx + \frac{\partial v}{\partial y} dy \]  \tag{3}

The iterative spatial domain cross correlation and peak finding algorithms are used to achieve sub-pixel displacements. When the displacement measurement is accurately and precisely evaluated using computer speckle images, the iterative spatial domain cross correlation algorithm will give high accurate values [X].

**Measurement of Strain**

The full field strain distribution is important and useful in testing of materials and stress analysis. The practical method for measurement of strain is the point wise local method of least-squares [XI], [XII], [XIII]. Watarris et al. [XI] used a method of local least-squares to calculate the strains of thin flat steel specimens loaded in tension by DIC method. Figure 5 shows the strains to determine from the current point by selecting the square window of \((2m + 1) \times (2m + 1)\) discrete points around it.

The following equations are used for strain calculations.

\[ u(i,j) = a_0 + a_1 x + a_2 y \]

\[ v(i,j) = b_0 + b_1 x + b_2 y \]  \tag{4}

In the above, \( i, j = -m; m \) represents local coordinates inside the strain measurement window. The method of least-squares is used to determine the unknown polynomial coefficients.

Fig. 5: Local window of \((2m + 1) \times (2m + 1)\) displacement data to measure the strain
Analysis of Error in Measurement

The primary advantage of using 2D DIC is simple experimental setup with few requirements. The accurate measurement of displacement and strain by 2D DIC depends closely on the quality of loading system, perfection of imaging system and the selection of correlation algorithm. The error estimation associated to diverse error causes is essential to determine the routes for improving the exactness in measurement by 2D DIC [XIV]. The main sources of errors occurred in 2D DIC are related to (i) specimen, imaging and loading and (ii) errors connected to correlation algorithm. The displacement error [XV] is proportional to the curvature of displacement and increases with square of the subset size. The expression for systematic error is as follows.

\[ \Delta u = \frac{1}{3} am(m + 1) \]  

Applications of 2D DIC

The 2D DIC is implemented for estimating the deformation field and analyzing it for various materials such as metals, nonmetals and biological components under mechanical, thermal and other loads. The Young’s modulus, Poisson’s ratio, stress intensity factor, residual stress and thermal expansion coefficient are various mechanical parameters of the material to determine based on the displacement or strain fields. The calculated deformation fields can also be used to validate with those of FEM or theoretical results and to bridge the gap among the results of experiments, simulations and theory.

IV. Three Dimensional Digital Image Correlation (3D DIC)

The 3D DIC is employed to measure both in-plane and out-of-plane deformations and in turn strains in three mutually perpendicular directions. This 3D DIC is an extension of 2D DIC proposed by Bay and Smith et al. [XVI], [XVII]. In 3D DIC system, two or more cameras are located to capture the images in the region of interest (ROI). The 3D DIC system has an ability of getting in-plane surface displacements accurately. In this system, three dimensional rigid body rotation and translation will undergo [III]. The line diagram of 3D DIC is shown in Fig. 6.

A modern 3D DIC system consists of a typical hardware namely (a) two CCD cameras, stereo-camera systems (b) computer system with data acquisition to record images at one from both cameras, (c) sturdy tripods (d) rigid bar for holding two cameras, (e) two high-quality lenses and (f) two 250 W halogen spotlights [XVIII].
A subset is chosen from the image of un-loaded state of camera 1 and through each pixel of the subset, a ray is projected. The local region on the member is approximated as a small plane. From Fig. 7, the equation for the plane can be written as follows.

\[ X_{B1}n_{xB1} + Y_{B1}n_{yB1} + (Z_{B1} - Z_0)n_{zB1} = 0 \]  

(6)

where, \((n_{xB1}, n_{yB1}, n_{zB1})\) and \(Z_0\) represent the corresponding unit normal to the plane and the position where the optical axis intersects object plane. Assuming the orientation of plane and initial values for the location, pixel locations are then projected onto the sensor plane of the un-loaded image in camera 2 and modified for distortion. Intensity values from camera 1 are matched with those of projected locations in camera 2 using a cross-correlation metric. The process is repeated for the plane to update all five parameters until convergence. The results represent 3D position of the object point. This process is continued until a dense set of 3D positions is acquired.
For object deformations, the same master camera and subsets for determining the initial 3D profile are chosen in camera 1. For a given subset in the un-deformed image of camera 1, the procedure outlined for un-loaded is repeated by means of a deformed image for camera 2. The result indicates 3D deformed location of each object point C. The displacement components for object point C are gained by subtracting the positions from un-loaded to loaded states. The procedure defined above is continued for each set of deformed images, with main camera subsets providing the basis for matching process. The process defined above can be reversed with camera 2 repeating the same process. The two dense sets of data again are calculated with respect to same object domain [XVIII].

The measures to be taken while experimenting with DIC under any loading conditions [IV] are as follows.

- Increasing contrast of the speckle pattern, keeping CCD target, using a camera lens and high-quality CCD camera and keeping even lighting throughout loading.
- Using a bigger subset when the shape function matches the original deformation field, employing the robust and ZNSSD or ZNCC correlation criterion, using the better NR method for optimizing the correlation criterion and a high-order shape function.

V. Conclusions

For the past twenty years, the digital image correlation is used in solid mechanics for testing of materials and structures. The algorithms used in the 2D DIC were modified and slowly improved to increase their computational efficiency and accuracy of measurement. The 2D DIC aids to measure only for in-plane deformations and strains whereas using 3D DIC, in-plane, out of plane deformations and strains are measured. One can believe that 3D DIC will receive additional attention and applications as compared to 2D DIC for quantities of surface deformation and strain of the object with the growth of high accuracy calibration technique.

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