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# Displacement measurement of specimen surfaces with damaged areas by digital image correlation

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ABSTRACT

A novel 2D digital image correlation technique is developed to calculate displacement of specimen surfaces with damaged areas. The effects of damaged areas in specimen surfaces to digital image correlation are investigated in this paper. In order to improve calculation accuracy and use all pixels sufficiently in subsets, coefficients are set to each pixel according to the qualities of them. With the calculation path which is from pixels with higher correlation to lower ones, the displacement calculation accuracy of the pixels near damaged areas is improved by the proposed method. The efficiency of the proposed method is tested by computer simulated images with random speckle. Compared with traditional DIC techniques which treat all pixels equally in a subset, the proposed technique is more suitable to specimen surfaces with damaged areas.



## 1. Introduction

Digital image correlation (DIC) [1–3] has been widely applied to measure surface deformation which is an optical technique based on image processing [4,5]. Displacements of specimen surface can be calculated from DIC with images which are captured during the deformation. Compared with traditional methods and some of the other optical techniques, DIC has significant advantages [6]. In the past several years, DIC has been improved significantly, including improving the accuracy, increasing the speed of computation and expanding the application range [7–9]. The accuracy of DIC is affected by many factors such as speckle quality, subset size, correlation criterion and etc. Some of the factors have been investigated by many researchers [10,11]. Usually, the gray level change of the same pixel in reference and target images should be small enough. However, the specimen surface may be damaged during the processing such as observation of rock structure, residual stress measurement and etc. Then, gray levels of some pixels in deformed images may be significantly different to which in reference images. DIC is sensitive to damaged areas of images, which leads to difficulty of tracking subsets in reference and target images.

Traditionally, regions of interest are defined before using DIC to a specimen surface with damaged areas. The pixels in the region are used to calculate deformations of the specimen surface while others are useless. There are many disadvantages of this method. First, it is difficult to define a valid region by simple geometric figures when the damaged areas are not regular. Second, all the pixels in a subset are treated equally no matter the importance

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of them to identify the target subset. The calculation accuracy of the pixels near the damaged areas will be affected by them.

We refined DIC techniques to use them for measurements with damaged areas. The basic principle of DIC is using pixels surrounding a point to identify it from target images. Our current focus is on using pixels efficiently in order to improve the measurement accuracy. First, the effects of damaged areas in images are investigated and all the pixels are treated separately. Coefficients are set to each pixel according to the importance of them to identify the target subset. Second, the calculation path is refined for the damaged images. In traditional DIC, the calculation path is from left to right and top to bottom of an image. The pixels in damaged areas may be calculated previous to others. Then, the calculation accuracy is inevitably affected by the damaged areas. In this paper, the calculation path is from pixels with higher correlation to others so that the effects of the damaged areas can be reduced.

The paper is organized as follows. The basic DIC method and the effects of damaged areas are present in Section 2. Section 3 details DIC for images with damaged areas. The correlation criterion with coefficients and the calculation path based on correlation are investigated. Section 4 presents experiments to test the proposed technique which use computer simulated images with random speckles.

## 2. Outline of digital image correlation

Random speckle patterns are used by DIC to obtain full-field displacements of specimen surfaces [12]. The basic principle of DIC is shown in Fig. 1. An essential step is searching the same points between reference and target images by matching subsets. Typically, a subset is selected from the reference image, then the location of it in the target image is calculated [13]. The deformation of the central pixel can be calculated from the positions of the subset in reference and target images.

The correlation criterion is critical for DIC which is predefined to calculate the similarity between reference and target subsets. Different definitions of correlation criterion have been proposed by researchers such as normalized cross-correlation, sum of squared differences and etc. [14,15]. Zero-mean normalized cross correlation (ZNCC) is used in this paper as it is robust to image noise and illumination lighting.

$$C = \sum_{i=-M}^{M}\sum_{j=-M}^{M}\left\{\frac{[f(x_i,y_j)-f_m]\times\left[g\left(x_i',y_j'\right)-g_m\right]}{\Delta f\Delta g}\right\}, \quad (1)$$

where $f(x_i,y_j)$ is the gray level at coordinates $(x_i,y_j)$ in the reference subset, $g(x_i',y_j')$ is the gray level at coordinates $(x_i',y_j')$ in the deformed subset. $f_m$ and $g_m$ are the mean intensity of reference and deformed subsets respectively.

$$f_m = \frac{1}{(2M+1)^2}\sum_{i=-M}^{M}\sum_{j=-M}^{M} f(x_i,y_j),$$
$$g_m = \frac{1}{(2M+1)^2}\sum_{i=-M}^{M}\sum_{j=-M}^{M} g\left(x_i',y_j'\right),$$

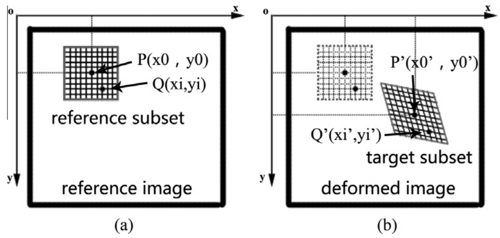


**Fig. 1.** Basic principle of DIC (a) A reference subset in the reference image; (b) The target subset in the deformed image.

$$\Delta f = \sqrt{\sum_{i=-M}^{M}\sum_{j=-M}^{M}[f(x_i,y_j)-f_m]^2},$$
$$\Delta g = \sqrt{\sum_{i=-M}^{M}\sum_{j=-M}^{M}\left[g\left(x_i',y_j'\right)-g_m\right]^2}. \quad (2)$$

Compare to other optical techniques, DIC has fewer requirements on measurement environment. However, the accuracy of DIC is still affected by many factors such as speckle pattern, deformation of specimen surface and etc. [16]. Some basic requirements must be met for use of 2D DIC: (a) The surface of specimen should be flat, (b) out-plane deformations should be small enough to be neglected and (c) the positions of camera and specimen surface should be parallel. DIC is also sensitive to damaged areas of images during processing, which lead to difficulty of tracking subsets in reference and target images, as well as yielding calculation errors. The correlation of pixels in reference and target images will reduce if the specimen surface is damaged. What's more, correlation methods will not work for completely damaged areas since they are not the same pattern before and after deformation. In some situations such as crack detection or drilling measurement, the deformations of pixels near damaged areas are extremely important [17,18]. Then, it is worth to improve the calculation accuracy of them. It's difficult to improve the calculation accuracy of pixels in damaged areas since the information of them has lost. However, which of the pixels near the damaged areas can be improved if the pixels in subsets are used more efficiently.

A subset near a damaged area with $11 \times 11$ pixels is shown in Fig. 2. The qualities of the pixels at the right top corner are much lower than others. The calculation result will be affected by the low quality pixels since all the pixels are treated equally in traditional DIC. To improve the calculation accuracy, the correlation of the central pixel should be mainly determined by high quality pixels. Thus, it is necessary to study the qualities of pixels and treat them separately in the correlation criterion.

## 3. Digital image correlation for images with damaged areas

### 3.1. Correlation criterion with coefficients

Traditionally, the gray levels of each pixel are assumed not change during the deformation. The correlation criterion is used to calculate the correlation degree based on the difference of pixels in a subset. The reliability of the