A COMPARATIVE STUDY OF RANDOM PATTERNS FOR DIGITAL IMAGE CORRELATION

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Abstract. Digital Image Correlation (DIC) is a computer based image analysis technique utilizing random patterns, which finds applications in experimental mechanics of solids and structures. In this paper a comparative study of three simulated random patterns is done. One of them is generated according to a new algorithm, introduced by the authors. A criterion for quantitative evaluation of random patterns after the calculation of their autocorrelation functions is introduced. The patterns' deformations are simulated numerically and realized experimentally. The displacements are measured by using the DIC method. Tensile tests are performed after printing the generated random patterns on surfaces of standard iron sheet specimens. It is found that the new designed random pattern keeps relatively good quality until reaching 20% deformation.

Key words: digital image correlation, correlation coefficient.

1. Introduction

The Digital Image Correlation (DIC) reached its “maturity” during the last years owing to the fast and successful development and elaboration of computers, digital cameras and specialized software for image processing. This fact is proved by the significant growth of the number of publications dealing with DIC and its applications. One of the pioneers in elaborating and applying a technique that utilizes random patterns for measurement of displacements and deformations defines it as “a major development in the art of experimental mechanics” [1]. He notes that the DIC genesis has its roots in the technique of
Speckle-photography, introduced by Burch [2, 3] also known as “single beam speckle interferometry”.

Speckle photography owes its birth to laser speckle patterns [4], which are observed in front of diffusely reflecting surfaces illuminated by coherent light. Almost at the same time it was found that the speckle photography procedure can also be realized by processing images of rough surfaces or surfaces with sprayed white spots on a dark background and illuminated by low coherent up to “white light” sources [5]. A theoretical description of the physical nature of “white light speckle photography” and its applications in solid mechanics was presented in [6]. Variety of methods for artificial generation of white-light speckle images on material and structure surfaces, applying paint spray, pilling retro pain structures, coupling metal particles with appropriate dimensions etc., were studied for example in [7].

Speckle-image direct registration in a computer memory at different moments of time, when tracking processes in solids or fluids, provides opportunity to facilitate the implementation of DIC [8]. With the DIC method two speckle images are compared. The initial (reference) image (the so called “Zones of Interest” – ZOI) is divided into “subsets”. ZOI is the region in which we want to determine the displacement/deformation field. One ”subset” is a square matrix of pixels used as basis of the image correlation technique. A correspondence of each reference subset to the respective calculated subset at the second (deformed) image is then established by defining the maximum value of the correlation coefficient [9].

A significant advantage of DIC is its capability to use natural variations of the image grey level, corresponding to the structure of the studied surface [10]. Hence, this method handles effectively images of artificial random patterns, painted on the surfaces of interest [11], as well as images obtained through optical [12, 13] and electron microscopy [8], atomic force microscopy [14], X-ray technique [15], etc. DIC provides a unique opportunity displacement and deformation fields in macro-, mezzo-, micro-, and nano-scales to be measured.

An important point is that a large number of experimental problems can be solved employing DIC [11, 12, 13, 16, 17, 18] performing correlation analysis of artificial random patterns, while spraying is widely used to create such patterns on surfaces.

In references [9, 19, 20, 21] it is studied how spray spot distribution regarding size and density, as well as ZOI size and the correlation coefficient, affects the measurement accuracy of homogeneous and non-homogeneous deformations and processing duration. Since spraying can hardly create speckle
patterns with in advance known characteristics, a necessity for numerical generation and printing of random patterns on a surface arises. We would like to note that the actuality of this matter is discussed in [9], while the present work aims at the initiation of such studies.

2. Computer generated random patterns

As noted above, applying artificial random patterns on specimen surface is performed most frequently by spraying. This technique is easily realized but can hardly control the random pattern characteristics. We perform comparative studies of three simulated random patterns. One of them is generated following a new algorithm introduced by the authors. A criterion for quantitative evaluation of random patterns and characterization of their effectiveness in the case of DIC algorithm implementation on one hand, and pattern printing on the surfaces of interest on the other, are introduced. In this way distribution of spots with respect to average diameter and location on the studied surface can be controlled and optimized in accordance with the requirements of each particular experiment. Three types of patterns are numerically generated. A subset size of 64 × 64 pixels is chosen. As known, the use of subset with the largest dimension improves the accuracy of subset localization within the respective (deformed) image [9, 19]. Yet, the increase of subset dimensions leads to the increase of computation time. An acceptable compromise proves to be the subset dimension selected herein. The numerically generated images of speckle patterns posses a maximal contrast – i.e. they consist only of white and black spots. Such patterns are shown in Fig. 1. A random pattern, almost similar to speckle pattern obtained by illuminating a rough surface with laser light is shown in Fig 1(a). This image is created using a generator of random numbers and a statistical distribution of white and black within the frame area (i.e. a visualization of the so called “white noise” is shown in this case) [22]. The image is transformed into grey scale. After that, the image is filtered by a “low-pass” filter whose threshold frequency defines speckle averaged size. The images are binarized to increase the contrast of. When dealing with values of pixel intensity in the interval [0-255], we chose a threshold value equal to 128.

The computer generated random patterns shown in Fig. 1(b) corresponds to a random pattern, obtained by spraying a dark surface with a white paint. Speckle distribution density is defined as a ratio of the integral spots area to the total frame area (0.5 in this case). Actually, white spots are equal in size. Their statistical random distribution on the surface determines the image random character. At the same time it introduces lower spatial frequencies into the pattern owing to randomly arising spot aggregations. It is
possible several spots to be at one and the same location, and no a spot gets into some of the frame subsets. This could be considered as a disadvantage of such random pattern.

Figure 1(c) presents a pattern in which the spots are generated in three stages [22].

1) Chosen in advance, a number of spots with diameter $d_{\text{max}}$ are randomly distributed in each subset. The distances between these spots should guarantee their non-overlaying or touching. Each new spot is checked for overlaying.

2) Spots having smaller diameter are added in the free areas between the bigger spots. The coordinates of their location are created by random number generator. Again, each spot should be clearly outlined.

3) The procedure is repeated many times with smaller spots, until attaining a spot diameter $d_{\text{min}}$ and maximal possible density of non-overlaying spots in a frame.

Thus generated pattern exhibits a random character. It is expected that non-overlaying spots and the maximal density of spots with different diameters within the frame would provide greater accuracy and reliability of ZOI displacements measured by DIC due to the evolution of the compared images during the deformation process. The presence of spots with different dimensions would yield a correlation function with a sharp peak and relatively wide base.

The possibility of using the three types of images in Fig. 1 to measure deformations via the DIC is assessed comparing image cross-correlation functions. Here a classical definition of a correlation function is used [23].

\begin{equation}
C_{fg}(u,v) = \frac{1}{N} \sum \sum f(i,j) g^*(i+u,j+v) \tag{1}
\end{equation}
where functions $f$ and $g$ are the gray values of the subset centre at the source and target point located in the reference and deformed images; $u$ and $v$ are the displacement of the subset centre along $i$ and $j$ direction; “$^*$” denotes a complex conjugation.

In Fig. 2 it is well seen that the difference between the main and secondary peak values of the respective correlation coefficient $C$ is the largest for the random pattern III. At the same time background variations are smaller. Therefore a more accurate localization of the correlation peak can be attained using this pattern. In addition the figure shows that the expectations for a sharp and narrow correlation peak are justified as a result of using pattern III.

3. Numerically simulated deformation of images

Deformation is simulated by consecutively applying deformation steps of 10% until reaching 50%. The frame left hand side is fixed but its right hand side moves uniformly along the frame horizontal axis. It is assumed that the Poisson ratio is zero. Deformation results in motion of respective subset centres and translation of the correlation peak in accordance with the
Fig. 3. Correlation function of pattern III changes in accordance with the deformation consecutive steps.

This effect is visualized in Fig. 3 for pattern III (shown in Fig. 1). Cross sections passing through the main and the secondary peaks of consecutive correlation functions calculated at several deformation steps are plotted within the same coordinate system. It is clearly seen that the correlation peak sharpness and the height decrease and gradually disappear due to the change of ZOI images as a result of the deformation applied.

We introduce a parameter $q$ to estimate the quality of random patterns, which affects the effectiveness of digital image correlation procedure. It is defined by

\[
q = \frac{C_{\text{max}} - C_{\text{sec}}}{S(C)}
\]

where $C_{\text{max}}$ is the main peak values and $C_{\text{sec}}$ is secondary peak values of the respective correlation function (see Fig. 3); $S(C) = \sqrt{\frac{\sum_{i=1}^{n} \sum_{j=1}^{n} (C_{ij} - \bar{C})^2}{n^2 - 1}}$ is standard deviation, where $C_{ij}$ is the correlation coefficient of each point and $\bar{C}$ is the mean correlation coefficient of the subset.

The proposed measure of quality proves to be reliable in finding a global maximum value of a correlation function close to a straight line, although that this value would be much smaller than the one corresponding to another function of the type shown in Fig. 3.
A dependence of parameter $q$ on the deformation degree is numerically found and presented in Fig. 4 for all the three studied random patterns. As seen, the quality of pattern III is relatively the best one according to equation (2) and for deformations up to about 25%. It enables one to clearly localize a correlation peak under a higher degree of deformation. Image I imitates a laser speckle pattern and its quality is the worst one when applying the same criterion.

4. Experimental verification

Axial tensile tests of specimens having standard form and dimensions [24] are carried out. The specimens are cut from a low carbon steel sheet with 0.5 mm thickness, and their “working area” is $80 \times 12.5$ mm$^2$. Each of the three random patterns (Fig. 1), generated and investigated numerically, is screen printed on the surfaces of specimens – Fig. 5. A standard testing machine type “Instron” is used, applying maximum tensile force of 100 kN and uniform deformation velocity of 0.1 mm/s. As a result of the tensile deformation, samples increase their length and decrease their width. The global parameters of deformation are defined through the dependence “applied tensile force – displacement of the machine moving traverse”, which is being recorded in “real time” until specimen fracture. A digital camera Canon G10 (focal length 6.1–30.5 mm, aperture f/(2.8–4.5), 15 Mpixel matrix) is used to register the working surface of the patterned specimens during testing. The camera optical axis is adjusted to be orthogonal to the studied surfaces, which are illuminated by “white light”. Special arrangements are not made for uniformity of illumination.
Digital image correlation procedure is performed on a selected (64 × 64 pixels) sub image of the studied surface, captured by a digital camera with 28 pix/mm resolution. The entire deformation process is tracked by taking twenty sequential images of the specimen working surface, recorded at time intervals of 10 s. A total deformation of about 50% is attained until fracture of each sample.

Software within “Microsoft Visual C++” environment, developed by the authors, is used to process the stored images. Before applying the DIC algorithm, the images are binarized. This procedure affects significantly the value of the quality parameter $q$ related to the random patterns (Eq. 2), eliminating the illumination non-uniformity and the other effects owing to the different reflective properties of the different surfaces.

Autocorrelation functions of the three types of random patterns, screen printed on the specimens surfaces and stored immediately before the start of the respective tensile experiment, are presented in Fig. 6.

A comparison of the autocorrelation functions in Fig. 6 shows that the basic difference between them shown in Fig. 2 as well as that the quality parameter $q$ of the random patterns, remain almost the same. Figure 7 illustrates the dependence between the quality parameter $q$ of the printed random patterns and the degree of specimen’s real deformation.

Figures 7 and 4 show that the quality of patterns is decreased when performing physical experiments. These effects can be related to noises in-
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Fig. 6. Autocorrelation functions of the three types of random patterns, printed on the specimen surfaces: (a) pattern I; (b) pattern II; (c) pattern III

Fig. 7. Dependence of parameter $q$ upon the real specimen deformation

Produced in the images and due to non-uniformity of the surface illumination, digital camera operation, as well as to environmental noise sources.
5. Conclusions and discussions

The physical implementation of the digital image correlation method to perform measurements of macro- and mezzo- deformations can be significantly simplified when the surface of interest is painted by spray. Artificial speckle patterns, created employing such a relatively easy procedure, are widely used when applying the DIC method in experimental mechanics. Yet, the spray technique provides a limited possibility to create random patterns with desired characteristics. Three random patterns with different textures have been generated numerically in this work. Comparative studies of the shape of their autocorrelation functions and of the behaviour of their cross-correlation functions under several degrees of simulated tensile deformation have been carried out. A criterion for the evaluation of random pattern quality is introduced. It is shown that the characteristics of the proposed synthetic random pattern, being generated by applying a more sophisticated technique (at three stages), justify the employment of the DIC for deformation values of up to 20%.

A method of screen printing the computer generated patterns on the surfaces of interest is applied. Three groups of specimens, with the three artificial patterns printed on their surfaces, are subjected to tensile tests. Real tensile experiments show that the quality of the printed patterns is good enough despite the lower “signal to noise” ratio of the cross-correlation functions of the respective patterns (i.e. the ratio between the main peak value and any secondary peak value). There are some indications that the proposed synthetic random pattern keeps its best quality until attaining a real deformation of about 20%.

A number of experimental problems related to DIC applications exist where any printing of a generated random pattern on a surface of interest proves to be impossible or unallowable. In such cases, scientists should utilize the local variations of brightness or colour of the object images due to variations of their stricture. The use of computer generated random patterns when possible, to solve metrological problems via image correlation analysis yields the increase of measurement accuracy as a result of the more precise localization of the respective correlation peaks. This approach provides prospects for selection and computer generation of optimal random patterns that can be easily printed on the imaged surfaces.
REFERENCES


