Journal of Testing and Evaluation

A. Hijazi and C. J. Kähler

DOI: 10.1520/JTE20150437

Contribution of the Imaging System Components in the Overall Error of the Two-Dimensional Digital Image Correlation Technique

VOL. 45 / NO. 2 / MARCH 2017
A. Hijazi and C. J. Kähler

Contribution of the Imaging System Components in the Overall Error of the Two-Dimensional Digital Image Correlation Technique

Reference

ABSTRACT
Digital image correlation (DIC) is one of the most widely used non-invasive methods for measuring full-field surface strains in a wide variety of applications. The DIC method has been used by numerous researchers for measuring strains during the plastic range of deformation where the strains are relatively large. The estimation of the amount of background strain error in the measurements is of prime importance for determining the applicability of this method for measuring small strains (such as the elastic strains in metals, ceramics, bone samples, etc.). In this study, the strain errors in 2D-DIC measurements associated with different types of imaging systems were investigated. In-plane rigid-body-translation, experiments were used to estimate the overall amount of error in DIC displacement and strain measurements. Different types of cameras having different types of sensors and different spatial resolutions were used in the study. Also, for the same type of camera, different types of lenses were used. Results show that the DIC measurement accuracy depends on the magnitude of image displacement and that different error estimation parameters can be used for quantifying the accuracy of the measurements. Also, the effect of the lens on measurement accuracy is more pronounced than that of the camera. Furthermore, imaging conditions such as image sharpness and camera gain also affect the accuracy. Further still, the measurement accuracy was found to be influenced by the direction of translation. The results indicate that measurement error can be reduced by orienting the camera such that the major displacement direction is parallel to the width direction of the image. The experimental approach used in this study can be used for quantitatively assessing the quality of the different types of
Introduction

Nowadays, digital image correlation (DIC), sometimes referred to as the digital speckle correlation method (DSCM), has become one of the most widely used full-field optical methods for motion and deformation measurements. The DIC method was first introduced by Sutton et al. [1] in the early 1980s, and during the past three decades it underwent continuous modifications and significant improvements [2,3]. In its simpler version, DIC is used for two-dimensional in-plane measurements (2D-DIC) using a single camera. Also, photogrammetric three-dimensional measurements (3D-DIC) [4] can be made using two cameras in stereo configuration. Besides the good measurement accuracy of the DIC method, it also offers other attractive features which include a relatively simple experimental setup, simple or no specimen preparation, and low requirements for the measurement environment. All of that has made the DIC method extremely popular among the experimental mechanics community, and both 2D-DIC and 3D-DIC are being increasingly used in a very wide range of applications ranging from material science to mechanical, manufacturing, biomedical, and structural engineering [5,6].

The basic idea of DIC is to compare two digital images, acquired at different states (e.g., one before deformation and the other one after), of a surface having a random speckle pattern to determine the magnitude of displacement (or deformation) between the two images. The comparison is done by dividing the reference image into subsets of several pixels, then mathematically matching those subsets with the other image (based on intensity levels). By doing such, the new location of each subset in the second image can be determined. From that, the full-field deformation map can be obtained and the strain map can then be easily determined.

Digital particle image velocimetry (DPIV, or usually just referred to as PIV) [7–9] is a technique that is somehow similar to DIC; however, it is used in experimental fluid mechanics for obtaining the fluid velocity map within a region of interest. Small seeding particles are introduced into the flow and the kinematics of the fluid flow is estimated by tracking the motion of these particles. The particles are chosen to have a density such that they will be near naturally buoyant in the fluid in order to faithfully follow the flow. The region of interest is illuminated using a thin planar light sheet (usually a laser is used for illumination) such that the seeding particles within this light sheet will be visible due to the light scattered off their surfaces. The motion of the particles within the light sheet is captured using a digital camera where typically two exposures with a small inter-frame separation are recorded by the camera. By comparing any two consecutive digital images (using techniques quite similar to those used in DIC), the magnitude and direction of motion of the seeding particles can be determined. Finally, the magnitude of motion is divided by the inter-frame time separation between the two images such that the 2D velocity field of the flow is obtained. Though DIC and PIV are used in totally different applications, however, the two techniques are quite similar in terms of the analyses performed on the captured images. The first step in both techniques is basically the same where the motion of each of the image subsets is determined, though different correlation algorithms are typically used [3,10]. The difference between the two techniques comes in the second step. In DIC, the motion map is used to calculate the strains, whereas in PIV the motion map is divided by the inter-frame time separation to calculate the velocity. Some of the commercial software packages available nowadays are capable of performing both DIC and PIV analyses.

In principle, 2D-DIC can be used for deformation measurements under three conditions: the specimen has a planar surface, it undergoes in-plane deformations, and the camera’s optical axis is perpendicular to the specimen surface. If any of these three conditions is not reasonably satisfied, the accuracy of the measurements will be compromised. The measurement accuracy of 2D-DIC depends on several factors, which include: (a) the speckle pattern, (b) quality and perfection of the imaging system (distortions, noise, resolution, etc.), and (c) the selection of the correlation algorithm and parameters (subset and step size, correlation and shape functions, sub-pixel algorithm, etc.) [3,5]. Numerous studies have investigated the different sources of error and tried to estimate the resulting errors and to suggest remedies in some cases. Listings of the different studies can be found in Refs. [3,5,11]. Similarly, there have been several studies that addressed the accuracy of PIV measurements [10,12–14]. The majority of the studies aimed at investigating the accuracy of the DIC or PIV measurements (especially for PIV) use simulated digital images with artificial deformation patterns in order to investigate the accuracy of the different correlation algorithms and the effects of the different correlation parameters.
In one of the key papers addressing the applications of DIC in experimental mechanics, Chu et al. [15] used in-plane rigid-body-translations to demonstrate the viability of the DIC method for actual measurements. When a body undergoes a rigid-body-translation, the measured strains should theoretically be zero. Thus, any obtained strain readings will actually reflect an error in the measurement and the magnitude of the obtained strains is simply the magnitude of error. In a rigid-body-translation experiment, the camera is directed perpendicularly to a surface having a random black and while speckle pattern, and an image is captured while the surface is at its initial position, then the surface is rigidly translated in-plane by a small amount and another image is captured. This simple experiment remains to be one of the most widely used experiments for estimating the magnitude of background strain error expected in DIC strain measurements. Several other researchers have also used in-plane rigid-body-translation experiments to estimate the expected background error in DIC measurements under several experimental conditions. Haddadi et al. [16] did an experimental investigation in which they used rigid-body-translations to investigate different sources of error in 2D-DIC measurements and to estimate these errors. In that study, they estimated the strain errors associated with the magnitude of in-plane translation, subset and step sizes, in-plane rotation, speckle pattern, out-of-plane displacement, lightening, and testing environment. Sutton et al. [17] studied the effects of out-of-plane displacements and rotations (that may occur during the loading) both theoretically and experimentally using rigid-body-translations. Their results show that out-of-plane translation could lead to significant error in 2D-DIC strain measurements, especially for short camera-to-object stand-off distance. They also showed that the use of telecentric lenses minimizes the error to a manageable level. Hijazi et al. [18] also used rigid-body-translations as well as theoretical analysis to study the influence of camera non-perpendicularity on the measurement accuracy of 2D-DIC. Their results showed that small amounts of misalignments could result in relatively large errors in strain measurements, especially if the camera-to-object stand-off distance is short. They also showed that the rigid-body-translation experiments can be used for verifying the perpendicularity of the camera with respect to the surface being observed.

Researchers have also studied the influence of the lens distortions on 2D-DIC measurement accuracy for both microscopic and macroscopic levels [19–22]. In fact, the effect of the lens is more obvious for 2D-DIC than it is for 3D-DIC. This is simply due to the fact that 3D-DIC measurements involve a rigorous pre-measurement calibration procedure, which can correct lens distortions to a reasonable extent. However, 2D-DIC, on the other hand, is generally used without any pre-measurement calibration where this is regarded as one of the attractive features for this method. Pan et al. [21] investigated the 2D-DIC strain measurement error due to lens distortion both theoretically and experimentally. They proposed a simple first order lens distortion correction method to correct for radial distortion and they applied it to images recorded using a telecentric lens during in-plane rigid-body-translation experiments. Similarly, Lava et al. [22] also studied the impact of lens distortions on 2D-DIC strain measurements accuracy using in-plane rigid-body-translation experiments. They developed a correction method that corrects for radial and tangential lens distortions and they applied their calibration procedure for three lenses having different focal lengths (12, 23, and 50 mm). Rue et al. [23] studied the influence of the imaging system (camera and lens) resolution on 2D-DIC measurements. They used synthetic and experimental images with different resolutions and concluded that a careful choice for the camera/lens combination should be made for DIC measurements where one of the two components can be resolution limiting. Barranger et al. [24] investigated the effect of the camera dynamic range (i.e., gray scale bit depth) on DIC measurement accuracy using in-plane rigid-body-translation experiments. They compared three different cameras with 8-bit, 10-bit, and 12-bit dynamic range and they observed that the 8-bit camera gives higher accuracy than the ones with higher dynamic range. Tiwari et al. [25] performed an assessment for the applicability of using high-speed cameras (frame rates higher than 1000 fps) for DIC measurements. They compared two types of high-speed cameras, an ultra-high-speed multi-channel intensified CCD camera and a high-speed CMOS camera. Their results showed that the CMOS camera gives slightly better accuracy for DIC measurements and that both cameras can yield reasonably accurate strain measurement after applying a calibration procedure to remove image distortions.

From the above literature survey it is evident that there is a lack of studies that discretely investigate and quantify the effect of the imaging system components (both cameras and lenses) on 2D-DIC measurement accuracy. Comparing different types/classes of cameras and lenses that are widely used in DIC and identifying the contributions of the cameras and lenses in the measurements error is of a particular interest for many DIC users. In the work presented in this study, the strain errors in 2D-DIC measurements associated with different types of imaging systems were quantified and compared. A rigorous experimental procedure that uses in-plane rigid-body-translation experiments was used to determine the overall amount of error in DIC displacement and strain measurements in order to compare the different cases that were investigated here. Different types of cameras having different types of sensors were used in the study. Also, for the same type of camera, different types of lenses were used. In addition, different measurement error estimation parameters that are typically used for DIC accuracy measurement were compared. Furthermore, the effect of the direction of the in-plane translation on measurement error was also investigated.
Digital Imaging Devices

An image capturing device consists of an imaging optic (i.e., lens) which collects the light emanating from a target and forms an image of that target on a light sensitive medium (electronic image sensor, photographic film, etc.). An electronic image sensor consists of a matrix of capacitor-like storage elements, known as pixels, formed on an oxide-covered silicon substrate. This type of sensor, which is known as the Metal Oxide Semiconductor (MOS) sensor, relies on the photoelectric property of silicon to convert the incident light to electrical charge. As an optical image is projected on the imaging sensor, which is usually referred to as the focal plane array (FPA), the photons reaching each pixel generate an electrical charge, usually electrons, the magnitude of which is proportional to the local intensity of light on that pixel. After the sensor has been exposed to light for a period of time (the integration or exposure time), a pattern of charges is collected in the pixels (i.e., a frame is captured). The pattern of charges is then readout to a storage device, freeing the sensor to capture another image. The two most widely recognized types of MOS sensors are the complementary metal oxide semiconductor (CMOS) and the charge-coupled device (CCD). Both the CMOS and CCD sensors were invented around the same time; however, due to the more complicated design of CMOS sensors, the CCD technology developed much faster and CCD sensors became more dominant. The technological advances during the last two decades made the manufacturing of CMOS sensors more economical and thus they are increasingly being used as an alternative to CCD sensors in many scientific, industrial, and consumer cameras. The basic difference between CCD and CMOS sensors is in the way an image (i.e., the pattern of charges collected in the pixels) is transferred out of the sensor after it has been captured [26]. There are three common types of CCD sensors which are the “full frame,” the “frame transfer,” and the “interline” CCDs [27]. The main difference between these three types is in the layout of the sensor where each of the three different designs has its advantages and disadvantages. A thorough review of the different types of electronic imaging sensors can be found in Ref. [26] and a comparison of the performance of different types of imaging sensors can be found in Ref. [28].

Unlike compact digital cameras used in regular photography, which have an electronic sensor and a lens that are integrated into a single unit, imaging systems used in scientific applications usually come as two separate units: the camera body and the lens (similar to professional photography cameras). The cost of cameras used in scientific applications vary significantly according to the type of sensor, its resolution, signal to noise level, readout speed, frame rate, etc. The same also applies to lenses according to the quality of the optics and the amount of optical distortions. Consequently, the cost of imaging systems used in scientific applications could vary from less than a thousand dollars to more than $100,000 for some of the high-speed systems.

Experimental Procedures

In this study, in-plane rigid-body-translation experiments were used to investigate the strain errors in 2D-DIC measurements associated with different types of imaging systems. Different classes of cameras having different types of sensors, resolutions, and dynamic range (bit depth) were used in the study. Also, for the same type of camera, different types of lenses were used in order to investigate the effect of the lens on strain error. The different cameras and lenses that were used in this investigation along with the main specifications for each are listed in Tables 1 and 2, respectively.

As can be seen from Table 1, four different cameras were used in this investigation. The SensiCam camera is one of the high-end scientific cameras; it features a cooled FPA which provides high stability and quantum efficiency. Also, this camera is capable of operating in a special mode known as “dual-frame mode,” where it can capture a pair of images with very short inter-frame time [26], and thus it is commonly used in PIV applications. The Genie camera is one of the moderate cost CCD industrial cameras, whereas the Photon Focus camera has a CMOS sensor with higher dynamic range, and thus its price is higher. The Canon camera is one of the typical high resolution SLR digital cameras used in professional photography. Though it will be elaborated later in the results and discussion section, it is also worth mentioning here that the Canon color-SLR digital camera is in fact not comparable to the other cameras that were used here, and even it was not compared on one-to-one bases in terms of the lens (as can be seen in Table 3). However, the

<table>
<thead>
<tr>
<th>Camera</th>
<th>PCO / SensiCam QE</th>
<th>DALSA / Genie-M1410</th>
<th>Photon Focus / MV1-D1312-80</th>
<th>Canon EOS 450D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor</td>
<td>Monochrome 2/3 in. interline CCD</td>
<td>Monochrome 2/3 in. interline CCD</td>
<td>Monochrome 1 in. CMOS</td>
<td>Color 1/4 in. CMOS</td>
</tr>
<tr>
<td>Resolution</td>
<td>1376 × 1040</td>
<td>1360 × 1024</td>
<td>1312 × 1082</td>
<td>4272 × 2848</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>12-bit</td>
<td>8-bit</td>
<td>12-bit</td>
<td>24-bit (color)</td>
</tr>
<tr>
<td>Frame rate</td>
<td>10 fps</td>
<td>22 fps</td>
<td>55 fps</td>
<td>3.5 fps</td>
</tr>
<tr>
<td>Lens mount</td>
<td>C-mount</td>
<td>C-mount</td>
<td>C-mount</td>
<td>EF-mount</td>
</tr>
</tbody>
</table>

| TABLE 1 | The main specifications of the different cameras used in the experiments. |
Canon camera was included in this investigation simply because similar cameras are used by some DIC users, in addition to the fact that some DIC software companies commercialize similar cameras as an alternative for applications where DIC measurements need to be done in the field.

Table 2 lists the four different types of lenses that were used in this investigation. The Zeiss lens is a high quality lens with high aperture (i.e., a fast lens) and very low optical and chromatic aberrations. The Pentax lens is a small size, good quality lens designed for machine vision applications and it comes at a moderate price. The Nikon zoom lens is an old model lens that was designed for use with old-style film SLR cameras. The Canon zoom lens is the default lens that is supplied with the Canon EOS camera, and it can be operated in the automatic or manual focus modes.

In order to investigate the influence of the different types of cameras and lenses on DIC measurements accuracy, different combinations of the cameras and lenses were used in the experiments as listed in Table 3. As can be seen in the table, six different camera/lens combinations were used in the experiments. The SensiCam/Zeiss, Genie/Zeiss, and Photon Focus/Zeiss combinations were used to study the effect of the camera, whereas the Genie/Zeiss, Genie/Pentax, and Genie/Nikon were used to study the effect of the lens. An F-mount to C-mount adaptor was used to fit the Zeiss and Nikon lenses on the cameras. The Canon camera, on the other hand, was only used with its own lens mainly because the other lenses do not fit this camera, as it has a large size FPA. Also, the Canon camera is basically different from the other cameras due to the fact that it is a color camera and it is not very common for this type of camera to be used for DIC or PIV applications.

Besides the experiments performed using the different camera/lens combinations, two additional experiments were performed using the Genie/Zeiss combination, but under different imaging conditions. One of the two additional experiments was performed while the lens was slightly defocused to produce slightly blurred images, whereas in the other one, the camera gain was set to a high value of 11 dB (the default setting of the camera is zero gain). In the experiment with high gain setting, the intensity of illumination was reduced to compensate for the increased gain such that the average image intensity level was comparable to the other experiments.

In the experiments conducted in this study, close attention was paid to ensure that the same experimental conditions, settings, and procedures were used for all experiments in order to obtain a one-to-one comparison between the different cameras/lenses that were investigated. A picture of the experimental setup is shown in Fig. 1. In each of the experiments, the camera was mounted on a multi-axis translating/rotating stage to allow adjusting the position of the camera with respect to the target and the same multi-axis stage was used for performing the rigid-body-translation experiments. To avoid any confusion, it might be worth mentioning here that the camera was translated during the experiments rather than translating the target and that basically gives the exact same outcome (that was done simply because the same setup was also used for other experiments that are out of the scope of this paper). A printed random speckle pattern having black dots on a white background was attached to a flat plate. The average diameter for the dots of the speckle pattern was about 0.5 mm and the average dot center-to-center spacing was about 1.2 mm. The target was illuminated using an adjustable intensity illumination source coupled with a fiber-optic delivery cable. The distance between the front end of the lens and the target surface (i.e., the working distance) was set to be between 750 and 800 mm according to camera/lens combination being used. The camera-target working distance or the zoom level (for zoom lenses) was adjusted such that the field-of-view observed by the camera is 100 mm wide for all camera/lens combination that were used. Since the field-of-view width was fixed for all experiments, the image scale-factor for

### Table 2

<table>
<thead>
<tr>
<th>Lens</th>
<th>Zeiss Makro-Planar - ZF</th>
<th>Pentax CS028-M</th>
<th>Nikon Series-E Zoom Lens</th>
<th>Canon EF-S Zoom Lens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>50 mm</td>
<td>50 mm</td>
<td>75 – 150 mm</td>
<td>18 – 55 mm</td>
</tr>
<tr>
<td>Aperture</td>
<td>f/2 - 22</td>
<td>f/2.8 - 22</td>
<td>f/3.5 - 32</td>
<td>f/3.5 - 5.6</td>
</tr>
<tr>
<td>Mount</td>
<td>F-mount</td>
<td>C-mount</td>
<td>F-mount</td>
<td>EF-mount</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Camera</th>
<th>SensiCam (SC)</th>
<th>Genie (Gn)</th>
<th>Photon Focus (PhF)</th>
<th>Canon (Cn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zeiss (Zs)</td>
<td>×</td>
<td>×</td>
<td></td>
<td>×</td>
</tr>
<tr>
<td>Pentax (Pn)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nikon zoom (Nk-z)</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canon zoom (Cn-z)</td>
<td></td>
<td></td>
<td>×</td>
<td></td>
</tr>
</tbody>
</table>
the different cameras varied according to the camera resolution. The scale-factors for the different cameras used here were: 13.8 pixels/mm for SensiCam, 13.6 pixels/mm for Genie, 13.1 pixels/mm for Photon-Focus, and 42.7 pixels/mm for Canon. Also, for all camera/lens combinations, the camera position was initially adjusted to capture the exact same region of the speckle pattern.

In each of the experiments conducted using the different camera/lens combinations, great care was taken to ensure the perpendicularity of the camera with respect to the target surface to prevent any measureable errors that might be caused by camera non-perpendicularity from hindering the results of this study. An electronic level with laser pointer was used for orienting the cameras perpendicular to the target surface. The camera perpendicularity was then verified using rigid-body-translation experiments based on the procedure presented in Ref. [18] where the perpendicularity error (if any is present) was determined to be less than 0.5°. Also, care was taken to obtain similar image brightness levels (an average image brightness of about 150 on 8-bit grayscale) regardless of the camera/lens combination being used, except for the Canon camera, which was run in its “Auto” mode. The image brightness was controlled by adjusting illumination intensity while the aperture of the lenses was set at an intermediate value (around f/11). Furthermore, all the cameras that were used in this study were allowed to run for 1 h, in order to let the FPA temperature to reach steady state (such that the image noise level is stabilized), before starting to capture images for the experiments. This is particularly important for the SensiCam camera since it has a cooled FPA.

It should also be noted here that some of the cameras used here have dynamic ranges higher than 8-bit, as can be seen from Table 1. However, in order to eliminate any effect that the dynamic range might have on the results, all the images used for the experiments were recorded at 8-bit. For the color images captured by the Canon camera, image processing software was used for converting the images into 8-bit grayscale images.

The exact same rigid-body-translation experiment was repeated for all camera/lens combinations. Starting from the initial position, the camera was translated in two steps along the x-direction, then in two steps along the y-direction and two duplicate images were captured at each position. Each of the two translation steps, in both the x and y directions, was equal to 8 mm (8% of the field-of-view width). As a result, images were captured while the camera was at five different positions; a reference position (i.e., the position after the first two translation steps in the x-direction), two translation steps in the x-direction, and two translation steps in the y-direction. Fig. 2 illustrates the positions of series of images captured during the experiments relative to the fixed target. The rectangular frames shown in the figure represent the boundaries of the image in each of the five different positions, where the solid line identifies the reference position and the dashed and dotted lines identify the two translated positions along the x and y directions. The figure also shows the square region of interest used for DIC analyses (identified using dashed line).
Analyses

DIC ANALYSES

The analyses were performed using a 2D-DIC software called MatchID-2D [29]. In order to use the exact same region of the image in all DIC analyses, a square region of interest corresponding to a size of about 59 × 59 mm of the speckle pattern was located in the upper central region in the reference image, as illustrated in Fig. 2. However, the size of this region of interest in pixels was different according to the resolution of the camera being used. Also, since the cameras have different resolutions, different DIC parameters in terms of subset size and step size were used in order to have a direct one-to-one comparison between the different cameras. Table 4 lists the size of the region of interest, subset size, and step size (in pixels) used for DIC analyses for the images captured by each of the four different cameras. From the table, it can be seen that the step was taken to be about half of the subset size in all cases in order to get 50 % overlap between adjacent subsets. It also should be noticed that though different values are used for the different cameras (as seen in the table), they actually correspond to about the same physical size on the speckle pattern (59 × 59 mm region of interest, 2.25 × 2.25 mm subset size, and 1.1 mm step size) since the image scale-factors are different. The Normalized Cross-Correlation algorithm was used for the DIC analyses of all the different experiments and no image pre-filtering was performed on the images. After obtaining the displacement maps in both x and y directions (i.e., u and v), the Green-Lagrange strains were calculated using a strain window size of 7 × 7 points for all cases (that corresponds to a physical size of about 6.6 × 6.6 mm for the strain window). No further smoothing was performed on the obtained strain maps.

As mentioned earlier, two duplicate images were recorded by the camera while it was at each of the different positions during the rigid-body translation experiments. These duplicated images were correlated with each other where one of the images was taken as the reference image, while the other was taken as the deformed image. Since the two images were captured at the same position, the correlation should give zero displacement at all points in the x and y directions. However, due to the noise in the digital images which cause some random fluctuation in the image intensity values, the DIC results show very small random sub-pixel displacements at all points. The displacements obtained from such correlation represent the baseline error in DIC analysis. Also, such correlation is useful in verifying whether the correlation parameters being used are appropriate or not. For each camera/lens combination, the correlations were performed between each of the five pairs of duplicated images,

![Fig. 2](image-url)  
The positions of the series of images captured during the experiments.

<table>
<thead>
<tr>
<th>Camera</th>
<th>SensiCam</th>
<th>Genie</th>
<th>Photon Focus</th>
<th>Canon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region of interest (pixel)</td>
<td>800 × 800</td>
<td>800 × 800</td>
<td>780 × 780</td>
<td>2520 × 2520</td>
</tr>
<tr>
<td>Subset size (pixel)</td>
<td>31 × 31</td>
<td>31 × 31</td>
<td>29 × 29</td>
<td>97 × 97</td>
</tr>
<tr>
<td>Step size (pixel)</td>
<td>15</td>
<td>15</td>
<td>14</td>
<td>48</td>
</tr>
</tbody>
</table>
which correspond to the five different positions during the rigid-body translation experiment, and the results of the five correlations were averaged to get a more reliable estimate of the baseline error.

For each group of rigid-body-translation experiments corresponding to a different camera/lens combination, the reference position image was correlated with the images corresponding to each of the two translation steps in each of the two directions. Since two duplicated images were captured at each position, a total of four duplicated correlations were performed for each translation step (e.g., position 1-1 & position 2-1, position 1-1 & position 2-2, position 1-2 & position 2-1, and position 1-2 & position 2-2). The results of the four replicates were averaged in order to eliminate any variation in the results that might be caused by the instability of the image intensity values (though such differences were found to be very small).

**ERROR ANALYSES**

As mentioned earlier, the measurement accuracy of 2D-DIC depends on several factors, and numerous studies have investigated the influence of the different sources of error on the accuracy of the results. However, there is still a lack of a common or standard procedure for evaluating the accuracy of DIC measurements. Patterson et al. [30] proposed and presented standardized test material and procedure for the evaluation of optical techniques and systems used for full-field strain measurements. They demonstrated the use of their proposed approach for DIC and electronic speckle pattern interferometry (ESPI); however, that approach is still not widely accepted among DIC users. Hoult et al. [31] compared DIC strain measurements to the strains measured using strain gauges during tensile testing. They averaged the DIC strain values within a region of interest and simply compared the averaged strain value to the strain measured using strain gages to evaluate the accuracy of DIC strain measurements. However, this simple approach does not evaluate the accuracy of DIC strain maps since it is based on an averaged value for DIC strain.

In general, the vast majority of studies related to DIC accuracy or error analysis can be grouped into two broad categories according to their procedure. In the first category, synthetic images are used where an image of a speckle pattern is numerically modified. A known amount of translation, rotation, homogeneous or heterogeneous deformation, is applied to the image; then this new modified image is correlated to the reference (i.e., initial) image to determine the deformation. The results are then compared to the applied translations or deformations in order to assess their accuracy [11]. These types of studies are useful for assessing the relative accuracy of the different correlation algorithms as well as evaluating the effect of different parameters (e.g., correlation parameters, speckle pattern, image intensity, image contrast, etc.) on the accuracy of the results. However, the effect of the imaging system and its optical components on DIC accuracy is not accounted for in the error estimates obtained by such studies. The use of such synthetic images is very common for evaluating the accuracy of the different correlation algorithms in PIV analyses [10].

The second category of studies basically uses in-plane rigid-body-translation (or rotation) experiments to investigate the accuracy of DIC measurements [15–18,21–24]. In rigid-body-translation experiments, the target surface can be translated with a known magnitude and direction, but, most importantly, all points on the surface are translated by the same amount; thus, the strains are zero. The accuracy of DIC measurements can be assessed based on the displacement or strain results. When the error assessment is based on displacement, usually, the standard deviation of the obtained displacement values of all points within the region of interest is calculated. Theoretically, all points have the same displacement during rigid-body-translation and thus the standard deviation should be zero. Therefore, the value of the displacement standard deviation, usually reported in pixel units, is considered to represent the magnitude of error in the displacement measurements. This kind of displacement error estimation is usually used in PIV analyses [12,13]. On the other hand, when the error assessment is based on strains, any strains obtained from the DIC analysis reflect an error in the results since the strain should in fact be zero. The “mean” strain value \( \left( \frac{1}{N} \sum_{i} e_i \right) \) for all points within the region of interest can be calculated; however, this value will be meaningful only when the strains obtained at all points are positive or negative. This will be the case if the camera was not perpendicular to the surface or if an out-of-plane displacement occurred during the experiment [18]. Instead, the mean of the strain absolute values \( \left( \frac{1}{N} \sum_{i} |e_i| \right) \) is calculated where it can be considered as a measure of the magnitude of error in DIC strain measurements [16,18]. In addition, the standard deviation of the strain values \( \sqrt{\frac{\sum (e - \bar{e})^2}{N}} \) is also considered by many researchers as a measure of the magnitude of error in DIC strain measurements [11]. Some other researchers report the maximum strain value as a representation of the magnitude of strain error [22]; however, such an approach is rarely used since it exaggerates the magnitude of error.

**Results and Discussion**

**THE DIFFERENT DIC ERROR ESTIMATION PARAMETERS**

As mentioned in the previous section, the accuracy of DIC analyses can be assessed based on the displacements or strains obtained during rigid-body translation experiments. Three different parameters are commonly used for estimating the magnitude of error in DIC analyses and these parameters are: (1) the standard deviation of the obtained displacements, (2) the mean of the absolute values of the obtained strains, and (3) the standard deviation of the obtained strains. The standard deviation of
the obtained displacement field is commonly used for reporting the accuracy in PIV analyses since no subsequent strain calculations are done. The accuracy (or magnitude of error) in such a case is usually given in pixel units, or it can be converted to displacement units (mm or so) knowing the scale-factor of the digital images. For DIC analyses, it is more common to report the accuracy as the magnitude of error in the strain measurements (the mean of absolute values or the standard deviation). The three different error estimation parameters were calculated for all the experiments performed in this study. Fig. 3 shows a comparison of the three different DIC error estimation parameters for one of the camera/lens combinations (SC/Zs) during rigid-body-translation along the $x$-axis. As can be seen in the figure, the three different error estimation parameters show a somewhat similar increasing trend as the magnitude of the rigid-body translation increases. This trend of increasing error as the magnitude of displacement increases can be seen in all the different experiments performed in this study and it is also consistent with the results reported in literature [5,11,15,16,18]. Comparing the mean of absolute values and the standard deviation of the obtained strains, it can be seen that the standard deviation has a consistently higher magnitude. This difference is quite understandable knowing that the errors are randomly distributed, and they usually follow a normal distribution [18,22]. Thus, the standard deviation value is bigger than about 68% of the data points, whereas the mean of absolute values is practically bigger than about 50% of the data points. Thus, since the standard deviation gives a more conservative estimate of the strain error (since it has a higher value), it will be used for representing the magnitude of DIC strain measurement error for comparing the different camera/lens combinations.

Furthermore, it can also be seen from Fig. 3 that the displacement error increases at a much faster rate compared to the strain error, as the magnitude of translation increases. By inspecting the values in the figure, it can be seen that the error in the measured displacements increases from about 0.005 pixel when the magnitude of translation is zero to about 0.039 and 0.076 pixels for 8 and 16 mm of rigid-body-translation, respectively. This observation calls for caution when dealing with PIV or DIC displacement error values reported in literature where any value must be associated with its corresponding magnitude of translation. The fast increasing trend of the displacement error, as compared to the strain error, can be attributed to the fact that the strain is calculated using a relatively large strain window ($7 \times 7$ points strain window size was used in this study, whereas the smallest possible window size setting is $3 \times 3$ points). As the strain calculation window size gets larger, more displacement data points are used for calculating each strain data point, and this results in smoothing out the random error in the measured displacements and thus the magnitude of the measured strain error is reduced. However, the use of large strain windows is common in DIC analyses where some researchers report using a strain window as large as $21 \times 21$ points [21]. In general, the use of large strain window sizes reduces the strain error, but at the same time, it reduces the effective spatial resolution of the strain map and thus can hinder any high strain gradients that might be present. Pan et al. [5] recommend using large strain calculation windows for measuring homogeneous deformation. On the other hand, for inhomogeneous deformation, they generally recommend smaller strain calculation windows such that a balance can be obtained between accuracy and smoothing.

Fig. 4 provides another insight regarding PIV or DIC displacement error. The figure shows a comparison of the displacement errors (in pixels) for four different camera/lens combinations. It can be seen in the figure that the displacement error for the Canon camera is much higher than it is for all the

**FIG. 3** Comparison of the three DIC error estimation parameters (mean of absolute strain values, strain standard deviation, and displacement standard deviation) for rigid-body translation along $x$-axis (SC/Zs).

**FIG. 4** Comparison of the DIC displacement error for four different camera/lens combinations.
other cameras. In fact, there are reasons for the higher DIC measurements error associated with the Canon camera, as will be discussed in a later section. However, the large difference seen in Fig. 4 is mainly attributed to the fact that this camera has a much higher image scale-factor than the other cameras (due to its much higher digital resolution). For instance, for 16 mm displacement, the displacement error for the Photon-Focus camera is 0.18 pixels, while for the Canon camera, the error goes to 1.18 pixels (about six folds the magnitude). However, since the scale-factor for the two cameras is quite different (13.1 pixels/mm for Photon-Focus, and 42.7 pixels/mm for Canon), if we convert these displacement error values and represent them in millimeters, the difference goes down and the displacement error for the Photon-Focus becomes 0.013 mm, whereas for the Canon it becomes 0.028 mm (about two folds the magnitude, only). This observation brings to attention that reporting the displacement error in pixel units can be misleading if it is not associated with the scale-factor of the digital images. In fact, reporting the displacement error in pixels as an independent measure of accuracy (i.e., without reporting the associated scale-factor) can lead to a false impression that higher measurement accuracy can simply be attained by using higher resolution cameras.

CAMERA EFFECT ON DIC STRAIN ERROR

A comparison showing the effect of the camera on DIC strain measurement error is presented in Fig. 5. The figure shows the strain error (standard deviation) for four different cameras. For the first three cameras (SensiCam, Genie, and Photon-Focus), the same lens was used in the experiments such that a direct one-to-one comparison can be made between the cameras. However, the fourth camera (Canon) was used with the zoom lens supplied with it since the other lenses do not fit this camera. Moreover, it should be noted that the Canon camera used here is a regular photography digital-SLR color camera and it is not intended to be used for scientific applications. Nevertheless, some DIC software companies commercialize similar cameras as an alternative for field measurements. Also, some researchers report using similar SLR digital cameras in DIC measurements [16,31,32]. Thus, the Canon camera was used in this study in order to compare its performance in DIC measurements with other cameras that are typically used in DIC or PIV applications. As can be seen in the figure, for all of the four cameras, the magnitude of strain error increases as the magnitude of displacement increases. For the Canon camera, though the strain error at zero displacement is relatively small, it increases at a faster rate as the displacement increases. The high magnitude of strain error for the Canon camera relative to the other cameras is most likely due to two reasons. Firstly, and most importantly, comes the fact that this is a color camera; secondly, that a zoom lens is used with this camera. Color cameras are equipped with imaging sensors that are covered with a mosaic pattern of red, green, and blue filters. As the target translates, points on the target that were initially imaged through one of the color filters get imaged through a different color filter and so on, causing variation in the image intensity at the pixel level between successive images. Regarding the zoom lens used with the Canon camera in general, it is well known that zoom lenses produce lower quality images than fixed focal length lenses. This is because optical aberrations cannot be effectively corrected at the entire focal length range of the zoom lens. However, it will be seen from the next section that the use of zoom lens will not result in very significant increase in error such as that seen with the Canon camera. In summary, though the Canon camera digital resolution is much higher than the other cameras used in this study, the fact that it has a color sensor and the zoom lens used with it, evade any benefit of the height digital resolution, if any. In fact, Reu et al. [23] report that there is no benefit for using high resolution cameras in DIC measurements if the lens resolution is lower than that of the camera.

As mentioned earlier, the magnitude of strain error at zero displacement represents the baseline error value for any camera/lens combination. The figure shows that strain error, at zero translation, is lower for the Photon-Focus and Canon cameras than that of the other two cameras. This difference can be attributed to the fact that the Photon-Focus and Canon cameras have CMOS sensor, whereas the other two cameras have CCD sensor. As mentioned previously, the CMOS sensors represent the latest technology in imaging sensors and, in general, they provide better stability in terms of the image intensity levels as compared to CCD sensors. A study done by Hain et al. [28], which compared CCD and CMOS sensors, showed that CMOS sensors have better signal-to-noise ratio (SNR) than CCD sensors. Thus, this lower strain error level at zero displacement is simply due to the higher stability in image intensity levels resulting from the height SNR of the CMOS sensors.
Comparing the strain errors for the SensiCam and Genie cameras, it can be seen that almost no difference can be seen between the results of the two cameras. These results suggest that the relatively low cost industrial machine vision cameras may perform as good as the more expensive specialized scientific cameras such as the SensiCam (however, it should be kept in mind that the SensiCam is capable of capturing image pairs with a inter-frame time of a few microseconds, which is a capability not available in the industrial machine vision cameras). Also, it can be seen from the figure that though the strain error for the Photon-Focus camera is clearly lower than that of the SensiCam and Genie at zero displacement, it increases and becomes slightly higher than that of the two cameras when the target is translated. As discussed previously, the low strain error at zero displacement is due to the stability of the image intensity levels for the CMOS sensors. However, CMOS sensors are known to have lower fill factor compared to CCD sensors due to the presence of the digitization circuitry for each pixel on the sensor itself [26]. Thus, when translation occurs, the low fill factor of the CMOS sensor comes into effect and, apparently, it evades the advantage of the higher stability of the image intensity levels.

Finally, the results presented in Fig. 5 show that the level of the strain error obtained with three of the cameras tested here is about 0.0003 (i.e., 300 micro-strains) for 8 mm displacement (which represents 8% of the field of view width, as mentioned earlier). This level of strain error seems to be very low when compared to plastic strains in ductile materials. However, traditional strain measuring devices, such as strain gauges for instance, still provide strain measurements with higher accuracy than DIC. A comparison done by Patterson et al. [30] showed that electronic speckle pattern interferometry (ESPI) and strain gauges give higher accuracy than DIC for the measurement of elastic strains. Hild and Roux [33] demonstrated that DIC can be employed for the identification of elastic properties of low stiffness materials using a Brazilian disk made of polycarbonate polymer. In general, the DIC method is a powerful and widely accepted method for measuring strains in the plastic range of deformation (or in the elastic range for low stiffness materials such as polymers) where the strains are relatively large, but, it found very limited success for measuring small strains such as the elastic strains in stiff materials (e.g., metals and ceramics). For instance, if we take carbon steel as an example, the maximum elastic strain for most carbon steels is in the range 0.002–0.004. The results presented here imply that though the magnitude of the DIC strain error is relatively small (about 300 micro-strains), but still it is not considered that small when compared to the values of elastic strains of stiff materials (such as carbon steel for example). Based on that, it is reasonable to believe that DIC method is not a good choice for accurately measuring elastic strains in stiff materials, especially when high strain gradients are present. It might be worth mentioning here that though smaller strain error estimates might sometimes be found in literature, that does not necessarily reflect higher accuracy. It should be kept in mind that it is possible to further reduce the estimated strain error by using larger strain window size (a 7 x 7 points strain window was used in this study, as mentioned earlier) and/or employing a filter to smooth the strain map. However, doing such will result in reducing the effective resolution of the 2D strain map.

The results presented here for comparing the different cameras shows that the rigid-body-translation experiments and the approach followed in this paper can be used as a simple and direct method for evaluating and comparing the metrological performance of cameras and in particular their suitability for use in full-field deformation measurement [28,34].

**LENS EFFECT ON DIC STRAIN ERROR**

Fig. 6 shows a comparison of the DIC strain error values obtained using three different lenses (Zeiss, Pentax, and Nikon zoom) with the same camera (Genie). From the figure it can be clearly seen that there is an appreciable difference between the strain error values obtained using the three different lenses. In fact, the difference in strain errors seen here is more pronounced than that seen previously in Fig. 5 (except for the Canon camera), which indicates that the effect of the lens on DIC strain measurement accuracy can be more significant than the effect of the camera. The figure shows that the Zeiss lens gives the highest accuracy rather than the Pentax lens then the Nikon zoom lens. This trend is actually not surprising where it is consistent with the known quality of these lenses (it is even consistent with the price tags of these lenses). As in the previous figures, the usual trend of increasing strain error as the displacement increases can also be in this figure. The reason behind the difference in the magnitude of strain measurement error obtained using the different lenses can simply be attributed to the presence and severity of optical aberrations in these lenses.

![Comparison of the lens effect on DIC strain error.](image)
Different types of optical aberrations such as field curvature, coma, distortion, astigmatism, spherical, etc., can be present in lenses [35]. Lens manufacturers design their lenses in order to correct these aberrations, but the effectiveness and accuracy of these corrections vary between the different types of lenses. Fig. 7(a) and 7(b) show the DIC horizontal displacement “U” maps obtained from the images captured using the Zeiss and Pentax lenses at zero, 8, and 16 mm rigid-body-translations. From the figure, it can be seen that the “U” displacement error looks random at zero translation, while there is a clear and distinct displacement error pattern associated with each of the two lenses that can be seen at both 8 and 16 mm translations. The displacement error patterns seen in the figure reflect the optical distortion in the images formed by each of the two lenses. However, at zero translation, the lens distortion cannot be captured by DIC analysis since the image is correlated with a reference image captured while the camera is imaging the same position (two duplicate images). But nevertheless, by referring again to Fig. 6, it can be seen that the effect of the lens on DIC strain error is also present at zero translation, which is a bit surprising but still explainable. The lens effect on DIC strain error seen at zero translation is basically related to the difference in definition (i.e., sharpness) of the optical images formed by the different lenses. Such difference cannot be recognized by the naked eye in many cases; however, its effect is captured by the DIC analysis. Higher definition images of the black and white speckle pattern will show steeper change in the intensity levels of the digital images between the black and white regions. This steep change in intensity levels makes the matching of image subsets more accurate and thus improves the displacement and strain measurements accuracy.

By referring again to Fig. 7 and inspecting the shape of displacement error patterns seen at 8 and 16 mm translations for each of the two lenses, it can be seen that the shapes of the error patterns for the two lenses are quite different. The difference in the error pattern shapes indicates that different types of optical
distortions are present in the two lenses. As mentioned earlier, Pan et al. [21] and Lava et al. [22] proposed mathematical models and procedures for correcting for radial, radial and tangential lens distortions, respectively. The shape of the error pattern associated with the Zeiss lens looks somehow similar to that caused by radial distortion [21]. However, the shape of the error pattern associated with the Pentax lens looks a bit unusual and cannot be entirely explained by radial and/or tangential image distortions. This indicates that there is still a need for more advanced models for correcting the different types of lens optical distortions. In general, the results of this study are in agreement with Refs. [21,22] in substantiating the call for carrying out a calibration procedure in order to correct for the lens distortions and thus reduce the magnitude of error in 2D-DIC measurements.

**IMAGE SHARPNESS AND CAMERA GAIN EFFECTS ON DIC STRAIN ERROR**

Fig. 8 shows a comparison of the DIC strain error values obtained using one of the camera/lens combinations (Genie camera with Zeiss lens) at three different imaging conditions. In the first condition, which is the ordinary condition, the image was well focused and the camera gain setting was set to its default value of zero. In one of the other two conditions being compared here, the image was slightly defocused (by changing the focus setting of the lens), while in the other, the camera gain was set to a high value. In the condition where the gain setting was increased, the intensity of the illumination was reduced in order to maintain the average image intensity level. As expected, the results presented in the figure show that decreasing the image sharpness reduces the DIC strain measurement accuracy. Indeed, this observed relation between image sharpness and strain error, confirms the conclusion drawn in the previous section regarding the lens effect on strain error at zero translation.

The second comparison is made between the ordinary operational condition of the camera (zero gain setting) and when the gain is set to a high value. Increasing the gain setting is an option available in most digital cameras, and it is intended to compensate for low illumination intensity. The figure shows that increasing the gain increases the DIC strain error. The gain effect seen here is rather expected since both the image intensity levels and the random image noise are amplified when the gain is increased.

**DIRECTION OF TRANSLATION EFFECT ON DIC STRAIN ERROR**

As mentioned previously in the experimental procedure section, the rigid-body-translation experiments performed in this study involved translation steps in both the x- and y-directions. In general, similar trends of increasing DIC strain errors as the displacement increases can be seen for translations along the x-axis or the y-axis. Typically, researchers who use rigid-body-translation experiments to study DIC strain measurement accuracy perform the translations along one direction. Moreover, all the results presented in the previous figures are for translations along the x-axis, since it is of most interest, because it is along the width of the image, which is larger than the image height. In all the DIC analyses performed in this study, the correlations were performed for a square region of interest located at the top center of the image. By using a square region of interest, the same number of data points is present in both directions, and thus, the obtained results will have the same statistical reliability in both directions.

Fig. 9 shows a comparison of the DIC strain errors, both $\varepsilon_{xx}$ and $\varepsilon_{yy}$, associated with translations along either the x-axis or the y-axis (using the Genie camera and Zeiss lens). From the figure, it can be seen that for zero translation, the error in both $\varepsilon_{xx}$ and $\varepsilon_{yy}$ is comparable. It can also be seen that when the translation...
Concluding Remarks

Though there is no standard approach for estimating the errors in DIC measurements, the use of in-plane rigid-body-translation experiments is one of the most realistic and widely accepted methods for estimating the errors in both the displacement and strain measurements of 2D-DIC analysis. In this study, rigid-body-translation experiments were used to investigate the uncertainty of DIC displacement and strain measurements associated with different types of imaging systems. Four different cameras (with different resolutions and imaging sensor types) and four different lenses (with different optical quality and focal length) were used in this study. By doing the rigid-body-translation experiments using different camera/lens combinations, the influences of both the cameras and lenses on DIC measurements accuracy were identified, and the magnitude of errors associated with these different types of cameras and lenses was determined. The influence of different imaging conditions such as out-of-focus effects (image un-sharpness) and high camera gain were also investigated. Furthermore, the influence of the direction of translation on DIC measurements accuracy was identified. The results of this study provide a more thorough understanding of the contribution of the imaging system components in the overall DIC measurements error. It is believed that the experimental approach used in this study can be used for quantitatively assessing the accuracy and quality of the different types of cameras and lenses and to determine their suitability for use in experimental techniques such as DIC or PIV. The main conclusions of this study can be summarized in the following points.

- In-plane rigid-body-translation, experiments are useful for estimating the magnitude of baseline error in 2D-DIC measurements. Such experiments, carried under close control of the experimental conditions and correlation parameters, can be used for comparing different imaging systems and for determining the contribution of the imaging system components in the measurement error.

- Three different parameters; namely, displacement standard deviation, mean of strain absolute values, and strain standard deviation, can be used as error estimation parameters in order to determine the accuracy of DIC measurements. The displacement standard deviation is suitable for estimating the accuracy if strain measurements are not required (such as the case of PIV analysis). The strain standard deviation is more suitable than the mean of strain absolute values for estimating the DIC strain error, since it is more conservative.

- Reporting the displacement error in pixel units as an independent measure of accuracy (i.e., without the scale factor) can be misleading where it gives a false impression that using cameras with higher resolution will automatically lead to higher measurement accuracy. For numerical error estimation studies, the displacement error can
simply be reported in pixels. However, for physical studies (i.e., ones performed using actual images), the displacement error “in pixels” must be reported in conjunction with the image’s scale-factor, or alternatively, the error can be reported in displacement units (e.g., mm or μm) along with the image’s magnification level.

- The estimated strain measurement error is dependent on both the correlation and strain calculation parameters, and thus all these parameters should be carefully chosen and controlled when comparing errors associated with different imaging systems. Also, it should be noted that the estimated strain errors are directly influenced by the choice and values of these parameters.

- All experiments show that the measurement error increases as the magnitude of translation increases. Thus, when reporting the magnitude of error, it should be associated with the corresponding magnitude of rigid-body-translation.

- For the cameras tested here, the results show that the type of camera and imaging sensor do not have a significant effect on measurement accuracy, except for color SLR cameras, which are not designed nor meant to be used for this type of applications.

- The type and quality of the lens has a clear effect on measurement accuracy, and it is generally more pronounced than effect of the camera itself.

- The lowest DIC strain error estimate for the camera/lens combinations used in this study is about 300 microstrains (at 8 mm translation and 7 x 7 points strain window size), which makes the applicability of DIC for accurately measuring small elastic strains in stiff metals like steel to be somehow questionable especially in the case of non-homogeneous strain fields. A calibration procedure to correct for lens optical distortions will be necessary to improve the measurement accuracy in such cases.

- There is a clear and significant effect for the direction of translation on measurement accuracy. For the cameras tested here, the measurement error is significantly lower when the translation is along the width direction of the image.

ACKNOWLEDGMENTS
The first author is pleased to acknowledge the financial support provided by the Hashemite University for his sabbatical leave. He also acknowledges the financial support provided by the German Research Foundation (DFG) for his research visit to the Institute of Fluid Mechanics and Aerodynamics at Universität der Bundeswehr München.

References