Studies on the influence of speckle density on the accuracy of digital image correlation method based on numerical simulation

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Abstract. Digital image correlation method is a high-precision non-contact modern optical mechanics method whose measurement accuracy is directly affected by the quality of the speckle pattern used. In this paper, a numerical simulation experiment is designed to measure and analyze the accuracy of DIC method using speckle patterns which are generated with different speckle densities. The results show that the measurement error of DIC decreases first and then increases with the increase of speckle density, and the error is minimum when the duty ratio is about 60% to 70%. The result show that in practical application the duty ratio of speckle on the specimen surface should be appropriately high, preferably between 60% and 70%. This study is helpful for speckle selection and related research in practical application.

1. Introduction

Digital Image Correlation (DIC) [1] is a non-contact modern optical mechanics method with simple measuring equipment, strong environmental adaptability, convenient implementation and high measurement accuracy. Now DIC method is attracting more and more attention in the fields of experimental mechanics and material property analysis, and has been more and more widely used [2, 3].

DIC is to obtain the deformation information using two speckle digital images of the specimen before and after deformation through correlation calculation. The surface of the tested specimen shall have a speckle field with random distribution as the carrier of displacement information. The basic principle is to subdivide the image before deformation into subregion, and then the correlation calculation is carried out according to the predefined correlation function according to a certain search method for each subregion. In the deformed image, the region with the maximum correlation coefficient with the subregion is found, which is the position of the subregion after deformation, so as to obtain the displacement of the subregion. The deformation information of the whole field can be obtained by calculating all the subregions. Since the DIC method was proposed by Yamaguchi[4] and Peters [5] in the early 1980s, scholars have carried out extensive research. The related theories of DIC are constantly enriched and improved, and its related applications have developed rapidly in recent years to meet the actual needs of scientific research and engineering applications. However, in practical application, the digital image correlation method based on digital speckle image is limited by
speckle quality. At present, there is no specific unified standard for speckle selection in engineering applications.

DIC is based on digital image, and the speckle pattern used directly affects the measurement accuracy. In practical engineering applications, speckle is usually manually made on the surface of the specimen, and the speckle patterns obtained with different densities are different, which affects the measurement accuracy of DIC. It is of great theoretical and practical significance to study the influence of speckle density on the accuracy of digital image correlation method, which can greatly promote the application and development of digital image correlation method. However, there are few relevant researches now. In order to solve this problem and provide some guidance for speckle selection in practical engineering experiments, the influence of speckle density on the accuracy of digital image correlation method is studied in this paper.

In this paper, simulation experiments are designed to generate speckle patterns with different speckle densities. Speckle pattern sequences with sub-pixel displacement are used to compare the measurement accuracy of the DIC using speckle patterns with different speckle densities, and the errors of measurement are analyzed. Finally, the conclusion is drawn that the speckle density will affect the measurement accuracy of DIC method. The measurement error of high density speckle is generally lower than that of low density speckle. With the increase of speckle density, the measurement error of DIC method shows a trend of decreasing first and then increasing, and there is an optimal speckle density to achieve a minimum error. For the speckle patterns used in this paper, the optimal speckle duty ratio is around 60% to 70%. The conclusions of this study can provide guidance for the selection of speckle in engineering practice and support the research of related aspects.

2. Principles of digital image correlation

DIC method measures the deformation of the test specimen by matching the corresponding subregion of the image before and after the deformation, and the surface of the measured specimen needs to be distributed with speckle field. The speckle field on the surface of the specimen can be its own natural texture or artificial speckle. In the process of measurement, the speckle field and the surface of the specimen deform together to show the deformation information of the measured specimen.

DIC matches the corresponding subareas according to the matching rule of correlation coefficient, and carries out correlation calculation on the subregion in the image before and after deformation. The position with the maximum value of the correlation coefficient is determined to be the position of the corresponding subregions in the digital image after deformation.

The specific matching process is shown in Figure 1. A rectangular region of \((2M+1) \times (2M+1)\) with the displacement point \((x, y)\) as the center is selected as the reference subregion in the digital image, and the correlation function \(C(x, y)\) is calculated at each position of the digital image after deformation to judge the similarity degree of the region in the image before and after deformation. The position of the image subregion in the deformed image can be determined by searching the extreme point of the correlation function, then the corresponding subregion centered on point \((x', y')\) can be obtained. The difference of coordinates between the center point \((x', y')\) of the image subregion after deformation and the center point \((x, y)\) of the original image subregion is the magnitude of displacement \(u, v\).

![Figure 1. The basic principles of digital image correlation.](image-url)
3. Numerical simulation experiment

In this chapter, numerical simulation experiment is used to study the influence of speckle density on the accuracy of DIC method. In order to simplify the experiment, only the horizontal displacement of speckle pattern is considered. A computer program was used to generate speckles with different duty ratios. A total of 8 sets of speckles were generated with duty ratios ranging from 20% to 90%. There are 11 speckles in each group, including 1 reference speckle pattern and 10 speckle patterns obtained by multiple displacement of the reference speckle pattern. The displacement of the two adjacent speckle patterns is 0.1 pixel, and the maximum displacement is 1 pixel.

The size of the reference speckle image is 300×300 pixels, the speckle radius is 4 pixels, and the variation is 40%. After generating speckle patterns, Gaussian noise with mean value of 0 and standard deviation of 4 was added to all speckle patterns. DIC program [6] was used to calculate the displacements of speckle patterns in each group, and the accuracy of the calculated results was obtained. In order to ensure the accuracy of the results, different sub-area sizes were set for multiple experiments. The radius of the experimental subset was set at 10 pixels, 15 pixels, 20 pixels and 25 pixels respectively. In order to reduce the influence of the speckle pattern boundary during measurement, the region of interest in the experiment was selected as the (H/2)×(W/2) pixel area of the image center to calculate the displacement, where H and W were the height and width of the speckle pattern respectively.

![Program generated reference pictures.](image)

The error of DIC is divided into systematic error and theoretical error. Among them, the systematic error is mainly generated by interpolation algorithm [7], which is a defect of the system itself. Systematic error can be evaluated by mean bias error. The formula of mean bias error is:

\[ u_c = \frac{1}{N} \sum_{i=1}^{N} u_i - u_i \]

The random error is caused by noise [8], which is a random fluctuation of a single measurement result relative to its mean value. The random error can be evaluated by the standard deviation of the error, which is expressed as:

\[ u_{std} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left( u_i - \frac{1}{N} \sum_{i=1}^{N} u_i \right)^2} \]
In Formula (1) and Formula (2), $u_e$ is the mean bias error, $u_{\text{std}}$ is the standard deviation, $u_i$ is the measured sub-pixel displacement, $u_t$ is the actual sub-pixel displacement, and $N$ is the total number of pixels. The systematic error usually presents the shape of a sinusoidal curve with a period of 1 pixel. In this paper, the peak value of the systematic error in the period of 1 pixel is used to measure the magnitude of the systematic error.

The total error of DIC method is equal to the sum of the systematic error and the theoretical error. The formula of the total error $U$ is as follows:

$$U = |u_e| - u_{\text{std}}$$

The results of the simulation experiment are shown in the figure followed:

Figure 3. Experimental results. The subregion radii in (a), (b), (c) and (d) are 10 pixels, 15 pixels, 20 pixels and 25 pixels respectively.

Figure 3 shows the total errors of the experimental measurement results of each group. It can be seen from the figure that, on the whole, the errors decrease first and then increase with the increase of speckle density, and the errors are minimum when the speckle duty ratio reaches about 60%-70%. When the speckle duty ratio is greater than 50%, the measurement error of DIC is significantly smaller than that of the case where the speckle duty ratio is less than 50%, and the effect of using the high-density speckle pattern is significantly better than that of the low-density speckle pattern. Selecting a larger subregion can effectively reduce the error but has little effect on the trend of the error changing with speckle density.
4. Conclusion
The measurement accuracy of DIC is affected by the speckle pattern used. In this paper, the influence of speckle density on the measurement accuracy of DIC is studied by numerical simulation experiment. The simulation results show that, overall, the effect of using high density speckle is obviously better than that of low density speckle. With the increase of speckle density, the measurement error of DIC shows a trend of decreasing first and then increasing, and there is an appropriate speckle density to minimize the error. For the speckle pattern used in this paper, the measurement error of DIC is minimum when the speckle duty ratio reaches about 60% to 70%. In practical application, the speckle density on the surface of the tested piece should be kept high, and the speckle duty ratio should be kept between 60% and 70%. In addition, for the low density speckle, the measurement error of DIC can be effectively reduced by appropriately increasing the size of subregion in the calculation.

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