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Experimental analysis of image noise and interpolation bias in digital image correlation

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A B S T R A C T

The popularization of the digital image correlation (DIC) method has raised urgent needs to evaluate the accuracy of this method. However, there are still some problems to be solved. Among the problems, the effects of various factors, such as the image noise caused by the camera sensors, the employed interpolation algorithm, and the structure of the speckle patterns, have become a major concern. To experimentally measure the position-dependent systematic error (i.e. interpolation bias) caused by non-ideal interpolation algorithm is an important way to evaluate the quality of the speckle patterns in the correlation method, and remains unsolved. In this work, a novel, simple and convenient method is proposed to measure the interpolation bias. In the new method which can avoid the out-of-plane displacements and the mechanical errors of translation stages, integral-pixel shifts are applied to the image shown on the screen so that sub-pixel displacements can be realized in the images captured by the camera via proper experimental settings. Besides, the fluctuations of the image noise and the sub-pixel displacement errors caused by the image noise are experimentally analyzed by employing three types of cameras commonly used in the DIC measurements. Experimental results indicate that the fluctuations of the image noise are not only proportional to the image gray value, but also dependent on the type of the employed camera. On the basis of eliminating the image noise via the image averaging technique, high-precision interpolation bias curves more than one period are experimentally obtained by the proposed method.

1. Introduction

The digital image correlation (DIC) method is an easy-to-use and reliable method of non-contact full-field optical methods for measuring [1]. Since its invention in the 1980s [2,3], it has been widely used in full-field measurement of morphology and deformation [4–8], and become one of the most successful methods in experimental solid mechanics. The principle of the DIC method is to find matching interesting regions with precise locations between the subsets in both the reference image and the target image using a correlation function, consequently realizing full-field deformation measurements. To reach sub-pixel accuracy, gray-value interpolation is required for sub-pixel positions in the image. Due to the effects of various factors [9], the typical displacement measuring accuracy using the DIC method is a few percent pixels [10], where the image noise caused by the camera sensors, the employed interpolation algorithm [11–13] and the structure of the speckle patterns play key roles.

The image noise, due largely to the coupling of the noise of image acquisition hardwares and the variations of the illumination source, has significant effects on the measuring accuracy using the DIC method. Most of the reported research literatures focus on simulations, for example, the effects of the image noise on the displacement measuring accuracy is discussed via applying artificial Gaussian noise [14] to the simulated speckle images and analyzing the fluctuations of the displacements calculated by the DIC method. One side, the underlying assumption is that the image noise is not dependent on the image gray value, which is not supported by any experimental evidence. On the other side, experimental researchers would prefer to know the actual image noise of the digital image in physical experimental environments [15], pursuing the root of the image noise from experimental environments and finding ways to suppress the image noise. The popularization of the DIC method requires high cost-effective image acquisition hardwares, which often have a low signal to noise ratio (SNR). Thus, investigations of the image noise for different types of cameras and the displacement errors caused by it are particularly important.

Another important factor that affects the measuring accuracy is the interpolation bias [16,17]. Previous studies have found that the

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increasing sub-pixel displacements produce sine-like distributed systematic errors with a period of one pixel. The systematic errors are caused by the non-ideal sub-pixel interpolation [12] in the correlation algorithm, known as the interpolation bias. Experimental measurements of the interpolation bias have an important significance for evaluating the quality of the speckle patterns and the interpolation algorithm [18]. Existing systems to estimate sub-pixel displacement interpolation bias are mostly via simulations, such as the Fast Fourier Transformation (FFT) method [19], providing a sub-pixel shift at each stage so that the corresponding interpolation bias can be carried out by the DIC method. However, experimental measurements are more critical and reliable. Regular translation experiments are carried out into the following steps: firstly, record the reference image; then, impose known displacements to the specimen using a mechanical translation stage; thirdly, record the target image; fourthly, repeat the second and third steps; lastly, calculate the displacements of the recorded images using the DIC method to obtain the interpolation bias. However, mechanical translation stages are not perfect and often have a mechanical error. Besides, there are out-of-plane displacements when the moving direction is not parallel to the surface of the specimen or when the optical axis of the camera is not perpendicular to the specimen. These problems make it difficult to measure the interpolation bias curves in the sub-pixel translation experiments using mechanical translation stages. Therefore, there are rarely researches reporting experimental studies of the sub-pixel interpolation bias. Mazzoleni [20] employed a coordinate measuring machine (CMM) to correct the displacements of the translation stage. They successfully achieved the first half period of the sine-like interpolation bias curves. Yet, the second half period had some abnormal points which was caused by the uncertainties of the CMM. Recently, experimental curves of the interpolation bias, with a complete period and high precise have been reported [21]. They used two orthogonal directional Twyman–Green interferometers to calibrate a precision dual axial displacement machine driven by piezoelectric ceramic transducers (PZTs), with the displacement accuracy improving to the magnitude of 2 nm using high precise hardwares. A strain gage was used as the feedback for the PZTs, which required stable environment temperature. A high SNR sensor (16 bit) with a telecentric lens to reduce the image noise and eliminate out-of-plane displacements was also employed. Their method has a significant quality requirement for the experimental environment and equipment, which would be difficult to be popularized and practically applied.

The structure of the speckle patterns influences the displacement measuring accuracy as well. The speckle patterns employed in engineering measurements vary dramatically from different preferences of the users and recommendations by the software providers. A tendency to study the effects of different structures of speckle patterns is to normalize the speckle images. The random distributed numerically designed speckle patterns have been proposed and prove to be feasible [20,22,23]. The numerically designed speckle patterns only depend on two parameters: the size of the occurring speckles and the coverage or the ratio of gray/black pixels over the entire number of pixels [22]. The comparable accuracy and the simplification make it patterns better to optimize and popularize the numerically designed speckle patterns.

In this work, we propose a novel, simple and convenient experimental method which can avoid the mechanical errors of translation stages and out-of-plane displacements. Three types of cameras commonly used in DIC experiments are employed to analyze the fluctuations of the image noise and the displacement errors caused by it. Section 2 introduces the novel experimental method, where integral-pixel shifts are applied to the image shown on the screen so that sub-pixel displacements can be realized in the images captured by the camera. Section 3 discusses the effects of the image noise on the accuracy of the DIC method via analyzing the image noise of different cameras and providing an effective denoising method. Section 4 experimentally measures the periodic curves of the interpolation bias caused by sub-pixel translation. Section 5 summarizes the whole work.

2. The novel experimental setup and parameter settings

Since the mechanical errors of translation stages and out-of-plane displacements make it difficult to measure the interpolation bias in regular translation experiments, a novel, simple and convenient experimental method is proposed. In the new method, speckle images are displayed on the screen in their original pixel size and then shifted by 1 pixel each time so that the camera focused on the screen can record images with sub-pixel shifts.

2.1. The novel experiment setup

Fig. 1 shows the experimental setup built in this work. Fig. 1 (a) shows that the camera and the screen used to display images (the Surface Pro 3) are placed at the opposite corners of the vibration isolation table. Before recording images, the light path must be adjusted to ensure the optical axis of the camera is vertical to the screen as shown in Fig. 1(d). The following steps explain the way to adjust the experimental devices to meet the requirement:

(1) A laser pen is attached to the top of the camera and a thin mirror is clung to the screen as well.
(2) Turn on the camera, make sure that the camera focuses on the screen.
(3) Turn on the laser pen. Note that the laser spot must locate at the center of the screen and at the center of the image captured by the camera as well.
(4) Make sure the laser spots on the mirror and the incident light and the reflected light coincide with each other.

The distance e between the center of the camera target the optical axis of the laser pen ($e \approx 30$ mm) is much smaller that the object distance ($l \approx 2$ m), shown in Fig. 1. When the laser spot is in the center of the captured image, the angle between the optical axes of the camera and the optical axis of the laser pen is smaller than 0.015 rad (0.86 degrees). Thus, we assume that the optical axis of the camera is parallel to the optical axis of the laser pen. In this way, the geometrical relationships among the experimental devices are easy to clarify: the optical axis of the camera is parallel to the optical axis of the laser pen (); the optical axis of the laser pen is vertical to the surface of the mirror; the mirror and the screen are parallel to each other. Therefore, the optical axis of the camera is vertical to the screen. Subsequently, the pre-generated numerically designed speckle image [22], as shown in Fig. 1(b), is displayed on the screen in its original size. Part of the image is selected to be imposed integral-pixel shifts to. Fig. 1(c) shows the shifted image where the vertical white line is the trace left by shifting 10 pixels. To avoid the effects of the mechanical forces, a wireless mouse and a wireless keyboard are employed to do the shift operation, shown in Fig. 1(d).

2.2. Parameter settings

Fig. 1 shows that the camera records the speckle image shown on the screen via proper experimental settings. According to the imaging theory of geometrical optics, the pixel number N of the screen which corresponds one pixel of the camera target depends on four parameters: the object distance l, the focal length of the