



EVALUATION OF THE EFFECT OF THE SPECIMEN IMAGE RESOLUTION ON NON-UNIFORM DISPLACEMENT ACCURACY OF 2D-DIGITAL IMAGE CORRELATION

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ABSTRACT

The enhancement of the accuracy in a 2D-DIC can be related to the image resolution. In a common sense, higher image resolution provides a better result than lower image resolution. However, it is expensive to produce a high resolution images and in many cases they are not necessary. On the other side, measurement accuracy by using DIC is related with the displacement field. In many cases on experimental mechanics, displacement field in an area of interest is usually non-uniform, in which the ratio between minimum and maximum displacement in that area of interest is high. The present work evaluates the accuracy of 2D-DIC algorithms in relation with image resolution and the effect of non-uniformity of the displacement. The evaluation was based on the input images of the algorithms, which were artificial and experimental images. It was observed that both type of input images produce the similar tendency on the effect of image resolution to the accuracy of the measurement. Higher image resolution reduced relative error significantly in case where the minimum displacement in the area of interest is much smaller than the maximum displacement (very low ratio or high non-uniformity of the displacement). However, even though lower resolution image has higher relative error than high resolution image, the effect of resolution is not significant if displacement field tends to be more uniform (the ratio between minimum and maximum displacement in an area of interest is higher than 0.5). The importance of the present result is to determine the applicability of DIC measurement field based on image resolution.

Keywords: 2D-DIC, resolution, accuracy, sub-pixel, displacement.

INTRODUCTION

Digital Image Correlation (DIC) has been widely used as the optical method for non-contacting measurement in solid mechanics since early 1980s [1][2]. The method has the ability to measure full-field deformation properties in a loaded structure such as displacement, stress and strain for both quantitative and qualitative [3]. Moreover, the capability of DIC method is not only restrict in two-dimensional but also in three-dimensional measurement field. The relatively simple and easy experimental setup of DIC, while maintaining its accuracy, has made this method found a wide range of applicability in experimental mechanics.

Even though DIC method has been extended into three-dimensional measurements, there is still a room to improve the accuracy of 2D-DIC [4]. The accuracy enhancement can be performed during experimental setup or within DIC algorithms. In the experimental setup, enhancement analysis was performed by utilizing bilateral telecentric [5]. Different speckle type and recording setup has been identified to affect the accuracy of 2D-DIC [6].

Accuracy enhancement of 2D-DIC algorithms is as complex as the accuracy in experimental setup. In correlation stage, various schemes of correlation criterions affect the accuracy of 2D-DIC [7]. By choosing the suitable correlation criterions, displacement errors can be minimized. The correlation scheme in DIC algorithm can be modified to accommodate the combination of cross-correlation and optical flow methods [8]. Another enhancement was performed in sub-pixel accuracy by using B-spline scheme [9]. High resolution DIC has been

achieved by using proper generalized decomposition method [10]. Accuracy analysis of the 2D-DIC algorithms in ultimate error region has been performed [11].

The present research is focused on the evaluation of 2D-DIC accuracy due to the effect of image resolution. Moreover, the analysis was relating the effect on the non-uniform displacement field. The correlation and sub-pixel algorithms followed previous work in [12], in which has been extended into three-dimensional fracture mechanics analysis [13]. The basic research of the 2D-DIC on the present algorithms has been performed by relating the speckle parameters on displacement accuracy [14]. The simulation result on the effect of dot radius on sub-pixel displacement accuracy as shown in Figure-1 provides a practical recommendation which is load on the specimen should give 8 pixels displacements in order to achieve 3% relative error of the measurement. The present evaluation utilized both artificial and experimental images of translated specimen in order to relate between image size, displacement and accuracy of the measurement.

EVALUATION METHOD

Evaluation of the parameters on the present work were divided based on the type of input images of the previously developed 2D-DIC algorithms. There were two type input images, i.e. artificial and experimental images. The evaluation method is shown in Figure-2.

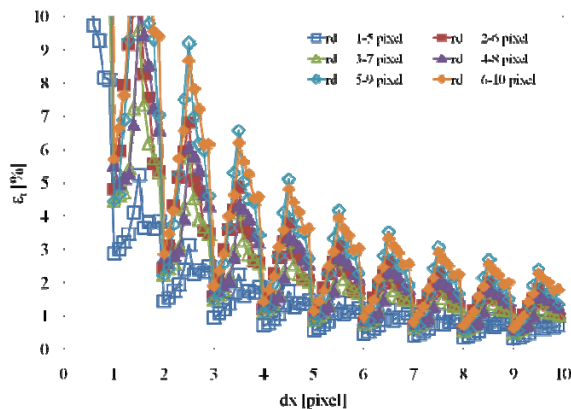


Figure-1. Effect of range of dot-radius (r_d) to the sub-pixel displacement (dx) [14].

In this work, in both types of images, images for several pure translation case were captured. The accuracy of a non-uniform displacement field is then evaluated by comparing the relative error of two different set of images having different value of pure translation case.

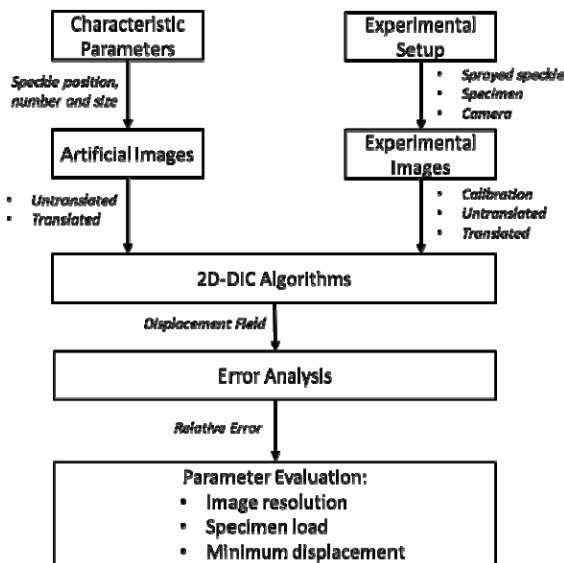


Figure-2. Evaluation method of the present research.

INPUT IMAGES

The initial step of DIC analysis was to provide input images to the DIC algorithms. In two-dimensional analysis, images were taken with a single camera. In the present configuration, the camera was in perpendicular direction to the specimen. As shown in Figure-2, the sources of input images for the present evaluation are artificial and experimental images. For the artificial images, displacement of the specimen was simplified into an ideal uniform translation motion. Hence, the first input image is the image before translation and the other input is the one captured after translation. For the experiment, the images were obtained from real specimen fitted to a

testing machine and being moved vertically. The accuracy of DIC results obtained from the experiment were then compared with the ones from artificial images to validate the evaluation result on the artificial images.

Artificial images in the present work were generated by using a Gaussian function. The function involved light intensity (I_p) and position (x, y) of the circular speckle on image and can be expressed as

$$I_p(x, y) = I_i \exp\left(-\frac{8}{d_i^2}((x - x_i)^2 + (y - y_i)^2)\right) \quad (1)$$

In Equation. (1), the known speckle parameters, subscripted by i , are maximum intensity on the center position (I_i), diameter of the speckle (d_i) and center position (x_i, y_i). Each speckle on the artificial image is assumed to have circular shape with uniform size. The number of the speckle in an artificial image is depend on the filled-pixels on the images. Ratio between total area of filled-pixels and image size determines the image density. The range of light intensity on images is scaled from 0 (black) to 255 (white) to represent grayscale-mode of images. Parameters of the generated artificial images on the present works is presented in Table-1.

Table-1. Artificial images parameters.

Image size [pixel ²]	500
Speckle number	30.000
Speckle radius, r [pixel]	2-5
Image density	0.97
Range of intensity value	0-255
Sub-pixel displacement [pixel]	0.1-1

In the experimental images, the speckle is not as uniform as in the artificial images, but the average size of the speckle is in the same order of the one from artificial image.

Figure-3 shows two modes of the two type of the evaluated images. Grayscale mode of the experimental image shows a lower sharp level due to noises. However, binary mode show a good similarity of the two images. Hence, the generated artificial images by using the present Gaussian function could be comparable to the experimental images.

CORRELATION AND SUB-PIXEL ACCURACY

The present algorithms of 2D-DIC utilized a normalized cross-correlation in order to find integer displacement of the translated images. It is a subset-template type of correlation. Intensity matrix of subset (A) from the untranslated image is correlated with a larger intensity matrix of template (B) on the translated image.

The size of A should be less than size of B . In order to minimize the effect of image noise, those images were subtracted with the mean value of the intensity as expressed in Equation. (2) and (3).



$$A = A - \bar{I}_A \quad (2)$$

$$B = B - \bar{I}_B \quad (3)$$

Normalized cross-correlation value (C) can be determined by using Equation. (4). The position of maximum normalized correlation value relative to the center position of the correlation matrix represents the integer displacement of the translated image (dx, dy). In order to increase accuracy of the measured displacements to the sub-pixel accuracy (dx', dy'), Gaussian interpolation

as in Equation. (5) and (6) were implemented in the present work.

$$C(i, j) = \frac{\sum_{m=0}^{M_A-1} \sum_{n=0}^{N_A-1} A(m, n) B(m+i, n+j)}{\sqrt{\sum_{m=0}^{M_A-1} \sum_{n=0}^{N_A-1} A^2(m, n) \sum_{m=0}^{M_B-1} \sum_{n=0}^{N_B-1} B^2(m, n)}} \quad (4)$$

$$dx' = dx + \frac{\ln C(i-1, j) - \ln C(i+1, j)}{2(\ln C(i+1, j) - 2 \ln C(i, j) + \ln C(i-1, j))} \quad (5)$$

$$dy' = dy + \frac{\ln C(i, j-1) - \ln C(i, j+1)}{2(\ln C(i, j+1) - 2 \ln C(i, j) + \ln C(i, j-1))} \quad (6)$$

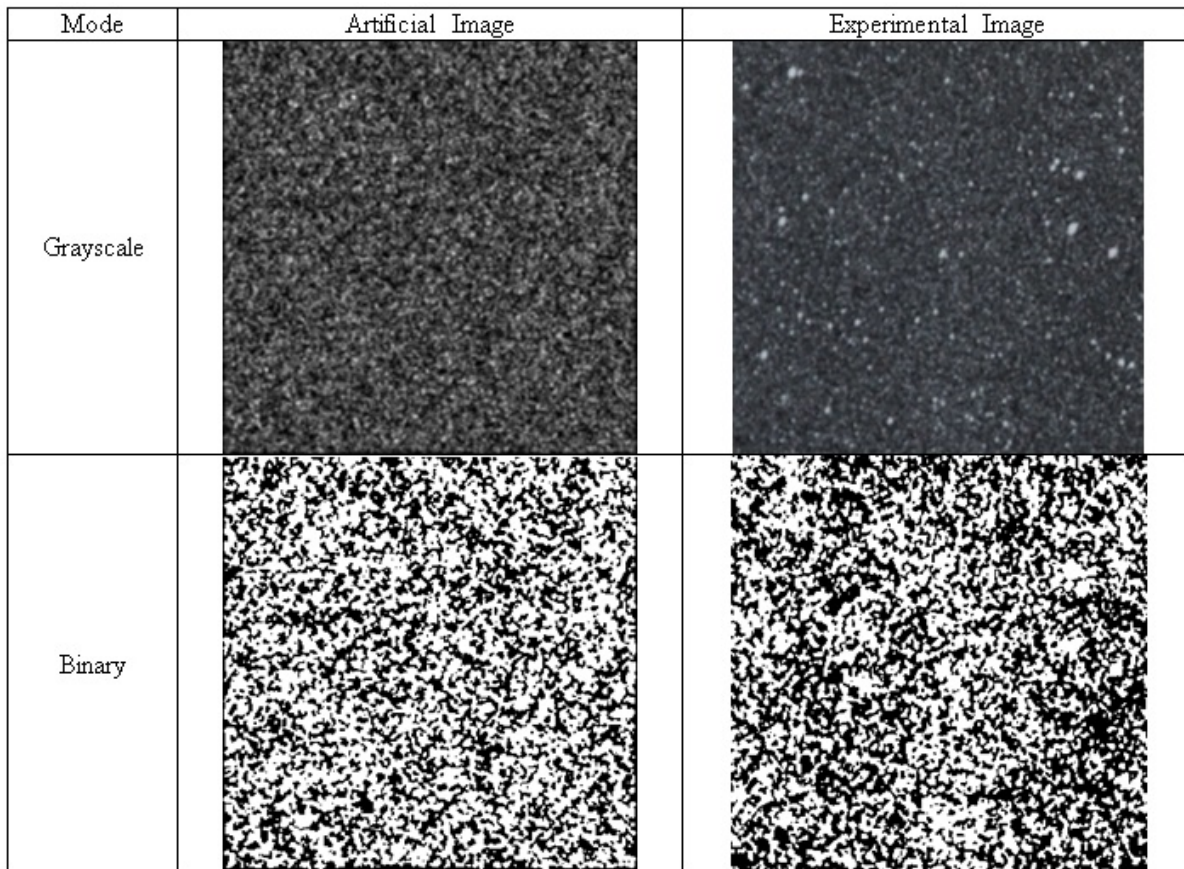


Figure-3. Grayscale and binary modes of the artificial and experimental images.

EXPERIMENTAL SETUP

The experimental translation test were performed to verify the results of the accuracy evaluation by using artificial images. The equipment of the present work consist of a Universal Testing Machine (Nexygen LRX Plus) to perform a controlled vertical translation on the specimen, a High Resolution Digital SLR Camera Canon EOS 20D as an image grabber, a speckled specimen, and a calibration board with checkerboard pattern. The setup can be seen in Figure-4.

ERROR ANALYSIS

The evaluations of the sub-pixel accuracy of the present algorithms were characterized by using bias error (BE) and relative error (RE). Those parameters represent the deviation of measured displacement (d_m) to the known initial displacement (d_i) and can be expressed as in Equation. (7) and (8).

$$BE = \varepsilon_{BE} = \frac{1}{n} \sum_{i=1}^n d_m - d_i \quad (7)$$

$$RE = \varepsilon_{RE} = \frac{\varepsilon_{BE}}{d_i} \quad (8)$$

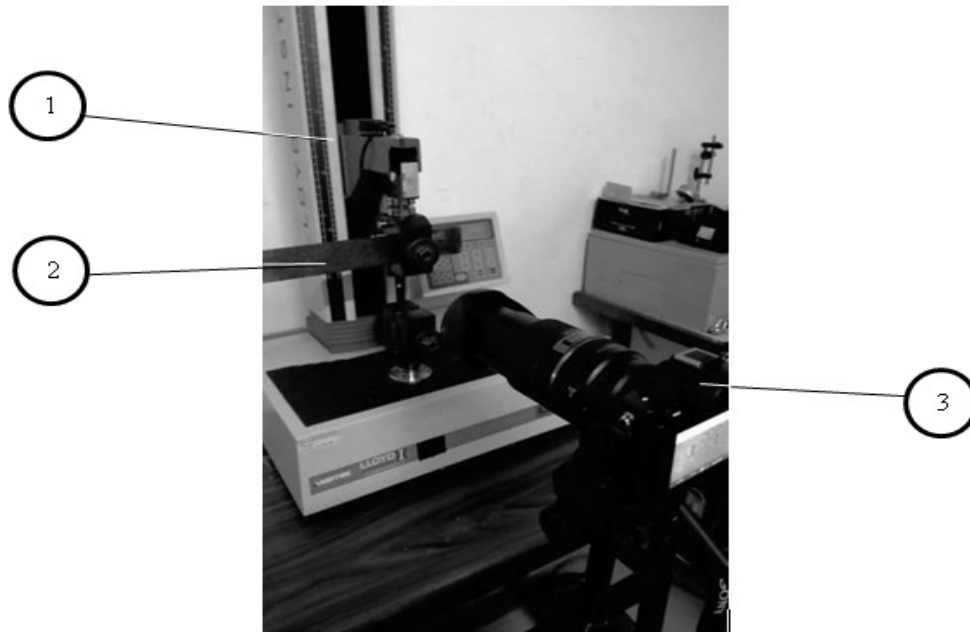


Figure-4. Experimental setup of the translation test: (1) Universal testing machine. (2) Speckled specimen. (3) Digital camera.

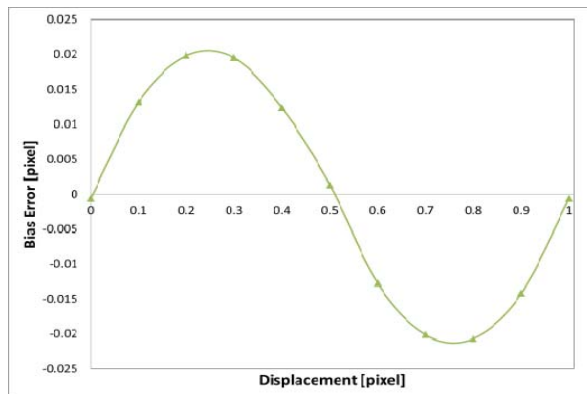
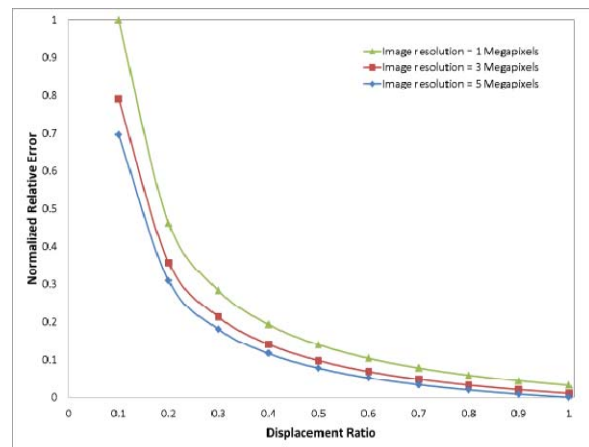
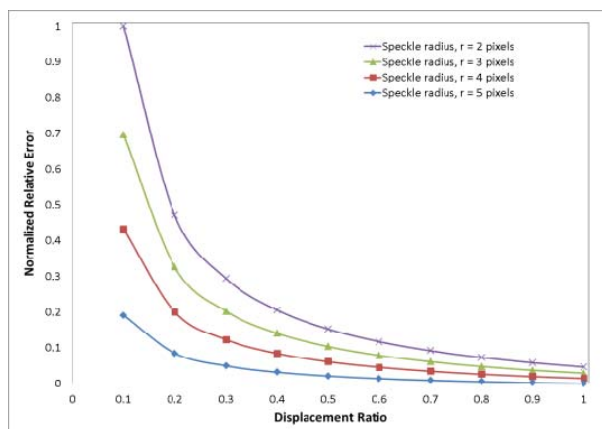


Figure-5. Bias error of the present 2D-DIC algorithms.



(b)

Figure-6. Effect of image resolution to the displacement ratio and normalized relative error. (a) Simulated 2D-DIC. (b) Experimental 2D-DIC.



(a)

RESULT AND DISCUSSION

Performance of the present 2D-DIC algorithms can be estimated by using simulated 2D-DIC with artificial images. Error characteristics in pure translation can be seen in Figure-5. Bias errors in Figure-5 are varied with the sub-pixel value of displacements. Bias errors show that integer displacements have a constant error in less than 0.001 pixel. It is also shown that maximum displacement deviation of the present algorithms is in the range of ± 0.02 pixel. The maximum displacement deviation occurs in 0.25 and 0.75 sub-pixel displacement.



Displacement ratio, D_R , in Figure-6 represents the ratio between minimum and maximum displacement on the analyzed image. The value of $D_R = 1$ occurs at the ideal translation case, in which all speckles on the image are translated uniformly.

Normalized relative error, RE_N , represents the ratio between relative error of minimum and maximum displacement for each displacement ratio, normalized with maximum relative error ratio in all displacement ratio.

On the present simulation result, translation with speckle radius, $r = 2$ pixels and $D_R = 0.1$ has the highest relative error, consequently it has $RE_N = 1$.

Simulated 2D-DIC in Figure-6(a). shows that increasing speckle radius (i.e. increasing image resolution) reduced the level of RE_N . It indicates the higher image resolution reduce DIC measurement error. The error reduction is significant for $D_R < 0.5$, especially for lower speckle radius. Hence, low image resolution can be used for cases with $D_R > 0.5$ without sacrificing accuracy significantly. Simulated data shows that when the minimum displacement in the area of interest is much smaller than the maximum displacement (very low displacement ratio or high non-uniformity of the displacement), reduction in relative error related with the image resolution.

Reduction in relative error due to higher image resolution was verified by the experimental data as shown in Figure-6(b). The significance of the image resolution on D_R has the similar trend as in the results using artificial images. Low resolution image can be used at $D_R > 0.5$. (very low displacement ratio or high non-uniformity of the displacement), increasing in image resolution will reduce relative error.

From this analysis, it can be said that in the cases in which a relatively uniform displacement field occurs (high displacement ratio), such as normal tensile test, the experiments does not necessarily required a high resolution images. However, experimental specimen in which has a low displacement ratio, e.g. in the case of higher stress concentration such as cracks or holes, higher resolution images is necessary in order to reduce the error of the displacement by 2D-DIC algorithms.

CONCLUSIONS

The present work has shown that image resolution affects the relative error of the displacement measurement by using DIC method. The trend is similar for results obtained from artificial images as well as the ones obtained from experimental images. When the minimum displacement in the area of interest is much smaller than the maximum displacement (very low displacement ratio or high non-uniformity of the displacement) the overall measurement accuracy will decrease. Hence at a highly non-uniform displacement field, the utilization of higher image resolution will reduce relative error significantly. Low resolution image can be used in cases where the displacement ratio is higher than 0.5.

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