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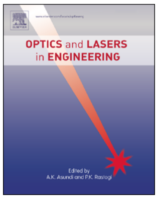

Uncertainty assessment of digital image correlation method in dynamic applications

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ABSTRACT

Even though digital image correlation (DIC) is a widely used optical full field measurement method, it still needs further performance investigations, when it comes to dynamic conditions. Dealing with a moving target, causes a motion effect (i.e. blurring) on the acquired images. This factor is an important source of uncertainty that needs to be quantified. Therefore, the present study aims to perform a systematic uncertainty assessment of DIC method in general dynamic applications. The study focuses on 2D DIC. In the case of 3D DIC similar problems will arise and therefore, a complete understanding of two dimensional conditions will be of great help to further studies which deal with 3D conditions. The whole work can be divided in to two parts. In the first part, a method to simulate the motion effect on a reference image is proposed to be applied. This method allows simulating the acquired images in a real dynamic test and estimating the measurement uncertainty caused by the motion effect. Using this technique, the uncertainty of DIC measurement is estimated. The second part of the study aimed to validate the simulation technique. Therefore, several tests are conducted by imposing harmonic motion to a target, in different frequencies and amplitudes. The results show good agreement between the experiments and the simulations, proving the introduced technique to be an effective method for motion induced uncertainty estimation.

1. Introduction

Over the recent years, optical full field measurement methods have been widely used in experimental mechanics. The main techniques are photoelasticity, moiré, holographic and speckle interferometry, grid method and digital image correlation (DIC) [1–6]. Digital image correlation [7,8] is a powerful technique, which has been mostly used in static applications. A group of articles have focused on quantification of performances of this method [9–36]. They perform the uncertainty assessment by analyzing either the deformed images acquired experimentally or the synthetic images obtained numerically. These studies are conducted in static conditions.

More recently, in some researches, DIC has been implemented also in dynamic applications such as mode shape recognition and vibration analysis [40–47]. Although some of these studies have performed an uncertainty analysis of the measurement in that particular application [37–47], there seems to be an absolute need of further investigations of DIC performances, to analyze the measuring uncertainty in generic dynamic conditions. The performances of DIC technique, depends on a set of static and dynamic parameters; the former include: image resolution and blurring, lighting conditions and processing parameters. As for the dynamics, the motion parameters (mainly the instantaneous velocity) and the shutter time are usually considered relevant in image-base measurement uncertainty assessment [9,10].

In dynamics, dealing with a moving target, causes a motion effect (i.e. blurring) on the acquired images. This motion effect would not exist, if the acquisition was instantaneous but in reality it is not a valid assumption to be made. The so called exposure time or the effective duration that a camera's shutter is open, is usually not negligible in respect to the velocity of the target. This means that the target slightly displaces during the exposure time which makes a single dot on the target to appear as a stripe on the acquired image. This factor is an important source of uncertainty that needs to be quantified. Therefore, the present study aims to perform a systematic uncertainty assessment of DIC method in general dynamic applications. The study focuses on 2D DIC. In the case of 3D DIC similar problems will arise and therefore, a complete understanding of two dimensional conditions will be of great help to further studies which deal with 3D conditions.

To analyze the effect of dynamics on the DIC uncertainty a numerical and experimental approach is proposed in this work. The use of a numerical technique, capable to simulate the effect of the motion on acquired images, allows us to keep all the other uncertainty sources under control and to explore the effect of

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dynamics. With this model and a given image of the target, it is possible to simulate the dynamic test and create a set of images that simulate the ones that would be obtained from a real test, with a known imposed vibration law. Analyzing the simulated image set by means of a digital image algorithm and comparing the obtained results with the known imposed motion law, the motion induced uncertainty can be easily quantified.

Moreover, set of experimental tests were conducted aiming first to validate the results obtained from the introduced numerical simulation procedure and second to perform an experimental uncertainty assessment. Results of this part show good agreement between the experiments and the simulations, proving the introduced technique to be an effective method for motion induced uncertainty estimation.

2. State of the art

Studying the uncertainty of DIC in static applications started early on and remarkable advances have been made in this area especially in the recent years. Schreier et al. analyzed the systematic error that arises from the use of under matched shape function, i.e. shape functions of lower order than the actual displacement field. They showed that, under certain conditions, the shape functions used can be approximated by a Savitzky–Golay low-pass filter applied to the displacement functions, permitting a convenient error analysis. They also claimed that, this analysis is not limited to the displacements, but also extends to strain′s systematic errors associated with an under matched shape function [11].

The sensitivity of displacement evaluation to the image acquisition noise (e.g. digitization, read-out noise, black current noise, photon noise [12]) were analyzed for the first time in Refs. [13,14]. Their analysis was based on corrupting reference image by different levels of zero mean Gaussian noise and without superimposing any displacement field on the image. They demonstrated that the standard deviation of the displacement error is proportional to the standard deviation of the image noise, and inversely proportional to the average of the squared grey level gradients and to the subset size. These results were also approved later on Refs. [15,16,17]. Wang et al. proposed a method to estimate the DIC error caused by intensity pattern noise [15] and reached to the same conclusion as in Refs. [13,14]. Later, Wang et al. quantified the expectation (bias) and variance in image motions in the presence of uncorrelated Gaussian intensity noise for each pixel location as a function of: interpolation method, sub-pixel motion, intensity noise, contrast, level of uniaxial normal strain and subset size. Their theoretical results in both cases of 1D and 2D showed that the expectations for the local parameters are biased and a function of: the interpolation difference between the translated and reference images, the magnitude of white noise, the decimal part of the motion and the intensity pattern gradients. They demonstrated that adding noise increases the systematic error amplitude [16,17].

Several studies performed an experimental uncertainty assessment and highlighted the influence of hardware, acquisition system, experimental condition and set up on DIC accuracy and precision. Um et al. experimentally obtained the correlation error distributions around the hole in a paper tensile specimen at three different load levels [18]. In the same year, Siebert et al. investigated the impact of facet (sub-image) size and camera noise on correlation error. They demonstrated that decreasing camera noise or increasing the facet size will reduce the correlation error [19]. In the same year, Tiwari et al. obtained the effect of image distortions type on variability and accuracy of ultra high speed and moderate speed image acquisition. They demonstrated that image correlation measurements using high speed imaging systems are unbiased and consistent with independent deformation measurements over the same length scale, with point-to-point strain variations that are similar to results obtained from translation experiments [20]. A year later, Haddadi et al. proposed numerical and experimental tests, based on rigid-body motion in order to quickly assess the errors related to lighting, the optical lens (distortion), the CCD sensor, the out-of-plane displacement, the speckle pattern, the grid pitch, the size of the subset and the correlation algorithm [21]. More recently, Lava et al. and Pan et al. investigated the impact of lens distortion on the uncertainty of DIC measurement [22,23].

Some efforts have been made to theoretically estimate the DIC uncertainty. Reu et al. quantitatively calculated the errors which will result from any given set of real images obtained in an experiment and concluded that the bias errors can be minimized by selecting higher ordered shape functions, increasing image contrast, and selecting a subset with adequate information content and suggested that the variance parameter can be minimized by decreasing intensity noise in the images which can be accomplished either through better imaging equipment, improved illumination, lower camera gain, or by averaging multiple images at each step. They showed that increasing the subset size up to a given threshold decreases the displacement bias error [24]. In the same year, Pan et al. investigated the influence of the speckle patterns on the accuracy and precision of displacement measurement. They derived a concise theoretical model, which indicates that the speckle pattern does not introduce systematic error but introduce random error in the measured displacement. Their Numerical experiments allowed them to conclude that the standard deviation error of measured displacement is closely related to the speckle patterns [25]. In a more recent study, Crammond et al. investigated the effect of speckle size and density on the uncertainty of measurement [26].

Group of studies investigated DIC uncertainty by creating set of synthetic images. In Refs. [27,28] the displacement error assessment was studied by generating synthetic speckle images, assuming a sinusoidal displacement field with various frequencies and amplitudes. Their results showed the general trends, rather independent of the implementations but strongly correlated with the assumptions of the underlying algorithms. They discussed various error regimes caused by parameters such as subset size, gray level interpolation, encoding image parameters or shape functions. In another interesting approach, Lava et al. investigated the impact of the adopted correlation function, the interpolation order, the shape function and the subset size on the systematic error mean and standard deviation. They analyzed numerically deformed images obtained by imposing finite element displacement field on an un-deformed image and proved that applying Gaussian smoothing, significantly decreases the systematic error amplitude [29]. In a study on the impact of a non-perpendicular camera alignment to a planar sheet metal specimen′s surface, Lava et al. estimated errors by numerically rotating deformed images [30]. Other works [31,32] focused on errors that can be directly attributed to the derivation of the strain fields, such as the strain-window size and the strain-window interpolation order using the same technique. Wang et al. by performing numerical 2D DIC tests on the deformation of numerically deformed images, taken from the real tensile specimens, found that the DIC accuracy and precision decrease under highly heterogeneous strain states. They also studied impacts of subset sizes, step sizes and strain window sizes for an optimum correlation [32]. More recently, some efforts have been done to reduce the estimation error in incremental DIC by means of adaptive subset offset [33].

There are some which studies which focus on the uncertainty estimation in 3D such as Refs. [34,35,36], but since the present