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

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ABSTRACT

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.

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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 hardware 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 hardware, 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
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 ($\lambda$); 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
In the sub-pixel translation experiments, make sure that there are more than 10-pixel shift on the screen when the pixel displacement of the image captured by the camera is 1 pixel. That is, $N > 10$. Thus, a bigger object distance $l$, a lens with shorter focal length $f$, a camera target with bigger pixel size $p$, and a screen with smaller pixel size $P$, are required.

The object distance $l$ is taken into account firstly. One side, Eq. (1) indicates a longer object distance $l$ is needed. On the other side, an excessive object distance $l$ limits the imaging process, because the decreasing angle of the incident light causes the loss of the high-frequency components, which reduces the contrast of the image captured and subsequently reduces the measuring accuracy using the DIC method. Considering the two aspects, the object distance $l = 2.186 \text{ m}$ is chosen in our sub-pixel translation experiments.

Secondly, the focal length of the lens $f$ should be small enough. A short focal lens with $f = 12 \text{ mm}$ is used in our work.

Thirdly, a camera with a target of bigger pixel size $p$ is necessary as well. The pixel size of the commonly used camera targets is generally between 3 $\mu\text{m}$ and 5 $\mu\text{m}$. The cameras available in this work have targets with pixel size $p = 3.45 \mu\text{m}$ (Point-Grey), $p = 5.5 \mu\text{m}$ (IDS), and $p = 7.1 \mu\text{m}$ (Beijing Join-Hope). Therefore, the Beijing Join-Hope camera with $p = 7.1 \mu\text{m}$ target pixel size and $640 \times 480$ pixels image resolution is chosen.

Fourthly, a screen with smaller pixel size is important. The pixel size $P$ of the screens of common cellphones is between 50 $\mu\text{m}$ and 60 $\mu\text{m}$. However, the size of their screens is so small that the corresponding size mapping to the camera target is much smaller than the size of the camera target because the size is shrinked $N \times N$ times during the mapping procedure. Overall, the screen of the Surface Pro 3 with pixel size $P = 117.6 \mu\text{m}$ and 4k image resolution is selected.

To sum up, all the four parameters are fixed and make the pixel number $N = 11$. In other words, one pixel of the camera target corresponds approximately 11 pixels of the screen.

What calls for special attention is that, the fastening ways of the cameras affect the experimental results badly. Fig. 2 shows two common ways to fasten the camera: screwing and clamping. The screwing way using a screw from the side to resist the camera, is shown in the left-bottom inset of Fig. 2, while the clamping way using an isotropic force clamp shown in the right-top inset of Fig. 2. 5000 images have been continuously recorded with a sampling frequency of 5 Hz while the two fastening ways are employed, respectively. The first image is taken as the reference image, and the pixel displacements of subsequent images have been calculated by the DIC method. The black and red points shown in Fig. 2 correspond the results of the screwing way and clamping way, respectively. The experiments were done after the cameras had been started more than 1 h to reach a thermal balance so that the thermal drift could be ignored. The screwing way loads from only one direction while the clamping way loads from all directions. Thus, the screwing way tends to drift along one direction after mounting while the clamping way does not. The different results also indicate that the screwing way leads to a whole drift while the screwing force is releasing while the clamping way does not. Therefore, an appropriate fastening way (e.g., the clamping way) for cameras is very important.

3. Experimental analysis and reduction of image noise

Fig. 2 indicates that the random fluctuations of displacements are about $\pm 0.001$ pixels due to the image noise. Therefore, the image noise should be analyzed and reduced first to avoid its effects on the DIC results before the sub-pixel translation experiments. Three types of cameras (Beijing Join-Hope, IDS, Point-Grey) are employed to analyze the image noise in the DIC measurements. The experimental results are detailedly discussed below.
3.1. Image noise of different cameras and relationship between image noise and image gray value

To statistically study the image noise of different cameras, multiple images of the same scene have been continuously recorded using the three types of cameras independently. The image averaging technique is employed to obtain the averaged image and image noise. Eq. (2) illustrates the image averaging method theoretically. The standard deviation of the images shown in Eq. (3) is evaluated as the image noise.

\[
I_n(x,y) = \frac{1}{N} \sum_{i=1}^{N} I_n(x,y)
\]  

(2)

\[
E(x,y) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (I_n(x,y) - \bar{I}_n(x,y))^2}
\]  

(3)

In the two equations, \(I_n(x,y)\) is the gray level at location \((x,y)\) of image \(n\), \(\bar{I}_n(x,y)\) is the average of the gray level at location \((x,y)\), \(E(x,y)\) is the standard deviation (the image noise) of the image gray value at pixel \((x,y)\), and \(N\) is the total number of images in the image averaging method.

To analyze the image noise of different acquisition devices, we tested three types of commonly used cameras: Beijing Join-Hope, IDS, and Point-Grey. To statistically discover the image noise of these cameras, 300 images have been continuously recorded. The exposure time of the three cameras were all set as 66.67 ms in this whole work and the flickering frequency of the used screen was 60 Hz. Thus, each captured image had undergone 4 periods of the flicker so that assume the captured images were considered to be sufficiently stable. The captured images were cropped into smaller pieces according to the same actual size (about 17.6 × 10.2 mm²). These smaller images with image size of 136 × 79 pixels, 210 × 118 pixels, and 328 × 190 pixels are used to analysis the image noise.

To achieve the averaged images and the image noise, the captured images were cropped into smaller pieces according to the same actual size (about 17.6 × 10.2 mm²). These smaller images with image size of 136 × 79 pixels, 210 × 118 pixels, and 328 × 190 pixels are used to analysis the image noise.

The averaged images and the image noise can be obtained by Eqs. (2)–(3). Fig. 3(a1, b1 and c1) shows the averaged images using the three types of cameras respectively. Fig. 3(a2, b2 and c2) illustrates the image noise (i.e. the standard deviations) of the three types of cameras, respectively. Compare Fig. 3(a1) with Fig. 3(a2), the image noise is small where the image gray value is small and big where the image gray value is big. Fig. 3(b1, c1) and Fig. 3(b2, c2) keep to the same rule. Fig. 3(a3, b3 and c3) further illustrate the relationship between the image noise and the image gray value by mapping the image noise to the image gray value. Thus,
we conclude that the image noise has a positive relationship with the image gray value. Fig. 3 (a4, b4 and c4) shows the histograms of the image noise of the three types of cameras. The maximum image noise of the CCD cameras is about 2.8 (Beijing Join-Hope: 2.7 and Point-Grey: 2.8) while the maximum image noise of the camera with CMOS target (IDS) is 3.2. The CCD cameras (Beijing Join-Hope and Point-Grey) tend to have a better SNR than the CMOS cameras (IDS).

To further discover the relationship between the image noise and the image gray value, the scatter diagrams of them are carried out for the three types of cameras, as shown in Fig. 4. The image noise tends to grow with the increment of the image gray value. There is an approximatively linear relationship between the image noise and the image gray value. Besides, the image noise of different cameras differs from each other as well. The image noise of Beijing Join-Hope, IDS and Point-Grey is 0.8, 1.1 and 1.0, respectively where the image gray value is 20. What is more, the image noise of Beijing Join-Hope, IDS and Point-Grey is 2.2, 2.9 and 2.4, respectively where the image gray value is 200. This accords with the above conclusion that the CCD cameras have a better SNR than the CMOS cameras.

To sum up, the fluctuations of the image noise not only are proportional to the image gray value, but also depend on the type of the camera. It provides an experimental support for simulations: the image gray value should be considered when imposing the image noise.

3.2. Effects and reduction of image noise

The experimental analysis of the image noise has been discussed above, this section focuses on the effects of the image noise which has become a major concern for the researchers of the DIC method. Fig. 2 shows the effects on the DIC displacements due to the image noise. Without the elimination of the image noise, the random errors due to the image noise and the interpolation bias due to the unperfect interpolation algorithms will couple together, making it difficult to study the displacement errors. Here, the image averaging technique is employed to reduce the image noise. Firstly, the effects when different numbers of images are used for the image averaging method are discussed.

In Section 3.1, 300 images have been continuously recorded in a static scene using the three types of cameras and the averaged images are obtained, shown in Fig. 3 (a1,b1 and c1). Here the averaged images are taken as the reference images for each DIC calculation. The 300 images without image averaging are used as the deformed images. Note that the whole cropped images (Beijing Join-Hope: 136 × 79 pixels, IDS: 210 × 118 pixels, and Point-Grey: 328 × 190 pixels) are used as the subset to make the random errors as small as possible. The same subset is employed all this work. Fig. 5(a), Fig. 6(a) and Fig. 7(a) show the displacement errors of the Beijing Join-Hope, IDS and Point-Grey camera respectively. The displacement errors due to the image noise of the three types of cameras are about ± 0.001 pixels. Besides, the displacement errors of 30 averaged images by every 10 images, 10 averaged images by every 30 images, 6 averaged images by every 50 images, 3 averaged images by every 100 images and 2 averaged images by every 150 images are evaluated as well, shown in Fig. 5(b,c), Fig. 6(b,c) and Fig. 7(b,c). The displacement errors reduce to about ± 0.0004 pixels (image averaging by 30 images) and ± 0.0001 pixels (image averaging by 100 images). It can be found that the image averaging method can effectively reduce the displacement errors. More images for image averaging lead to smaller errors.

Figs. 5–7 indicate that the effects of noise on the accuracy of DIC method can be effectively reduced by using the image averaging method. Here the standard deviations of the displacement errors and the maximum error of the displacements caused by the
image noise are evaluated to analyze the effects, shown in Fig. 8. It can be clearly seen that the standard deviations and the maximum error fall sharply at first and tend to remain constant with the increment of the image number for image averaging. The DIC displacement errors caused by the image noise can be ignored (< 0.0001 pixels), when the image number for image averaging reaches 100.

The above analysis provides a way to judge if cameras are suitable for current experiments. The image averaging technique can effectively reduce the image noise and the errors due to it. In static and quasi static experiments which has no requirements in terms of real-time, multi images in the same scene can be continuously sampled and used to reduce the image noise using the image averaging technology to meet the demand for high SNR. Experimental results indicate that 100 images are enough to reduce the image noise.

4. Experimental measurement of interpolation bias

To avoid the mechanical errors of translation stages and the out-of-plane displacements, the novel sub-pixel translation experiment has been proposed in Section 2. On the basis of the reduction of the image noise, the sub-pixel translation experiment has been carried out to measure the interpolation bias curve with a whole period. In addition, two different interpolation algorithms (the Keys and B Spline interpolation algorithms) and three different size of speckles (diameters: 4 pixels as small, 6 pixels as medium, and 8 pixels as large) are used to study the effects of the interpolation algorithms and the speckle patterns.

According to the experimental setup (Fig. 1) mentioned in Section 2.1, 100 images have been continuously recorded by the Beijing Join-Hope camera for each shift stage in the sub-pixel translation experiment. The image averaging method is used to reduce the image noise. Fig. 9 (a1, b1 and c1) shows the averaged images by the first 100 images (the reference images) when the small, medium and big speckles are used, respectively. Fig. 9 (a2) shows the displacements calculated by the DIC method using the Keys (black points) and B Spline (red points) interpolation algorithms when the small speckles are used. The similar displacements of the medium and big speckles are shown in Figs. 9(b2 and c2). Since the shift increases one screen pixel size each stage, the calculation errors can be obtained by the DIC displacements and the given displacements. In Section 3, we state that 100 images are enough to reduce the effects of the image noise. Therefore, the calculation errors here can be considered as the interpolation bias without regard to the image noise. The interpolation bias curves are shown in Fig. 9 (a3, b3 and c3). The solid curves represent the results when the FFT method [19] is used to apply deformations to the reference images shown in Figs. 9 (a1, b1, and c1). The interpolation bias by the proposed sub-pixel translation experiments fit well with the interpolation bias curves via the FFT method. In addition, the B Spline interpolation algorithm leads to smaller interpolation bias than the Keys algorithm, and the interpolation bias decreases with the increment of the speckle size.

To further illustrate the effects of the image noise, the curves of the calculation errors when the images without image averaging and the averaged images by less than 100 images (10 images and 50 images) are shown in Fig. 10. The calculation errors of the images without image averaging is bigger than the interpolation bias given by the FFT simulations and the calculation errors of the averaged images by less than 100 images do not coincide well with the interpolation bias given by the FFT simulations. The disagreement is due to the image noise. The calculation errors of the
image noise have a magnitude of several thousandths and the increment of the image number makes the errors smaller. Only when the image noise has been enoughly reduced, the calculation errors are approximatively the interpolation bias, which are shown in Fig. 9.

5. Conclusion
A novel, simple and convenient experimental method is proposed to experimentally measure the interpolation bias caused by the sub-pixel displacements in this work. The method applies
The proposed method is employed to measure the interpolation bias and experimental results prove its validity. Besides, the interpolation bias curves are carried out while different interpolation algorithms and speckle patterns are used. The accuracy of this method will be further improved with the improvement of the technique for manufacturing screens.

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References