Digital Image Correlation

Introduction

The Digital Image Correlation (DIC) technique has been developed over the past two decades into what is currently known as stereo or 3D-DIC, a full field, non-contact and portable measurement technique that has the capability to resolve in-plane strains as well as out-of-plane deformation with sub-pixel accuracy. In the laboratory class 2D-DIC will be used, with a single camera. While both techniques have been used successfully to measure in-plane deformation from flat surfaces, only 3D-DIC has the capability to resolve out-of-plane deformation on curved or nonuniform surfaces that exhibit 3D motion or change in shape as the load is being applied. A typical set-up for 3D-DIC is shown in Figure 1 it comprises:

i. Two high resolution CCD cameras mounted on an adjustable rail and a tripod
ii. A computer-camera interface to allow the cameras to be triggered at a user-defined rate
iii. A computer for controlling the DIC measurement procedure and processing the images to calculate deformation

The selected area for DIC measurement is called the region of interest.

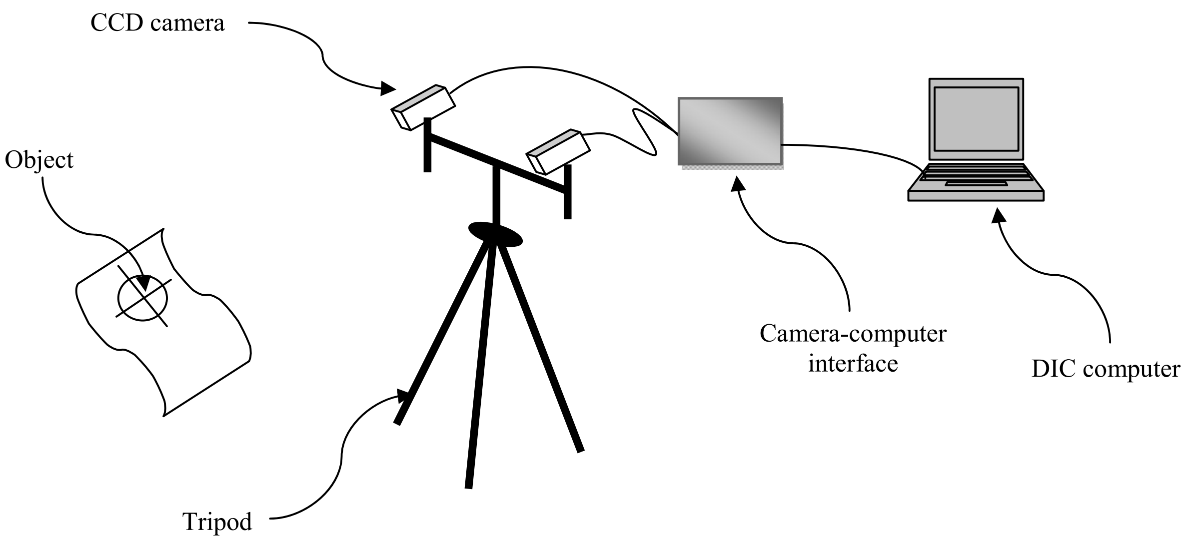

Figure 1 Diagram of a 3D-DIC system set-up

The 2D DIC technique is typically applied to images collected from a single camera positioned normal to the surface under investigation. A typical setup is shown in Figure 2.

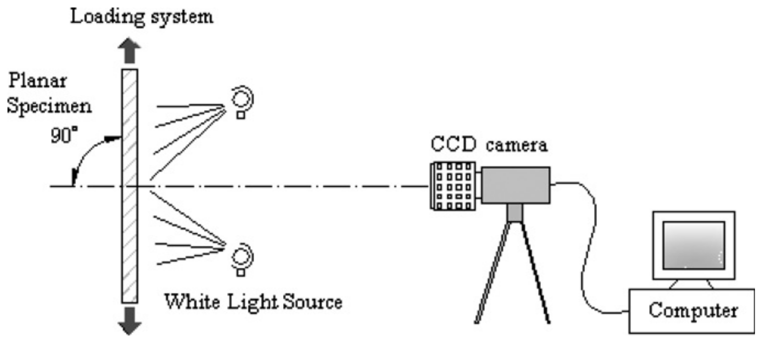

Figure 1: Schematic experimental setup for 2D DIC

Basic procedure

The typical stages of the DIC deformation measurement process is given below and summarised by Figure 3:

i. **Specimen preparation**: DIC computes deformation by tracking random surface patterns. If the surface of a specimen does not contain adequate contrast then a speckle pattern needs to be applied. Some surfaces naturally possess such a surface pattern and no further surface preparation is required. The most common method for creating a speckle pattern and the method is to apply a light coat of acrylic spray paint.

ii. **Camera calibration**: This stage is essential in 3D-DIC because it determines the position and orientation of each of the cameras with respect to the surface of the specimen and relates the pixel size of the object's image to the metric scale. The calibration procedure is performed by means of a calibration plate that contains a grid of dots with known sizes and distances. By considering multiple views of the calibration plate at different positions and orientations the software determines the required parameters. The calibration procedure for 2D strain measurements does not require a calibration plate. The important parameter in this case is the pixel/mm ratio which can be determined using an image of a ruler placed on the surface of the specimen.

iii. **Image acquisition**: At least two images are needed to perform DIC measurements. These are typically referred to as the reference and deformed images. The former being the image taken when the specimen is subject to no load, the latter referring to the image recorded at a particular loading stage. In practice, various images are taken at different loading stages or at fixed times as a load is applied. The image acquisition rate is dependent on the application. The speed of the deformation process determines the optimal image acquisition frequency. The recent advances in the field of CCD camera imaging has led to the development of cameras that can be set to acquire images over a wide range of frequencies.

iv. **Displacement vector field computation**: The acquired images are divided into sub-regions of user defined size; these are called subsets. The pattern contained in each subset is tracked to compute a displacement vector. This is achieved by applying a correlation function that searches for the best match between the subsets of the reference image pair and the deformed image pair. The resulting set of vectors from all the subsets is called the displacement vector field.

v. **Full field strain data**: In-plane strains are finally extracted by computing the gradient of the displacement vector field.

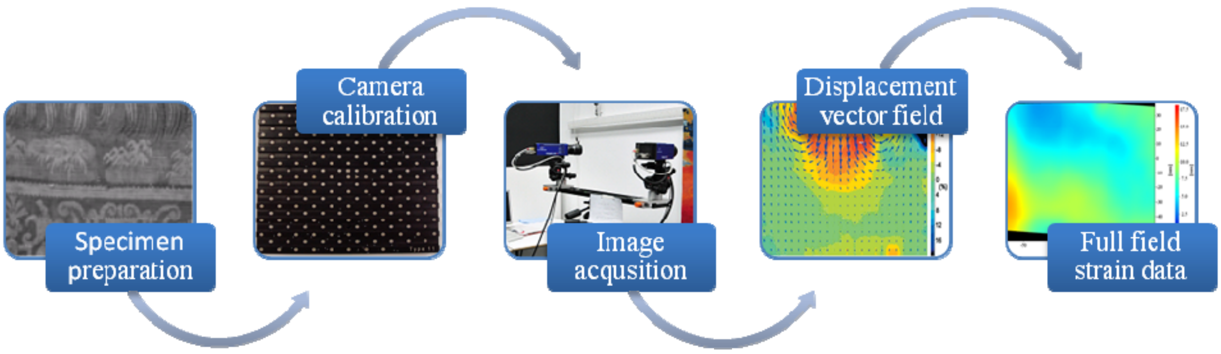

Figure 3 Block diagram for DIC deformation measurement stages

Specimen preparation

DIC tracks the surface displacements of deformed structure by recognition of geometrical changes in grey scale distribution of surface patterns before and after a strain has been applied. Therefore it is essential that a random pattern of suitable contrast is applied to the specimen. This is done usually by application of a paint coating. The paint adheres to the surface and deforms with the specimen. It is recommended that the size of the random speckles should be larger than 3 pixels in diameter to obtain a precise measurement. It is essential that the pattern is not periodic. A typical speckle pattern is shown in Figure 4 with an enlarged image in Figure 5 showing the contrast pixel by pixel; note how the areas of different contrast are greater than two pixels.

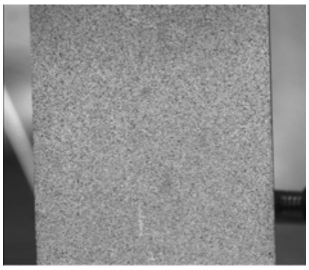

Figure 4 Application of speckle paint coating to a steel specimen

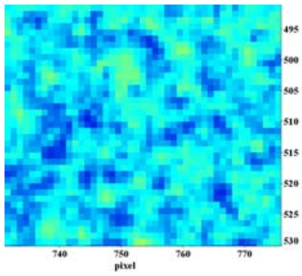

Figure 5 Magnified area used to check the size of the random pattern

Measurement

The purpose of image based correlation is to locate the same feature from one image in another image. Typically, this is performed on square shaped sub-images know as subsets or interrogation cells. The centre points of these interrogation cells are located by correlating the corresponding interrogation cells from the two images until a matching intensity pattern is found. All that is required for DIC is an unstrained (reference image) and a strained (deformed image) that can be compared to the reference image. Since the entire surface is covered in the pattern, rather than a grid a relatively small area is required for the pattern matching. The reference image is divided into interrogation cells of a given number of pixels, typically from 2 x 2 pixels to 1024 x 1024 pixels. In Figure 6a, a 2 x 2 interrogation cell configuration with no overlap is shown. It can be seen that the undeformed image has a grey scale pattern within the interrogation cells before deformation. After deformation the grey scale pattern is retained except its spatial position has moved. By recognition of the grey scale pattern from the undeformed to the deformed condition the deformation of the specimen can be obtained. The processing of the images can be controlled by selecting optimum combinations of the two main processing parameters; interrogation cell size and overlap. The choice of interrogation cell size selection is a compromise between accuracy and spatial resolution; the larger the cell size, the more data there is to average over. A second factor to be considered in the compromise is cell overlap, as shown in Figure 6b. The strain is calculated from the deformation vectors in each cell, or in the case of overlapping data each sub-cell. This is indicated by the gauge length shown in Figure 6a and 6b; the overlap shortens the gauge length. Therefore the increase in spatial resolution shortens the distance over which the strain is measured. This inevitably will create more scatter as the measurement region decreases. For high resolution work high magnification optics are essential; particularly in applications where displacements are low.

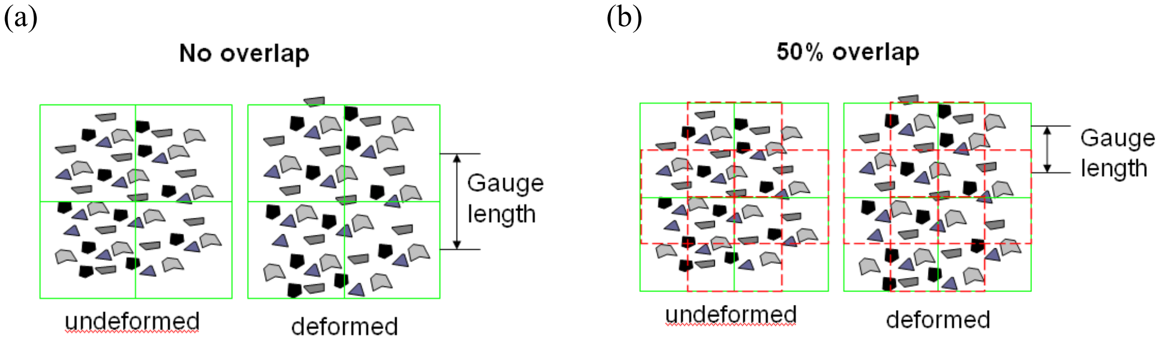

Figure 6 Correlation subsets or interrogation cells

Correlation algorithms

To match the patterns seen in each interrogation cell it is necessary to apply an algorithm. Different proprietary software uses different algorithms so the following is a summary of some typical approaches and their limitations. For more detailed descriptions of the algorithms students are referred to reference [1].

Cross-correlation: This generally requires quite large interrogation cells and is sensitive to lighting fluctuations, pattern type and image noise.
Cross-correlation in the Fourier domain: Also requires large interrogation cells but is insensitive to lighting fluctuations, pattern type and image noise.
Variational (Sum of Squared Differences): Can use smaller interrogation cell sizes and provides a rapid calculation, however is sensitive to lighting fluctuations and pattern type but insensitive to image noise.

To perform DIC, an initial reference image, taken at time t, is split into a regular array of regions known as subsets. The size of the subset can be set by the user, but an area of 20 x 20 pixels is typical. Each subset will ideally sample over multiple speckles on the specimen surface and have a unique distribution of pixel intensities. A second, deformed image taken at time t+Δt is searched for the new subset position by comparing the intensity patterns of the two cells through use of a correlation function. This procedure is shown schematically in 7, where a reference subset at initial position $P(x_0, y_0)$ composed of an intensity distribution of $f(x_i,y_j)$, moves by rigid body motion to position $g(x_i,y_j)$ at time t+Δt. The vector connecting points P and P' is the displacement vector of the subset, composed of the horizontal and vertical components, u and v. The deformed subset will never be an exact match of the reference subset due to various factors, including subset rotation, camera noise and strain within the subset. The best match for the new subset position must therefore be found by an optimisation procedure.

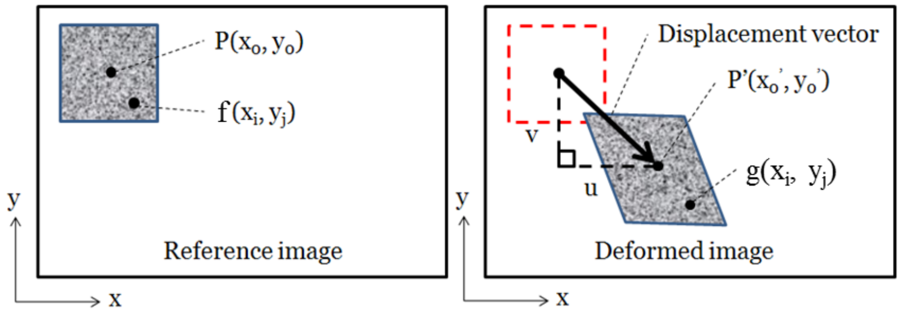

Figure 7: Schematic of a reference subset (left) at time t, and the same cell after a deformation (right) at time t+Δt

The exact function used depends on the DIC software employed. DaVis 8.1.3 by LaVision uses the least square difference (LSM) method (also known as sum of squared difference (SSD)). This is a common method used in many other DIC software and is explained in depth in the literature. The LSM method computes the position of the deformed subset to the nearest pixel accuracy by minimising the result of the following function:

$$C_{SSD} = \sum_{i=-M}^{M} \sum_{j=-M}^{M} [f(x_i, y_j) - g(x'_i, y'_j)]^2$$

A plot showing the correlation values across a 150 x 150 pixel search area is shown in Figure 8 with the correct displacement location indicated by the centre maximum point. In cases where the subset has a low uniqueness, multiple maximum points may occur, increasing the chances of decorrelation.

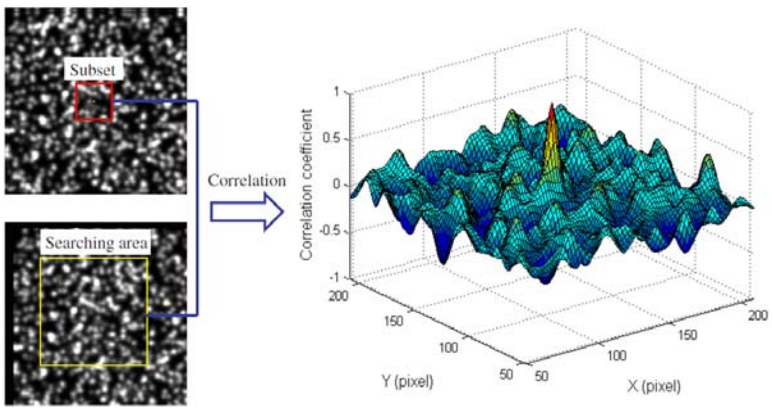

Figure 8: Correlation values for a search area of integer pixel displacements, showing the maximum value at the correct new cell location

To compute the subset displacement to greater accuracy, grey levels values must be evaluated at subpixel locations using an interpolation method and the LSM method repeated in an iterative manner. DaVis allows the use of two subpixel interpolation methods; a bilinear approximation and a 6th order spline method. The former yields lower displacement accuracy but faster convergence, whilst the latter gives greater accuracy at the cost of greater computation time. The effect of subpixel interpolation on the accuracy of DIC measurements is provided in a later lecture.

Interrogation cell shape functions are used to cope with complex displacement in the ROI. The shape function enables the transformation of the reference pixel coordinates into the image after deformation. The greater the order of the shape function, the better the accuracy, but this is at the cost of computational efficiency. For example a zeroth order shape function can allow a simple rigid body shift of patterns but cannot cope with displacements if there is rotation or shear across an interrogation cell. A first order shape function can cope with translation, rotation, shear and normal strains. Higher order shape functions are generally more sensitive to noise than lower order shape functions.

The strain is calculated using the following standard formulation:

$$\varepsilon_x = \frac{du}{dx}$$
$$\varepsilon_y = \frac{dv}{dy}$$
$$\varepsilon_{xy} = \frac{du}{dy} + \frac{dv}{dx}$$

where du and dv is the difference between adjacent displacement vectors in the longitudinal and transverse directions, dy and dx are the distances between the centres of two adjacent cells and $\gamma_{xy} = 2\varepsilon_{xy}$ is the engineering shear strain.

In the DaVis a software, a central difference algorithm is used to compute the strain values as shown below for the case of horizontal strain ε_{xx}:

$$\varepsilon_{xx}(m,n) = \frac{dv_x(m,n)}{dx} = \frac{\left(v_x(m+1,n) - v_x(m,n)\right) + \left(v_x(m,n) - v_x(m-1,n)\right)}{2g}$$

where $\varepsilon_{xx}(m,n)$ is the transverse strain at grid position (m,n), $v_x(m,n)$ is the x component of the displacement vector for the cell located at grid location (m,n) and g is the step size.

DIC Error Sources

The accuracy of DIC is influenced by numerous factors, these can be summarised concisely as those resulting from errors in the ‘measurement’ space and as those resulting from the correlation algorithm. In this section we will concentrate only on the former as the latter are discussed in detail in the following lecture.

The measurement space comprises the distinct errors sources which are summarised in Figure 9. Some of these error sources are discussed in detail in the following.

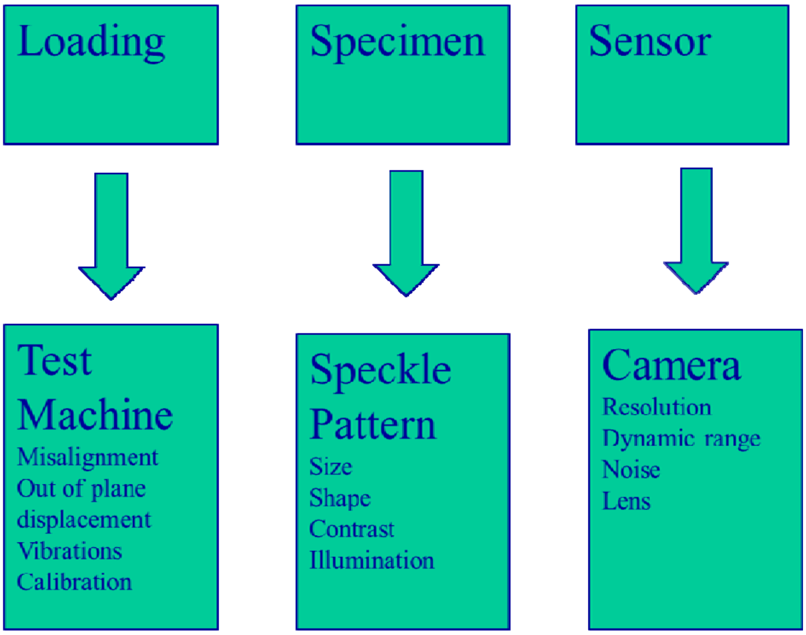

Figure 9 Measurement space

Out of Plane Motion
A surface that moves away from a camera will appear to have been subjected to an isotropic compressive strain, whilst a surface moving closer will appear to undergo tensile strain. Such a strain will be in addition to and indistinguishable from any real in-plane strains. The effect of out of plane motion on the DIC recorded strain can be calculated as follows:

$$\varepsilon_{xx} = \frac{\partial u(\Delta Z)}{\partial x_s} \cong -\frac{\Delta Z}{Z}$$
$$\varepsilon_{yy} = \frac{\partial v(\Delta Z)}{\partial y_s} \cong -\frac{\Delta Z}{Z}$$
$$\gamma_{xy} = \left(\frac{\partial u}{\partial y_s} + \frac{\partial v}{\partial x_s}\right) \cong 0$$

where *Z* object to camera distance and *ΔZ* is the out of plane motion.

A stereo DIC system does not encounter strain errors due to out of plane motion as in plane strains and out of plane movements can be separated and quantified, as previously described.

Camera Misalignment
For a 2D DIC system, a camera that is not aligned perpendicularly to the surface under investigation creates a uniform in-plane strain after correlation due to difference in magnification across the width. For small angles this effect is small. Since a camera alignment within 5° is easily achievable, camera misalignment does not cause significant error in 2D DIC.

Speckle Pattern and Image Quality

Acquiring high quality images is paramount for achieving reliable DIC measurements. Certain artefacts are likely to increase the chance of decorrelation, all of which should be avoided. These include contamination on the lens, reflections on the specimen surface, sensor saturation and variations in lighting levels across the image. Image blurring can also result in decorrelation due to a change in the imaged speckle pattern. It is also recommended that the image contrast is maximised through use of the full dynamic range of the sensor.

The speckle pattern is intrinsically linked to the spatial resolution of the image, and in turn, the spatial resolution of the camera and the lens magnification. Various parameters have been proposed to quantify the quality of a speckle pattern. Speckle size influences the useable subset sizes for DIC. Very large speckles are liable to contain an entire subset within their area, reducing uniqueness and giving a high chance of decorrelation. Speckles smaller than 2 pixels diameter are liable to encounter the *pixel locking effect*, whereby displacement vectors become biased towards integer pixel values. As a general rule for accurate subset matching, a speckle should be sampled by at least a 3 x 3 array of pixels with each subset containing approximately 9 speckles.

Camera Hardware

As previously mentioned in the white light imaging section, digital sensors may introduce errors into the image as a result of random noise, which can be reduced by sensor cooling. The image noise produced varies greatly between camera manufacturers and models. Variations in pixel sensitivity across a sensor can cause a decrease in similarity between reference and deformed subsets after image correlation. For this reason a non-uniformity correction is recommended. Dead pixels in a digital sensor can similarly cause a decrease in similarity after image correlation. Such pixels are usually taken into account by defining the intensity value of a dead pixel as an average of its near neighbours. Cameras with low dead pixel counts are recommended for DIC.

References

1. Sutton, M.A., Orteu, J-J and Schreier, H.W., "*Image correlation for shape, motion and deformation measurements*", Springer, New York, 2009.