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Evaluation and improvement of digital image correlation uncertainty in dynamic conditions

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ABSTRACT

Dealing with a moving target causes a motion effect (i.e. blurring) on the acquired images. This factor is an important source of measurement uncertainty while exploiting the Digital Image Correlation (DIC) technique. Therefore, the present study aims to evaluate and improve DIC uncertainty in dynamic conditions in the case of translating target. The study focuses on 2D DIC. In the case of 3D DIC similar problems arise, and therefore a complete understanding of two dimensional conditions will be of great help for further studies which deal with 3D conditions. The whole work can be divided into two main parts. In the first part, two different methods to simulate the motion effect on a reference image are proposed, discussed and validated. These methods allow simulating the acquired images in a real dynamic test and estimating the measurement uncertainty caused by the motion effect. The validation is performed by conducting several harmonic vibration tests with an electromagnetic shaker. In the second part of the study a numerical technique is proposed to estimate the motion effect present in an acquired image. This technique gives two main advantages. First of all, since the motion effect itself has a known influence on the uncertainty of measurement (first part of the study), we can predict the DIC's uncertainty by just having an acquired image. Furthermore, this numerical technique is used in the last part of this work to improve the performances of DIC in dynamic applications. In this way the bias error and the uncertainty of measurements were considerably decreased.

1. Introduction

Digital Image Correlation [1,2] is a powerful technique, which has been mostly used in static applications. More recently, in a variety of studies, DIC has been exploited also in dynamic applications. However, reviewing the literature reveals that further investigations of DIC performances in generic dynamic conditions need to be done. The performances of DIC technique depend on a set of static and dynamic parameters; the formers 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 [3,4].

Dealing with a moving target causes a motion effect (i.e. blurring) on the acquired images. This factor is an important source of measurement uncertainty. Therefore, the present study aims to evaluate and improve DIC uncertainty in dynamic conditions in the case of translating target. The study focuses on 2D DIC. In the case of 3D DIC similar problems arise, and therefore a complete understanding of two dimensional conditions will be of great help for further studies which deal with 3D conditions.

The whole work can be divided into two main parts. The first part aims to analyze the effect of dynamics on the DIC uncertainty by proposing numerical and experimental approaches. The numerical approach is based on implementing two innovative methods to simulate the motion effect on a reference image. These numerical methods allow keeping all the other uncertainty sources under control and exploring the effect of dynamics. The performances of the two methods are then evaluated in different dynamic conditions. With these models and a given static 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. The simulated image sets are analyzed by means of DIC technique and the discrepancy between the imposed and the estimated time histories is utilized to estimate the uncertainty. The simulations are successively validated by conducting several harmonic vibration tests.

In the second part of the study a numerical technique is proposed to estimate the motion effect present in an acquired image. This technique gives two main advantages. First, since the motion effect itself has a known influence on the uncertainty of measurement (thanks to the first part of the study), it is possible to predict the DIC's uncertainty by just having an acquired image.

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Second, this numerical technique is used to improve the performances of DIC in dynamic applications.

1.1. State of the art

Studies related to DIC uncertainty in static applications started early on and remarkable advances have been made in this area in the recent years [5–13]. The available literature in the case of static DIC applications is wide, as summarized in [14]. Different approaches to DIC uncertainty analysis have been proposed and implemented in the literature.

Some efforts have been made to theoretically estimate the DIC uncertainty [15–17]. In 2009, groups of researchers presented theoretical formulae defining the effect of noise in the intensity pattern, image contrast and interpolation method on both bias and variability in one-dimensional motion measurements [18,19]. Wang et al. [20] used basic equations for stereo-vision with established procedures for camera calibration, to provide error propagation equations that can be used to determine both bias and variability in a general 3D position and successively experimentally validated them [21]. In another approach a group of studies investigate the DIC uncertainty by creating a set of synthetic images [22–26].

Although, the above mentioned works were concerned with static cases, the implementation of DIC did not remain limited to static applications. Recently, in a group of studies, DIC has been implemented for modal shape recognition and vibration analysis [27–36], while a group of researchers focused on defining reference materials for dynamic conditions [37–39].

In a previous paper the authors focused on systematic evaluation of the uncertainty of DIC in dynamic conditions [14]. In this work, further investigations have been done in this regard by introducing an improvement motion simulation technique and above all, proposing a deconvolution-based numerical technique capable of decreasing the bias and random components of error in DIC measurements in dynamic conditions (Section 4).

2. Methods

In order to analyze the uncertainty of DIC in dynamic conditions, sets of reference images of a target are required; the current section describes the numerical and experimental approaches applied to obtain these sets of images. Section 2.1 addresses the issue of sub-pixel shifting using Fourier Transform since this operation is required in the proposed methods for motion effect simulation (Section 2.2). Then two methods to simulate the motion effect are discussed in detail. They will be implemented in different conditions in order to estimate the uncertainty of DIC in dynamic cases. In Section 2.3, details of the experimental tests are explained which were carried out not only to validate the simulations but also to perform a systematic uncertainty assessment in real conditions.

2.1. Sub-pixel shift using DFT

The simulation of the pure translation of the target is the first step towards simulating the motion effect, as explained in Section 2.2. Among several techniques introduced in this regard, Fourier shifting method is claimed to be the optimum sub-pixel shifting technique [40]. This method is composed of three steps. The image is first transformed into the frequency domain via Discrete Fourier Transform (DFT). Then, a linear phase shift (i.e. with a phase shift linearly proportional to the spatial frequency) is applied in the complex plane. The amount of added phase determines the amount of the spatial shift. Finally the image is transformed back to the spatial domain via an Inverse Discrete Fourier Transform. The transforms are done via 1D DFT/IDFT of a single row or a single column at a time [40]. Note that, applying a linear phase shift to the image in frequency domain is equivalent to convolving the image with an impulse function with impulse at time different from zero.

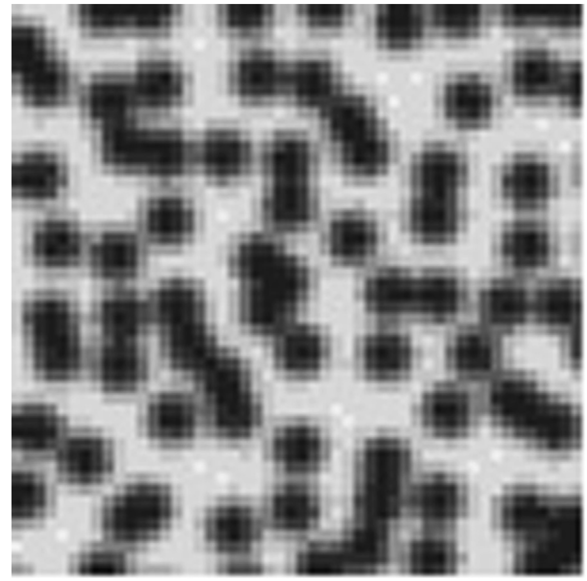

Fig. 1. Reference image.

Fig. 1 shows the reference, un-deformed speckle pattern image used in all of the simulations. It is a 2000×2000 pixels speckle pattern with grain size of 4 pixels.

2.2. Generation of images with motion effect

As discussed already in the last section, convolving the image with impulse function is a recognized method to simulate the sub-pixel shifting. In order generate images with motion effect, two main techniques can be considered. The first technique is the square pulse method which is based on convolution of reference image with a square pulse (previously introduced by authors in [14] to simulate the motion effect for DIC uncertainty in dynamic condition). The second one is the averaging method which will be explained in Section 2.2.2. As demonstrated later, in some dynamic cases the latter better simulates the real conditions.

2.2.1. Motion effect simulation using square pulse

The numerical method for motion effect simulation using square pulse is based on convolution of the reference image with square pulse [14]. Therefore for simulating an acquired image in any dynamic condition the width of the square pulse 'w' and the corresponding shift 'a' have to be determined. Fig. 2 shows a square pulse function $g(x)$ and the two corresponding parameters 'w' and 'a'.

Moreover, convolution in space domain is equivalent to multiplication in spatial frequency domain. The technique to simulate the motion effect in horizontal direction proposed in [14] is to calculate the DFT of each row of the image and multiply it by DFT of square pulse and finally calculate the inverse DFT of the product. The same procedure can be followed in operating with image columns to simulate a vertical motion effect. We name this procedure as the numerical method of motion effect simulation. It should be mentioned that if we convolve the image with shifted