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Speckle pattern quality assessment for digital image correlation

G. Crammond, S.W. Boyd, J.M. Dulieu-Barton *

University of Southampton, Engineering Sciences, Southampton SO17 1BJ, UK

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ABSTRACT

To perform digital image correlation (DIC), each image is divided into groups of pixels known as subsets or interrogation cells. Larger interrogation cells allow greater strain precision but reduce the spatial resolution of the data field. As such the spatial resolution and measurement precision of DIC are limited by the resolution of the image. In the paper the relationship between the size and density of speckles within a pattern is presented, identifying that the physical properties of a pattern have a large influence on the measurement precision which can be obtained. These physical properties are often overlooked by pattern assessment criteria which focus on the global image information content. To address this, a robust morphological methodology using edge detection is devised to evaluate the physical properties of different speckle patterns with image resolutions from 23 to 705 pixels/mm. Trends predicted from the pattern property analysis are assessed against simulated deformations identifying how small changes to the application method can result in large changes in measurement precision. An example of the methodology is included to demonstrate that the pattern properties derived from the analysis can be used to indicate pattern quality and hence minimise DIC measurement errors. Experiments are described that were conducted to validate the findings of morphological assessment and the error analysis.

1. Introduction

Digital image correlation is a white light technique based on the comparison of images before, during and after the deformation of a test specimen, typically acquired using a monochromatic CCD camera. The images are divided into a grid of interrogation cells or subsets containing a finite number of pixels. The spatial resolution and accuracy of the displacements are limited by the total number of pixels within the image. DIC uses a correlation algorithm to obtain the displacements by identifying areas of matching grey scale values between the speckle pattern in each subset of the deformed and undeformed images. The position where the correlation function value is maximised in the deformed image corresponds to the movement of the pattern during deformation. To facilitate the correlation a stochastic speckle pattern is applied to the specimen surface to provide random grey level variations, the quality of which is fundamental to the precision of the measured displacement data. Spatial resolution of the data is maximised by reducing the size of the subsets, but as the interrogation cell size decreases, the uncertainty in the strain measurement increases due to a reduction in the number of features to track within the subset [1].

The majority of research into the accuracy of the DIC technique has focused on the many different correlation algorithms and processing parameters, such as subset size [2], shape function selection [3] and methods of obtaining sub-pixel accuracy [4]. Less attention has been paid to the effect of the quality of the speckle pattern on the measurement accuracy of the DIC technique, particularly, differences due to changes in the spatial resolution of the image. It is also important for the speckle pattern to be matched to the expected displacement field to maximise measurement accuracy, as speckles can be both too large and too small for accurate measurement [5]. In references [6,7] patterns with a range of speckle sizes, applied using different methods were examined. Haddadi and Belhabib [6] identified that finer patterns with more speckles and more 'randomness' performed better in comparison to larger 'dotted' patterns in ridged body motion tests. Barranger et al. [7] noted the importance of matching the pattern to the expected deformation, with differences between pattern types becoming greater at larger levels of strain. The reasons behind the performance differences for the patterns were not assessed, nor were the suitability of the patterns tested for different applied strain levels, allowing only qualitative conclusions to be made which cannot be used to benchmark pattern quality.

A number of pattern assessment criteria have been presented in the literature, generating a range of different pattern quality measurement parameters. These parameters do not provide the definition of a perfect pattern to be used, as there is insufficient

* Corresponding author. Tel.: +44 2380596522.
E-mail address: janice@soton.ac.uk (J.M. Dulieu-Barton).

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control in the application of the speckle pattern or imaging methods to consistently achieve the same quality of pattern from user to user. Rather the parameters are best used as comparative assessment tools to inform application methods and inform error analyses of DIC measurements. Broadly these metrics can be separated into global and local assessments. Measures such as the sum of squared subset intensity gradients [8] and mean intensity gradient [9] have both been developed directly from an understanding of the sum of squared differences correlation algorithm, measuring pattern quality locally at each pixel location. However these two parameters are presented as a summation and a mean of the image intensity gradients at each pixel location within the entire image. This approach provides global measures from local criteria. The summation and mean values are not considered to be appropriate as the speckle pattern is stochastic across the region of interest and unrepresentative of the pattern quality, as there is no indication of the variation in quality across the image. This is important as the values can be significantly biased by areas with anomalously high or low intensity gradient values. The mean subset fluctuation [10] and subset entropy [2] provide metrics which assess the difference between the grey level of each pixel within the image to the mean grey level value of each subset, and the grey level values of the eight surrounding pixels at each location. These metrics are also calculated locally within the subset, and then presented as a mean, global, value for the whole of the image, ignoring variation between subsets in the pattern.

Morphological approaches have been used to apply local analysis of pattern quality based upon the physical properties of the pattern, such as the size and frequency of the speckles within the pattern [5,11]. Typically this is undertaken using an image thresholding technique, converting all pixels with grey levels above/below a certain threshold value into black and white values to form a binary image of the pattern. The thresholding method is a fast and practical solution, but can fail to identify the true edge of shapes in patterns. Alexander et al. [12] noted that the size and shape of the generated binary speckles are highly dependent upon the chosen grey level threshold value, which can result in the edge of the speckles being poorly defined and not representative of the actual speckle size or shape. The threshold method also prevents the identification of discrete speckles below/above the threshold values, which is especially evident where there is a very broad grey level distribution, or where the edges of the speckles are very soft. These local measures are more adept at quantifying differences between patterns due to changes in the application method or pattern style i.e. black paint on white background and vice versa, both of which are important considerations for experiments with different materials and scales. Importantly, using these morphometric techniques, the local information from within the pattern is not lost or masked in the attempt to form a global parameter from what are highly variable and complex analysis problems. As a result the local, morphometric, pattern analysis approach is used in this paper. For completeness a summary of recently used global and local pattern assessment criteria is provided in Table 1.

The aim of the present paper is to identify the relationship between the size and density of the speckles locally within an interrogation cell. The relationship is used to show that the morphometric properties, such as size, shape and distribution of the speckles in the pattern are an important indicator of pattern quality. An image processing approach is developed to analyse the properties of a number of speckle patterns, showing fundamental changes to the pattern as magnification levels and spatial resolution are increased. In the present paper a case study is presented that uses the morphological analysis to identify the most suitable pattern application method when conducting 2D DIC at the mesoscopic scale using magnifying optics. Under high levels of magnification the appearance of the patterns changes significantly, resulting in very different patterns to those viewed with lower magnification. The errors in the DIC measurements at this high magnification level are shown to be large due to the sparseness of the patterns. The local analysis demonstrates large differences in the properties of the speckles within the pattern's grey level between application methods. It is shown that a change from a spray paint to an airbrush has a large beneficial effect on the overall measurement error. This is supported by simulations of pattern deformations and experimental validation against strain gauge readings, which provide excellent agreement with the predicted results from the morphological assessment.

Table 1
Review of recent pattern assessment criteria.

	Pattern assessment criteria	Global	Local	Pros	Cons
Sum of square of subset intensity gradients [8]	$SSSIG=\sum_{i=1}^{N}\sum_{j=1}^{N}[f_{x,y}(x_{ij})]^2$	X		Intensity gradients directly used in the sum of squared differences correlation procedure Provides a direct measure between the pattern and correlation process.	Total value for image does not show variability within the pattern SSSIG does not describe how or why patterns are different to each other—difficult to comparatively analyse application methods.
Mean intensity gradient [9]	$\delta_f=\frac{\sqrt{f_x(x_{ij})^2+f_y(x_{ij})^2}}{WH}$	X		Intensity gradients directly used in the sum of squared differences correlation procedure.	Mean value for image introduces bias as the calculation as it does not show variability within the pattern.
Mean subset fluctuation [10]	$\frac{S_f=\sum_{P\in F}\sum_{i=1}^{3}\sum_{j=1}^{3}\left\|a_{ij}-\overline{a}\right\|}{HV}$	X		Compares pixel grey level values to the mean grey level value of each subset. Provides a measure of contrast within the pattern.	Mean value for image does not show variability within the pattern. Bias towards patterns with very high contrast where $\|a_{ij}-\overline{a}\|$ is maximised. Cannot distinguish influence of speckle size i.e. one large speckle of size 50 pixels in the subset will yield same results as 10 speckles each with an area of 5 pixels distributed within the subset.
Subset entropy [2]	$\frac{\delta=\sum_{P\in s}\sum_{i=1}^{8}\left\|I_P-I_i\right\|}{2^{\beta}MN}$	X		Identifies differences between each pixel to its surrounding 8 pixels grey levels giving an indication of the fluctuation, or 'randomness' of the pattern.	Mean value for image does not show variability within the pattern.
Speckle radius distribution [11]	Image thresholding		X	Fast and easy to implement.	Speckle radius does not account for speckle shape which influences speckle size. Threshold method inaccurate.
Average speckle size [5]	Image thresholding		X	Fast and easy to implement.	Average speckle size does not show variability within pattern. Threshold method inaccurate.