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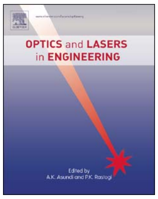

Benchmarking of depth of field for large out-of-plane deformations with single camera digital image correlation

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ABSTRACT

A problem that arises when performing stereo digital image correlation in applications with large out-of-plane displacements is that the images may become unfocused. This unfocusing could result in correlation instabilities or inaccuracies. When performing DIC measurements and expecting large out-of-plane displacements researchers either trust on their experience or use the equations from photography to estimate the parameters affecting the depth of field (DOF) of the camera. A limitation of the latter approach is that the definition of sharpness is a human defined parameter and that it does not reflect the performance of the digital image correlation system. To get a more representative DOF value for DIC applications, a standardised testing method is presented here, making use of real camera and lens combinations as well as actual image correlation results. The method is based on experimental single camera DIC measurements of a backwards moving target. Correlation results from focused and unfocused images are compared and a threshold value defines whether or not the correlation results are acceptable even if the images are (slightly) unfocused. By following the proposed approach, the complete DOF of a specific camera/lens combination as function of the aperture setting and distance from the camera to the target can be defined. The comparison between the theoretical and the experimental DOF results shows that the achievable DOF for DIC applications is larger than what theoretical calculations predict. Practically this means that the cameras can be positioned closer to the target than what is expected from the theoretical approach. This leads to a gain in resolution and measurement accuracy.

1. Introduction

1.1. DIC

The term digital image correlation refers to the class of non-contact measurement methods that acquire surface images of an object, store them in digital form, and perform image similarity metrics to extract full-field shape and deformation data [1]. It allows for a sub-pixel measurement accuracy of displacements and strains on the surface of complex parts. To be able to perform stable and sub-pixel accurate correlation, a random, non-repetitive, isotropic and high contrast speckle pattern has to be applied to a specimen in order to ensure distinction between the pixels. Next, since a (grey scale) pixel-value is not a unique signature, a so-called subset is introduced which is a small, mostly square, surface of pixels that contains a combination of speckles and represents a unique signature in the reference image (Fig. 1, a). Each subset is compared between the reference state and the deformed state. The subset is shifted step by step (with a user-defined step size) and for each step the comparison between reference and deformed image is performed until the complete surface of the specimen is covered. Since the subset can change position, shape and size during the forming process, the coordinates of the material points in the deformed state are related to the coordinates of the material points in the reference state through a deformation function (the so-called shape function). This shape function is chosen as function of the expected deformation mode. For a rigid body motion, only a first order term is required for the shape function, but when an affine or irregular transformation is expected, higher order terms need to be used (Fig. 1, b).

When for example an affine transformation is expected, the relation between the coordinates of the reference coordinates (x, y) and the deformed coordinates (x′, y′) can be approximated by the following shape functions:

$$x' = x + u + \frac{\partial u}{\partial x}\Delta x + \frac{\partial u}{\partial y}\Delta y \tag{1}$$

and

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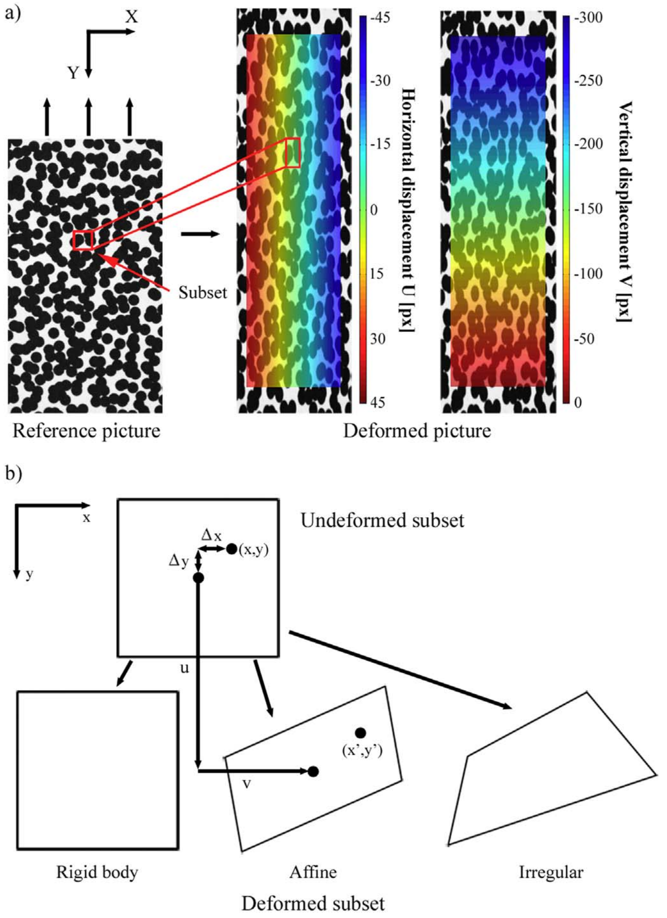

Fig. 1. Horizontal (U) and vertical (V) displacement fields of a specimen in uniaxial tension (a) and possible subset transformations to be fitted by the appropriate shape functions (b).

$$y' = y + v + \frac{\partial v}{\partial x}\Delta x + \frac{\partial v}{\partial y}\Delta y \tag{2}$$

where u and v represent the translation of the centre of the subset in x and y direction respectively. The distance from the centre of the subset to the reference point (x, y) is denoted as Δx and Δy.

DIC as used in present day applications started its development in the 1980's at the University of South Carolina [2,3]. The initial single camera calculations, also called 2D-DIC, were based on the cross-correlation algorithm, which is an algorithm that is sensitive to changes in brightness of the images. In subsequent decades researchers improved the quality of the correlation results by developing more powerful correlation algorithms that are less sensitive to the offset and linear scale in illumination. A comprehensive review of the capability of different correlation algorithms was published by Pan et al. [4]. In their research, they concluded that the zero-normalised sum of squared differences (ZNSSD) or the zero-normalised cross-correlation (ZNCC) criteria offer the most robust noise-proof performance and that these algorithms are insensitive to the offset and linear scale in illumination. Besides the developments and fine-tuning of 2D-DIC, the importance of stereo correlation [5,6], a correlation technique using two cameras instead of one rose thanks to the application of a simple and flexible calibration procedure developed by Zhang [7]. More recent research topics focus on the evaluation of the calculation accuracy and the estimation of sources of error [8–11], the matching of DIC data to finite element simulations [12] or on the implementation of a self-adapting global DIC algorithm [13]. The main advantage of the latter technique over subset-based (also termed local) DIC is that the results of the correlation are less dependent on the size of the chosen subset and thus on the experience of the user, making DIC more easily applicable for non-experts. Thanks to the initial developments, the constant improvements and the increase in the computational power of current CPUs, DIC is nowadays widely used in experimental mechanics and material science. It is one of the most applied optical measurement technologies with increasingly broad application prospects.

1.2. 2D-DIC

Most of the DIC applications use a 2D single camera setup and special care is taken to position the camera exactly perpendicular to the specimen surface. The purpose of this meticulous alignment is the reduction of out-of-plane displacements since these displacements will result in erroneous 'virtual' strains. Several solutions have been proposed to reduce the magnitude of these errors: the first is to use a telecentric lens making image magnification independent of the object distance with respect to the lens. A second solution is to place the camera as far as possible from the specimen since this distance is inversely proportional to the out-of-plane strain error. When combining a large object distance with a lens with a longer focal length, the resolution over the field of view can still be optimised. A third solution to reduce the errors originating from a non-perpendicular camera alignment is to use a second camera and perform stereo correlation. With this approach, the out-of-plane displacement will be quantified and will not be evaluated by mistake as 'virtual' strain. Of course adding a second camera and the associated calibration procedure introduce extra cost and new sources of error. It is therefore important to evaluate which of the proposed solutions yields the results with the smallest error. Relevant papers on the error estimation of a non-perpendicular camera alignment are published by Lava et al. [14] and Sutton et al. [15]. Recently Wittevrongel et al. [16] published an interesting paper on the comparison of different techniques to compensate for a non-perpendicular camera alignment. The latter includes a mechanical/experimental solution, a numerical solution based on the camera pinhole model and a method using a region of compensation that does not deform with the specimen. All three methods have proved to be successful to reduce the effects of out-of-plane motions.

1.3. Stereo DIC

The stereo correlation approach can not only be used to eliminate unwanted out-of-plane motions, but can also be used to measure surface displacements and strains in situations where (large) out-of-plane motions are unavoidable. These applications of DIC are gaining interest over the past couple of years and range from lab scale material testing such as membrane inflation [17,18], Erichsen testing [19] or drapability studies [20], to real-life military and industrial applications. Some examples of the latter are military applications such as blast loading experiments [21], the numerous DIC experiments performed by the Sandia National Laboratory (e.g. [22]), and in-situ displacement and strain measurements of thermoplastic thermoforming processes [23,24].

Some techniques allow to obtain 3D displacements using a single camera without any other optical system such as a bi-prism, mirrors or by combining DIC with fringe projection. An example of such a technique is the use of the magnification change due to the out-of-plane displacement and the unfocusing of the object, a method that was recently published by Réthoré et al. [25]. Their approach is based on the works of Tay et al. [26] and Quan et al. [27]. In applications where very large out-of-plane displacements are to be expected however, a stereo setup still remains mandatory.

Fixed focal lenses are used in all stereo correlation applications and adjusting the lens focus during the experiments is impossible since this would jeopardise the calibration parameters of the setup. Therefore, it is of utmost importance that the target remains within the field of view and the depth of field of the cameras during the entire experiment. If