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Implementation of the direct evaluation of strains using a phase analysis code for random patterns

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ABSTRACT

A new approach for decoding directly strains from surfaces encoded with random patterns has been developed and validated. It is based on phase analysis of small region of interest. Here we adapt to random patterns new concepts proposed by Badulescu (2009) on the grid method. First metrological results are encouraging: resolution is proportional to strain level, being 9% of the nominal value, for a spatial resolution of 9 pixels (ZOI 64×64 pixels^2). Random noise has to be carefully controlled. A numerical example shows the relevance of the approach. Then, first application on a carbon fiber reinforced composite is developed. Fabric intertwining is studied using a tensile test. Over-strains are clearly visible, and results connect well with the previous studies.

1. Introduction

Digital image correlation is one of the most diffused image processing techniques among experimental mechanics community [1]. The system has been extended to different cases and first on warp surfaces (stereocorrelation) [2,3]. But basically, one of the most interesting problems in DIC is the sub-pixel detection. Usually, authors use either correlation peak interpolation either sub-pixel deformation of the target sub-image. The deformation hypothesis can be a rigid body motion or a complete transformation function of the zone of interest (ZOI) [4]. Recently, Hild [5] proposed an original work, based on a correlation algorithm coupled with Finite Element based transformation functions, allowing for strongly regularized displacement fields with solid mechanics assumptions. In all these cases, the assumptions on the interpolation level are believed to have a direct influence on metrological properties of the correlation core [6].

Beside the classical DIC approach, the grid method, even if less used, has rather comparable features: it is basically an image processing technique allowing for in-plane displacement fields. In the previous case, images are random patterns; in the latter, surface signature is a periodic grid. In this case, displacements derive from a spatial phase extraction [7]. The choice of surface encoding should orient the user toward one method or the other, but in fact, the nature of the pattern is not crucial: DIC has been successfully applied to periodic pattern for a very long time [8], and a random pattern can be seen has the superimposition of many frequencies. This last remark has been made recently by some authors [9–11] and will be developed hereafter. Random pattern are of more practical use than periodic pattern for two basic reasons: first, periodic pattern generation and transfer is not as easy as someone could think. Second, it is almost impossible to generate a periodic pattern on a non-flat surface—and to develop a 3D surface grid method, even if industrial demand for measurement on real structures is high.

Finally, one should note that DIC is a genuine large-strain approach because it is based on re-correlation of decorrelated informations, whereas Grid technique is a genuine small perturbation method because the phase difference is merging initial and final state of the investigated object, and because phase information is fairly more sensitive than amplitude. Consequently, it could be of great interest to adapt advances made in the context of grid techniques to random patterns, and to compare the results to those obtained by classical image correlation technique. In the past, specific "phase culture" items has brought very interesting results, for example on camera distortion [12], or shape, shape variation and 3D displacements [13].

Recently, the grid technique has been made sensitive to strain rather than displacements by using special wavelet functions [14]. Because of the simplicity of the encoding procedure, adapting this technique to random patterns should bring a breakthrough compared to DIC techniques; it will be developed in the following.

2. 2D displacement method using phase-based analysis

2.1. Digital image correlation principle

Assuming a reference image im0 described by $f(x, y)$, a deformed image im1 of im0 after a small strain is described by

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$g(x, y)$ by the following equation:

$$g(x,y) = f(x-\delta_x, y-\delta_y) + b(x,y) \quad (1)$$

where δx and δy are the components of the displacement of im1 and $b(x, y)$ the noise measurement. A way to find δx and δy is to maximize the function h defined by

$$h(x,y) = (g*f)(x,y) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} g(\xi,\eta) f(\xi-r, \eta-s)\, d\xi\, d\eta \quad (2)$$

where $*$ denotes the cross-correlation product. The obtained $\hat{r}$ and $\hat{s}$ correspond to the maximal probability of displacement $(\delta\hat{x}, \delta\hat{y})$ ($\hat{}$ denotes an optimized value with the considered procedure). This method can be applied in Fourier space using Fast Fourier Transform function, noted FFT2D. Eq. (2) becomes:

$$g*f = FFT2D^{-1}(FFT2D(g)\overline{FFT2D\tilde{f}}) \quad (3)$$

where the overline denotes the complex conjugate, and $\tilde{f}(x,y) = f(L_x - x, L_y - y)$ where L_x and L_y are the dimension of the domain. Eqs. (2) and (3) are used at a local scale, on typical 32×32 zone of interest (ZOI). The work is repeated all over the map, giving a final displacement chart.

Now, classical digital image correlation performs the cross-product either in Fourier or real space. More refined approaches exist by the way: for example, the signal could be normalized respect to the mean local intensity, and/or the mean local contrast [6]. The cross-correlation peak is commonly interpolated in order to reach sub-pixel displacement accuracy. The interpolation function is not the same for all the implementations. It could be for example a Gaussian or polynomial function. Basically, this choice does not have a strong theoretical basis, and authors have an empirical approach. We propose hereafter an alternative to this weak point in the image correlation approach.

2.2. Sub-pixel algorithm

The sub-pixel algorithm is based on the phase estimation of each ZOI. Because Fourier Transform requires continuity, in particular at the boundaries, the ZOI is windowed using a bi-triangular function. So far, the algorithm is an extension of the windowed Fourier Transform (WFT) algorithm proposed by Surrel [15]. As shown in Fig. 1, in the frequency domain, each couple of frequencies is characterized by an amplitude and a phase. This phase variation $\Delta\Phi_\theta$ is proportional to the displacement normal to the corresponding fringe direction. Note that the phase is defined only if the amplitude is higher than zero. Then, in the absence of any phase jump, displacements can be related to any defined phase using the relationship:

$$\left\{ \vdots\, \Delta\Phi_\theta^i \,\vdots \right\} = \begin{bmatrix} \vdots & \vdots \\ \frac{2\pi}{p_e^i}\cos\theta^i & \frac{2\pi}{p_e^i}\sin\theta^i \\ \vdots & \vdots \end{bmatrix} \begin{Bmatrix} \delta_x \\ \delta_y \end{Bmatrix} \quad (4)$$

Displacements can then be derived from Eq. (4) using the pseudo-inverse of A. This operation is possible if $\det((A^tA)) \neq 0$. In practice, this means that at least two phases along two different directions exist

$$\begin{Bmatrix} \delta_x \\ \delta_y \end{Bmatrix} = (A^tA)^{-1}A^t \begin{Bmatrix} \vdots \\ \Delta\Phi_\theta^i \\ \vdots \end{Bmatrix} \quad (5)$$

Practical problem of this approach is that the signal to noise ratio is weak for each couple of frequencies. Then, the quality of the measurement is obtained by averaging all the available information through the pseudo-inverse function.

One should note also that a phase jump can occur in the Fourier domain. Even if a specific treatment should be developed, it sounds better to first use a classical pixel correlation algorithm based on the intensity pattern, as described in Section 2.1. This ensures that the two ZOIs will be as superimposed as possible and that the fringe order is zero for any point and any couple of frequencies. No deformation of the ZOI is proposed here, considering that target applications will be in the small transformation domain. Finally, the displacement extraction procedure is the following:

1st: classical pixel correlation algorithm,
2nd: sub-pixel estimation using locally shifted ZOI in the deformed image.

2.3. Characterization

The method has been characterized using a simulation of a rigid body translation. A single ZOI is generated and translated from -0.5

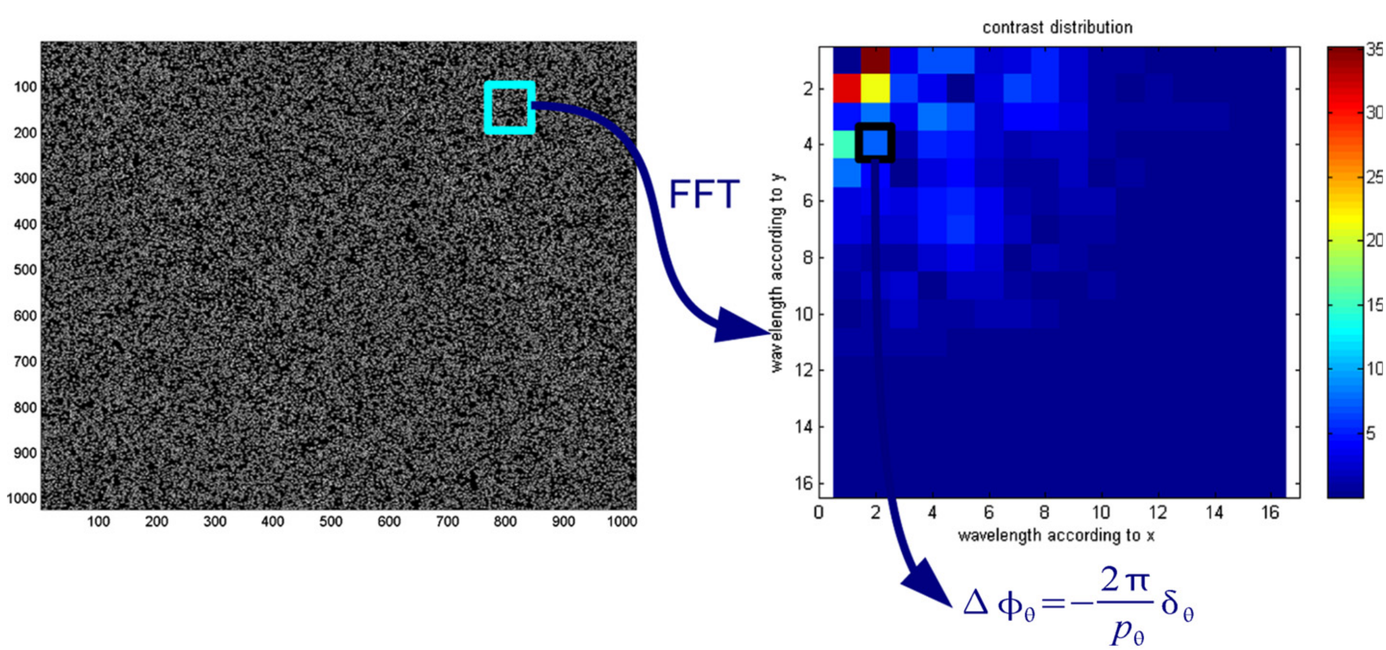

Fig. 1. Basic principle of sub-pixel algorithm.